SCHWEIZ. MINERAL. PETROGR. MITT. 79, 297–307, 1999

Conditions of eclogite formation and age of retrogression within the Sieggraben unit, Eastern Alps: Implications for Alpine-Carpathian tectonics

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Abstract

The Austroalpine basement nappe complex, Eastern Alps, resulted from Mesozoic A-subduction which predated Paleogene collisional tectonics in the Alps. We present a new model for the age and P-T conditions of eclogite formation in the Sieggraben unit of the Austroalpine nappe complex. This unit is a tectonic melange which includes eclogite-bearing metamorphic units with both ophiolite-like fragments (retrogressed N-MORB type eclogites and serpentinites) and supracrustal, probably pre-Alpine, continental rocks. Mineral chemistry and textural characteristics indicate a three stage metamorphic evolution of the eclogites: (1) Inclusions of hornblende and epidote in eclogite-facies garnets suggest that an epidote amphibolite facies assemblage dehydrated to eclogite; (2) P-T conditions maintained during eclogite formation were c. 670–750 °C and 14–15 kbar; and (3) retrogression of eclogite included replacement of omphacite by symplectite including sodic augite, sodic plagioclase and formation of epidote + hornblende-bearing assemblages (c. 500–600 °C, c. 6–10 kbar). $^{40}Ar/^{39}Ar$ analyses of hornblende concentrates within retrograde assemblages yielded internally-discordant age spectra in which intermediate-temperature increments record similar apparent ages and plateau isotope correlation ages between 136.1 ± 0.5 Ma and 108.2 ± 0.3 Ma. These date the last cooling through c. 500 °C. We interpret Late Jurassic to early Late Cretaceous eclogite metamorphism and deformation of the Austroalpine nappe complex as having resulted from subduction of continental crust after consumption of the Meliata/Hallstatt ocean.

Keywords: eclogite, P-T path, Ar–Ar dating, orogeny, A-subduction, Cretaceous, Eastern Alps.

Introduction

The Eastern Alps have been classically interpreted as the product of Cretaceous subduction of the Jurassic Penninic oceanic domain and Early Tertiary collision between Europe and the Austroalpine/South Alpine promontory of the Adriatic microplate (e.g., FRISCH, 1979; Fig. 1). These concepts are inconsistent with regional evidence which argues for a nearby Triassic oceanic element in the Alps (LEIN, 1987; KOZUR, 1991; CHANNELL and KOZUR, 1997). In addition, geochronology and geothermobarometry document Cretaceous high-pressure metamorphism within the Austroalpine units (FRANK et al., 1987; HOINKES et al., 1992; HUNZIKER et al., 1989; HSÜ, 1991; HUNZIKER et al., 1989; THÖNI and JAGOUTZ, 1992; for recent reviews, see FROITZHEIM et al., 1996, and SPALLA et al., 1996). This would have developed within the upper-plate unit of the supposed continent-continent collision and is unlikely to have been associated with subduction of the Penninic oceanic element beneath it. However, the internal structure of the Austroalpine nappe complex may be formed by imbrication of a unique, coherent basement-cover sheet without an enclosed oceanic segment (FRANK, 1987; TOLLMANN, 1987; RATSCHBACHER et al., 1989; BEHRMANN, 1990).

We have investigated the age and formation conditions of the Sieggraben unit, an eclogite-bearing tectonic melange which includes an ophi-

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olite-like rock association within the Austroalpine basement nappe complex. These eclogites virtually represent the easternmost Cretaceous eclogite exposure. The results are significant for the Mesozoic geodynamic evolution within the Alpine/Carpathian junction.

Geology

Along the eastern edge of the Eastern Alps, the Austroalpine unit comprises a structural succession of basement nappes (Fig. 2) all emplaced on top of the Penninic ophiolite-bearing suture (KOLLER, 1985). The Austroalpine nappes comprise of basement and Permo-Triassic cover sediments. In the study area the nappe complex includes from bottom to top (Fig. 2): (1) the Wechsel nappe with greenschist facies conditions (c. 300–350 °C: MÜLLER et al., 1999); (2) the large flat-lying Kirchberg-Stuhleck nappe sheet with predominantly Carboniferous metagranite basement ("Grob Gneiss" unit), and (3) the Sieggraben unit exposing in several tectonic klippen which have been conventionally regarded to be part of the middle Austroalpine thrust sheet exposed in the Koralpe and Saualpe c. 100 kilometres further to the WSW (e.g., TOLLMANN, 1978; DALLMEYER et al., 1998). The Kirchberg-Stuhleck nappe was overprinted by greenschist facies conditions in northern sectors, and amphibolite facies conditions in southwestern sectors (e.g., DALLMEYER et al., 1998, and references cited therein).

