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Major, minor, trace element, Sm–Nd and Sr isotope compositions of mafic rocks from the earliest oceanic crust of the Alpine Tethys

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Abstract

Recent isotopic and biochronologic dating has demonstrated that the Gets nappe contains remnants of the oldest part of the oceanic crust of the Alpine Tethys. The ophiolites are associated with deep sea sediments, platform carbonates and continental crustal elements suggesting a transitional environment between continental and oceanic crust. Therefore, the ophiolites from the Gets nappe provide the opportunity to assess the nature of mantle source and the magma evolution during the final rifting stage of the European lithosphere. Trace element analyses of mafic rocks can be divided into two sets: (1) P, Zr and Y contents are consistent with those of mid-ocean ridge basalts and REE patterns have a P-MORB affinity. (2) P, Zr Ti and Y contents are compatible with within-plate basalts and are characterized by REE spectra similar to that of T-MORB. Both have Nd isotopic compositions similar to those of synrift magma of the Red Sea and to the Rhine Graben. The model ages are in agreement with an LREE-enriched subcontinental mantle source derived from depleted mantle 800 to 900 Ma ago. Minor, trace element and Sm–Nd compositions suggest that these rocks are basaltic relics of an earliest stage of oceanic spreading i.e. an embryonic ocean. Comparison between REE patterns, Nd and Sr isotope compositions, isotopic and biochronologic ages from different Alpine Tethys ophiolites shows that samples with enriched LREE are from the older ophiolitic suites and are relics of the embryonic ocean floor. Later phases of ocean spreading are characterized by basalts that are depleted in LREE .

Keywords: ophiolites, geochemistry, Sm–Nd and Rb–Sr isotopes, Tethys, Prealps .

1. Introduction

The importance of Alpine ophiolites as indicators for the evolution of the Mesozoic ocean was suggested in the 19th century by NOVARESE (1895; 1899) and STEINMANN (1895; 1897; 1906). With the acceptance of the plate tectonics concept by Alpine geologists in the late sixties, the importance and significance of the ophiolites was reconsidered (e.g. LAUBSCHER, 1969; DERCOURT, 1970; DEWEY and BIRD, 1970; SMITH, 1971; DEWEY et al., 1973). Relics of oceanic crust in the Alps are usually observed as tectonically dismembered ophiolites. Ophiolites assumed to be of Piemont basin origin are scattered in several tectonic nappes. The geochemical characteristics of the mafic and ultramafic rocks of nappes are studied largely to identify the magma type, to test a petrogenetic model and thus to assign the most probable paleotectonic setting (e.g. BICKLE and PEARCE, 1975; BEARTH and STERN, 1979; VENTURELLI et al., 1981; BECCALUVA et al., 1984; BERTRAND et al., 1987; PFEIFER et al., 1989; DÜRR et al., 1993; FRISCH et al., 1994; VENTURINI et al., 1996). In the inner metamorphic zones of the western Alps studies of ophiolites have been made to constrain the regional metamorphic history and to reconstruct the paleotectonic situation (BEARTH and STERN 1971; 1979; PFEIFER et al., 1989).

Recent isotopic and biochronologic dating has demonstrated that relics of the onset of Alpine Tethys ocean spreading are present in the ophio-

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lites of the Gets nappe. Ophiolitic gabbros from the Gets nappe were dated with U–Pb on zircons at 166 ± 1 Ma and with $^{40}Ar/^{39}Ar$ on amphiboles at 165.9 ± 2.2 Ma (BILL et al., 1997). These geochronological data correspond to the age of magmatic crystallization. Radiolarian assemblages from radiolarites associated with ophiolitic rock indicate a middle Bathonian age (UAZone 6,

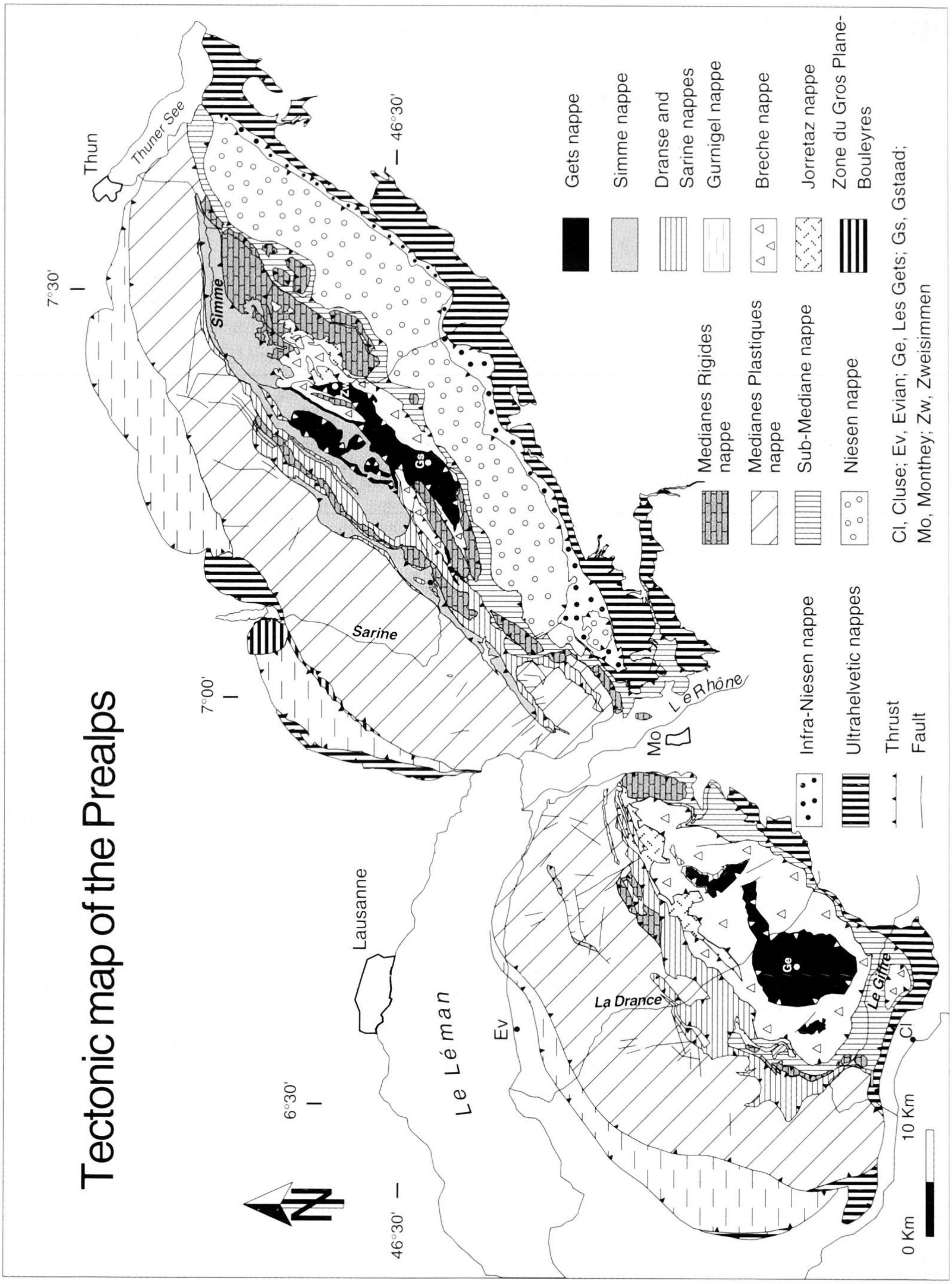

Fig. 1 Tectonic map of the Prealps.

BILL, 1998). Several geological constraints suggest that isotopic and biochronologic ages obtained in the Gets nappe date an early stage of the opening of the Alpine Tethys:

– The bluish to black color of middle Bathonian radiolarites from the Gets nappe are lithologically quite different from younger deposits of other supra-ophiolitic radiolarites in the Alps, Corsica and Apennines. This observation suggests very poorly oxygenated conditions at the sea floor, which presumably reflect a stratification of water mass during the initial stage of oceanization.

– The association of ophiolites, deep sea sediments, platform carbonates and elements of continental crust are typical of a stratigraphic sequence indicating a depositional environment at the boundary between the continental and the oceanic crust.

– The isotopic ages coincide with the end of tensile fracturing of the NW shoulder of the Piemont rift (Briançonnais s.s.). Because fracturing never affected transgressive deposits of Late Bajocian–Early Bathonian age (Middle Jurassic) (e.g. PAGE, 1969; FURRER, 1977; SEPTFONTAINE, 1983) a change in the stress state of the Briançonnais crust corresponding to the final continental break-up is indicated.

