

Formation, subduction, and exhumation of Penninic oceanic crust in the Eastern Alps: time constraints from $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

Lothar Ratschbacher^{a,*}, Christian Dingeldey^a, Christine Miller^b,
Bradley R. Hacker^c, Michael O. McWilliams^d

^a*Institut für Geowissenschaften, Technische Universität Bergakademie Freiberg,
Bernhard-von-Cottastr. 2, D-09596 Freiberg/Sachsen, Germany*

^b*Institut für Mineralogie und Petrographie, Universität Innsbruck, A-6020 Innsbruck, Austria*

^c*Department of Geological Sciences, University of California, Santa Barbara, CA 93106, USA*

^d*Department of Geology and Environmental Sciences, Stanford University, Stanford, CA 94305-2215, USA*

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Abstract

New $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology places time constraints on several stages of the evolution of the Penninic realm in the Eastern Alps. A 186 ± 2 Ma age for seafloor hydrothermal metamorphic biotite from the Reckner Ophiolite Complex of the Pennine–Austroalpine transition suggests that Penninic ocean spreading occurred in the Eastern Alps as early as the Toarcian (late Early Jurassic). A 57 ± 3 Ma amphibole from the Penninic subduction–accretion Rechnitz Complex dates high-pressure metamorphism and records a snapshot in the evolution of the Penninic accretionary wedge. High-pressure amphibole, phengite, and phengite+paragonite mixtures from the Penninic Eclogite Zone of the Tauern Window document exhumation through ≤ 15 kbar and > 500 °C at ~ 42 Ma to ~ 10 kbar and ~ 400 °C at ~ 39 Ma. The Tauern Eclogite Zone pressure–temperature path shows isothermal decompression at mantle depths and rapid cooling in the crust, suggesting rapid exhumation. Assuming exhumation rates slower or equal to high-pressure–ultrahigh-pressure terrains in the Western Alps, Tauern Eclogite Zone peak pressures were reached not long before our high-pressure amphibole age, probably at ≤ 45 Ma, in accordance with dates from the Western Alps. A late-stage thermal overprint, common to the entire Penninic thrust system, occurred within the Tauern Eclogite Zone rocks at ~ 35 Ma. The high-pressure peak and switch from burial to exhumation of the Tauern Eclogite Zone is likely to date slab breakoff in the Alpine orogen. This is in contrast to the long-lasting and foreland-propagating Franciscan-style subduction–accretion processes that are recorded in the Rechnitz Complex.

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Keywords: Alps; Penninic unit of the Eastern Alps; Ar/Ar geochronology; Spreading; Subduction; Exhumation

* Corresponding author. Tel.: +49 3731 393758; fax: +49 3731 393599.

E-mail address: lothar@geo.tu-freiberg.de (L. Ratschbacher).

1. Introduction

The Tertiary evolution of the Alps is related to roughly south-directed subduction of Penninic oceanic lithosphere, collision of Penninic continental units, and, ultimately, the European continent with the Austroalpine micro-continent (e.g., Frisch, 1979). The Penninic oceanic crust formed during the Jurassic. In the Eastern Alps, its age is loosely constrained by Callovian to Oxfordian fossils (~164–154 Ma; summary in Faupl and Wagerich, 2000), a 182 ± 31 Ma Sm/Nd plagioclase–clinopyroxene isochron from an ophiolite remnant in the Engadine Window (Fig. 1; Idalpe; Thöni, 1999), and a 217 ± 59 Ma (186 ± 12 Ma, see later) Sm/Nd whole rock isochron from the Reckner Ophiolite Complex (Fig. 1; Meisel et al., 1997). In the Western Alps, fossil evidence suggests Middle to Late Jurassic (~180–145 Ma) deposition of oceanic sediments (e.g., Baumgartner, 1987) and spreading between ~185–155 Ma, with a cluster of radiometric ages at ~160 Ma (Sm/Nd, U/Pb, and Ar/Ar methods applied mostly to gabbros; summary in Rubatto et al., 1998).

The onset of Penninic subduction is poorly constrained. In the Eastern Alps, accretion along the Austroalpine margin was certainly active from late

Early Cretaceous to earlymost Tertiary (~110 to 60 Ma; Faupl and Wagerich, 2000), but the presence of pelagic Eocene sediments requires that the final ocean closure occurred no earlier than the early Eocene (~55 Ma; e.g., Oberhauser, 1991). Penninic high-pressure metamorphic rocks are well known from the Tauern Window (“Tauern Eclogite Zone”, Fig. 1; e.g., Miller, 1977) and occur as small blueschist bodies within the Recknitz Window group along the eastern edge of the Alps (Fig. 1; Koller, 1985). Zimmermann et al. (1994) presented the first reliable ages on the high-pressure metamorphism in the Tauern Eclogite Zone; phengite, closed during cooling of the nappe pile through blueschist–facies metamorphic conditions, yielded ~35 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$ geochronology). In the Western Alps, the age of deepest subduction of Penninic crust is well-dated at ~44 Ma in the Zermatt–Sass-Fee ophiolites (Rubatto et al., 1998) and at ~35 Ma in the Dora Maira ultrahigh-pressure continental massif (Gebauer et al., 1997) by U/Pb ionprobe zircon geochronology.

Here, we present new $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole and mica ages from the Penninic oceanic and transitional crust of the Eastern Alps. A late Early Jurassic age (186 ± 2 Ma) of oceanic metamorphism records initial spreading within strongly attenuated crust along the

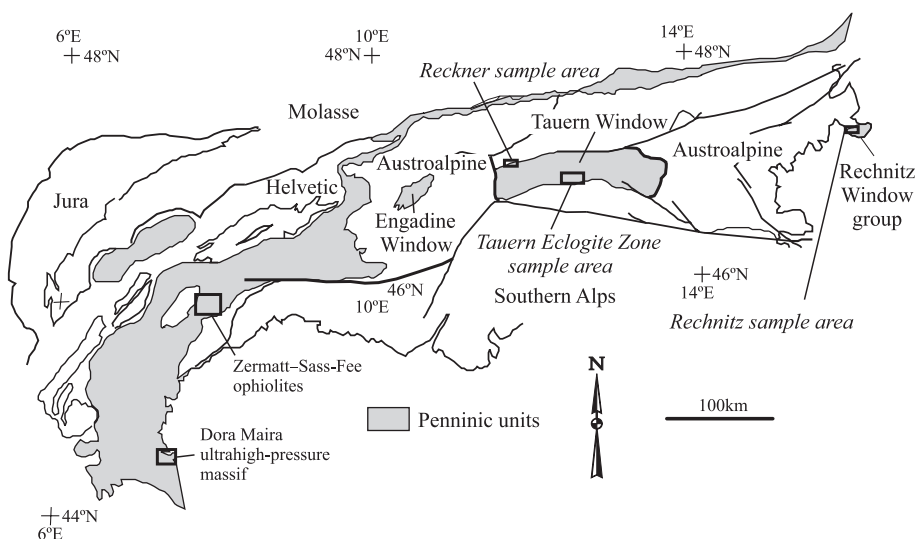


Fig. 1. Simplified tectonic map centered on the Eastern Alps with the major tectonic units of the Tertiary Alpine orogen (Molasse, Jura, Helvetic: European continental basement and cover; Penninic: continental and dominantly oceanic units; Austroalpine and Southern Alps: basement and cover of African affinity and hanging wall plate during Alpine collision). (□) Sample areas (location names in italics) and well-dated high-pressure and ultrahigh-pressure localities.