The Sieggraben tectonic unit contains granulite-like gneisses, pegmatite gneiss, orthogneisses, retrogressed eclogites, some serpentinite bodies and minor marbles (KÜMEL, 1935; RICHTER, 1973). Chemical compositions of retrogressed eclogites range from N-MORB to transitional basalts (KIESL and WEINKE, pers. comm.; own unpubl. data). All lithologic units form a tectonic melange in which eclogite, carbonate-rich eclogite and amphibolite occur as boudins, on a decimetre to metre scale, within the gneisses (KÜMEL, 1935). Contacts between all lithologic elements are penetratively foliated. No Permo-Triassic cover sequences have been found within the Sieggraben unit. The metamorphic assemblages developed contrast markedly with other Austroalpine basement units in the footwall.

Mineralogy and P-T path of eclogite

Four coarse-grained eclogite and two orthogneiss samples have been collected from the abandoned Zöbersdorf quarry in the eastern margin of the Schaeffern klippe (Fig. 2). There, the eclogites form a layer within light-colored orthogneisses which is several metres thick. The eclogites are coarse-grained and nearly unfoliated in the center of the layer, and gradually change to fine-grained, mylonitic, retrogressed eclogites towards the margins. There is also an increase in the amphibole content of the eclogite from the center to the periphery. The surrounding orthogneiss is strongly

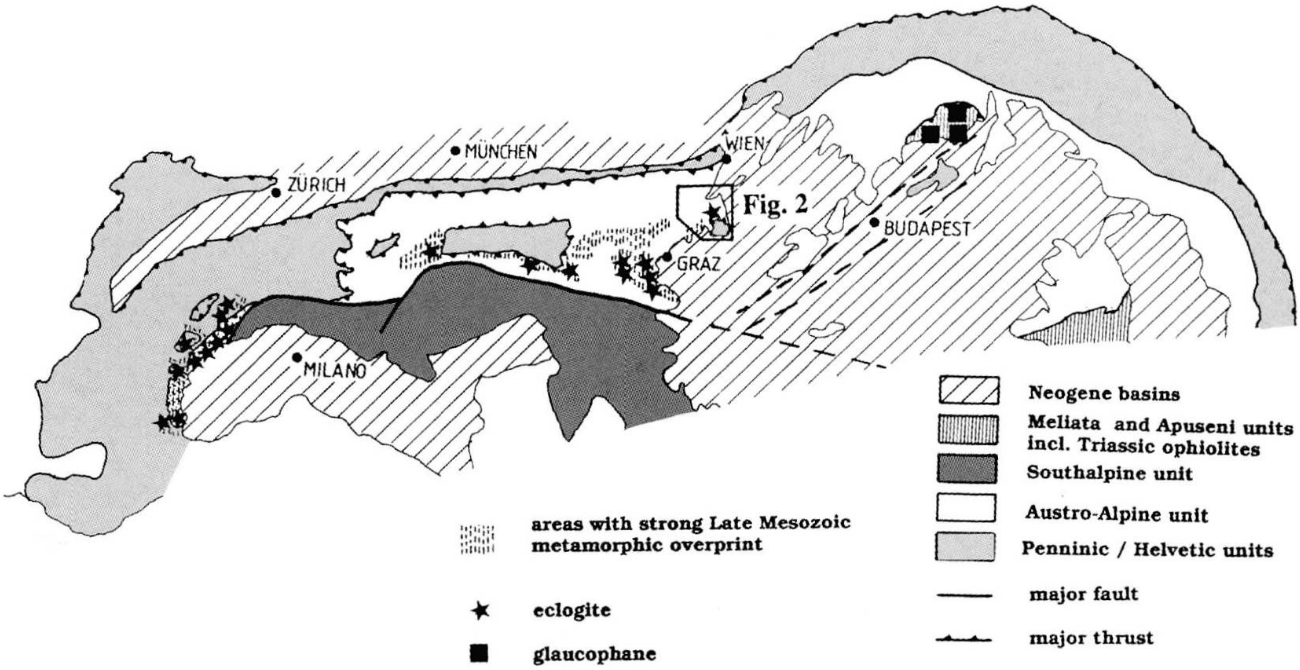

Fig. 1 Simplified tectonic map of the Alpine-Carpathian orogen including distribution of Mesozoic high-pressure rocks.

