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## The Ordovician orogeny in the Alpine basement: constraints from geochronology and geochemistry in the Aar Massif (Central Alps)

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### Abstract

A sequence of magmatic and metasedimentary rocks from the Susten pass area (Aar Massif, Central Alps of Switzerland) provides evidence of an orogenic cycle of Ordovician age overprinted by the Variscan orogeny. Several stages of this evolution have been dated by U–Pb on zircon, titanite and monazite, complementing previously published U–Pb zircon data from the same area. A gabbro, with  $\epsilon\text{Nd}$  values of +4 to +7 was formed at  $478 \pm 5$  Ma and was then affected by a HP metamorphic stage. A subsequent HT metamorphic event was succeeded by partial melting during decompression at about 450 Ma. Titanite in calcsilicate marble and monazite in metapelite formed at  $319 \pm 3$  Ma and  $317.5 \pm 2$  Ma, respectively. This Variscan metamorphism probably reached amphibolite facies conditions and considerably changed the whole-rock chemical and isotopic compositions of the amphibolites, but it left the U–Pb systems in zircon virtually unaffected. The association of mafic and ultramafic rocks together with sediments could be generated in both convergent and divergent settings. The metamorphic overprints blurred the original geochemical and isotopic characteristics too much to permit a specific geodynamic interpretation. The studied rock association is suggested to be part of an ancient active or passive margin sequence of the peri-Gondwanan Hun terrane.

**Keywords:** Ordovician orogeny, Alpine basement, geochronology, U–Pb, Aar Massif.

### Introduction

The Central European basement in the Alpine realm is polyorogenic and was intensely reworked mainly during the Variscan and Alpine orogenic cycles. Remnants of pre-Variscan geological events have, however, been preserved in some places, for example in the External Crystalline Massifs (e.g., Rubatto et al., 2001; von Raumer et al., 1999; Schaltegger and Gebauer, 1999) and in the Austroalpine realm (Hoinkes et al., 1999; Klötzli-Chowanetz et al., 1997; Schaltegger et al., 1997). The pre-Variscan occurrences have been interpreted in terms of oceanic and/or arc magmatism (Schaltegger et al., 1997, 2002) or orogenic acid magmatism in compressional and extensional settings (Poller, 1997; Sergeev and Steiger, 1995; Zurbriegen et al., 1997). Unequivocal relationships between magmatic and metamorphic rocks are often lacking and have so far only been established in some rare cases using precise U–Pb

dating of monazite and zircon (e.g., Bussy et al., 1996). Eclogites defining an HP stage during subduction are found in different areas but could not be clearly related to a P–T–t path (Oberli et al., 1994).

We present here data from the area of the Susten pass, Aar Massif (Crystalline External Massifs, Helvetic domain) that provide evidence for a complete orogenic cycle of Ordovician age, including mafic magmatism, granulite-facies HT metamorphism, and HT-LP anatexis. A superimposed Variscan high-temperature metamorphism resulted in recrystallization and the growth of new mineral assemblages, resetting of isotopic systems and probably some anatexis, but nevertheless leaving well-preserved remnants of the pre-Variscan metamorphic assemblage. The association of igneous and sedimentary rocks had originally been described in Schaltegger (1984, 1989) and a first set of age determinations was reported by Schaltegger (1993). The present study

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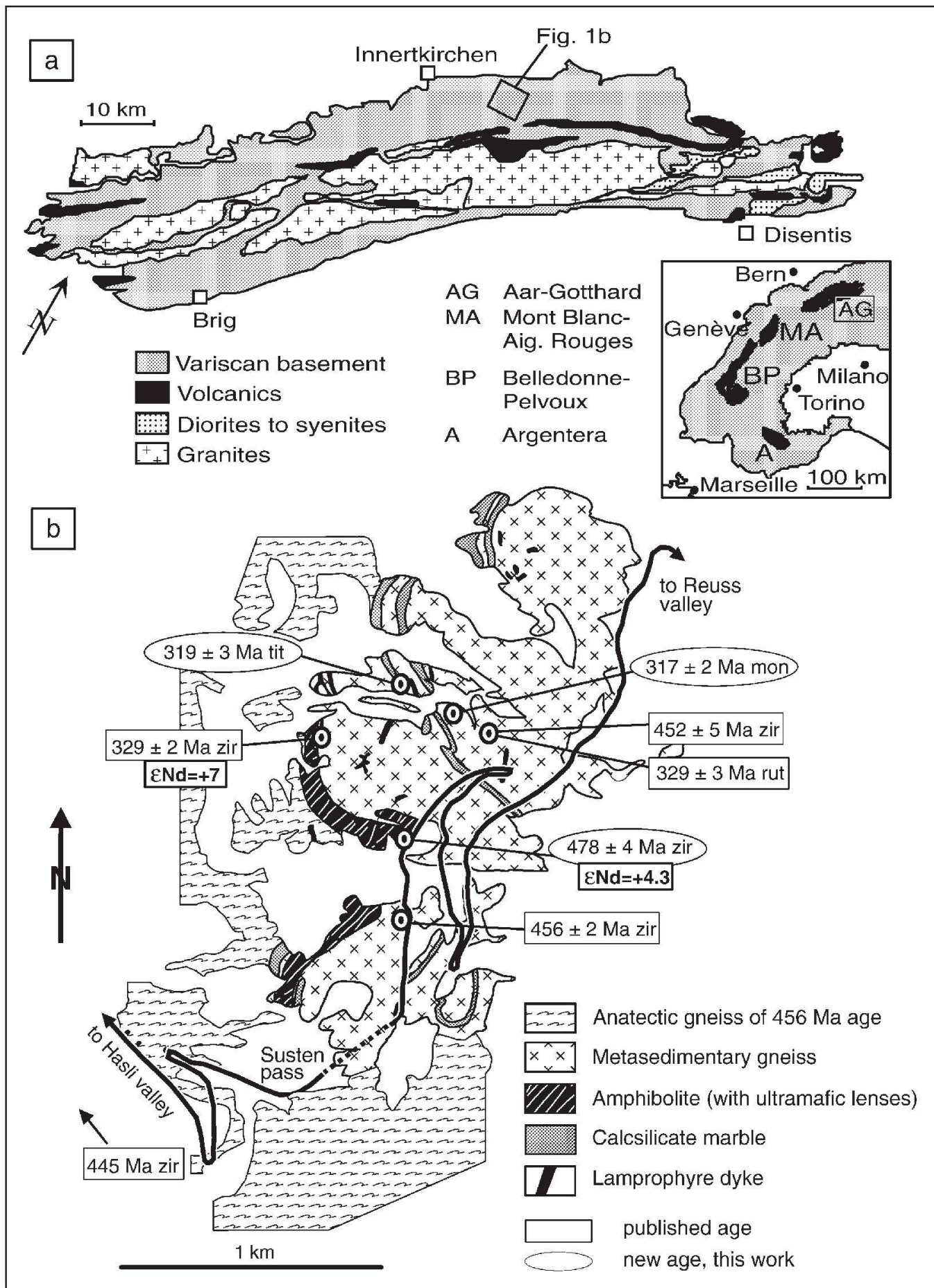


Fig. 1 Geological sketch map of the Susten pass area with sample localities. Published U-Pb ages (Schaltegger, 1993) and new isotopic data from this work are indicated.



provides additional data that support the presence of a late Ordovician magmatic system and yield a first age estimate for the peak conditions during the Variscan metamorphic overprint. The studied area in the region of the Susten pass is considered to be unique because the Alpine tectonics were brittle and non-pervasive, and the metamorphic overprint occurred at sub-greenschist facies conditions (Frey et al., 1980).