Austroalpine–Pennine transition (Reckner Ophiolite Complex). Penninic accretionary–wedge sediments (Rechnitz Complex) contain Late Paleocene (57 ± 3 Ma) blueschists, and Tauern Eclogite Zone gabbros and related metasedimentary rocks were on an exhumation path by at least the Middle Eocene (≤ 42 Ma).

2. Geological setting

The Austroalpine–Penninic border area in the northwestern Tauern Window (Fig. 1) constitutes a fragmented continental margin in which the Reckner Ophiolite Complex represents one of the oldest sections of Alpine oceanic lithosphere. It likely was originally situated close to, or even within, the Austroalpine unit (e.g., Dingeldey et al., 1997). The Reckner Ophiolite Complex is the largest exposure of ultramafic–mafic structural units with the lowermost Austroalpine thrust system. It consists primarily of serpentinized lherzolite with subordinate harzburgite, dunite, and gabbro. A high-temperature (HT) mineral assemblage, including large crystals of magnesiohornblende, pargasite, and Ti-biotite, was interpreted by Dingeldey et al. (1995, 1997) as having formed during seafloor hydrothermal metamorphism shortly after crystallization of the host rocks. The Reckner Ophiolite Complex also contains relics of a high-pressure (HP), low-temperature metamorphic event: blueschists occur in fine-grained, laminated, albite, quartz, sodic amphibole (crossite to Mg–riebeckite), titanite, phengite, and (rarely) sodic pyroxene-bearing sedimentary to volcanoclastic rocks (Dingeldey et al., 1995, 1997). Whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ ages of abundant, high-Si phengite-bearing phyllites and cherts are around 50 and 44–37 Ma (Dingeldey et al., 1997), indicating incorporation of the Rechnitz Ophiolite Complex into the Penninic subduction–accretion wedge at that time.

The “Rechnitz Complex” in the Rechnitz Window group—a series of small tectonic windows exposing Penninic units below Tertiary sediments of the Pannonian basin and Austroalpine nappes along the Alpine–Carpathian transition (Fig. 1, e.g., Ratschbacher and Behrmann, 1990)—comprise calcareous phyllites, schists, quartzites, and ophiolite complexes. The latter consist of serpentinized ultramafic rocks,

meta-gabbro, ophicarbonates, and greenschist. Blueschists occur as small lenses of meta-dioritic to metaplagiocratic composition and consist mainly of alkali amphibole and albite (Koller, 1985). Large, strongly zoned alkali amphibole replaced alkali pyroxene, which occurs as relics ($\leq 20\%$ jadeite). Small idiomorphic alkali amphiboles also occur in the groundmass. The amphiboles are crossites to riebeckites with glaucophane components $\leq 60\%$. The mineral paragenesis within the blueschist, Mg-rich pumpellite, ferroglaucophane, alkali pyroxene, relics of lawsonite, and stilpnomelane, indicates PT conditions of 330–370 °C at 6–8 kbar (Koller, 1985). The HP assemblage was overprinted at 390–430 °C and ≤ 3 kbar (Koller, 1985); this thermal event and subsequent cooling is dated at ≤ 22 Ma (K/Ar white mica and zircon fission-track data; summary in Dunkl and Demény, 1997).

The Tauern Eclogite Zone of the south-central Tauern Window (Fig. 1) occurs at the base of an imbricate stack of mostly oceanic and accretionary–wedge sedimentary rocks and at the top of Penninic

Table 1
Geochronology sample descriptions and locations

Sample	Location	Description
<i>Reckner Ophiolite Complex hydrothermal biotite</i>		
D1	Tarntaler Berge, Staffelsee	Serpentinized lherzolite, ultramafic cumulate, >2 cm biotite crystals, partly chloritized
<i>Rechnitz Complex blueschist alkali–amphibole</i>		
R23	Glashütten bei Schleining	Blueschist metamorphic ferrodiorite and plagiogranite
<i>Penninic Eclogite Zone hornblende and mica</i>		
ES40	Timmelbachtal, S of Eissee	Late-stage garnet and amphibole in garben–micaschist
TS4035	Frosnitztal, Steinsteig	Omphacite–kyanite–amphibole–talc–apatite vein in kyanite–eclogite
ES25	Timmelbachtal, NW of Eissee	Massive, weakly foliated eclogite
ES27	Timmelbachtal, NW of Eissee	Garnet–micaschist
JH1	Dorfertal, Johannishütte	Retrogressed garnet–micaschist from the top of the Venediger nappe (base of Eclogite Zone)
ES3	Timmelbachtal, N of Eissee	Garnet–micaschist
ES20	Timmelbachtal, base of Eclogite Zone	Garnet–micaschist at the top of massive eclogite

continental basement nappes (Venediger nappe; summary in Kurz et al., 1998a). Miller et al. (1980) interpreted the rock association—eclogites of tuffaceous to gabbroic protholiths and meta-sediments (quartzite, paragneiss, garnet–micaschist, calcareous schist, marble)—to indicate initial oceanic rifting along a highly attenuated passive continental margin influenced by terrigenous sedimentation. The metamorphic evolution encompasses a prograde greenschist–blueschist facies event, preserved only as inclusions in garnets, the eclogite–facies stage (550–630 °C, ~20 kbar), a retrograde blueschist stage (~450 °C, 10–15 kbar), and a widespread upper greenschist to lower amphibolite facies event (the “Tauern event”; 500–550 °C, 6–7 kbar; summaries in Zimmermann

et al., 1994 and Kurz et al., 1998b). Zimmermann et al. (1994) obtained ~35 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ ages on phengitic micas attributed to the retrograde blueschist event, and 27 Ma and younger ages on low-Si micas.

We obtained samples from the Reckner Ophiolite Complex oceanic metamorphic mineral assemblage, a Rechnitz Complex blueschist, and the Tauern Eclogite Zone meta-sedimentary and meta-volcanic rocks for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. Sample descriptions and locations are given in Table 1. We only sampled localities where a detailed petrologic framework has been established by previous quantitative studies (see below). In addition, prior to the mineral selection and isotopic analysis, thin sections were examined by optical microscopy, and minerals close to those dated