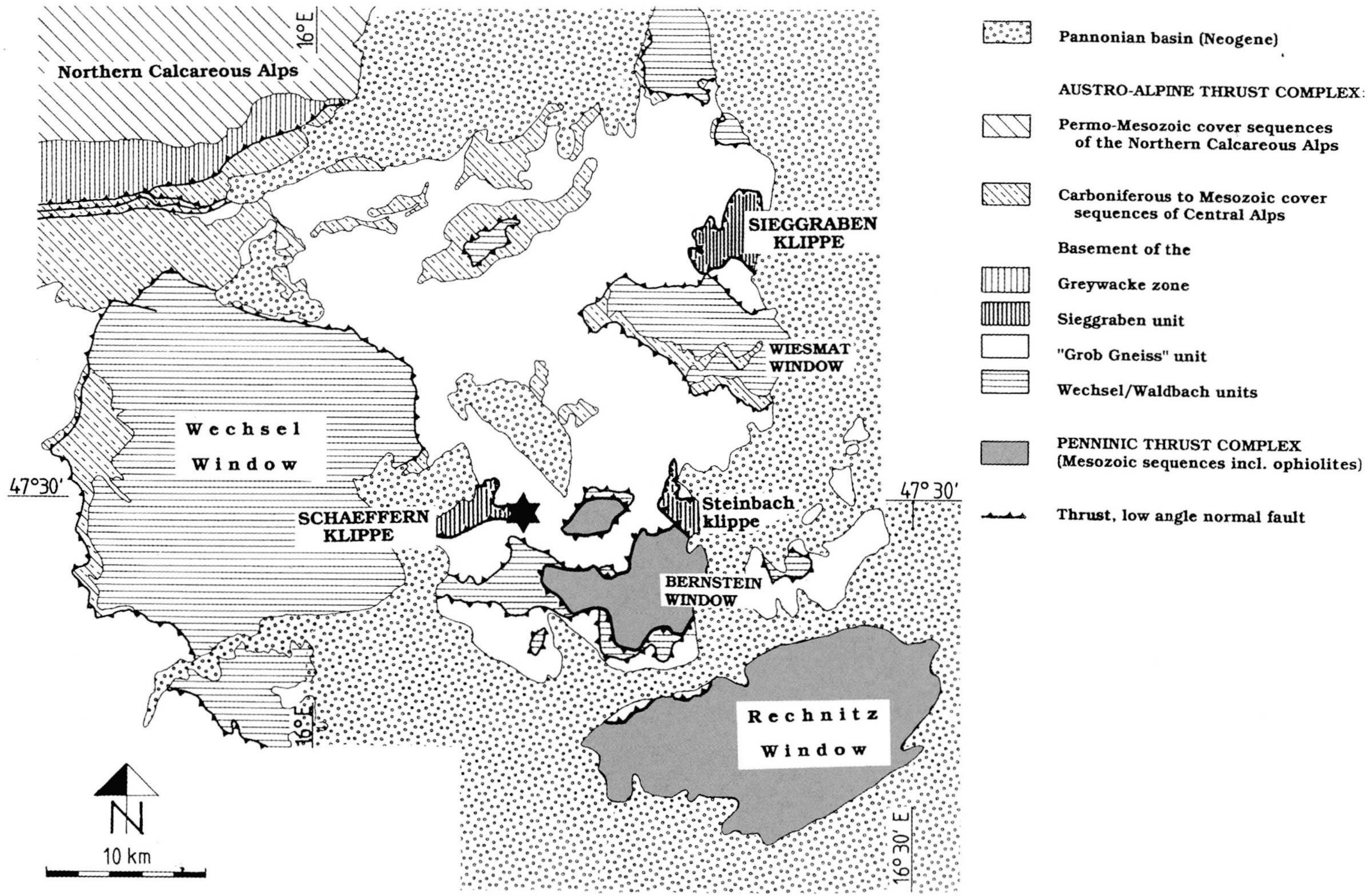

Fig. 2 Simplified geological map of eastern sectors of the Alps. Star locates the eclogite samples studied in detail. For location of the map, see figure 1.

foliated and composed of feldspar (K-feldspar and plagioclase), garnet and variable amounts of amphibole.