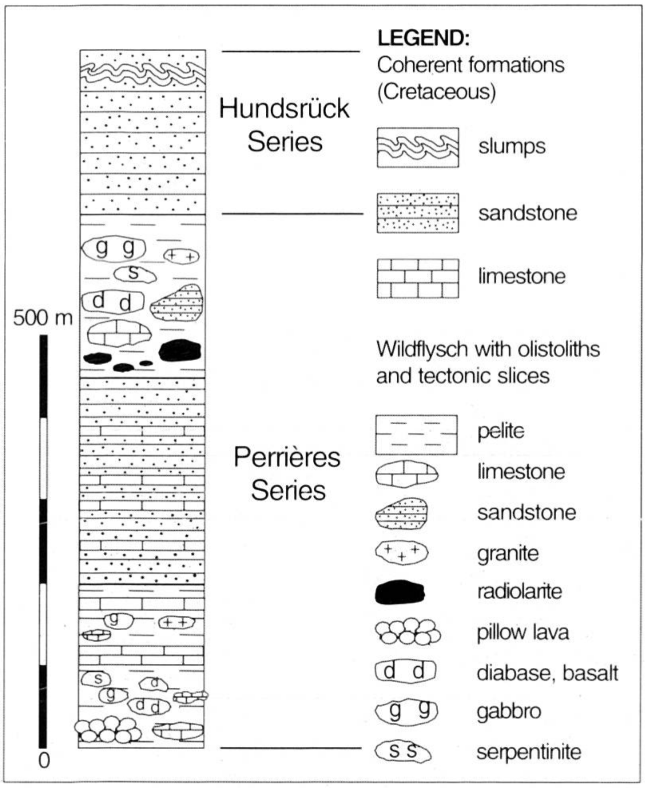

Fig. 2 Simplified stratigraphic section of the Gets nappe (modified from CARON and WEIDMANN, 1967; CARON, 1972; FLÜCK, 1973).

The Gets nappe is not affected by the metamorphism and deformation that characterizes the Penninic domain. Therefore the ophiolites of the Gets nappe provide the opportunity to assess the nature of the source, generation and evolution of the magma during the final break-up of the European lithosphere.

On the basis of stratigraphic similarities, age of ophiolitic gabbros and radiolarites, the paleogeographic origin of the Gets nappe is usually accepted as Piemontais (e.g. TRÜMPY, 1965; CARON et al., 1989; BILL et al., 1997).

To contribute to a better understanding of the evolution of the Alpine Tethys ocean we have made both chemical and Nd- and Sr-isotope measurements of mafic rocks from the Gets nappe. We discuss correlations with other nappes bearing ophiolites and propose a paleotectonic setting of the Gets nappe.

2. Geological setting

The Gets nappe extends from Gets (French Prealps) to Zweisimmen (Swiss Prealps) (Fig. 1). It forms the tectonically highest unit of the Prealps nappe system, a thick pile of decollement cover nappes in the exterior part of the Western Alps. This nappe consists of two series (Fig. 2):

(i) The Perrières series at the base of the Gets nappe is essentially a chaotic and composite wildflysch. Argillites and shaly arenite encompass abundant blocks and lenses of oceanic and continental origin. The blocks and lenses are composed of ophiolites (serpentinites, basalts and more rarely gabbros and ophicalcites), deep-water sediments (radiolarites, pelagic limestones and manganiferous shales), Paleozoic granites and clastic and platform carbonates. This association of rocks is a typical "ophiolitic mélange" in the sense of GANSSER (1974). Such associations play a prominent role in several Tethyan Belts where they are related to oceanic sutures at convergent plate boundaries. The base of the wildflysch is dated with planktonic foraminifera at Neocomian. For detailed field descriptions and stratigraphic or petrographic studies of the wildflysch and its various lenses, see JAFFÉ (1955), SALIMI (1965), ELTER et al. (1966), CARON and WEIDMANN (1967), and BERTRAND (1970).

(ii) The Perrières Series is overlain by the Hundsrück series, which consists mainly of arenite, shaly interlayers and pebbly sandstones interpreted as a coarse clastic turbiditic sequence (FLÜCK, 1973; CARON et al., 1989). The Hundsrück Flysch is dated with nannofossils and planktonic foraminifera at late Coniacian to Early Campanian (upper Cretaceous, FLÜCK, 1973).

Preliminary measurements of illite crystallinity (BILL, 1998) display a metamorphic gradient. The interior part of the Gets nappe was subjected to anchizone metamorphic conditions (200 to 300 °C) and the exterior part is diagentically altered (100 to 200 °C).

3. Occurrence and petrography of mafic rocks in the Gets nappe

3.1. BASALTS

Basaltic rocks of the Gets nappe crop out in the basal wildflysch (Perrières Series) of the Gets nappe as:

– Fragments, lenses and blocks from one centimeter to hundreds of meters on a side in a pelitic matrix. Locally they are associated with ultramafic, granitic, ophicalcite and sedimentary rocks.

– Dikes intruding granitic blocks.

– Components of polymict breccia blocks.

The most common basaltic rocks found in the Gets nappe are characterized by an intersertal texture where interstices between laths of plagioclase and sometimes pyroxene (often chloritized) are occupied by fine-grained chlorite which may represent an altered glass. Rare pseudomorphs after olivine are observed. Basaltic rocks forming pillow lava have an arborescent texture in the center of the pillow and a spherulitic texture formed by plagioclases at the margin.

Basaltic rock components in the breccia are observed associated with fragments of ultramafic rocks and/or granitic, metamorphic and sedimentary rocks in different kinds of matrices:

– Polymict breccias are made of mafic, granitic, metamorphic and sedimentary components in a matrix of millimeter-sized grains. The mafic rocks contain albite and chlorite and have intersertal spherulitic and sometimes porphyritic textures. The grains of the matrix were formed by the destruction of various components of the breccia.

– Polymict breccias contain basaltic components occasionally associated with granitic and coarse grained crinoidal limestone fragments. The mafic rocks contain plagioclases and chlorite and sometimes pyroxene and have intersertal, branching or spherulitic textures. The components of the breccia are contained in a hematitic matrix.

– Polymict breccias with basaltic components in an argillaceous matrix are often associated with granitic and sedimentary fragments. Mafic rocks contain plagioclases and chlorite and also have intersertal and branching textures.

3.2. GABBROS

Outcrops of gabbro are rare in the Gets nappe. Such rocks were sampled in the French Prealps near the Col des Gets. Gabbros are found as blocks and are associated with serpentinite and radiolarites lenses. Two different kinds of textures characterize these gabbos:

– Sample MR3 has a pegmatitic texture with cm long crystals of plagioclase and euhedral pale-green to brownish amphibole. The amphibole is a Ti-rich ferroan pargasite. The large size, the euhedral shape of the amphiboles, the absence of pyroxene relics, chemical zoning, and the pegmatitic nature of the rocks all suggest that the amphibole crystallized from a rather evolved hydrous melt. Moreover the pargasitic composition, its high Ti content (0.4 per formula unit), validate a late-magmatic/deuteric origin (e.g. RAASE, 1974; GIRARDEAU and MÉVEL, 1982). The gabbros are strongly sheared and are characterized by preferred mineral orientation, deformation and synkinematical recrystallization of plagioclase into small polygonal grains, and pargasites with rare shear bands that include small angular grains of identical composition.

– Gabbro RB3 is coarse-grained with a subophitic texture. It consists of euhedral and sericitized plagioclase, Ti-bearing augitic clinopyroxene (sometimes with a high-Ti pargasitic rim) and includes a few resorbed olivine crystals.

4. Geochemistry

4.1. ANALYTICAL METHODS

Bulk rock analyses were obtained by X-ray fluorescence (XRF) methods using a Philips PW 1400 spectrometer (Sc–Mo tube). Major and minor elements were measured on glass beads and common trace elements on powder pellets at the Centre d'Analyse minérale, Lausanne. The spectrometer calibration was based on international standards from the U.S. Geological Survey, ANRT-France and NIM-South Africa.