### Geological outline

The Aar Massif is one of the Crystalline External Massifs in the Alps (CEM) and presents an elongated outcrop complex of pre-Variscan and Variscan rocks (Fig. 1a). The most important lithology of the Aar Massif are Variscan granitoids that intruded an older basement (Schaltegger and Corfu, 1992) and locally also Lower to Upper Carboniferous basin sediments (Schaltegger and Corfu, 1995) between 350 and 295 Ma ago. Alpine deformation and metamorphism overprinted mainly the southern part of the Massif; whereas most of the pre-Alpine structures are well preserved in the northern part. The observed pre-Alpine metamorphic mineral assemblages have commonly been considered to be Variscan (Carboniferous) in age.

Along the northern rim of the Aar Massif there is a strip of high-grade gneisses and migmatites, called Erstfeld gneisses, transitional to migmatites in the west, called Innertkirchen-Lauterbrunnen crystalline unit (Rutishauser, 1972; Schaltegger, 1993; Olsen et al., 2000). The Erstfeld gneiss unit is rather monotonous except for an inlier in the area of the Sustenpass (Fig. 1b), which is made up of Late Proterozoic to Early Paleozoic metasedimentary sequences containing anatectic metasedimentary gneisses, micaschists, calc-silicate gneisses and marbles, and quartzites. The metasedimentary rocks are narrow-banded and have been tentatively interpreted as a turbiditic sequences of greywackes deposited in a continental margin setting (Biino et al., 1999). This unit contains layers of mafic rocks with local ultramafic lenses, and is crosscut by lamprophyre dykes of Variscan age (Schaltegger, 1984, 1986, 1993).

The high-grade metamorphism of the Susten area has been dated by Schaltegger (1993) by U-Pb on zircon from different gneissic lithologies. The major structural imprint on the rocks was found to be Ordovician in age, as indicated by zircon ages of  $456 \pm 2$  Ma for an anatectic gneiss and  $452 \pm 5$  Ma for a metapsammitic gneiss; a slightly younger age of ca. 445 Ma was reported from a migmatite of the Innertkirchen crystalline com-

plex, 15 km to the west (Fig. 1a). The pre-Variscan metamorphic conditions have been characterized by Biino et al. (1999), who found evidence for a HP event in meta-gabbros, predating the HT event and the anatexis of granitoid lithologies between 456 and 445 Ma. The Variscan metamorphism and recrystallization has been dated at  $329 \pm 2$  Ma by concordant zircon from a garnet-bearing amphibolite and by coeval metamorphic rutile in a metapsammitic gneiss (Schaltegger, 1993). Monazite ages of  $306 \pm 5$  Ma, found by Olsen et al. (2000) and Olsen and Livi (1999) in the Innertkirchen-Lauterbrunnen Massif, have also been interpreted as products of the Variscan metamorphic overprint. The latter authors suggest that the Variscan metamorphism most probably exceeded the greenschist-facies conditions originally estimated by Schaltegger (1993). The age of 329 Ma is significantly older than dates of 317 and 321 Ma obtained for the Variscan HT metamorphism and incipient anatexis in gneisses of the Aiguilles Rouges and Mt. Blanc Massifs (Bussy and von Raumer, 1993; Bussy et al., 2000). This difference raises the question why this high-grade Variscan overprint at ca. 320 Ma was not registered by the zircon data of Schaltegger (1993; see discussion in Olsen et al., 2000). Ages of around 320 Ma for the Late Carboniferous anatexis contrast, on the other hand, with the presence of only weakly metamorphosed Lower Visean volcano-sedimentary sequences elsewhere in the Aar Massif (Schaltegger and Corfu, 1995). Different parts of the Helvetic basement of the Aar Massif are therefore thought to represent different levels of crustal exposure.

### Investigated rocks and their geochemical composition

To get more complete information on the pre-Variscan evolution of this part of the Aar Massif, we have studied the chemical and isotopic composition of different types of amphibolites and one ultramafic rock (serpentinite). U-Pb age determinations were carried out on zircon, titanite and monazite from a coarse-grained amphibolite, a calc-silicate rock and a metapelitic gneiss. The investigated rocks have been strongly re-equilibrated during the Variscan and less intensely during Alpine metamorphic overprints and thus do not represent original mineral assemblages any more. Geochemical and isotopic analyses have thus to be used with greatest caution for any geodynamic reconstruction. The description of mineralogical compositions and textures may be found in Schaltegger (1984, 1986).



Table 1 Geochemical composition of mafic and ultramafic rocks from the Susten pass, Aar Massif.