Table 2
Mineral chemistry^a

	Biotite	Amphibole	Amphibole	Amphibole		Paragonite ^b	Paragonite ^c	Phengite ^b	Phengite ^c	Phengite ^c
	D1	R23	ES40	T4035 core	T4035 rim	ES25	ES27	ES25	ES20	ES3
SiO ₂	38.96	54.20	54.0	56.91	57.22	48.78	47.4	50.66	49.50	50.00
Al ₂ O ₃	16.80	6.59	7.5	10.6	10.8	39.59	38.8	28.10	28.99	26.93
TiO ₂	6.67	-	0.10	0.08	0.12	0.01	0.14	0.21	0.24	0.34
MgO	19.65	4.36	17.0	15.3	14.7	0.39	0.39	3.50	2.35	2.83
CaO	0.48	0.44	8.2	4.7	3.72	0.13	0.17	0.02	0.00	0.00
K ₂ O	7.59	0.07	0.17	0.03	0.08	0.62	1.07	10.00	10.78	10.40
Na ₂ O	0.39	6.69	3.6	5.1	5.8	6.39	7.39	1.00	0.69	0.34
Cr ₂ O ₃	0.29	-	0.05	0.02	0.06	0.00	0.03	0.07	0.00	0.01
MnO	0.05	0.14	0.07	0.02	0.03	0.00	0.01	0.00	0.00	0.01
Fe ₂ O ₃	na	7.06	3.7	na	na	na	na	na	na	na
FeO	7.46	17.35	3.3	5.64	5.42	0.39	0.42	2.00	2.66	3.58
Total	98.34	96.9	97.69	98.4	97.95	96.3	95.82	95.56	95.21	94.44
Si ^d	5.404	7.994	7.460	7.620	7.701	6.682	6.017	6.732	6.640	6.780
Al ^d	5.388	1.145	1.210	1.673	1.715	6.391	5.862	4.401	4.582	4.30
Al ^{IV}	2.596	na	na	0.380	0.299	na	na	na	na	na
Al ^{VI}	0.098	na	na	1.293	1.416	na	na	na	na	na
Cr ^d	0.046	0.000	0.005	0.000	0.008	0.000	0.003	0.006	0.000	0.000
Fe ^d	0.880	2.918	0.752	0.636	0.607	0.045	0.040	0.243	0.296	0.382
Fe ²⁺	na	na	na	0.244	0.361	na	na	na	na	na
Fe ³⁺	na	na	na	0.392	0.246	na	na	na	na	na
Mg ^d	3.862	0.949	3.530	3.058	2.953	0.080	0.070	0.689	0.460	0.580
Mn ^d	0.000	0.015	0.008	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Ti ^d	0.724	0.000	0.010	0.008	0.016	0.001	0.015	0.020	0.024	0.040
Ca ^d	0.014	0.065	1.233	0.676	0.534	0.019	0.024	0.001	0.000	0.000
Na ^d	0.252	1.914	0.965	1.328	1.513	1.697	1.830	0.264	0.175	0.082
K ^d	1.636	0.011	0.031	0.008	0.016	0.108	0.173	1.663	1.850	1.798
Total	15.386	15.011	14.518	15.007	15.063	15.023	14.035	14.019	14.027	13.962

na, not analyzed.

^a Given analyses are representative only for portions of the dated material and may vary due to mineral zoning (see text for details).

^b From eclogite (garnet–omphacite–kyanite–talc–quartz–rutile±pyrite).

^c From garnet–micaschist (garnet–phengite–zoisite) in contact with eclogite.

^d Calculated for 23 O for amphibole and 22 O for mica.

were analyzed by electron microprobe (Table 2). Using the previous petrologic studies and the thin section and mineral chemistry data, the minerals were assigned to particular stages of the polyphase Alpine metamorphic evolution.

3. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

3.1. Analytical techniques

Amphibole and micas were broken from rock slabs and thick sections that were used for electron-microprobe mineral characterization (after removing the carbon coating by polishing) and finally handpicked under a binocular microscope. This procedure allowed a semiquantitative comparison of mineral chemical data (here K/Ca ratios) derived by microprobe spot analyses and release of Ar isotopes during step heating (see, e.g., Villa et al., 2000 for a comparable but more rigorous analysis). Ultimately 1 to 15, optically inclusion-free, ultraclean grains were selected. The $^{40}\text{Ar}/^{39}\text{Ar}$ analyses were performed at Stanford University with analytical procedures identical to those published in Hacker et al. (1996). In short, the minerals were cleaned by ultrasound, rinsed in acetone, isopropyl alcohol, and distilled water, packaged in pure Cu foil, stacked in SiO_2 vials together with neutron fluence monitors, and irradiated in four different irradiations (S10, S16, S22 and S24) at the Oregon State University TRIGA reactor. We used Taylor Creek sanidine (USGS standard 85G003; Duffield and Dalrymple, 1990) with an assigned age of 27.92 ± 0.17 Ma as a neutron fluence monitor. The grains were heated under UHV conditions in a double-vacuum Staudacher-type resistance furnace. The evolved gas was purified during extraction by SAES ST-172 and ST-101 getters and a stainless steel cold finger and was analyzed on a MAP 216 mass spectrometer fitted with a Baur–Signer ion source and a Johnston MM1 multiplier with a sensitivity of approximately 2×10^{-14} mol/V. Analyses were corrected for system blanks and instrumental mass discrimination using the program EyeSoreCon written by B.R. Hacker.

Uncertainties for ages quoted in this paper are 1σ standard deviation. “Internally concordant” and “externally concordant” refer to statistically equivalent

intrasample step ages and intersample ages, respectively. Fig. 2 displays $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and K/Ca ratios; isotope correlation diagrams are displayed only for those separates that contain excess ^{40}Ar ; however, all these samples can be fitted reasonably well with an isochron. Table 3 provides analytical details, including the calculated total fusion ages (TFAs), isochron ages (IAs), weighted mean plateau ages (WMPAs), and weighted mean ages (WMAs), and our interpretation of the data. We use “weighted mean age” (WMA) to describe an age calculated from a sequence of step ages that are not serially increasing or serially decreasing (i.e., $\partial_{\text{age}}/\partial_{\text{cumulative } ^{39}\text{Ar}}=0$), but are not statistically concordant (i.e., not a plateau). The raw data can be obtained from http://www.geo.tu-freiberg.de/tektono/E_links.htm.

3.2. Results: ocean metamorphism, Ti-biotite from the Reckner Ophiolite Complex

Biotites (Table 2) of up to 2-cm size are preserved in chlorite shells in various stages of chloritization. Finely dispersed titanite–leucosene inclusions occur. Dingeldey et al. (1995) suggested that the host rock was a (ultra)mafic cumulate affected by metasomatic alteration during HT oceanic metamorphism, during which the large biotite crystals grew as pseudomorphs after clinopyroxene. The Reckner Ophiolite Complex was affected later by a high-pressure metamorphic event ($\sim 380^\circ\text{C}$, 10–12 kbar), for which there is no evidence in the investigated sample, and a pervasive greenschist-grade event ($\sim 440^\circ\text{C}$, 3–4 kbar), which transformed most of the biotite to chlorite (Dingeldey et al., 1995, 1997). To address the problem of alteration, we cut small pieces under the binocular microscope from the center of a large crystal, and analyzed separately five, three, and one, optically unaltered pieces comprising 1.0 to 0.1 mg. All three splits provided internally discordant ages; however, the TFA, WMA, and IA of each split overlap within error (Fig. 2a). The K/Ca ratios of the steps used in the age calculation are 0.4–6.0, lower than the 12–117 ratios obtained from three microprobe spots; this indicates that the optically pristine biotite pieces are altered, likely by chlorite. The isochrons for the chosen steps are close to a good fit and the $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts are about atmospheric (Table 3). Combining

all data and removing the possibly chloritization-induced humps in the spectra yields a ~ 186 Ma age (Fig. 2a). Taken together, an age of 186 ± 2 Ma likely describes cooling of the oceanic metamorphic biotite after host-rock emplacement.