Rare Earth Elements (REE) of eighteen samples were analysed by a VG PlasmaQuad Inductively Coupled Plasma/Mass Spectrometer. A Na_2O_2 fusion technique was used to ensure total dissolution of the sample. Samples were measured in the XRAL Laboratories, Toronto, Canada. Isotopic measurements were carried out at the Laboratory for Isotope Geology at the Mineralogy and Petrography Institute, University of Bern, Switzerland. For Sm and Nd analyses samples were spiked ($^{149}Sm/^{150}Nd$) and dissolved in Teflon screwtop containers. The chemical separation of Sm and Nd was that of NÄGLER et al. (1995). Nd isotope ratios were measured as NdO^+ on a Re filament in a VG sector mass spectrometer in single collector mode. Nd isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. The fractionation correction followed the exponential law. Runs of La Jolla Nd standard yielded a value of 0.522869 ± 28 (2σ; n = 6) during the course of this work. Sm isotope analyses were performed on an AVCO single collector mass spectrometer. Standard ion-exchange techniques were used to extract Sr from mafic rocks. Sr was loaded onto a Ta filament by using a solution of H_3PO_4 and isotopic ratios were measured in single collector dynamic mode on a VG mass spectrometer. The SRM standard was measured at a value of 0.710223 ± 11 (2σ; n = 4).

4.2. MAJOR ELEMENT COMPOSITIONS

Chemical compositions of the diabases and gabbros of the Gets nappe are reported in table 1. For oceanic magmatic rocks affected by an orogenesis, it is a prerequiste to test possible element mobility to constrain the original magmatic signal. Most of the samples are spilitized. For the basalts loss on ignition varied between 3.89 and 12.32. A large amount of Na_2O linked with a high loss on ignition (LOI) characterises most of the samples. Sample ER1 has a particularly high LOI and lacks K_2O and Na_2O. This observation suggests a chemical metasomatic change in connection with a hydration event. Therefore the high mobility of alkalies does not permit the use of TAS or CIPW classifications.

The mobility of the major elements was tested against REE which are known for their low mobility. A good correlation with REE is measured for TiO_2 and P_2O_5. Moreover the $^{147}Sm/^{144}Nd$ ratios show the same trend for TiO_2 and P_2O_5. Fe_2O_3 shows a slight mobility. The concentrations of other major elements are not correlated with concentrations of REE implying variable mobility. The major elements of basalts show a bimodal distribution of Fe_2O_3, MgO, TiO_2 and P_2O_5. Al_2O_3 and TiO_2 contents have a composition close to that of basaltic liquid.

Different gabbros have different chemical compositions. Samples MR1 and MR3 with alkali contents of 5.4–5.72 fall in the field of gabbros with normative olivine and nepheline. Data for sample RB3 with 52.2% SiO_2 and 6.6% alkalies plot in the field of olivine gabbros and the rock contains normative olivine and hypersthene. Ti, Zr, and P elements have a tholeiitic affinity (FLOYD and WINCHESTER, 1975).

4.3. TRACE ELEMENT COMPOSITIONS

The mobility of trace elements was also tested against REE. A good correlation with REE was observed for Zr and Y suggesting that these elements were relatively immobile. On the same basis, Cr and V were slightly mobile.

The basalts of the Gets nappe exhibit a bimodal distribution of Zr, Y, Cr and trace element contents (Tab. 1):

- The first group is characterized by Zr < 130 ppm, Y< 20 ppm and Cr > 140 ppm.
- The second set is characterized by Zr > 200 ppm, Y > 20 ppm and Cr < 140 ppm.

The Ti–Zr plot (PEARCE et al., 1981) allows a distinction to be made between intermediate and evolved melts (Fig. 3). In fact crystallization of a Ti-bearing oxide provoked Ti depletion in the magma which is correlated with an increase in SiO_2 and Zr. Thus, only points plotting above the line separating basic and evolved melts should be used to discriminate basalts (PEARCE et al., 1981). Moreover this plot separates the basic and evolved rock into volcanic arc basalt (VAB) and within-plate basalt (WPB). Two groups of samples can be distinguished in this plot. A first set is characterized by a clearly basic composition and forms a group within mid-ocean ridge basalt (MORB) field overlapping the volcanic VAB field. The other set is included in the WPB field.

The Cr–Y plot (Fig. 4) proposed by PEARCE (1980) is particularly useful because neither Y nor Cr participate in the processes that cause mantle heterogeneity. Moreover this plot separates island arc tholeiite (IAT) from WPB and MORB.

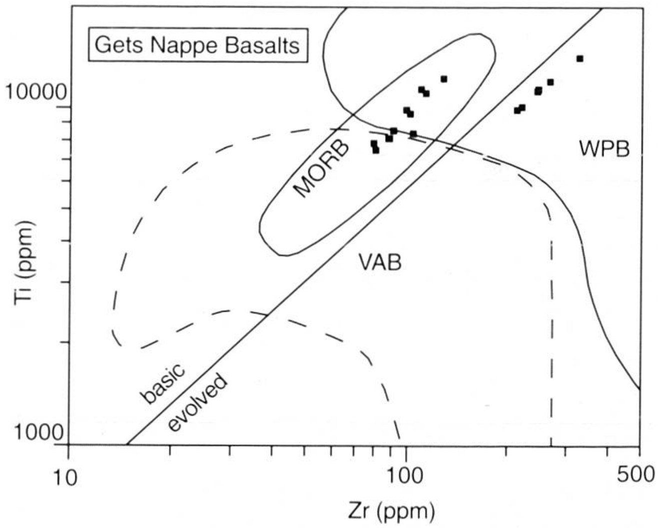

Fig. 3 Ti–Zr covariation diagram (PEARCE, 1981) showing the fields of MORB: mid-ocean ridge basalt; VAB: volcanic-arc basalt; WPB: within-plate basalt. The straight line separates basic from evolved melts.

Again, the basaltic rocks of the Gets nappe exhibit a bimodal distribution, with one group characterized by a high concentration of compatible Cr and low concentration of incompatible Y. This chemical composition suggests a relatively primitive magma that has not undergone strong fractionation of olivine, Cr-spinel and/or pyroxenes (PEARCE, 1980; 1982). This group exhibits an IAT affinity and coincides with the group characterized by Zr content < 200 ppm exhibiting Zr–Ti affinity with MORB (Fig. 3). The second group is marked by lower Cr contents and higher Y contents. This group overlaps the MORB-WPB fields and has a Zr–Ti affinity with WPB mid-ocean ridge basalt. The two clusters are marked by gabbros with low Cr concentrations suggesting that the magmas underwent fractionation of Cr-bearing minerals.

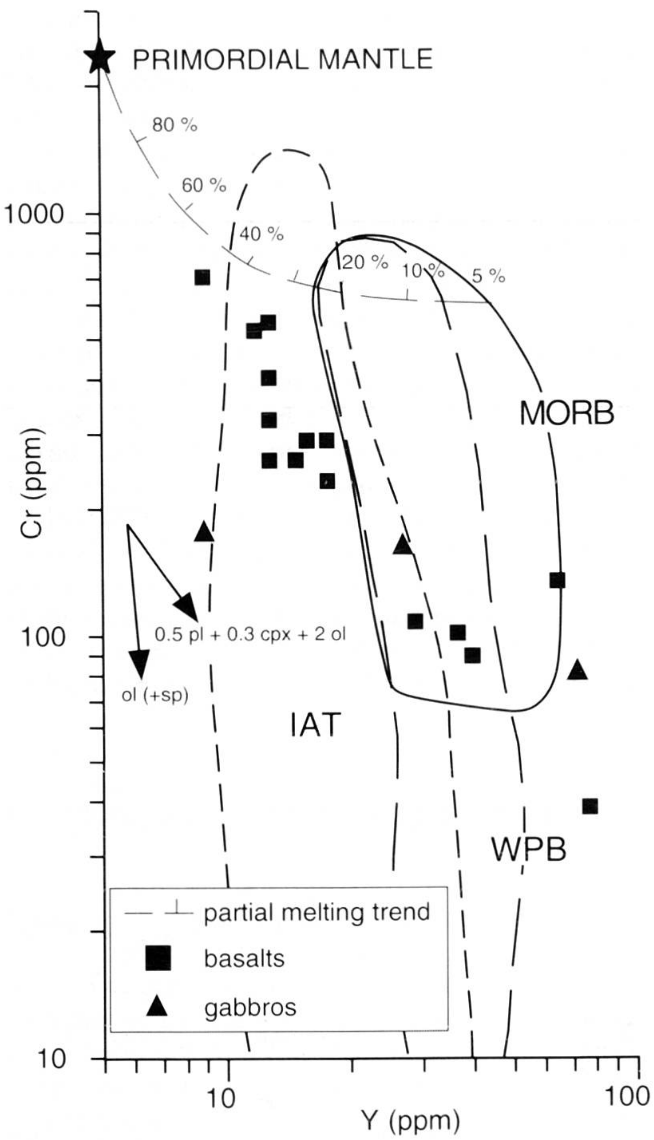

Fig. 4 Cr–Y diagram after PEARCE (1980). The dashed line shows the partial melting degree of primordial mantle source magma (C_3 chondrite). Arrows indicate the evolution of the Cr–Y composition of the magma during the fractional crystallization (ol: olivine and Cr-spinel; cpx: clinopyroxene; pl: plagioclases) after HÖCK and MILLER (1987). Discrimination fields are IAT: islands arc tholeiite; MORB: mid-ocean ridge basalt; WPB: within plate basalt; squares are basalts, triangles are gabbros.