element	AMPHIBOLITES				HORNBLLENDE-FELSES		SERPENTINITE	CALCSILICATE ROCKS	
	SU-81-55	SU-81-72	AJ 1193	AJ 1192	SU-81-61	SU-81-69	SU-81-66	AJ 1190	AJ 1191
SiO <sub>2</sub> [%]	49.11	51.17	52.40	51.30	42.63	45.83	40.55	53.70	39.80
Al <sub>2</sub> O <sub>3</sub>	13.23	15.71	14.90	14.80	19.41	20.3	0.94	12.50	8.40
Fe <sub>2</sub> O <sub>3</sub>	2.52	2.58	11.60	11.40	2.02	0.78	4.49	5.00	3.20
FeO	12.72	5.97	n.d.	n.d.	4.53	2.79	3.32	n.d.	n.d.
MgO	6.43	6.97	6.48	7.11	15.17	8.88	3.73	2.61	1.92
CaO	10.15	9.51	8.20	9.50	10.07	13.68	0.29	20.00	31.10
K <sub>2</sub> O	0.22	0.62	0.38	0.24	1.29	1.64	0.05	1.65	1.06
MnO	0.24	0.15	0.23	0.21	0.09	0.07	0.11	0.10	0.09
TiO <sub>2</sub>	2.54	0.81	1.33	0.81	0.08	0.13	0.03	0.57	0.43
P <sub>2</sub> O <sub>5</sub>	0.25	0.05	0.21	0.14	0.02	0.03	0.02	0.26	0.22
Na <sub>2</sub> O	2.33	3.5	3.49	3.43	0.79	0.97	0.05	0.31	0.80
Cr <sub>2</sub> O <sub>3</sub>	b.d.l.	b.d.l.	n.d.	n.d.	b.d.l.	b.d.l.	0.27	b.d.l.	b.d.l.
NiO	0.02	0.02	n.d.	n.d.	0.07	0.03	0.26	b.d.l.	b.d.l.
LOI	1.15	2.46	0.98	1.94	4.13	4.07	1.18	2.92	13.89
CO <sub>2</sub>	0.07	0.16	n.d.	n.d.	0.08	0.14	0.59	n.d.	n.d.
Sum	100.98	99.68	100.20	100.88	100.38	99.34	55.88	99.62	100.91
Nb [ppm]	12	b.d.l.	2.34	0.86	b.d.l.	b.d.l.	b.d.l.	6.71	5.02
Ta	0.44	0.16	0.37	0.17	0.03	0.09	0.05	0.77	0.56
Sc	41.1	31.2	33.9	39.9	6.9	17.1	7.2	11.1	7.8
Zr	156	24	109	40	b.d.l.	b.d.l.	b.d.l.	131	104
Hf	n.d.	n.d.	3.2	1.3	n.d.	n.d.	n.d.	4.0	3.4
Y	55.5	10.1	33.7	17.6	1.7	2.7	1.1	24.8	19.0
Ba	15	97	74	33	219	206	1	114	196
Sr	150	196	181	108	45	309	1	171	1184
Rb	5	17	8	8	51	77	2	31	23
Pb	b.d.l.	116	40	29	b.d.l.	b.d.l.	22	22	22
Ga	18	17	n.d.	n.d.	10	11	b.d.l.	n.d.	n.d.
Zn	76	57	96	78	32	22	74	82	65
Cu	36	22	34	48	15	3	15	10	15
Ni	57	43	178	77	407	179	1814	68	60
Co	38	27	38	42	47	27	96	19	10
Cr	92	181	314	72	365	769	2267	69	53
Mn	1610	990	1424	1362	604	457	767	708	587
V	439	248	247	312	25	63	37	99	69
Th	0.8	4.6	1.1	0.3	0.1	0.0	0.1	7.5	5.1
U	0.3	1.5	0.5	0.2	0.1	0.2	0.1	3.2	4.0
La	5.87	2.73	6.34	2.29	0.28	0.14	0.09	22.68	17.42
Ce	20.4	8.00	16.55	6.47	0.94	0.42	0.51	46.11	35.68
Pr	3.18	0.90	2.65	1.24	0.13	0.06	0.09	6.65	4.84
Nd	17.5	4.06	14.30	7.51	0.63	0.44	0.50	26.98	18.92
Sm	5.56	1.12	4.39	1.71	0.16	0.18	0.11	5.01	4.06
Eu	1.99	0.57	1.43	1.09	0.16	0.20	0.02	1.03	0.81
Gd	6.42	1.17	5.96	3.13	0.16	0.25	0.09	4.83	4.14
Tb	1.32	0.23	0.97	0.57	0.03	0.05	0.01	0.75	0.59
Dy	8.91	1.64	5.60	2.72	0.19	0.34	0.08	4.32	3.29
Ho	1.90	0.34	1.39	0.62	0.04	0.08	0.01	0.89	0.75
Er	5.32	0.96	4.06	1.88	0.12	0.21	0.06	2.54	2.00
Tm	0.95	0.15	0.59	0.24	0.02	0.04	0.01	0.39	0.29
Yb	5.31	0.86	3.74	1.99	0.12	0.23	0.06	2.35	1.75
Lu	0.84	0.14	0.56	0.27	0.02	0.04	0.01	0.35	0.25
ΣREE	85.44	22.87	68.53	31.73	3.00	2.68	1.65	124.88	94.79

Major, trace and rare earth elements were measured at the Centre de Géochimie de la Surface (CNRS), Strasbourg by OES, ICP and ICP-MS. For detailed description of analytical techniques see Schaltegger et al. (2002). b.d.l. — below detection limits; n.d. — not determined.

*Amphibolites:*

Different types of amphibolites occur in a several 100 meters wide band (Fig. 1b), containing lenses of ultramafic rocks (serpentinites). They contain garnet-bearing amphibolites, interpreted as retrograded eclogites (Biino et al., 1999; SU-81-55, AJ1192); and fine-grained plagioclase-amphibolites with white schlieren and bands of plagioclase (SU-81-72, AJ1193), as well as layers of hornblende-felses (not sampled). They have highly variable major and trace element compositions (Table 1) and most show a distinct negative Nb anomaly. There is also a strong and variable fractionation between Nb and Ta (except for SU-81-55; Fig. 2a). These two elements may show poor accuracy because the values are either close to the limits of detection or may be biased by solubility problems during sample digestion. This casts doubts on the validity of the Nb-Ta data, and we have to be aware that this phenomenon could be

an analytical artifact. Th is either strongly enriched (SU-81-72) or depleted (AJ1192). The REE patterns are flat and show some variation in concentration and extent of Eu-anomaly (Fig. 3a).

*Hornblende-felses:*

They occur as massive, nearly monomineralic rocks within the amphibolites. They contain 60–90% actinolite (SU-81-61, SU-81-69), besides a green-brown hornblende and some secondary phyllosilicates, and lack any feldspar. These rocks are geochemically very distinct from the amphibolites being characterized by extremely low HFSE (no Zr!) and REE (Table 1). Positive spikes of Rb, K and Sr probably reflect metasomatism with the secondary growth of fine-grained white mica (Fig. 2b). The REE patterns are flat at very low concentrations and exhibit a conspicuous positive Eu-anomaly (Fig. 3b), which may indicate that cumulus plagioclase was originally