3.3. Results: blueschist-metamorphism, Rechnitz Complex accretionary assemblage

We selected mostly idiomorphic, alkali amphibole crystals from a pure albite–alkali amphibole cluster. It is part of a homogeneous blueschist sample consisting of alkali amphibole and albite and rare epidote and alkali pyroxene; the locality was studied in detail by Koller (1985). The amphibole can be classified as crossite, but Koller (1985) showed that some amphiboles have riebeckitic rims. As inclusions are a major obstacle in amphibole dating (e.g., Sisson and Onstott, 1986), we analyzed two splits, consisting of 15 and 3 grains comprising 4.7 and 1.0 mg, respectively. The splits appear inclusion free, except for few very fine-grained titanite and undetermined opaque minerals in the larger separate. The 15-grain spectrum is U-shaped, suggesting excess ^{40}Ar in its low- and high-temperature steps. However, the central age steps yield a plateau with $>70\%$ of the gas (Fig. 2b). The smaller separate gave little gas; three of the four steps are internally concordant and yield within error an age identical to the larger split (Fig. 2b). The average K/Ca ratio is ~ 0.07 and thus lower than the 0.16 ratio determined from microprobe analysis (Table 2). This suggests that (i) no K-bearing phase other than amphibole (e.g., mica, see Sisson and Onstott, 1986) contributed to the evolved gas and (ii) either another Ca-bearing phase is present or the dated minerals are more heterogeneous as our microprobe work indicates. We interpret the 57 ± 3 Ma age of the combined separates as the age of the amphibole.

3.4. Results: high-pressure cooling path, Tauern Eclogite Zone, Tauern Window

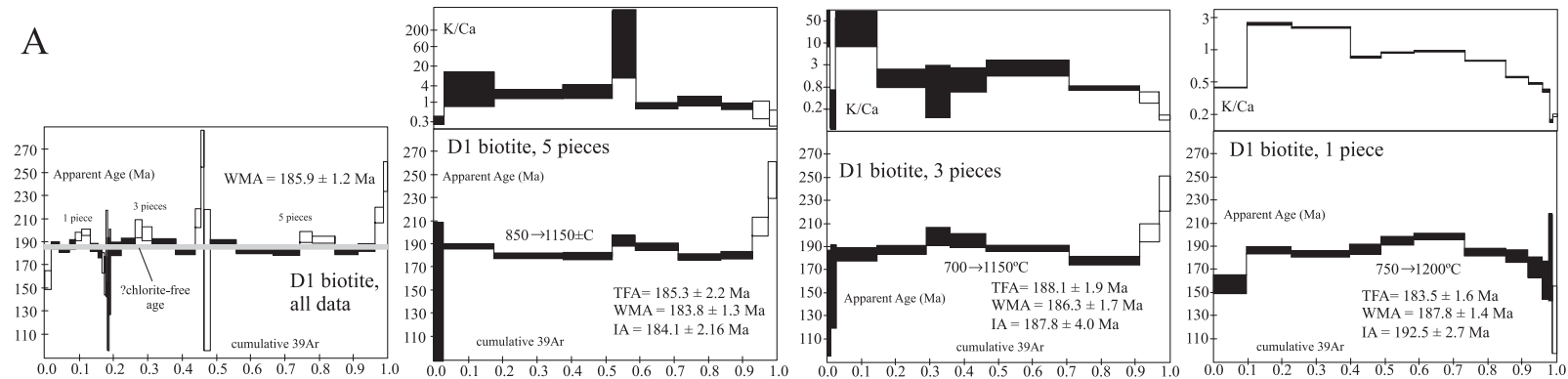
We dated two amphibole separates. Separate ES40 comprises post-eclogitic amphiboles with a composition between barroisite and actinolite, grown within a garben micaschist (stage M_{a2} of Alpine metamorphism; Holland, 1979; Zimmermann et al., 1994). These amphiboles occur as replacements of omphacite

and barroisite that characterize the peak-pressure assemblage (e.g., Miller, 1977). The spectrum is complex, containing U- and saddle-shaped portions indicating excess ^{40}Ar (Fig. 2c). The youngest steps form a plateau comprising 7% of the gas. We suggest a maximum age of 35 ± 2 Ma for this separate.

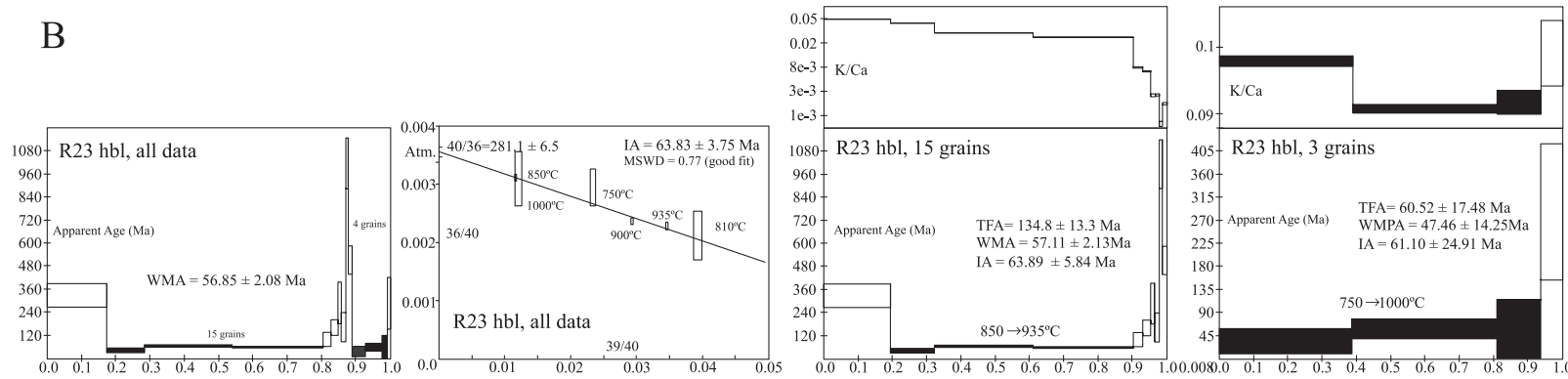
Separate T4035 comprises strongly zoned amphiboles with sodic–calcic cores and alkali–amphibole rims from an omphacite–kyanite–amphibole–talc–apatite vein (Table 2). These veins formed during deformation at eclogite–blueschist conditions (stages M_{a0} and M_{a1} ; Holland, 1979; Zimmermann et al., 1994) during initial exhumation of the Tauern Eclogite Zone (e.g., Behrmann and Ratschbacher, 1989; Kurz et al., 1998b). Single crystals of these amphiboles were analyzed with a continuous Ar-ion laser to probe potential age differences between core and rim, but the obtained ages do not show a consistent older–younger zonation from core to rim, suggestive of excess ^{40}Ar . Subsequent resistance furnace analysis was performed on two splits of different weight. Both fractions gave U-shaped spectra with a central plateau, comprising the youngest steps and $\sim 25\%$ of the gas (Fig. 2c). The K/Ca ratios of ~ 0.030 of the central plateau steps are identical to the ratios determined by microprobe from the rims of these amphiboles. We suggest that these zoned mineral formed 40 and 45 Ma and we use a combined maximum age of 42 ± 4 Ma for the two T4035 amphiboles splits.