Multi-element diagrams normalized to N-type MORB (PEARCE, 1982) also define two different populations (Fig. 5):

– in figures 5A and 5C, the basalts are characterized by a depletion in K in the first part of the curve, probably linked to alteration. The pattern of the second part of the curve is flat, with normalized concentrations of elements from Ce to Ti close to unity. Y and Yb display a negative anomaly. Cr concentrations are close to unity and the signal of Ni is ubiquitous. The pattern of the curves suggests a T-MORB affinity.

– in figure 5B, the second part of the curve for basalts is characterized by a relative enrichment in P and Zr. Sm, Ti, Y and Yb are close to unity and Cr and Ni show a negative anomaly. A basaltic dike (sample P4) intruding granite shows an identical pattern but is characterized by higher K, Rb, Ce and P values and more pronounced Cr and Ni negative anomalies. The pattern of the curves suggest a WPB affinity (PEARCE, 1982).

Gabbro samples exhibit different patterns (Fig. 5D). Samples MR1 and MR3 are characterized by a lower content of elements with low ionic potential probably corresponding to partial leaching. MR1 and MR3 gabbros are enriched in Zr. The pattern for elements from Zr to Yb of sample MR3 is relatively flat. The chemical pattern of these rocks has a transitional character.

Rare Earth Element (REE) compositions normalized to chondrites (SUN and MCDONOUGH, 1989) show two principal patterns (Fig. 6). One set (Figs 6A, C) is characterized by an increasing enrichment from heavy REE to light REE. $(La/Sm)_N$ ratios range from 1.7 to 2.3. Samples OES1 and ER1 have a small negative Eu anomaly suggesting plagioclase fractionation. The parallel patterns of REE are consistent with a common magmatic source. The light-REE enrichment suggests a light-REE enriched source or small degrees of partial melting. Such REE patterns are characteristic of plume type MORB composition (SUN et al., 1979). The other set (Fig. 6B) exhibits a "horizontal" pattern suggesting a transitional MORB composition. $(La/Sm)_N$ ratios range from 1 to 1.5.

Gabbros (Fig. 6D) show relatively parallel patterns with a depletion in heavy REE. Gabbro sample MR3 is characterized by a negative Eu anomaly which could suggest plagioclase fractionation during the evolution of magma.

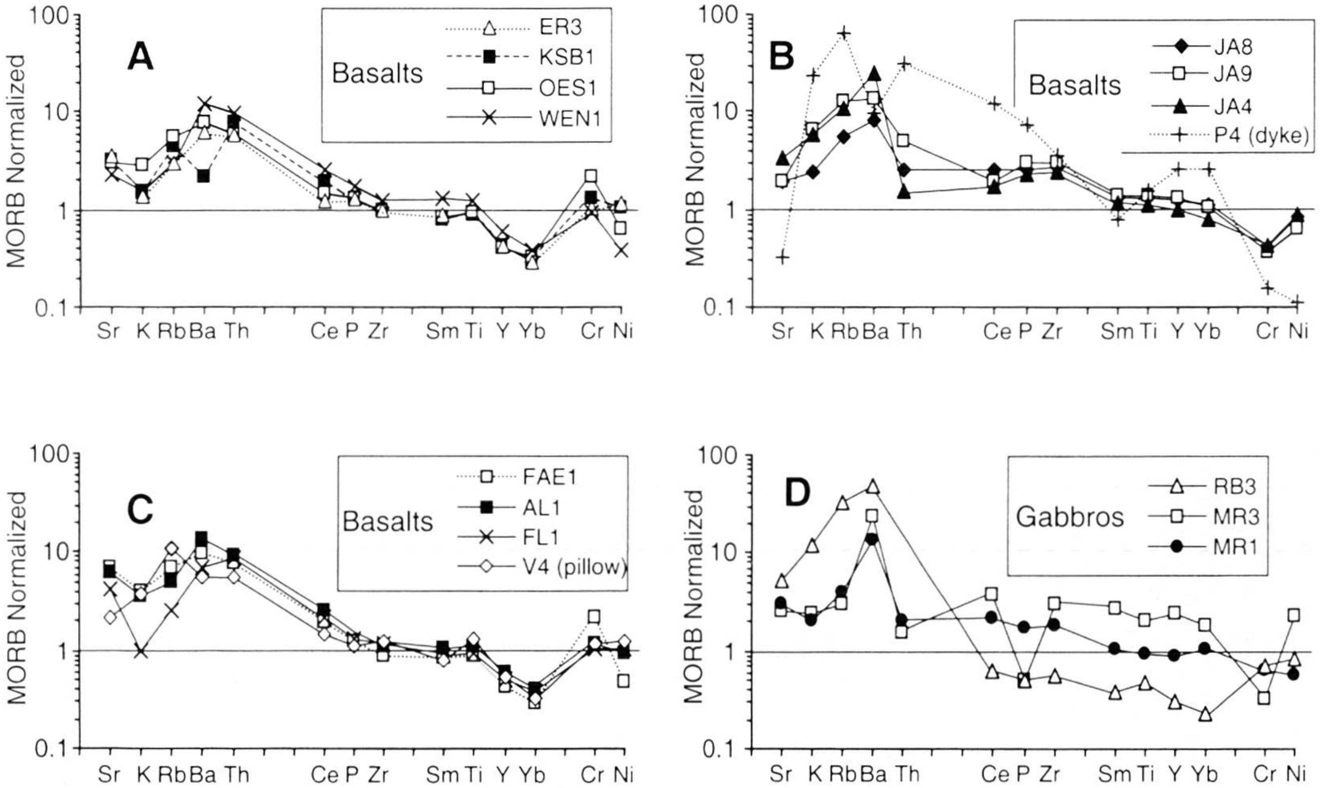

Fig. 5 MORB normalized trace element patterns for mafic rocks of the Gets nappe. Normalization values after PEARCE (1982). A, B and C are basalts; D are gabbros.