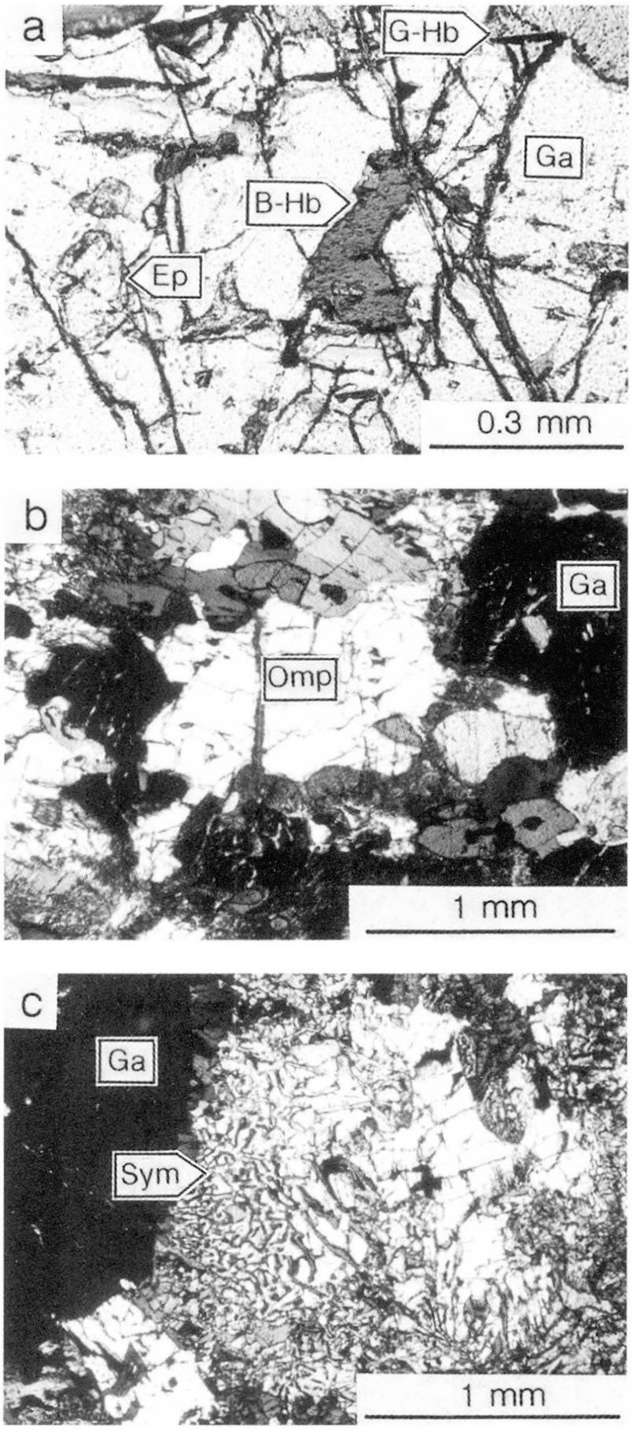

Fig. 3 Mineral reaction textures relevant to the P-T path. (a) Inclusions of epidote and hornblende of stage 1 within garnet: B-Hb – bluish green hornblende within garnet; G-Hb – green hornblende outside garnet; Ep – epidote. (b) Eclogite mineral assemblage of stage 2: Omp – omphacite; Ga – garnet. (c) Symplectite of stage 3a due to retrogression after the eclogite stage: Sym – symplectite of sodic augite and sodic plagioclase.

The eclogites consist mainly of garnet, omphacite and hornblende with accessory sodic plagioclase, sodic augite, clinozoisite, quartz, titanite, opaque minerals and small amounts of apatite and rutile. Symplectite comprising sodic augite and sodic plagioclase, which partially replaces omphacite, is developed throughout the rock (Fig. 3c). Garnet includes omphacite (only close to garnet rims), hornblende, epidote, rutile and titanite. Omphacite in the matrix is euhedral to anhedral and it has been variably replaced by hornblende (Fig. 3 a–c). Hornblende occurs as: (1) discrete grains in the matrix; (2) symplectite with sodic augite and sodic plagioclase; (3) replacing omphacite and (4) inclusions in garnet (Fig. 3a). Hornblendes of type (1), (2) and (3) have a similar pleochroism with X = pale greenish yellow, Y = yellowish green and Z = green, but hornblende inclusions in garnet are Z = bluish-green.