Microprobe work identified variable amounts of paragonite in the eclogites and less so in the micaschists in contact with the eclogites (see also Miller, 1977). We attempted to enrich paragonite in samples ES25 and ES27 by breaking out pieces of mica from the areas where microprobe spots had identified paragonite. Concentrate ES25 is from an unaltered and unretrogressed eclogite and ES27 from a nearby eclogite–facies garnet–micaschist overlying the massive eclogite. In the sampled locality, paragonite was classified as having formed at peak-PT conditions and during early decompression (e.g., Miller, 1977; Kurz et al., 1998b; stage M_{a0} , Holland, 1979; Dachs, 1986; Spear and Franz, 1986; Zimmermann et al., 1994; Hosccek, 2001). “Paragonite” concentrate ES25 is internally discordant and yielded a poorly defined isochron with a $^{40}\text{Ar}/^{36}\text{Ar}$ ratio greater than the atmosphere (Fig. 2c). However, a

Reckner Ophiolite Complex; oceanic metamorphism



Rechnitz Complex; blueschist-bearing subduction-accretion unit



Tauern Window; Penninic Eclogite Zone

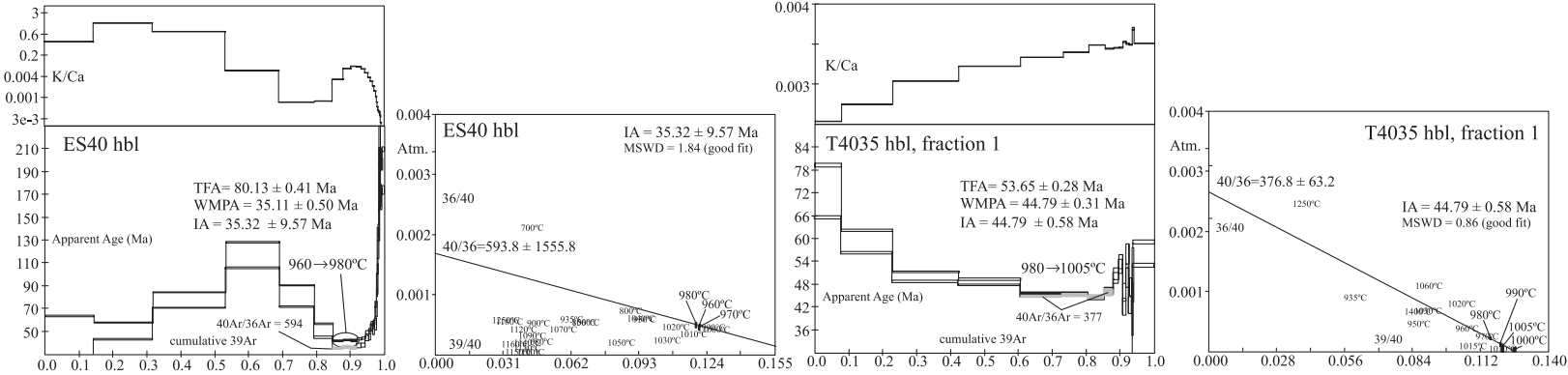


Fig. 2. New $^{40}\text{Ar}/^{39}\text{Ar}$ data from the Eastern Alps. Data are displayed as “plateau” ages and isotope correlation diagrams are shown only for those mineral separates which contain excess ^{40}Ar . Steps used to compute weighted mean (WMA) and isochron ages (IA) are shaded black. One-sigma uncertainties are shown excluding error in irradiation parameter J. TFA, total fusion age; WMPA and WMA, weighted mean plateau and weighted mean ages, respectively. MSWD, mean squared weighted deviation. WM(P)A of samples T4035 and ES25 are recalculated with the $^{40}\text{Ar}/^{36}\text{Ar}$ ratios given in Table 3.

Tauern Window; Penninic Eclogite Zone

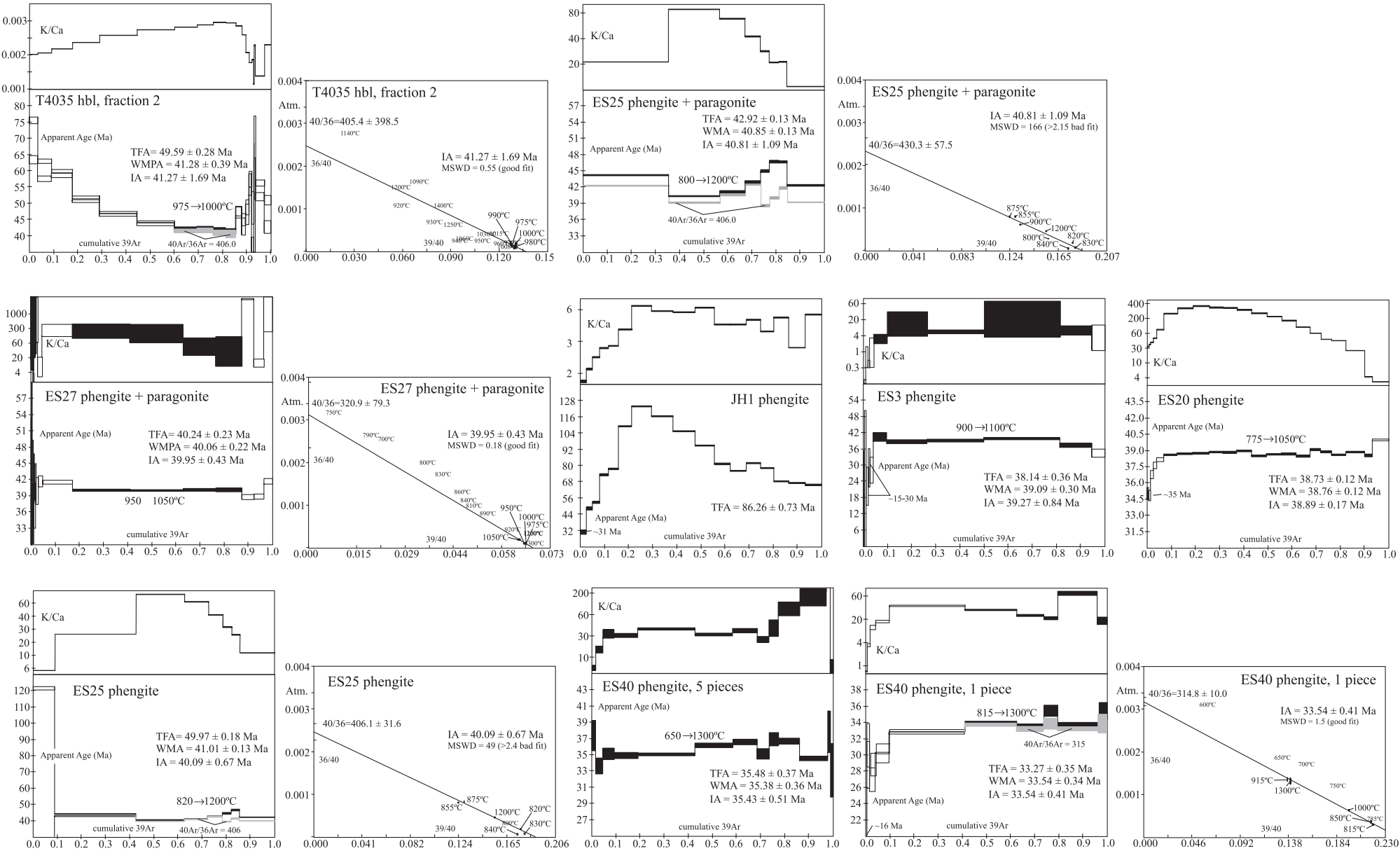


Fig. 2 (continued).