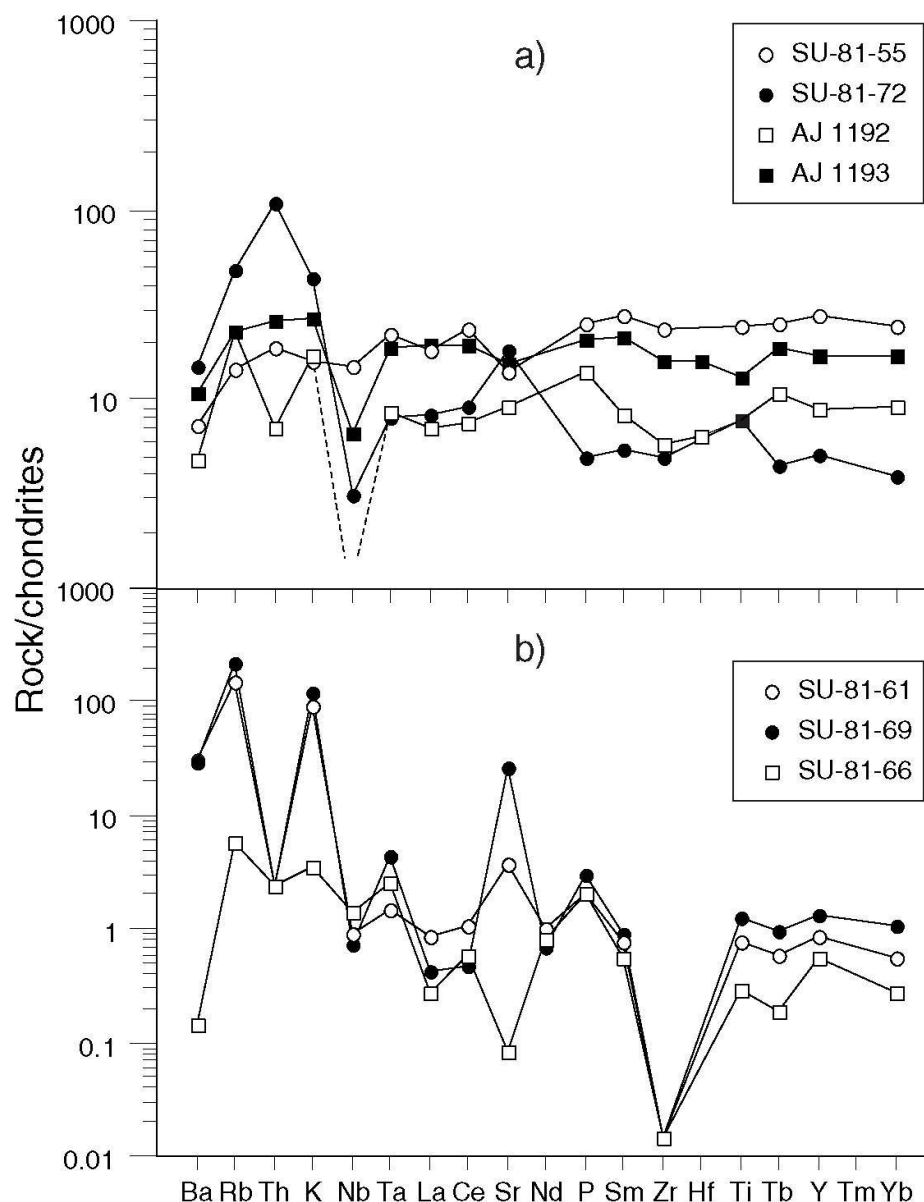


Fig. 2 Trace element variation diagrams for: (a) amphibolites; (b) hornblende-felses and serpentinite.



Table 2 Rb–Sr and Sm–Nd isotopic data of mafic rocks.

sample No.	Rb [ppm]	Sr [ppm]	$^{87}\text{Rb}/^{86}\text{Sr}$	sample (0)	$\pm 2$ sigma	$^{87}\text{Sr}/^{86}\text{Sr}$	Sm [ppm]	Nd [ppm]	$^{147}\text{Sm}/^{144}\text{Nd}$ sample (0)	$^{143}\text{Nd}/^{144}\text{Nd}$ sample (0)	$\pm 2$ sigma	$\varepsilon\text{Nd}(0)$	$\varepsilon\text{Nd}(T)$	TDM (Ga)
SU-81-66	7.44	2.16	10.01	0.743729	4	0.736900	—	0.31	—	—	—	—	—	—
SU-81-55	4.75	152	0.090	0.706873	4	0.706812	5.60	16.0	0.2002	0.512999	5	7.0	6.8	1.71
SU-81-61	204	46.9	12.63	0.717100	4	0.708490	—	0.49	—	—	—	—	—	—
SU-81-69	73.7	311	0.686	0.710889	4	0.710421	—	0.36	—	—	—	—	—	—
SU-81-72	18.2	206	0.255	0.708329	4	0.708155	1.58	5.50	0.1743	0.512787	6	2.9	4.3	1.41

Uncertainties refer to last digits.

For detailed description in analytical techniques please consult Schaltegger et al. (1994)

Standard values: La Jolla,  $^{142}\text{Nd}/^{144}\text{Nd} = 511852 \pm 2$  ( $2\sigma$  mean;  $n=10$ ); NBS 987,  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710266 \pm 3$  ( $2\sigma$  mean,  $n=18$ )

Table 3 Results of U–Pb age determinations on zircon, monazite and titanite.

Nr.	Description	Weight [mg]	nr. of grains	Concentrations			Atomic ratios				Apparent ages [Ma]		Error corr.					
				U [ppm]	Pb rad. [ppm]	Pb nonrad. [pg]	model Th/U b)	206/204	206/238	Error 2σ [%]	207/235	Error 2σ [%]		206/238	207/235			
Garnet amphibolite, Sustenloch (AJ 1192)																		
1	zir, prism corroded abr	0.071	28	203	17.10	4.2	0.70	16358	0.07647	0.47	0.5970	0.53	0.05662	0.17	475.0	475.3	476.7	0.94
2	zir, round no incl abr	0.109	57	242	19.20	8.9	0.48	14057	0.07581	0.41	0.5933	0.48	0.05676	0.18	471.1	473.0	482.1	0.93
3	zir, bulk abr	0.094	—	238	19.20	16.0	0.52	6659	0.07593	0.62	0.5932	0.71	0.05666	0.24	471.8	472.9	478.3	0.94
4	zir, euh prism abr	0.007	10	189	15.50	7.6	0.43	847	0.07587	0.60	0.5931	0.86	0.05670	0.60	471.4	472.9	479.8	0.72
5	zir, subround abr	0.007	11	269	21.30	1.9	0.51	4719	0.07539	0.47	0.5877	0.56	0.05654	0.22	468.6	469.4	473.6	0.92
6	zir, euh abr	0.002	1	75.6	6.90	1.7	1.02	440	0.07673	0.57	0.6044	2.10	0.05708	1.90	476.9	479.9	494.7	0.47
7	zir, prism euh abr	0.001	1	674	57.70	1.5	0.81	2197	0.07651	0.54	0.5883	0.70	0.05577	0.48	475.3	469.8	443.1	0.73
8	zir, subround abr	0.002	1	97.0	7.30	1.3	0.32	713	0.07529	0.70	0.5888	1.24	0.05672	1.12	468.0	470.1	480.8	0.45
Calcsilicate marble, Silberberg (AJ1190)																		
9	tit, coarse, no incl	0.063	12	132	6.60	215	0.15	142	0.05110	0.56	0.4112	2.50	0.05835	2.40	321.3	349.7	543.1	0.29
10	tit, disks, black incl	0.075	22	83.5	4.10	167	0.18	138	0.05076	0.56	0.3725	2.80	0.05323	2.70	319.3	321.6	338.5	0.28
11	tit, disks, no incl	0.089	29	73.6	3.60	158	0.13	152	0.05134	0.92	0.3817	4.70	0.05392	4.50	322.8	328.3	367.8	0.31
12	tit, coarse, dark brown	0.088	18	124	5.98	143	0.21	257	0.05009	1.16	0.3641	2.55	0.05271	2.20	315.1	315.3	316.5	0.51
13	tit, frags abr	0.112	40	180	5.17	139	0.19	291	0.05001	0.53	0.3656	1.30	0.05302	1.20	314.6	316.4	329.7	0.39
14	tit, frags abr pale br	0.160	—	159	7.90	232	0.25	369	0.05101	0.60	0.3722	1.20	0.05292	1.00	320.7	321.3	325.6	0.56
15	tit, disks abr	0.031	—	66.7	3.19	54.0	0.10	142	0.05127	0.54	0.3760	2.60	0.05320	2.50	322.3	324.1	337.1	0.28
Metapelite gneiss, Silberberg (SU-82-138)																		
16	mon, yellow	0.0027	1	5181	957	12.0	10.67	3793	0.05102	0.34	0.3667	0.39	0.05213	0.15	320.8	317.2	290.9	0.92
17	mon, yellow	0.0076	1	6239	1310	30.7	12.82	5041	0.05124	0.36	0.3675	0.41	0.05201	0.13	322.1	317.8	285.9	0.95

a) abr = abraded; br=brown; euh = euhedral, incl = inclusions, prism = prismatic

b) Calculated from radiogenic  $^{208}\text{Pb}$

c) Corrected for fractionation and spike

d) Corrected for fractionation, spike, blank and common lead (Stacey and Kramers, 1975)