Many garnets in eclogites have inclusions of hornblende and clinozoisite, suggesting that the minerals of the epidote amphibolite facies (stage 1) dehydrated to form eclogite (stage 2) (Figs 3a, 4). Representative mineral analyses are presented in table 1. The peak metamorphic conditions of the eclogite have been estimated by the garnet-clinopyroxene geothermometer (KROGH, 1988) and the jadeite geobarometer (GASPARIK, 1985; BANNO, 1986). Pairs of omphacite (inclusion in garnet) and adjacent garnet, and pairs of rims of garnet and omphacite in the matrix were used for the P-T calibration with P = 15 kbar. The distribution coefficient of Fe and Mg between garnet and omphacite (K_D: 8.4–11.5) suggests a temperature of 670–750 °C. When the temperature is 670–750 °C, the jadeite content of 30 percent indicates 14–15 kbar. Therefore 670–750 °C and 14–15 ± 1 kbar are estimated for peak metamorphic conditions.

Eclogite omphacite was initially replaced by sodic augite (jadeite content: 9–18 percent) + sodic-plagioclase symplectite (stage 3a) and then by epidote + hornblende assemblages (stage 3b) (Fig. 3c). These suggest that eclogite underwent retrogressive reactions to epidote amphibolite facies after peak metamorphic conditions. If the symplectite formed at c. 500–600 °C in the epidote amphibolite facies, a pressure of 6–10 kbar may be estimated.

The chemical compositions of garnet and hornblende in surrounding hornblende gneisses are similar to those in retrograde assemblages (Tab. 1). This probably indicates that metamorphic P-T conditions of the hornblende gneiss were similar to those of the retrograde alteration of eclogite.

$^{40}Ar/^{39}Ar$ amphibole dating of eclogite retrogression

Two amphibole concentrates have been prepared from retrogressive eclogite exposed in a abandonded quarry at the village of Zöbersdorf. The amphiboles developed during various stages of retrogression, mainly in the coarse-grained matrix. For analytical procedures during $^{40}Ar/^{39}Ar$ analysis, see DALLMEYER and GIL-IBARGUCHI (1990). Results are presented in tables 2 and 3 and portrayed in figure 5. The potassium content of matrix amphibole within eclogite is low (Tab. 1). Both amphibole concentrates record similar internally discordant age spectra. No variation in the intermediate and high temperature increments of the apparent K/Ca ratios were recorded throughout the experiments suggesting evolution of argon from compositionally uniform sites within amphiboles. Most intermediate temperature increments record similar apparent ages. Isotope correlation of these data yield plateau isotope correlation ages of 108.2 ± 0.3 Ma and 136.1 ± 0.5 Ma (Tab. 3). These are interpreted as dating the last, slow cooling through c. 500 ± 25 °C during retrogression of the eclogite. No evidence was found for extraneous argon. The large age difference (28 Ma) between the two concentrates may result from compositional variations which influence the argon retention in amphibole (e.g., MCDOUGALL and HARRISON, 1988). Large compositional variations in amphiboles were observed both within and between the two samples used for $^{40}Ar/^{39}Ar$ dating (Fig. 6).

DALLMEYER et al. (1998) interpreted white mica ages of 78–77 Ma from nearby localities within the Sieggraben unit to record cooling through c. 400–350 °C. These mica ages are similar to those observed in footwall units (DALLMEYER et al., 1998; MÜLLER et al., 1999).

Discussion

The suggested evolutionary P-T path of the Sieggraben eclogites indicates that retrogression like-