Table 3
Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ data

Sample	Mineral	<i>J</i>	Weight (mg)	Grain size (μm) ^a	TFA (Ma)	IA (Ma)	MSWD	$^{40}\text{Ar}/^{36}\text{Ar}$	WM(P)A (Ma)	Steps used	% ³⁹ Ar used
<i>Reckner Ophiolite Complex; hydrothermal biotite, oceanic metamorphism</i>											
D1 all data ^b	bio		na	na	na	na			185.9±1.2	14/32	70
D1 5 pieces	bio	0.0015211	0.9	na	183.8±1.3	184.1±2.2	4.3/2.2	292±9	183.8±1.3	1-8/10	93
D1 3 pieces	bio	0.0015185	1.0	na	188.1±1.9	187.8±4.0	2.9/2.2	280±34	186.3±1.7	1-8/10	91
D1 1 piece	bio	0.0032970	0.1	na	183.5±1.6	192.5±2.7	3.9/1.9	281±5	187.8±1.4	1-11/12	99
<i>Rechnitz Complex; blueschist-bearing subduction–accretion unit</i>											
R23 all data	amph		na	na	126.8±12.0	63.83±3.75	0.8/1.9	281±6	56.85±2.08	6/14	74
R23 15 grains	amph	0.0033430	4.7	na	134.8±13.3	63.89±5.84	2.3/3.8	281±10	57.11±2.13	2-4/10	71
R23 3 grains	amph	0.0033450	1.0	na	60.52±17.48	61.10±24.91	0.3/3.8	269±25	47.46±14.25	1-3/4	94
<i>Tauern Window; Penninic Eclogite Zone, high-pressure metamorphic complex</i>											
ES40	hbl	0.0033050	23.1	na	80.13±0.41	35.32±9.57	1.8/3.8	594±1556	35.11±0.50	7-9/28	7
T4035	hbl	0.0031720	41.5	na	53.65±0.28	44.79±0.58	0.9/3.0	377±59	44.79±0.31	5-8/15	27
fraction 1											
T4034	hbl	0.0031450	35.0	na	49.59±0.28	41.27±1.69	0.6/3.0	405±297	41.28±0.39	7-10/19	25
fraction 2											
ES25	ph+pg	0.0042500	2.9	250	42.92±0.13	40.81±1.09	166/2.2	430±58	40.85±0.13	1-8/8	100
ES27	ph+pg	0.0015179	3.1	250	40.24±0.22	39.95±0.43	0.2/3.0	321±34	40.06±0.22	11-14/17	70
JH1	ph	0.0041810	0.8	125	86.26±0.73	na		na	na	1-17/17	100
ES3	ph	0.0015255	1.1	250	38.14±0.36	39.27±0.84	3.6/2.6	288±30	39.09±0.30	6-10/11	91
ES20	ph	0.0042415	5.0	250	38.73±0.12	38.89±0.17	5.3/1.8	270±22	38.78±0.12	8-20/21	87
ES25	ph	0.0042500	2.9	250	49.97±0.18	40.09±0.67	49/2.4	406±32	41.01±0.13	3-8/8	58
ES40 5 pieces	ph	0.0045170	0.8	na	35.48±0.37	35.43±0.51	6.3/1.9	291±32	35.38±0.36	1-13/13	100
ES40 1 piece	ph	0.0045450	0.3	na	33.27±0.35	33.54±0.41	1.5/2.6	315±10	33.54±0.35	6-10/10	59

J is the irradiation parameter; MSWD is the mean square weighted deviation (Wendt and Carl, 1991), which expresses the goodness-of-fit of the isochron. (Roddick, 1978); isochron and weighted mean ages are based on fraction of ^{39}Ar listed in the last column. Italics: weighted mean plateau ages.

Abbreviations: na, not analyzed; bio, biotite; amph, alkali–amphibole; ph, phengite; hbl, hornblende; pg, paragonite.

Age interpretations: D1 bio all data: 186 ± 2 Ma; R23 hbl: 57 ± 3 Ma; High-pressure hbl, total data (T4035 both fractions): 42 ± 4 Ma. T4035 hbl fraction 1: WMPA recalculated with $^{40}\text{Ar}/^{36}\text{Ar}=377$; 44 ± 2 Ma; T4035 hbl fraction 2: WMPA recalculated with $^{40}\text{Ar}/^{36}\text{Ar}=405$; 41 ± 2 Ma. High-pressure ph+pg, total data (ES25, ES27): 40.5 ± 2.0 Ma. ES25 ph+pg: WMA recalculated with $^{40}\text{Ar}/^{36}\text{Ar}=430$; 41 ± 2 Ma; ES27 ph+pg: 40.0 ± 0.5 Ma; High-pressure ph, total data (ES3, ES20, ES25): 39 ± 2 Ma. ES3 ph: 39 ± 1 Ma; ES20 ph: 38.8 ± 0.3 Ma; low-temperature loss profile, youngest step: 35.0 ± 0.5 Ma; ES25 ph: WMA recalculated with $^{40}\text{Ar}/^{36}\text{Ar}=406$; 40.5 ± 1 Ma; Retrogression from high-pressure assemblage. ES40 hbl: 35 ± 2 Ma; ES40 ph: 34 ± 2 Ma; JH1 ph: excess ^{40}Ar , youngest step at 30.9 ± 1.4 Ma.

^a Grain size distribution depends on hand picking of optical clear, unaltered, inclusion-free grains in case of na.

^b Calculated from combining the five, three and one piece splits and excluding the ?chloritization-induced humps in the spectra.

41 ± 2 Ma age describes the TFA, IA, and WMA of the separate. Concentrate ES27 displays a well-behaved age spectrum with the central 70% of the gas yielding a plateau (Fig. 2c). The TFA, WMPA, and IA yield a consistent 40.0 ± 0.5 Ma age. The Ar-isotope-derived K/Ca ratios (11–369) for the steps used for age calculation are higher than the microprobe-derived ones (6–7) for paragonite and similar to those of the phengite concentrates (see below), demonstrating that the “paragonite” concentrates comprise mostly phengite. We suggest that a

40.5 ± 2.0 Ma age best describes closure during cooling from peak-PT conditions of those micas.