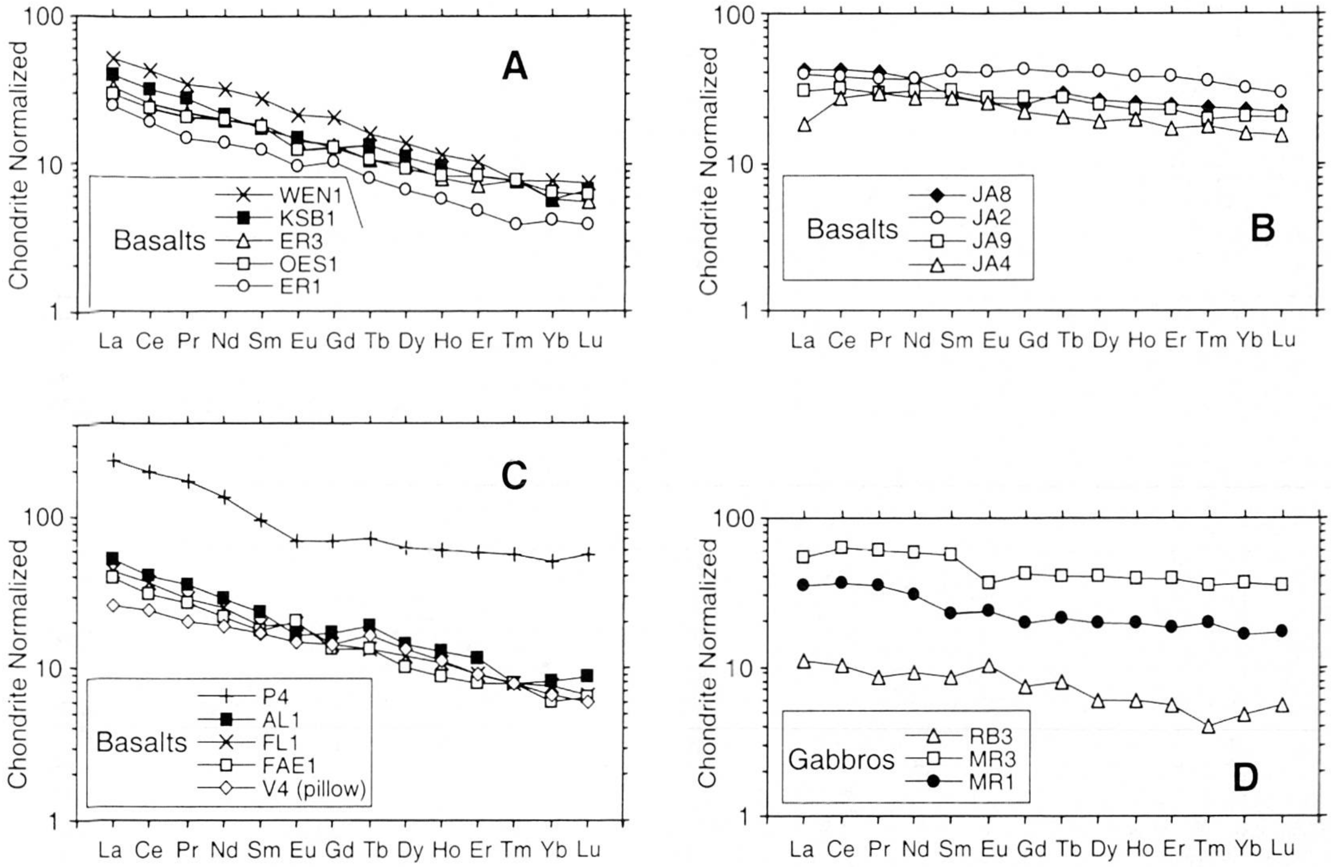

Fig. 6 Chondrite normalized REE patterns for basalts and gabbros of the Gets nappe. Normalized values after SUN and MCDONOUGH (1989). A, B and C are basalts; D are gabbros.

Tab. 1 Chemical composition of mafic rocks of the Gets nappe.

	Basalts																Gabbros			Dike	Pillow
Sample	ER1	ER3	OES1	OEN1	FAE1	KSB1	WEN1	WES1	AL1	MO2	FL1	JA2	JA4	JA6	JA8	JA9	RB3	MR1	MR3	P4	V4
SiO_2 (wt%)	49.23	51.22	54.38	52.83	47.99	48.96	52.11	50.29	50.85	47.77	52.21	47.89	52.86	51.58	51.97	48.26	52.21	49.77	47.59	52.74	54.02
TiO_2	0.78	1.36	1.43	2.05	1.31	1.36	1.85	1.65	1.61	1.25	1.41	1.88	1.65	1.69	1.90	2.01	0.70	1.42	3.02	2.36	1.90
Al_2O_3	8.20	16.45	17.37	15.60	15.87	17.52	16.71	15.74	16.86	15.82	16.16	16.84	18.55	17.57	17.79	17.90	20.14	17.66	15.54	15.29	18.26
Fe_2O_3	8.46	8.91	8.12	10.55	6.69	8.74	10.10	9.28	9.53	9.64	8.72	6.67	7.11	8.19	8.40	9.21	4.22	6.91	10.26	10.75	5.94
MnO	0.12	0.07	0.06	0.09	0.12	0.13	0.09	0.12	0.07	0.08	0.11	0.14	0.12	0.12	0.11	0.09	0.10	0.11	0.16	0.08	0.08
MgO	9.91	9.83	6.52	6.24	4.78	8.34	7.01	6.93	6.44	13.84	7.73	9.05	4.40	4.20	4.17	5.56	7.20	9.50	8.63	5.91	3.41
CaO	9.82	1.05	0.83	1.84	7.57	2.15	1.07	3.84	2.68	0.68	2.22	3.65	2.20	3.31	2.69	3.31	4.94	2.68	5.68	1.55	3.05
Na_2O	0.00	4.48	5.61	4.79	5.70	5.64	5.84	5.39	5.16	3.43	5.36	5.99	7.01	7.03	7.23	5.88	4.82	5.42	5.04	1.80	7.64
K_2O	0.00	0.21	0.42	0.14	0.58	0.23	0.23	0.27	0.54	0.10	0.15	0.06	0.86	0.56	0.35	0.96	1.78	0.30	0.36	3.54	0.57
P_2O_5	0.10	0.16	0.16	0.24	0.15	0.15	0.21	0.19	0.18	0.15	0.16	0.33	0.27	0.28	0.31	0.35	0.06	0.21	0.06	0.88	0.13
LOI	12.33	5.40	4.19	4.92	8.41	5.89	3.89	5.62	5.32	6.26	4.86	6.69	4.07	4.62	4.27	5.56	2.99	5.18	2.82	4.26	4.30
Total	98.95	99.14	99.09	99.29	99.17	99.11	99.11	99.32	99.24	99.02	99.09	99.19	99.10	99.15	99.19	99.09	99.16	99.16	99.16	99.16	99.30
Nb (ppm)	< 5	< 5	< 5	8	< 5	< 5	7	6	5	< 5	5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	33	10	< 5
Zr	51	88	90	127	79	87	112	98	101	80	103	242	211	218	245	265	50	161	276	323	109
Sr	313	421	350	313	839	377	267	505	747	172	510	156	399	257	234	232	613	357	297	39	252
Rb	< 1	6	11	5	14	9	6	8	10	3	5	< 1	22	16	11	26	66	8	6	125	22
Ga	7	14	13	19	13	14	17	16	16	13	15	11	15	15	13	14	7	9	12	17	15
Zn	81	84	81	109	74	71	83	67	98	80	78	72	83	90	84	92	30	53	75	102	99
Cu	112	37	42	< 4	33	32	< 4	< 4	36	42	43	31	31	< 4	28	< 4	< 4	46	47	< 4	68
Ni	717	106	58	8	42	91	35	37	83	228	94	158	80	46	76	56	74	50	204	10	108
Co	70	47	40	49	33	43	48	42	49	51	62	34	35	39	37	35	27	32	45	39	46
Cr	712	260	521	47	547	324	234	228	288	410	260	135	107	138	102	90	174	161	81	39	290
V	96	152	150	179	163	155	193	185	195	131	128	127	153	163	145	187	114	163	324	239	213
Nb	10	3	6	12	6	8	14	8	7	5	5	20	12	15	21	14	< 3	9	29	61	8
Ba	< 3	121	156	77	194	43	242	155	263	37	139	33	493	239	165	269	955	268	478	195	109
S	90	117	162	84	1021	89	55	91	73	101	104	0	23	26	87	30	37	40	40	56	139
Y	9	13	12		13	13	18		18	13	15	65	29		37	40	9	27	72	77	16
La	6.0	7.8	7.1		9.1	9.4	12.5		12.1	8.6	10.4	9.2	6.4		10.0	7.1	2.6	8.2	12.8	55.7	6.0
Ce	12.0	16.0	14.6		18.9	19.5	26.0		24.7	18.5	21.9	22.8	17.6		25.9	18.9	6.2	21.9	37.7	119	14.4
Pr	1.4	2.1	2.0		2.5	2.6	3.3		3.3	2.4	2.7	3.4	2.6		3.8	2.8	0.8	3.3	5.7	16.1	1.9
Nd	6.4	9.5	9.2		10.2	10.1	14.8		13.2	10.2	11.4	17.2	12.5		17.1	14.3	4.2	13.9	27.0	62.6	8.8
Sm	1.9	2.9	2.7		2.7	2.6	4.3		3.5	2.5	2.9	6.2	3.8		4.3	4.6	1.3	3.5	8.6	14.5	2.6
Eu	0.56	0.85	0.73		1.18	0.87	1.26		0.95	0.87	1.13	2.32	1.25		1.45	1.58	0.59	1.38	2.08	3.19	0.84
Gd	2.1	2.8	2.7		2.7	2.7	4.2		3.5	2.6	2.9	8.6	4.2		5.0	5.6	1.5	4.0	8.6	13.9	2.9
Tb	0.3	0.4	0.4		0.5	0.5	0.6		0.7	0.5	0.5	1.5	0.7		1.1	1.0	0.3	0.8	1.5	2.6	0.6
Dy	1.7	2.5	2.4		2.5	2.8	3.5		3.6	2.7	3.0	10.3	4.9		6.6	6.2	1.5	4.9	10.2	15.4	3.4
Ho	0.33	0.45	0.47		0.49	0.55	0.65		0.72	0.51	0.60	2.15	0.97		1.42	1.29	0.34	1.10	2.18	3.32	0.63
Er	0.8	1.2	1.4		1.3	1.4	1.7		1.9	1.4	1.5	6.3	2.9		4.0	3.7	0.9	3.0	6.4	9.4	1.5
Tm	0.1	0.2	0.2		0.2	0.2	0.2		0.2	0.2	0.2	0.9	0.4		0.6	0.5	0.1	0.5	0.9	1.4	0.2