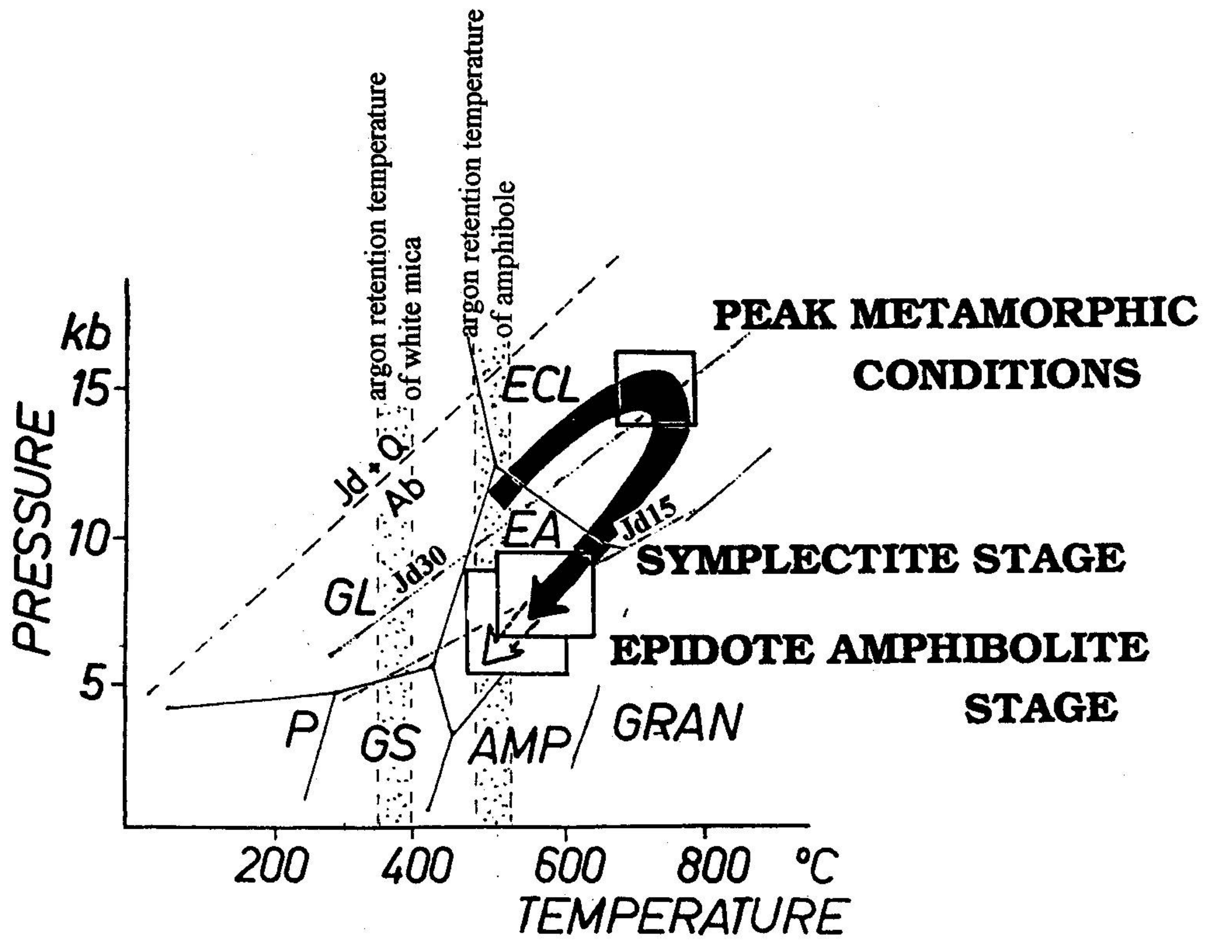

Fig. 4 Suggested P-T path of retrogression in the Sieggraben eclogites. AMP – amphibolite facies, EA – epidote amphibolite facies, ECL – eclogite facies, GL – glaucophane facies, GS – greenschist facies, GRAN – granulite facies, P – pumpellyite facies.

Tab. 1 Chemical compositions of minerals from the Sieggraben metamorphic complex.

	Garnet								
	Eclogite				Hornblende gneiss				
	core	core	rim	rim	core	core	rim	core	rim
SiO_2	38.71	37.93	38.29	37.47	38.40	38.15	38.73	38.19	38.37
TiO_2	0.10	0.06	0.08	0.25	0.22	0.10	0.08	0.26	0.07
Al_2O_3	20.80	21.30	21.65	21.51	20.48	20.93	21.36	20.52	21.21
FeO*	23.58	23.26	23.28	23.93	25.85	25.93	27.18	26.38	25.64
MnO	0.69	0.69	0.83	0.90	0.98	0.97	0.93	0.93	0.93
MgO	3.76	3.87	3.62	3.59	3.23	3.27	3.68	3.35	3.29
CaO	12.06	12.70	12.17	12.64	10.69	10.36	9.02	10.68	10.37
Total	99.70	99.81	99.92	100.56	99.85	99.71	100.98	100.31	99.88
Si	3.033	2.974	2.992	2.949	3.013	3.013	3.017	3.008	3.017
Ti	0.006	0.004	0.005	0.014	0.031	0.006	0.005	0.015	0.004
Al	1.920	1.969	1.994	1.981	1.905	1.949	1.962	1.906	1.965
Fe	1.545	1.526	1.521	1.564	1.706	1.713	1.771	1.738	1.686
Mn	0.045	0.046	0.055	0.059	0.065	0.065	0.062	0.062	0.062
Mg	0.440	0.452	0.421	0.418	0.380	0.385	0.427	0.393	0.386
Ca	1.012	1.067	1.019	1.059	0.904	0.877	0.753	0.901	0.874
Total	8.001	8.038	8.007	8.044	8.004	8.008	7.997	8.023	7.994