Analyses 1 to 8 were carried out at the Royal Ontario Museum, Toronto (Canada); analyses 9 to 17 at ETH Zürich (Switzerland). For description of analytical techniques see Schaltegger (1993) for ROM procedures, and Schaltegger et al. (1999) for ETH procedures.

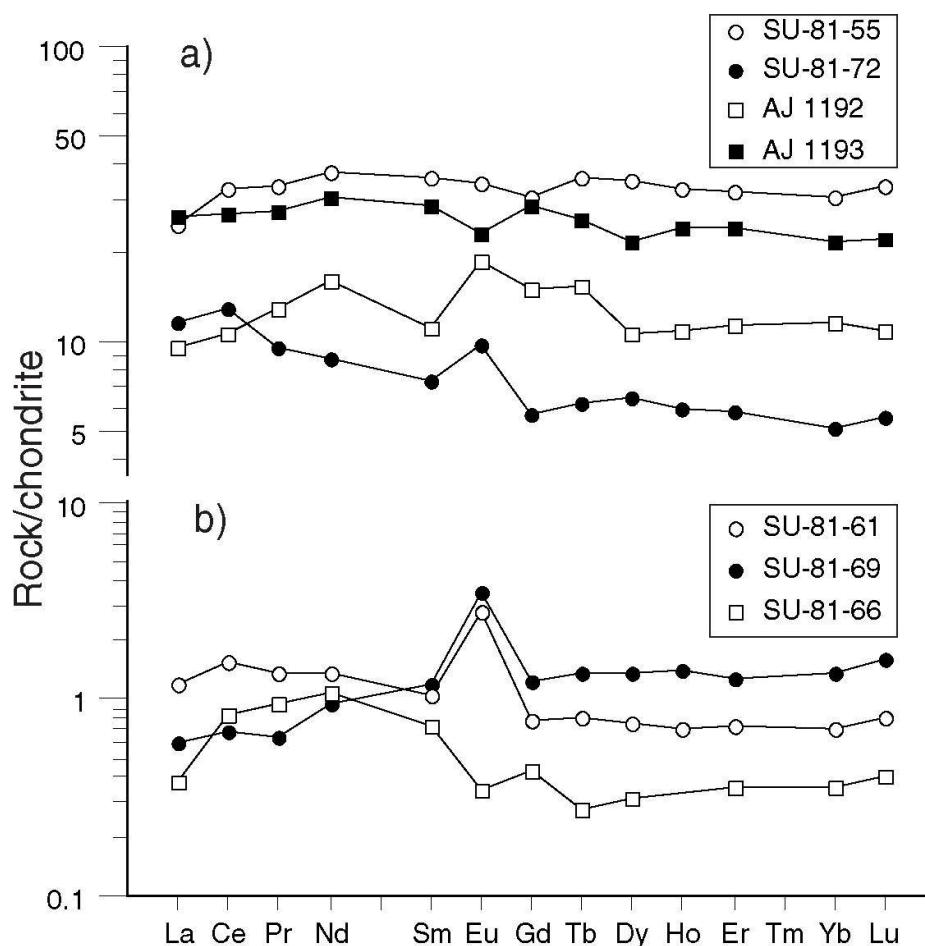


Fig. 3 Rare earth element variation diagram for: (a) amphibolites; (b) hornblende-fels and serpentinite.

present but was later completely replaced by white mica. Although the geochemical signature was strongly overprinted by metamorphic mineral transformations with uptake of Rb, K and probably Sr, it probably still retains some original features; the rocks may possibly represent meta-troctolites.

#### *Serpentinite, SU-81-66:*

The sample is taken from a 100 m<sup>2</sup> lens within amphibolite, featuring spectacular reaction rims with Cr-bearing tremolite and anthophyllite (see detailed description in Schaltegger, 1984). It consists of chrysotile, antigorite, Cr-muscovite, relics of tremolite, talc and some magnesite. Major and trace elements signatures are clearly indicative of an ultramafic protolith (Table 1), but were strongly altered during metamorphic overprints (enrichment in some LILE and LREE; Figs. 2b and 3b).

#### *Calc-silicate gneisses and marbles (AJ 1190, 1191):*

The samples feature idiomorphic silicates (titanite, amphibole, epidote, wollastonite, grossular, vesuvianite, diopside) with variable contents of

calcite. The calc-silicate rocks occur as conspicuous white-colored, 0.3 to 50 m wide bands within different types of metasedimentary gneisses.

## Results from isotopic analyses

### *a) Sr and Nd isotopes (Table 2)*

The measured <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd isotopic values of five whole-rock samples clearly reflect the variable and high degree of metamorphic alteration. Two amphibolites (SU-81-55 and 72) have elevated Sr isotopic ratios assigned to metamorphic overprinting. The Nd isotopic system being known are more resistant during metamorphic recrystallization, the age-corrected  $\epsilon$ Nd values of 6.8 and 4.3, respectively, may also reflect ancient seawater alteration and/or crustal contamination, as other amphibolites of similar age and setting (Schaltegger et al., 2002). The depleted mantle Nd model ages of the two samples are 1.7 and 1.4 Ga. The hornblende-fels (SU-81-61, -69) and the serpentinite (SU-81-66) have elevated Sr isotopic ratios up to 0.7369 for the latter, clearly pointing out the high degree of contamination.