4.4. ISOTOPIC COMPOSITIONS

Nd and Sr isotope analyses of basalts covering the two different sets of chemical compositions are given in table 2. The two chemical sets are not characterized by different isotopic signals. $\varepsilon_{Nd(T)}$ is calculated by using 166 ± 1 Ma, the U–Pb zircon age of gabbros from the Gets nappe (BILL et al., 1997). Apparent $\varepsilon_{Nd(T)}$ values of the mafic rocks vary only slightly from 4.4 to 5.9 except for sample JA2 which has a lower value. Strontium isotope ratios are high and vary widely from 0.7071 to 0.7084. The high $^{87}Sr/^{86}Sr$ ratios suggest interaction of mafic rocks with fluid-bearing continental crust. This observation is consistent with the high loss on ignition and partial leaching of alkalies. The $^{87}Sr/^{86}Sr$ signal can be explained by two different episodes of fluid-rock interaction:

(a) $^{87}Sr/^{86}Sr > 0.708$ can not be explained by interaction with middle Jurassic or Cretaceous sea water, which had an average $^{87}Sr/^{86}Sr < 0.708$ (BURKE et al., 1982; VEIZER 1997; VEIZER et al., 1997). However, isotopic and biochronologic data have demonstrated that oceanic crust is present in the ophiolite suite of the Gets nappe (BILL et al., 1997; BILL, 1998). Consequently the $^{87}Sr/^{86}Sr$ ratio can be explained by interaction with water of a small basin not connected to marine water from the Tethys and contaminated by input of radiogenic Sr from an old shield (such as Western Gondwana and the Laurasian continental crust).

(b) The mafic rocks of the Gets nappe are embedded in a chaotic wildflysch representing an ophiolitic melange typical of an accretionary prism. The high $^{87}Sr/^{86}Sr$ ratio can be explained by water-rock interaction in the accretionary prism during subduction. Such a mechanism is in agreement with illite crystallinity and data for associated clay phases which indicate an abnormal paleothermal gradient in the Gets nappe. The paleothermal gradient is explained by warm fluid flow through the thrust or through a zone with high porosity (BILL, 1998).

$\varepsilon_{Nd(T)}$ values (Fig. 7) suggest that basalts of the Gets nappe are similar to the Red Sea and the Rhine Graben rifting magmas (CHAZOT and BERTRAND, 1993; ALIBERT et al., 1983; WÖRNER et al., 1986). Samples having high $\varepsilon_{Nd(T)}$ values (> 4.4) preclude important crustal contamination. Sample JA 2, having $\varepsilon_{Nd(T)} < 0$, suggests important fluid-rock interaction or contamination by continental crust. The important fluid-rock interaction of sample JA 2 is consistent with partial leaching of alkalies and the high loss on ignition. In the ε_{Nd} vs time diagram (Fig. 8), the basalts defined a linear array with $^{147}Sm/^{144}Nd$ slopes ranging from 0.156 to 0.179. The intersection with the depleted mantle evolutionary path (DM model of NÄGLER and KRAMERS, 1998) suggests that mafic rocks of the Gets nappe were derived from a light-REE enriched source separated 800 to 900 Ma ago. The scatter of $\varepsilon_{Nd(T)}$ values at time 0 can be explained by a heterogenous source and/or by contamination. These results are in remarkable agreement with those of mafic and ultramafic rocks from the Alpine belt and adjacent region in Central Europe (STILLE and SCHALTEGGER, 1996). The ages of these rocks range from 1000 to 17 Ma. These authors suggest the presence of a Central European Enriched Mantle (CEEM) which decoupled from the convecting mantle 700 to 900 Ma ago.

5. Discussion

5.1. MAGMA TYPE AND PALEOTECTONIC SETTING

Chemical features of the mafic rocks of the Gets nappe allow them to be separated into two groups:

(1) Mafic rocks characterized by a Y concentration lower than 15 ppm, Zr lower than 170 ppm and Cr higher than 170 ppm. The low concentra-

Tab. 2 Sr and Nd isotopic composition of basalts of the Gets nappe.

Sample	ER3	OES1	WEN1	JA2	JA4	JA9
Sm (ppm)	3.43	3.73	4.59	7.08	4.42	5.43
Nd (ppm)	12.92	13.89	17.51	20.77	15.67	18.34
$^{147}Sm/^{144}Nd$	0.1604	0.1625	0.1585	0.2060	0.1704	0.1790
$^{143}Nd/^{144}Nd$	0.51285 ± 21	0.51283 ± 17	0.51284 ± 15	0.51264 ± 25	0.512890 ± 19	0.51292 ± 26
$\varepsilon Nd(0)$	4.1	3.7	4.0	0.0	5.0	5.5
$\varepsilon Nd_{(166\ Ma)}$	4.9	4.4	4.8	–0.2	5.6	5.9
T DM *	0.86	0.96	0.84	9.54	0.88	0.99
$^{87}Rb/^{86}Sr$	0.026	0.059	0.040	0.024	0.139	0.284
$^{87}Sr/^{86}Sr_0$	0.708454 ± 28	0.708221 ± 43	0.707424 ± 23	0.708354 ± 16	0.707491 ± 49	0.707117 ± 14
$^{87}Sr/^{86}Sr_{(166\ Ma)}$	0.7084	0.7081	0.7073	0.7083	0.7072	0.7064

* after NÄGLER and KRAMERS (1998)

tion of incompatible Y and high concentration of compatible Cr suggests a relatively primitive magma. Their high concentration in light REE $(La/Sm)_N > 1.5$ suggests a P-MORB affinity. This group is compatible with a source enriched in light REE.

(2) Mafic rocks with a within plate basalt (WPB) affinity (Fig. 3) are characterized by Zr content > 200 ppm, Y concentration > 20 ppm and Cr < 170 ppm. REE patterns show $(La/Sm)_N < 1.5$ and suggest an affinity to transitional mid-ocean ridge basalts. In the field these rocks intrude granites or formed breccia associated with granitic, metamorphic and sedimentary elements.

The chemical features of these two groups are consistent with those of basalts from the onset of oceanic spreading, i.e. an embryonic ocean. The chemical features also suggest that these two groups belong to different magmatic events or stages of magmatic differentiation. Morever,

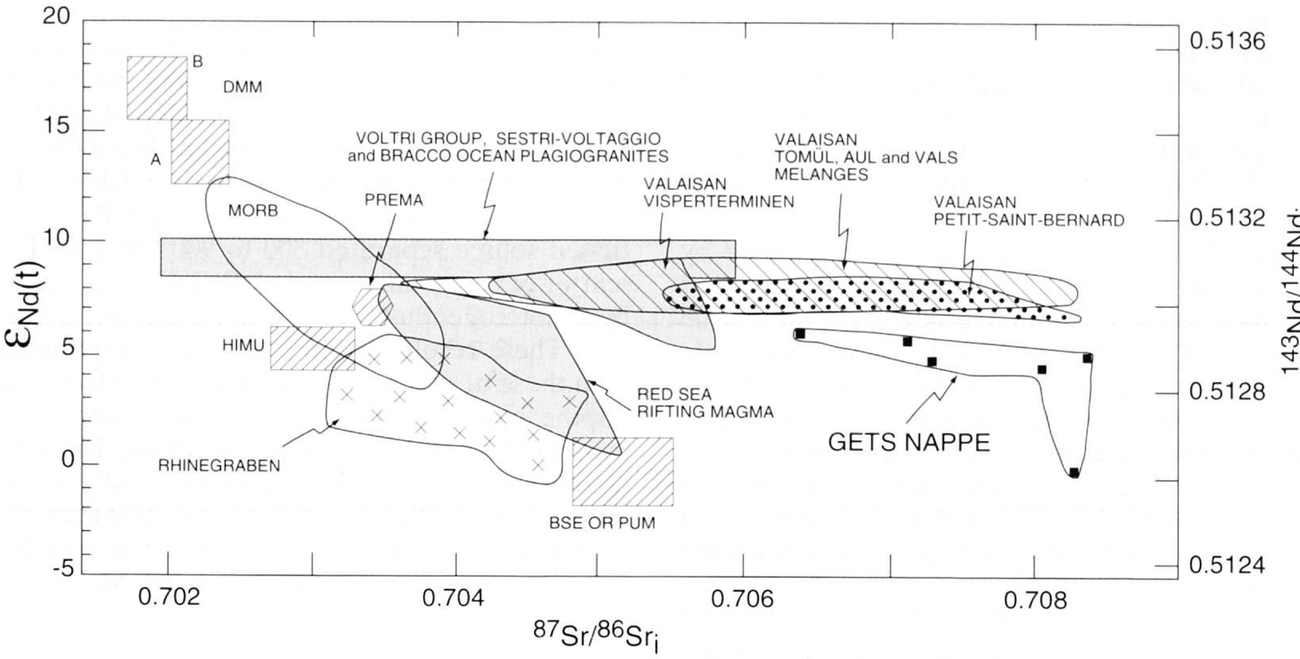

Fig. 7 $\varepsilon_{Nd(T)}$ versus $^{87}Sr/^{86}Sr_i$ for basalts of the Gets nappe. DMM, HIMU, PREMA and BSE mantle after ZINDLER and HART (1986); Rhinegraben field after ALIBERT et al. (1983) and WÖRNER et al. (1986); Mantle source of early Red Sea rifting after CHAZOT and BERTRAND (1993); Valaisan fields after CANNIC (1996) and STILLE and SCHALTEGGER (1996); Voltri group and Bracco unit after BORSI et al. (1996).