Separates JH1, ES3, ES20, ES25, and ES40 are phengites. The microprobe-derived Ca-concentrations of most of our phengite spots are too low to derive reliable K/Ca ratios, preventing a direct comparison with the Ar-isotope derived ones, which are with exception of sample JH1 in general between 10 and 300. Separate JH1 is from a strongly retrogressed garnet–micaschist from the top of the Venediger nappe, the footwall of the Tauern Eclogite Zone and

it also contains chlorite. The spectrum is highly discordant and hump shaped, thus indicative of excess ^{40}Ar ; no isochron could be fitted to the data (Fig. 2c). The low-temperature part of the spectrum shows ages that decrease monotonically to 30.9 ± 1.4 Ma, which is interpreted to give an indication of the age of retrogression of the micaschist. The low K/Ca ratios likely indicate intergrown chlorite. Separate ES40, from the same garben micaschist of amphibole separate ES40 (see above), comprises second generation, post-eclogite facies mica (stage M_{a2} , Holland, 1979). We analyzed two fractions (Fig. 2c). The five-piece fraction constitutes portions broken from the center of large grains and the one-piece fraction comprises the outer edge of a large grain. For the larger fraction, the TFA, WMA, and IA are equivalent for all steps at 35.4 ± 0.5 Ma. The data for the single-grain rim yielded a good fit isochron for the middle- and high-T steps, with a slightly greater than atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and a 33.5 ± 0.5 Ma age. The low-temperature steps decrease to 15.8 ± 4.3 Ma.

Phengite separate ES25 is from the same pristine, unretrogressed massive eclogite layer as “paragonite” concentrate ES25 (stage M_{a0}). It shows a weakly discordant spectrum and a poorly defined isochron with a $^{40}\text{Ar}/^{36}\text{Ar}$ intercept larger than atmosphere and a 40 ± 1 Ma age (Fig. 2c); this is within error identical to the phengite+paragonite age. Phengite separates ES3 and ES20 are from different garnet–micaschist layers within an eclogite–meta-sediment sequence and show locally weak retrogression from the eclogite–facies assemblage (stages M_{a0} to M_{a1} , Holland, 1979; Dachs, 1986; Spear and Franz, 1986). Both separates show within error identical TFA, WMA, and IA and acceptable isochron fits with atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts (Fig. 2c); their combined age is 39 ± 1 Ma. Both samples show monotonously decreasing low-temperature steps, the youngest steps are ~ 35 Ma and 15–30 Ma for ES20 and ES3, respectively. The phengite garnet–micaschist age is within error identical to its phengite+paragonite age (sample ES27). The ages of the weakly deformed, massive eclogite (ES25) are older than the ages (ES27, ES3, ES20) of the more strongly deformed, well-foliated garnet–micaschists (Fig. 2c), likely reflecting a higher degree of deformation-driven retrogression.

4. Discussion

The $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology reported here places constraints on several stages of the evolution of the Penninic–Austroalpine realm. Meisel et al. (1997) reported a Sm/Nd isochron age of 217 ± 59 Ma using various samples from the Reckner Ophiolite Complex (lherzolite, harzburgite, ultramafic cumulate, gabbro); excluding the gabbro, which experienced strong hydrothermal activity, they obtained a 186 ± 12 Ma age. Our 186 ± 2 Ma age from ocean metamorphic biotite of the (ultra)mafic cumulate provides support for this age and is more precise. These Reckner Ophiolite Complex ages, the 182 ± 31 Ma age from the Engadine Window (see above), and the origin of these ophiolitic complexes from the Pennine–Austroalpine transition and attenuated Austroalpine crust, suggest that these dates constrain the early stages of Penninic ocean formation. We conclude that Penninic ocean spreading occurred in the Eastern Alps as early as the Toarcian (late Early Jurassic)—about 20 Ma earlier than currently assumed (e.g., Faupl and Wagreich, 2000).

Plate–tectonic scenarios (e.g., Frisch, 1979) and lithofacies models (e.g., Wagreich, 1995) indicate Cretaceous and Paleocene subduction of Penninic ocean floor underneath the Austroalpine microcontinent. However, this has not been proven directly by geochronologic data. As the closure temperature of ferroglaucofane likely exceeds the ~ 350 °C blueschist–facies event of the Rechnitz Complex subduction–accretion complex, we interpret our 57 ± 3 Ma amphibole age from this complex as the time of high-pressure metamorphism. However, due to poor outcrop conditions and incomplete preservation, it is unclear which part (leading, central, or trailing) of the Alpine accretion–subduction wedge is represented by the Rechnitz Complex. Thus, our date is likely to record a snapshot in the evolution of the Penninic accretionary wedge.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of Tauern Eclogite Zone HP metamorphism constrains cooling during exhumation after peak-PT conditions at 570–630 °C. No reliable amphibole ages have been published from the Tauern Eclogite Zone due to the common problem of ^{40}Ar excess in HP hornblende (e.g., Zimmermann et al., 1994). Even high-potassium minerals like phengite are unreliable in many high-pressure terrains (e.g.,

Arnaud and Kelley, 1995; El-Shazly et al., 2001). All our amphibole and some of our mica ages have demonstrable excess ^{40}Ar (Fig. 2); nevertheless, they have geological significance for four reasons. First, even internally discordant spectra yielded isochrons. Second, the age of HP hornblende sample T4035 is only slightly older than the HP phengite and phengite+paragonite ages, and all the HP phengite+paragonite and phengite ages are externally concordant. Third, hornblende from sample ES40, clearly related to the late-stage second temperature maximum of the Tauern Eclogite Zone, is younger than all the high-pressure amphibole and mica ages, and again only slightly older than the late-stage phengite from the same sample. Fourth, different splits of individual samples, comprising 1 to 15 grains, yielded reproducible ages.

Using our hornblende and mica data and the phengite ages of Zimmermann et al. (1994), we place time constraints on the well-established PT path of the Tauern Eclogite Zone in the following (Fig. 3). For

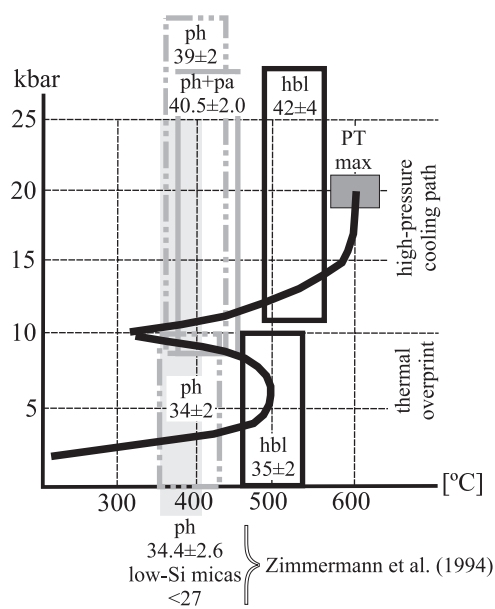


Fig. 3. Pressure–temperature–time (P–T–t) path of the Penninic Eclogite Zone of the Tauern Window. Thick black line: average PT-path (little known prograde path omitted for clarity) from Miller (1974, 1977), Holland (1979), Dachs (1986), Spear and Franz (1986), Zimmermann et al. (1994), Kurz et al. (1998b), and references therein. Time data are from this study and Zimmermann et al. (1994). Ph, phengite; pa, paragonite; hbl, hornblende.

this interpretation, we use closure temperatures for hornblende and mica derived by Von Blanckenburg et al. (1989) from a well-established PT path in the western Tauern Window and data from Harrison (1981). Harrison's (1981) hydrothermal experiments and diffusion data from a contact aureole yielded 530 ± 40 °C for hornblende closure. Assuming diffusion radii of dimensions similar to the in average ~ 150 – 250 μm grain size of our hornblende crystals and a relatively low cooling rate of ~ 10 °C/Ma, as may apply to exhumation through uppermost mantle–lower crust sections in HP terrains (e.g., Grasemann et al., 1998), a similar to somewhat lower hornblende closure temperature is suggested using Dodson's (1973) equations and Harrison (1981) diffusion parameters. Following Von Blanckenburg et al. (1989) and Zimmermann et al. (1994), we assume a closure temperature for HP phengite of 400 ± 40 °C.