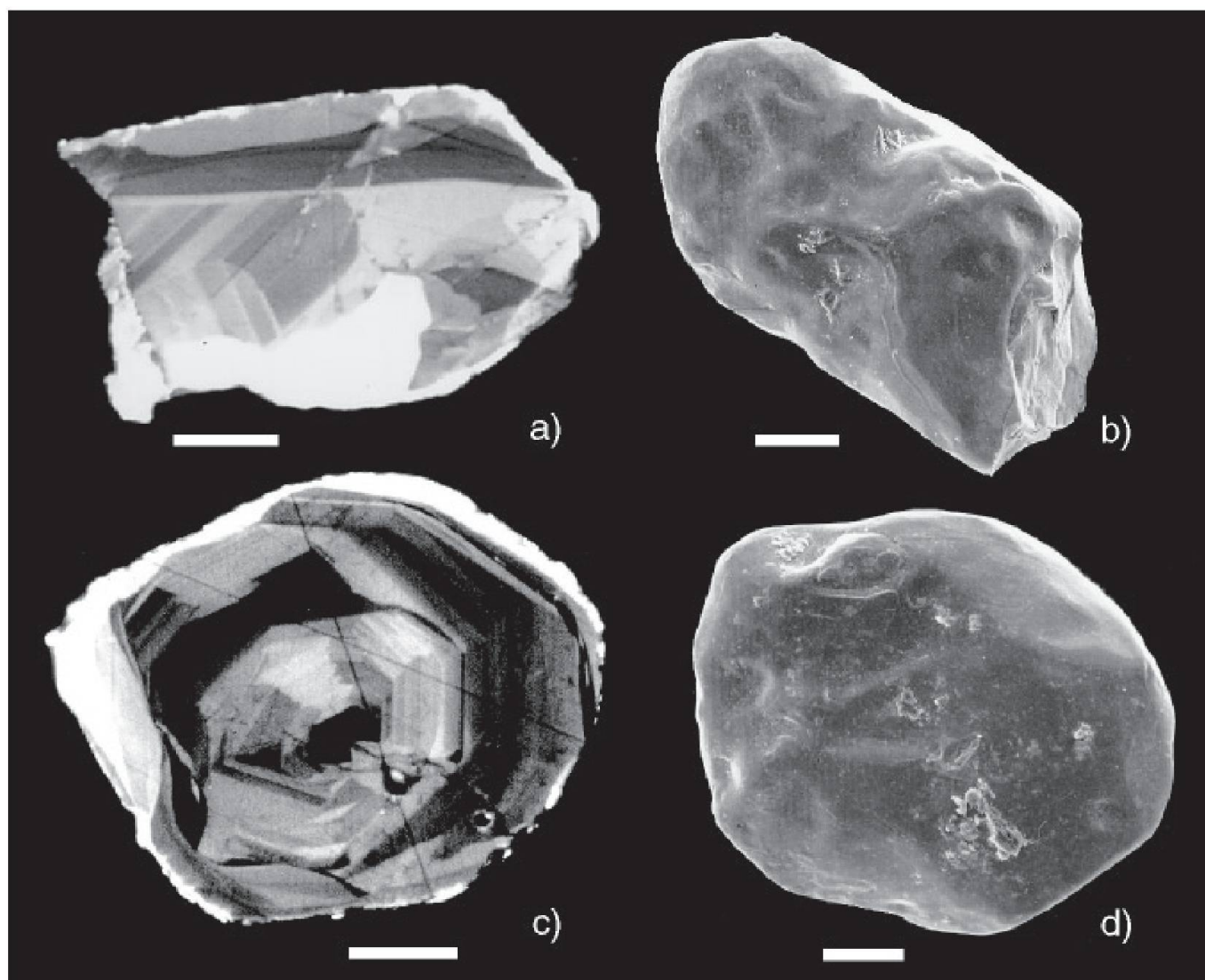


Fig. 4 Cathodoluminescence and secondary electron images of representative zircons in metagabbro AJ1192 used for U–Pb dating; bars denote 30  $\mu\text{m}$ . All zircons show evidence of chemical resorption. Upper row: Prismatic zircon with different growth stages and high-luminescence recrystallization features along the rims; lower row: round zircon with younger overgrowth and/or replacement textures along the rims.

tion during metamorphic overprinting and hydration.

#### **b) U–Pb age determinations (Table 3)**

*Garnet amphibolite (AJ 1192):* Eight U–Pb determinations, carried out on fractions and single grains, show a cluster of  $^{206}\text{Pb}/^{238}\text{U}$  ages between 468 to 477 Ma. The sample contained prismatic grains with a partially resorbed surface that were assumed to be of magmatic origin (Fig. 4b) and round grains with incipient development of crystal faces, of possible metamorphic nature (Fig. 4d). In the CL image, the prismatic grains show isolated recrystallized areas cutting across domains with oscillatory growth zoning (Fig. 4a), whereas round zircons have CL-bright, structureless rims overgrowing complexly zoned interiors; these rims are most likely of metamorphic origin (Fig. 4c). The relatively constant U concentrations

of the multi-grain zircon fractions (analyses 1 to 5) appear to reflect the mixtures of high- and low-U grains, as evidenced by single-grain analyses 6 to 8. The U–Pb data for the fractions are subconcordant and yield a mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $478 \pm 5$  Ma (fractions 1 to 5; Fig. 5a), interpreted as the age of crystallization and emplacement of the protolith. The analyses of two single zircon grains of prismatic shape (analyses 6 and 7) resulted in  $^{206}\text{Pb}/^{238}\text{U}$  ages of 477 and 475 Ma, close to the  $^{207}\text{Pb}/^{206}\text{Pb}$  age, whereas the age of analysis 8 of a round zircon (468 Ma) is younger and could approximate the time of metamorphic growth (or overgrowth) during any metamorphic reaction producing free zirconium liberated from former Zr-bearing minerals (such as, e.g., pyroxenes). The latter zircon is also characterized by a relatively low Th/U ratio, a common feature of subsolidus zircon growth (Schaltegger et al., 1999; Hoskin and Black, 2000).



**Calc-silicate gneiss (AJ 1190):** Seven fractions containing 12 to 40 pale yellow titanites were analyzed to constrain the age of metamorphic growth of this mineral. The titanites are low in U (67 to 180 ppm) and yield somewhat scattered  $^{206}\text{Pb}/^{238}\text{U}$  ages between 315 and 323 Ma. All analyses except for point 9 are analytically concordant and provide a mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $319 \pm 3$  Ma (Fig. 5b).

**Metapelitic gneiss (SU-81-138):** Two yellow-colored single monazite grains yielded reversely concordant results with a mean  $^{207}\text{Pb}/^{235}\text{U}$  age of  $317.5 \pm 2$  Ma (Fig. 5b). This age is within analytical errors coeval to the result from titanite determinations and is interpreted as age of monazite crystallization during the Variscan metamorphic overprint.

## Chronology of orogenic events

### Mafic magmatism

The zircon population in amphibolite AJ1192 is considered to be of magmatic nature (with an unknown degree of metamorphic reworking and overprinting), which points to a gabbroic or doleritic protolith as zircon is not supposed to crystallize in basaltic flows. It was intruded (or tectonically emplaced?) into continental sedimentary sequences that were deposited between 620 and 480 Ma, and also contain detrital zircons of Proterozoic age (Schaltegger, 1993). The clastic sequences are characterized by a variable primary grain size (from conglomerates to pelites) and a generally highly variable lithology. The gabbro has not preserved any primary contact relationships, thus it is impossible to tell whether it was intrusive or was emplaced as an olistolithic block. However, its occurrence as small bodies with recognizable gabbroic texture within a coherent layer of amphibolites of about 100 m thickness may point to an intrusive emplacement. The  $\epsilon\text{Nd}$  values of 4.3–6.8 are not of much a diagnostic value; they are compatible with a subduction-related origin combined with contamination from subducted sedimentary material (plus metamorphic-hydrothermal alteration), but also with an extensional back-arc or even a passive margin situation. Neither trace nor rare earth element provide unequivocal evidence to discriminate between these different scenarios. The emplacement and crystallization of the gabbro is dated by the zircon age of the amphibolite AJ1192 at  $478 \pm 5$  Ma.