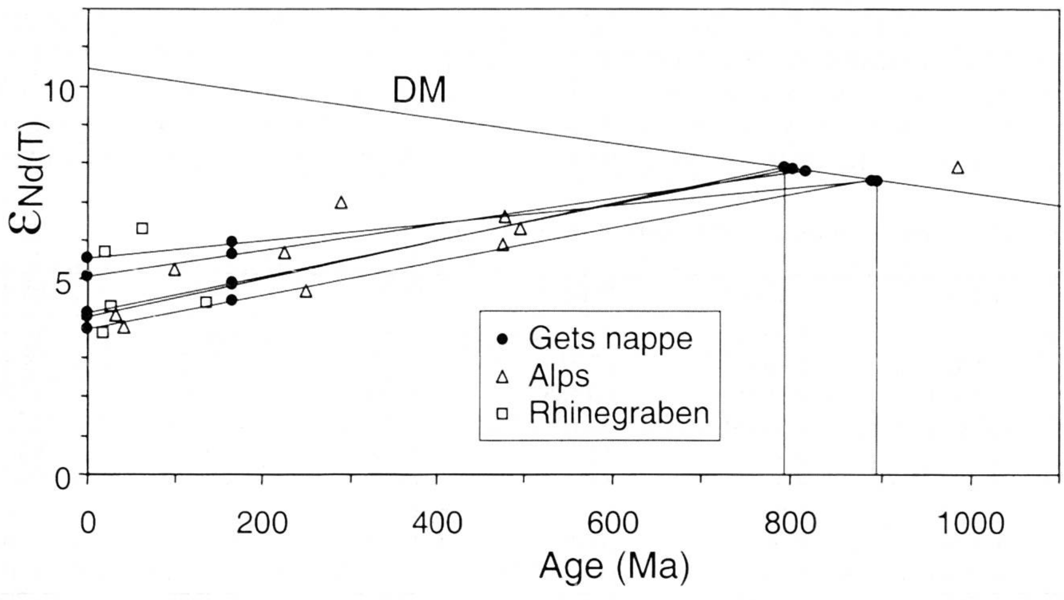

Fig. 8 $\varepsilon_{Nd(T)}$ versus age for basalts of the Gets nappe and for lithospheric mantle derived rocks in Central Europe after STILLE and SCHALTEGGER (1996). Depleted mantle evolution model from NÄGLER and KRAMERS (1998).

Paleozoic granites associated with the ophiolites are intruded by basaltic dikes showing a light REE enriched pattern (Fig. 6). These blocks record tensile fracture of the continental crust during its break-up. This suggests a fracturing of the continental crust favoring the decompression of magma from the deep mantle during the rifting.

The similarity of Nd isotopic composition to the synrift magma from the Red Sea and from the Rhine graben is another indication of a synrift paleotectonic setting. Moreover the model ages and REE pattern are compatible with a magmatic source derived from an enriched lithospheric mantle source (STILLE and SCHALTEGGER, 1996). Lithospheric mantle can be expected to be found where the continental plate breaks up and represents a primitive stage of oceanization (e.g. VOGGENREITER et al., 1988).

These results are in remarkable agreement with isotopic, biochronolologic, dating and geological constraints showing that the age of an ophiolitic suite represents an early stage of the opening of the Alpine Tethys as outlined in the introduction. We conclude that Nd isotopes, chemical features, isotopic and biochronologic dating and geological constraints are consistent with at least a part of the Gets ophiolites and represents an early stage of oceanic spreading.

5.2. COMPARISON WITH OTHER OPHIOLITES FROM THE ALPINE TETHYS

In order to constrain the paleogeographic and paleotectonic history of the Alpine-Mediterranean Tethys and to understand the structural position of relics of oceanic lithosphere having particular REE pattern in Alpine belt, we have compiled data from five different cross sections: 1) the Eastern Swiss Alps (VENTURELLI et al., 1981; FRISCH et al., 1994); 2) the Western Swiss Alps (BECCALUVA et al., 1984; PFEIFER et al., 1989; this study); 3) Corsica (DURAND-DELGA et al., 1997; VENTURELLI et al., 1979); 4) Ligurian units from the Apennines (VENTURELLI et al., 1981) and 5) the Nevado-Filabride Complex from the Betic Cordillera (BODINIER et al., 1987; PUGA 1990; PUGA et al., 1995).

The Gets, the Zermatt-Saas and the Balagne nappes have light-REE enriched basalts suggesting a source enriched in light REE or residual garnet in the source or a small degree of partial melting (Fig. 9). The Gets and Balagne nappes are located in the most external tectonic position of the ophiolitic nappes and were affected by a weak metamorphism. Ophiolitic gabbros from the Gets nappe have U–Pb ages of 166 ± 1 Ma (BILL et al., 1997). Gabbros from the Zermatt-Saas nappe have SHRIMP U–Pb ages of 164.0 ± 2.7 Ma and 163.5 ± 1.8) (RUBATTO et al., 1998). Considering the uncertainty in the geochronologic scale (ODIN, 1994), the ages of Gets and Zermatt-Saas gabbros are located between the base of the Bajocian (170 +4/–3 Ma) and the Bathonian (164 ± 2 Ma). The presence of inherited Proterozoic and Archean zircons in the ophiolitic gabbros from the Zermatt-Saas nappe also suggests contamination by continental lithosphere at an early stage of oceanization (RUBATTO et al., 1998). The oldest supraophiolitic radiolarites are located in the Gets and Balagne nappes, and are middle Bathonian in age.

Outside the Alps and the Apennines, in the Betic Cordillera, the eclogitic ophiolites from the Nevado-Filabride Complex are considered relics of oceanic lithosphere of the southwestern part of the Alpine Tethys. The chemical composition of eclogitic metabasites have light-REE enriched spectra (Fig. 9 L) (BODINIER et al., 1987; PUGA, 1990; PUGA et al., 1995). Metadolerites and metabasalts associated with pillow lavas have $^{40}Ar/^{39}Ar$ ages of 158 ± 4 Ma (PUGA et al., 1991; PUGA et al., 1995) and K/Ar ages ranging from 164 ± 4 Ma to 174 ± 4 Ma (PORTUGAL et al., 1988). Moreover HEBEDA et al. (1980) published a Rb/Sr age of 146 ± 4 Ma for this sample and associated samples have excess ^{40}Ar contents. $^{87}Sr/^{86}Sr$ ratios from 0.7028 to 0.7031 were obtained on ophiolitic gabbros from Nevado-Filabride Complex (HEBEDA et al., 1980). These Sr isotope ratios are similar to those of mid-ocean ridge basalts. The mafic rocks from the Nevado-Filabride Complex are composed of oceanic relics with ages ranging from Bajocian-Bathonian (Middle Jurassic) to middle Kimmeridgian (Late Jurassic) and have an enriched light-REE composition reflecting a continuous and similar process of partial melting or persistence of garnet in the source.