Our ages on HP minerals document exhumation of rocks through ≤ 15 kbar and > 500 °C at ~ 42 Ma to ~ 10 kbar and ~ 400 °C at ~ 39 Ma (Fig. 3). The average age of the HP phengites obtained in this study is older but within error equal to those obtained by Zimmermann et al. (1994). We speculate that this is due to the use of very small sample weights in our study, a consequence of multiple handpicking, selection of pieces of grains, and the ultimate choice of only a few grains; we were thus able to sample micas closely corresponding to the eclogite–facies assemblage (stage Ma_0 , see above). Although our hornblende age adds additional time constraints to the HP event in the Tauern Eclogite Zone, the peak-PT event remains undated and awaits a single-grain U/Pb study. Grasemann et al. (1998) showed theoretically that fast exhumation of HP rocks is characterized by extremely rapid crustal cooling following minor heating or isothermal decompression in the mantle. The Tauern Eclogite Zone PT path shows isothermal decompression at mantle depths and rapid cooling in the crust (Fig. 3), suggesting rapid exhumation. Given that very high exhumation rates have been derived from well-dated HP–ultrahigh-pressure terrains in the Western Alps (e.g., 0.5 – 3.4 cm/year; Rubatto and Hermann, 2001), we suggest that the peak-pressure conditions were reached just before our HP hornblende age, probably at ≤ 45 Ma. This would correspond to the ages obtained from the likely paleogeographically similar Zermatt–Sass-Fee

ophiolites. The late-stage thermal overprint, common to the entire Penninic thrust system (“Tauern metamorphism”), occurred within the Tauern Eclogite Zone rocks at ~35 Ma and subsequent cooling is required by our data to postdate ~30 Ma (probably 15 Ma).

Fig. 4 summarizes what is currently known or inferred about the pressure–temperature–deformation evolution of the Penninic nappe stack in the Eastern Alps (from Selverstone, 1993; Thöni, 1999; Zimmermann et al., 1994; time constraints for the Tauern Eclogite Zone from this study). Burial (prograde accretion) of the lowermost stack of nappes occurred prior to ~30 Ma and likely also prior to 55 Ma (Selverstone, 1993; Christensen et al., 1994), in accordance with our 57 ± 3 Ma age from the Penninic wedge farther east. Burial of the uppermost stack of nappes ended at about 35 Ma; because Penninic imbrication progressed northward, accretion must have begun much earlier. Both Penninic mega-units experienced the burial–exhumation switch during the late Eocene, when large-scale extensional exhumation started in the Eastern Alps (e.g., Selverstone, 1988; Ratschbacher et al., 1991). In contrast, exhumation of the much more deeply subducted Tauern Eclogite Zone started earlier, probably in the mid-Eocene. Its exhumation from mantle to crustal depths was attributed to buoyancy and wholesale extensional thinning by Behrmann and Ratschbacher (1989) and to corner flow aided by vertical extrusion by Kurz et al. (1998b) and Kurz and Froitzheim (2002). At ~35 Ma, the Tauern Eclogite Zone joined the rest of the Penninic stack.

What geological event is actually dated by the HP metamorphism and burial–exhumation switch in

the Tauern Eclogite Zone? We suggest that the peak-P dates slab breakoff in the Alpine orogen, in contrast to snapshots during the long-lasting and foreland-propagating Franciscan-style subduction–accretion processes recorded, for example, in the Rechnitz Complex. The slab breakoff hypothesis suggested by Von Blanckenburg and Davies (1995) for the Alps is anchored on two points: slab breakoff at ~45 Ma was (a) immediately followed by exhumation of the remaining slab and (b) after some time, was delayed by magmatism. Our inference of ~45 Ma for the attainment of peak-PT conditions in Tauern Eclogite Zone from our new $^{40}\text{Ar}/^{39}\text{Ar}$ data is consonant with the requirement of a nearly contemporaneous along-strike onset of rapid exhumation of the remaining slab, reflected in the preservation of HP rocks of that particular age all along the Alps (e.g., Von Blanckenburg and Davies, 1995). Lithotectonic units similar to the Tauern Eclogite Zone, a strongly attenuated passive continental margin (of Penninic origin, its more weakly attenuated equivalent is for example represented by its footwall) affected by oceanic rifting, are envisioned as breakoff zones.

Acknowledgements

This paper is dedicated to Wolfgang Frisch, former boss of the first author. Although due to various circumstances this paper did not make it into the “Festschrift” on the occasion of his 60th birthday, LR feels privileged to have learned from and shared a significant part of his career with him. Ultimately, we

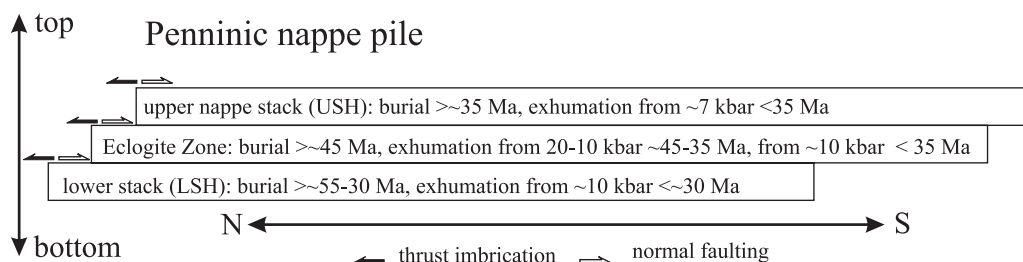


Fig. 4. Schematic pressure–temperature–time–deformation evolution of the Penninic tectonic mega-units in the Eastern Alps (from Selverstone, 1993; Thöni, 1999; Zimmermann et al., 1994; time constraints for the Penninic Eclogite Zone from this study). LSH: Untere Schieferhülle, lower, mostly continental rock nappe stack; USH: Obere Schieferhülle, upper, mostly oceanic rock nappe stack.

owe it to Wolfgang Frisch that these data made it into publication. Sampling was performed together with Bruce Nelson. Martin Thöni provided pertinent reprints. LR acknowledges hospitality and support at Stanford University when he was a Heisenberg Fellow and Consulting Professor at Stanford. Microprobe work was done at UC Berkeley and the Universities at Tübingen, Innsbruck, and Vienna. The German National Science Foundation provided financial support through grant Ra442/6. We acknowledge stimulating comments by two anonymous reviewers, Michael Wagreich, and, in particular, by Wolfgang Müller, who provided one of the most constructive reviews we have ever had.

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