### HP metamorphism

The amphibolites AJ1992 and SU-81-55 both contain the mineral assemblage garnet+titanite

+rutile and a phase that decomposed to diopside + oligoclase and hornblende + oligoclase symplectites (Biino et al., 1999). This assemblage is interpreted to reflect HP re-equilibration from the magmatic precursor paragenesis. The maximum age of this HP overprint is given by the  $^{206}\text{Pb}/^{238}\text{U}$  age of 468 Ma for the round zircon 8 of sample AJ1992 (Fig. 5a). The existence of a HP paragenesis by itself favours the active margin hypothesis; however, eclogitic mafic rocks may have been incorporated into metasedimentary sequences during exhumation processes in all scenarios considered.

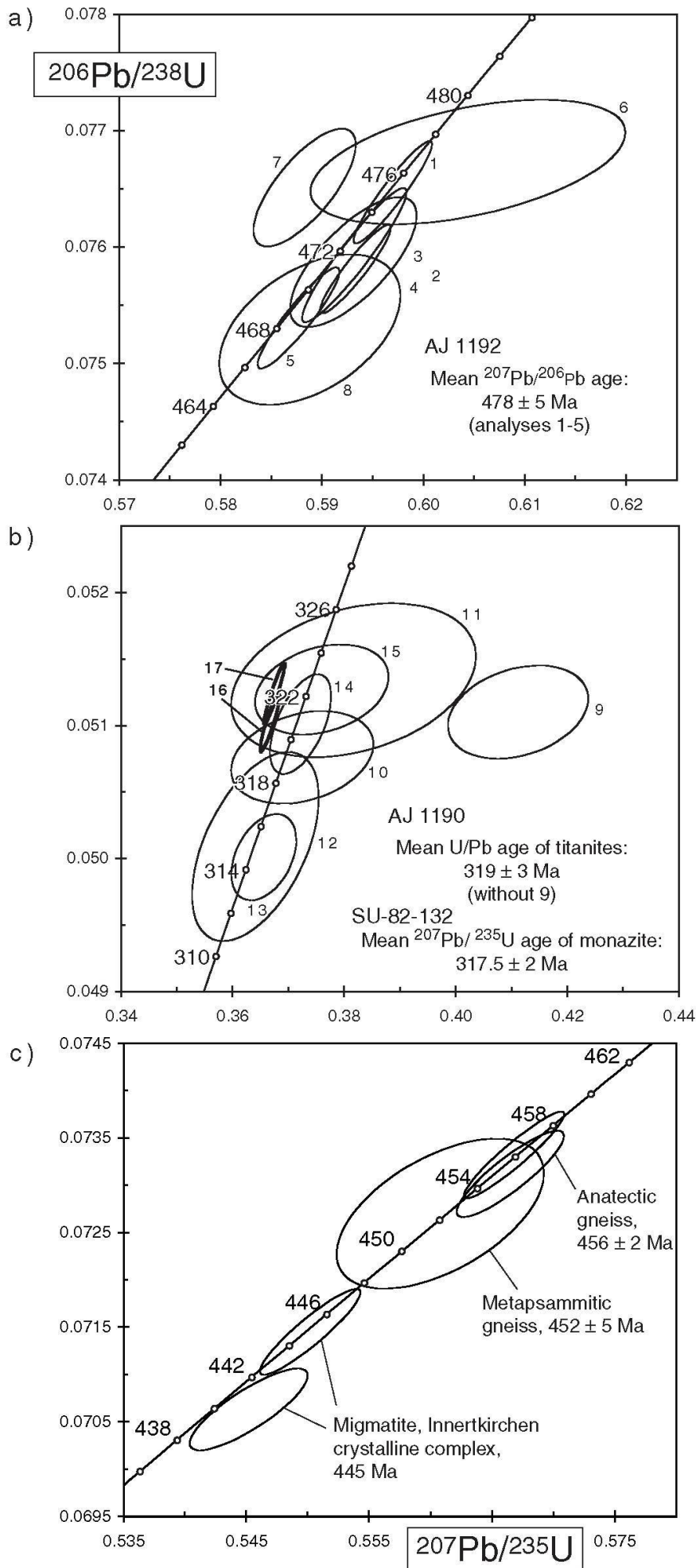
### HT equilibration in granulite facies, partial anatexis and decompression

The HP assemblage was followed and overprinted by a much better preserved high-grade metamorphic assemblage: It is represented by gar + plag + hbl  $\pm$  dio  $\pm$  bio + tit in amphibolites, by qtz + plag + gar + sill + bio + kfs and probably cordierite in metasediments, and by calc + qtz + dio + plag + gar + woll + ves + ep in calcsilicate rocks (Biino et al., 1999). This HT overprint also caused some local partial melting in metasedimentary rocks. Anatectic metasedimentary rocks are, however, not easily distinguished from orthogneisses due to textural and compositional convergence. The major lithology, the anatectic Erstfeld gneiss (Schaltegger, 1986, 1993) is considered to be derived from a metasedimentary protolith based on the multiple inheritance observed in the analyzed zircons (Schaltegger, 1993) as well as due to the intimate association with meta-conglomeratic and meta-pelitic gneisses (Schaltegger, 1984). The observed HT stage has been dated at ca. 456 to 450 Ma by U–Pb in zircon both in a migmatite and in a metasedimentary gneiss showing no sign of partial melting (Schaltegger, 1993; see Fig. 5c). Nearly isothermal decompression led to the formation and intrusion of cordierite-bearing pegmatites at  $445 \pm 2$  Ma (U–Pb zircon data; Schaltegger, 1993); the latter are thought to be coeval to the cordierite-bearing anatectic granite in the Innertkirchen area. These data provide the evidence for a pre-Variscan age of the HT parageneses within the Susten rocks, whereas in other areas of the Helvetic basement they are considered to be Variscan in age (Bussy et al., 1996; von Raumer et al., 1999).

### Variscan metamorphism

The Variscan metamorphic overprint is of lower grade and is recorded by mineral assemblages formed at upper greenschist and lower amphibolite facies conditions. The age of the Variscan meta-





*Fig. 5* (a) U–Pb concordia diagram for zircon from metagabbro AJ 1192. The mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $478 \pm 5$  Ma is taken as the age of intrusion of the protolith.

(b) U–Pb concordia diagram for titanites of calc-silicate gneiss AJ 1190 (analyses 9 to 15); and of monazite from a metapelitic layer (bold ellipses; sample SU-81-132). The titanite ages scatter between 315 and 323 Ma, whereas the two monazite analyses yield a precise  $^{207}\text{Pb}/^{235}\text{U}$  age of  $317.5 \pm 2$  Ma, interpreted as the age of Variscan metamorphism.