REE patterns of basalts from the Ligurian nappes (Fig. 9J, K), Inzecca (Fig. 9H) and Cap Corse (Fig. 9I) units have light-REE depleted patterns. Ophiolitic plagiogranites from the Voltri group (Ligurian Alps) and from the Bracco unit (Internal Ligurian units) (BORSI et al. 1996) have higher $\varepsilon_{Nd(T)}$ values than basalts from the Gets nappe (Fig. 7). $\varepsilon_{Nd(T)}$ of plagiogranites in ophiolites of the Voltri group and the Bracco unit are similar to MORB values and have U–Pb zircon ages of between 150 ± 1 Ma and 153 ± 1 Ma (BORSI et al. 1996). In the Internal Ligurian units two ophiolitic diorites have $^{40}Ar/^{39}Ar$ ages in amphiboles of 158.3 ± 2.9 Ma (BORTOLOTTI et al., 1990; BORTOLOTTI et al., 1995) and ophiolitic plagiogranites have ages of between 157.2 ± 2 Ma and 158 ± 1.1 Ma (BORTOLOTTI et al., 1995) which are

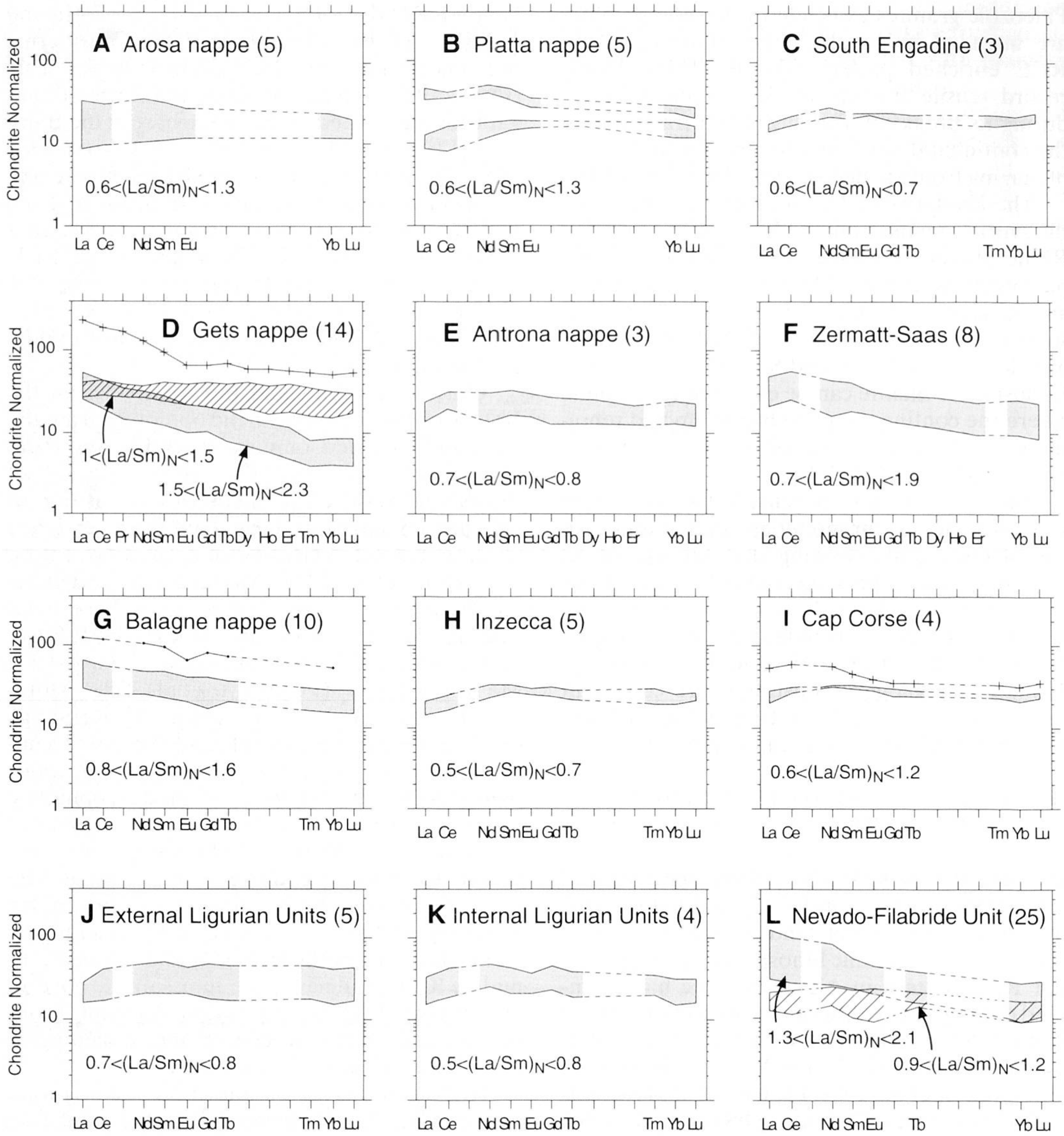

Fig. 9 REE pattern comparison of basalts from the Alpine Tethys. ( ) number of samples, (A) Arosa nappe, (B) Platta nappe after FRISCH et al. (1994); (C) South Engadine, (D) Gets nappe; (E) Antrona nappe and (F) Zermatt-Saas nappe after BECCALUVA et al. (1984) and PFEIFER et al. (1989); (G) Balagne nappe after VENTURELLI et al. (1981) and DURAND-DELGA et al. (1997); (H) Inzecca, (I) Cap Corse, (J) External Ligurian Units and (K) Internal Ligurian Units after VENTURELLI et al. (1981); (L) Nevado-Filabride Units after BODINIER et al. (1987), PUGA (1990) and PUGA et al. (1995).

interpreted as the time of magmatic emplacement or of immediate subsequent oceanic metamorphism. Supraophiolitic radiolarites from the internal and external Ligurian units have a biochronological age between Upper Callovian and Middle Kimmeridgian (BILL, 1998). These ages are slightly younger than the Upper Bathonian to Callovian ages of radiolaritic cover from ophiolites with depleted light REE. In the Inzecca units U–Pb of two oceanic plagiogranites have ages of 161 ± 3 Ma (OHNENSTETTER et al., 1981). Again the correlation between ages and REE patterns suggests that the younger basaltic relics of Alpine Tethys are depleted in light REE. The basalts from the Platta nappe have two different REE patterns, one characterized by enrichment in light REE and the other by a depleted REE composition (FRISCH et al., 1994). Phlogopite in a pyroxenite from the Totalp ultramafic body gave an $^{40}Ar/^{39}Ar$ age of 160 ± 8 Ma which is interpreted as the cooling age of upwelling of subcontinental mantle (PETERS and STETTLER, 1987). The melting of subcontinental mantle can be related to an early stage of ocean spreading. Zircons from gabbros and a dioritic vein from the Platta nappe have an U–Pb age of 161 ± 1 Ma (DESMURS et al., 1999). This age of the Platta ophiolite (161 ± 1 Ma) is located on the geochronological scale (ODIN, 1994) at the base of the Callovian (160 ± 2 Ma). For Platta gabbros to be younger than the Gets and Zermatt-Saas gabbros suggests that at least a part of the Platta ophiolites are relics of a later phase of Alpine Tethys spreading.

These data are consistent with those of an embryonic ocean floor with a light-REE enriched source. The later phases of oceanic spreading are characterized by basalts with light-REE depletion. The REE spectra of these different ophiolitic nappes record the evolution of the magmatic source of Alpine Tethys oceanic crust.

6. Conclusions

The geochemistry and Nd isotope composition of basaltic ophiolites from the Gets nappe indicate that this nappe consists essentially of relics of embryonic oceanic crust. The chemical composition of mafic rocks from the Gets nappe are divided into two groups:

(1) The chemical composition of the first group is characterized by Zr < 130 ppm, Y < 20 ppm and Cr > 140 ppm; the high concentrations of light REE suggests a light REE enriched source or small degrees of partial melting and is consistent with P-MORB.

(2) A second group is characterized by Zr > 200 ppm, Y > 20 ppm, Cr < 140 ppm; the horizontal REE spectrum is consistent with mixing between normal type MORB and plume type MORB.

$\varepsilon_{Nd(T)}$ values of these two groups are similar to those of the Red Sea and the Rhine Graben rifting magmas. Model age calculations and REE-enriched compositions are compatible with the European subcontinental mantle source separating from the convecting mantle 800 to 900 Ma ago. Such a lithospheric mantle can be expected to be found where the final continental lithosphere break-up occurred and therefore represents the earliest stage of oceanic spreading.

The comparison between REE patterns, Sm–Nd and Sr isotope compositions, isotopic and biochronologic ages of ophiolitic suites from different relics from the Alpine Tethys show that:

– The basalts with a light-REE enriched composition correspond to embryonic ocean as in the Gets, Zermatt-Saas and Balagne nappes and probably are a part of the ophiolites from the Platta Nappe.

– The relics of oceanic lithosphere representing later phases of ocean spreading are found in the internal and external Ligurian units and in Inzecca and Cap Corse units. The mafic rocks from these nappes are characterized by a light-REE depleted composition. $\varepsilon_{Nd(T)}$ of ocean gabbros and plagiogranites from the Ligurian Alps and Internal Ligurian units have higher values than those of the Gets, and are similar to MORB values. These correlations suggest the spreading of Alpine Tethys was marked by a change of mantle source.

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