	Clinopyroxene **					Hornblende			
	Eclogite					Eclogite		Hornblende gneiss	
	inclusion	inclusion	matrix	matrix	sympl.	matrix	inclusion	matrix	matrix
SiO_2	52.83	52.19	51.68	52.33	52.31	41.28	36.03	42.01	42.26
TiO_2	0.23	0.26	0.18	0.26	0.10	0.84	0.18	1.07	0.95
Al_2O_3	8.23	8.23	7.98	7.01	4.14	12.08	19.45	12.74	12.30
FeO*	8.95	9.13	9.35	9.02	10.27	18.48	22.33	17.63	18.54
MnO	0.13	0.14	0.15	0.12	0.09	0.23	0.32	0.27	0.32
MgO	8.36	8.22	8.46	8.96	10.26	9.31	3.86	9.30	8.95
CaO	16.29	16.43	16.23	16.90	18.92	10.89	11.30	10.47	10.23
Na_2O	5.22	5.34	5.07	4.57	3.46	3.44	3.44	2.78	2.78
K_2O						0.28	0.07	1.28	1.15
Total	100.24	99.94	99.10	99.17	99.55	96.83	96.98	97.55	97.48
Si	1.943	1.932	1.931	1.950	1.966	6.334	5.641	6.368	6.428
Ti	0.006	0.007	0.005	0.007	0.003	0.097	0.021	0.122	0.108
Al	0.357	0.359	0.351	0.308	0.183	2.185	3.590	2.277	2.206
Fe	0.275	0.283	0.292	0.281	0.323	2.371	2.923	2.236	2.358
Mn	0.004	0.004	0.005	0.004	0.003	0.029	0.042	0.035	0.041
Mg	0.458	0.453	0.471	0.498	0.574	2.130	0.901	2.102	2.029
Ca	0.642	0.652	0.650	0.675	0.762	1.790	1.896	1.701	1.668
Na	0.372	0.383	0.367	0.330	0.252	1.023	1.045	0.816	0.819
K						0.054	0.014	0.248	0.223
Total	4.057	4.073	4.072	4.053	4.066	16.013	16.073	15.905	15.880

* Total Fe as FeO.
sympl. – symplectite
** The jadeite content is calculated from Al(VI). The acmite molecule is estimated from the rest of Na after forming jadeite molecule with Fe.

Tab. 2 $^{40}Ar/^{39}Ar$ analytical data for incremental heating experiments on hornblende concentrates from retrogressed eclogite within the Sieggraben nappe complex, Eastern Alps, Austria.