(c) Summary concordia plot of all concordant and near concordant zircons from Schaltegger (1993) that are indicative for an Ordovician age of the HT anatexis stage.

morphic overprint has been dated at  $329 \pm 2$  Ma by Schaltegger (1993) based on a zircon U–Pb age of amphibolite SU-81-55 and a rutile U–Pb age from sample SU-81-138. This is in agreement with an age of  $330 \pm 2$  Ma for monazite of a metasediment of the Pennine area in the western Alps (Bussy et al., 1996) and  $327 \pm 2$  Ma for monazite from non-migmatitic micaschists from Lac Emosson in the Aiguilles Rouges Massif (Bussy et al., 2002). The new titanite and monazite ages of  $319 \pm 3$  and  $317.5 \pm 2$  Ma, respectively, (samples AJ1190 and SU-82-138; Fig 5b) raise some question concerning the interpretation of the 329 Ma age as the peak of metamorphism: The scatter of the titanite data points along the concordia in Fig. 5b may be interpreted as continuous growth over some My (Frost et al., 2000), but the data define nevertheless a reliable average age of  $319 \pm 3$  Ma. The combined age of  $318 \pm 2$  Ma of titanite and monazite is in perfect agreement with U–Pb monazite ages from the Aiguilles-Rouges and Mt. Blanc Massifs of  $317 \pm 2$  and 321 Ma (Bussy and von Raumer, 1993; Bussy et al., 2000). The suggestion of Schaltegger (1993) that Variscan metamorphism did not exceed upper greenschist facies is thus probably wrong. The question remains whether the 330–329 Ma age of zircon and rutile from Schaltegger (1993) dates peak amphibolite facies metamorphism, in which case titanite and monazite would have recorded some secondary metamorphic pulse and reflect prolonged growth over some My (e.g. Corfu and Easton, 1997; Vavra and Schaltegger, 1999). In the case that the 329 Ma age may be biased towards a higher age by unresolved inherited Pb in both zircon and rutile, it would correspond to a maximum value for the Variscan metamorphic overprint. As a final and possibly most likely alternative, rutile and zircon may date mineral reactions during the prograde path (rutile precipitation from pre-existing Ti-oxides in the metapelitic gneiss, as well as coeval zircon crystallization during the decomposition of the pyroxene-bearing HP assemblage in the garnet-amphibolite). The young monazite age of  $306 \pm 5$  Ma from the Innertkirchen-Lauterbrunnen massif (Olsen et al., 2000; Olsen and Livi, 1999) may indicate that the granitoid intrusions persisting between 300 and 299 Ma (Schaltegger and Corfu, 1992) added enough heat and fluids to cause the growth of monazite.

#### ***Late Variscan intrusion of lamprophyre dykes***

The pre-Variscan high-grade rocks are crosscut by a series of minettes with undisturbed magmatic textures, which were shown to have cooled to 300 °C at approximately 312 Ma ago on the basis of

K–Ar systematics (Schaltegger, 1984, 1986). They represent a generation of high-Mg lamprophyre dykes with an  $\varepsilon_{\text{Hf}}$  value of +6 (Stille et al., 1989), which is thought to be indicative for derivation from an enriched subcontinental mantle source. They are therefore older than the Central Aar granite pluton (Schaltegger and Corfu, 1992) and it may be speculated that they are coeval with the  $332 \pm 2$  Ma old Giuf-Punteglias high-K suite (Schaltegger and Corfu, 1992; Schaltegger et al., 1991).

#### **The geodynamic position of Alpine basement terranes in the Ordovician**

The studied sequence near the Susten pass features an association of metasediments of different grain size (conglomerates to pelites), quartzites and carbonate rocks, beside massive units of amphibolites containing lenses of ultramafic rocks. We do not consider this rock association to be discriminant between an accretionary wedge and a passive margin situation. The tectonic mixing of sediments and mafic-ultramafic rocks is of course typical for a subduction scenario. Large-scale rifting along a passive margin would, however, produce an association of platform carbonates, slope sediments, possibly together with slices of continental rocks in extensional allochthons. Low-angle detachment faulting could lead to the exhumation of eclogites of a former subduction stage as well as of mantle rocks from the sea floor. The existence of eclogites is the only argument for a convergent setting, but they may be introduced into the geological context by tectonic mixing and would thus be to some extent unrelated to the evolutionary path of the host rocks. It may be speculated that the sequence represents coeval rock sequences from an active margin and a back-arc rift, mixed together by large-scale rifting. Unfortunately, this hypothesis cannot be corroborated by the results of geochemistry and isotope analyses.

The results of this study demonstrate that the northern Helvetic basement in the Central Alps hosts rocks that were formed during plate tectonic processes in the Early to the Late Ordovician (480 to 445 Ma) over a period of 35 My, including (convergent or divergent?) mafic magmatism, HP metamorphism in a subduction zone, crustal thickening and subsequent exhumation to a middle crustal level. An similar evolution has been found in the Gotthard Massif (Sergeev and Steiger, 1995; Oberli et al., 1994) and in the Aiguilles Rouges Massif (von Raumer et al., 2003). Similar rock associations in the Austroalpine Silvretta unit evidence an evolution starting with oceanic and active margin magmatism in the Late



Cambrian (Müller et al., 1995, 1996; Schaltegger et al., 1997) and ending with granitoid magmatism during an Ordovician to Silurian continental collision (Poller, 1997; Poller et al., 1997a,b).

The data fit the Ordovician paleogeographic reconstruction for the different units of the Alpine basement as parts of the Gondwana-derived Hun superterrane (Stampfli et al., 2000; von Raumer et al., 2002, 2003) or „European Hunic Terrane“ (Stampfli et al., 2002). Any reconstruction has to take into account that the Austroalpine nappes contain remnants of (back-arc) oceanic crust of late Cambrian age (530 Ma; Müller et al., 1996) which was subsequently consumed during closure of this back-arc basin and subduction (525 Ma; Schaltegger et al., 1997), and thus must have been positioned on both sides of an embryonic (and in a first stage abandoned) Paleotethys (see the reconstruction of Stampfli et al., 2002). The new oceanic basin of the Paleotethys possibly formed during back-arc spreading behind a renewed subduction which may be dated by the 478 Ma gabbro. Alternatively, the discussed Susten pass rock association may represent the tectonic mélange produced by rifting processes in the back-arc of ongoing subduction at an active margin.

The Helvetic and Pennine basements are considered to be relatively similar with respect to their lower Paleozoic evolution. The Pennine basement records active margin magmatism as early as 520 Ma (Schaltegger et al., 2002), whereas convergent and possibly coeval back-arc divergent processes studied in the Helvetic basement of the Aar and Gotthard Massifs are no older than 480 Ma. Intracontinental rifting within Penninic units, however, has been documented to be as old as 500 Ma (Bussy et al., 1996) and has been closely followed by granitoid magmatism during crustal thickening between 480 and 450 Ma (e.g., Guillot et al., 2002). As a general conclusion, independent of the possible geodynamic interpretations of individual units, one has to envisage complex microplate tectonics within this „European Hunic Terrane“, remnants of which are now spread over different Alpine nappe and basement units.

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