Release temperature (°C)	$(^{40}Ar/^{39}Ar)$*	$(^{36}Ar/^{39}Ar)$*	$(^{37}Ar/^{39}Ar)^c$	^{39}Ar % of total	% ^{40}Ar non-atmospheric +	$^{36}Ar_{Ca}$ %	Apparent age (Ma)	2σ error (Ma), intralaboratory
Sample 1: J = 0.009235								
660	98.89	0.12701	2.613	1.03	62.25	0.56	813.1	± 39.3
720	23.28	0.02728	5.644	0.58	67.30	5.63	244.6	± 18.1
780	11.35	0.01099	7.911	3.71	76.93	19.58	140.5	± 5.1
795	7.67	0.00567	7.304	3.83	85.73	35.03	106.8	± 3.0
810	7.18	0.00306	7.090	4.90	95.27	63.09	110.9	± 1.1
825	7.00	0.00269	7.096	5.10	96.73	71.87	109.9	± 1.4
840	6.88	0.00238	7.081	10.27	97.98	81.02	109.4	± 1.4
860	6.90	0.00266	7.037	16.15	96.71	71.89	108.4	± 1.0
870	7.05	0.00266	7.035	5.97	96.81	72.06	110.7	± 1.3
880	6.81	0.00192	6.993	7.48	99.83	99.00	110.4	± 1.1
890	6.78	0.00209	7.035	12.73	99.16	91.72	109.2	± 0.9
900	6.70	0.00193	7.006	10.59	99.80	98.71	108.5	± 0.5
915	6.73	0.00200	7.004	7.65	99.50	95.33	108.7	± 1.2
935	7.34	0.00242	7.109	7.45	97.95	79.84	116.5	± 1.2
Fusion	10.38	0.00503	7.736	2.55	91.63	41.87	152.6	± 2.5
Total	8.23	0.00429	7.050	100.00	96.14	76.94	120.0	± 1.5
Total without 600–795 °C and 935 °C-fusion				80.84			109.3	± 1.0
Sample 2: J = 0.008886								
680	99.83	0.06470	1.642	2.97	80.98	0.69	977.4	± 8.5
760	22.70	0.01650	5.868	1.68	80.58	9.67	272.7	± 6.7
795	20.75	0.02029	11.193	2.94	75.41	15.01	236.4	± 2.5
805	13.21	0.00947	10.134	2.89	84.94	29.11	172.5	± 3.1
820	10.36	0.00561	8.771	5.08	90.75	42.53	145.5	± 3.6
835	9.21	0.00333	7.361	9.11	95.69	60.19	136.6	± 1.4
845	8.99	0.00242	7.007	14.36	98.23	78.61	136.9	± 1.2
855	9.15	0.00289	6.913	12.40	96.69	65.15	137.0	± 0.8
865	9.12	0.00278	6.761	9.32	96.89	66.14	137.0	± 1.6
875	9.22	0.00295	6.695	7.90	96.33	61.82	137.7	± 1.1
885	8.86	0.00194	6.675	6.82	99.51	93.51	136.6	± 1.5
900	8.66	0.00211	6.923	9.57	99.15	89.18	133.1	± 1.7
915	8.52	0.00195	6.843	8.58	99.61	95.28	131.7	± 1.3
935	9.58	0.00202	6.903	4.37	99.49	92.85	147.3	± 2.5
Fusion	12.72	0.00347	6.636	2.12	96.08	52.01	186.7	± 6.3
Total	12.55	0.00552	7.048	100.00	95.59	67.70	169.3	± 1.5
Total without 680–820 °C and 935 °C-fusion				59.80			137.0	± 1.0

* measured.
[c] corrected for post-irradiation decay of ^{37}Ar (35.1 day $^1/_2$-life).
[+] $[^{40}Ar_{tot.} - (^{36}Ar_{atmos.})(295.5)] / {}^{40}Ar_{tot.}$

Tab. 3 $^{36}Ar/^{40}Ar$ vs $^{39}Ar/^{40}Ar$ isotope correlations from incremental heating experiments on hornblende concentrates from retrogressed eclogite within the Sieggraben nappe complex, Eastern Alps, Austria.

Sample	Isotope correlation age (Ma) *	$^{40}Ar/^{36}Ar$ intercept**	MSWD	Increments (°C)	% of total ^{39}Ar	Calculated $^{40}Ar/^{39}Ar$ plateau age (Ma)
1	108.2 ± 0.3	388.8 ± 36.2	2.04	810–915	80.84	109.3 ± 1.0
2	136.1 ± 0.5	337.3 ± 36.8	0.61	835–915	59.80	169.3 ± 1.5

Calculated using the inverse abscissa intercept ($^{40}Ar/^{39}Ar$ ratio) in the age equation.
* Inverse ordinate intercept.
** Table 2.

ly resulted from decompression from peak metamorphic conditions. There is no evidence for a second metamorphic overprint within amphibolite facies conditions. Therefore, the Cretaceous $^{40}Ar/^{39}Ar$ hornblende ages reflect cooling after retrogression from the eclogite stage. We therefore conclude that eclogite formation immediately predates the Late Cretaceous cooling. Textural relationships indicate that transition to the eclogite stage occurred from epidote amphibolite facies. These relationships suggest that the first epidote amphibolite facies assemblages probably record a pre-Alpine metamorphic event. This would imply that the serpentinite-eclogite assemblage could not represent a Mesozoic ophiolite but might be part of a pre-Alpine basement unit.

Similar continental sequences recording a Cretaceous high-pressure metamorphism (Fig. 1) are known from several Austroalpine areas (HOINKES et al., 1992; MOINE et al., 1989; MILLER, 1990; THÖNI and JAGOUTZ, 1992; FROITZHEIM et al., 1996; SPALLA et al., 1996) and with glaucophane-bearing schists in the Western Carpathians which are associated with Middle Triassic ophiolitic sequences of the Meliata zone (FARYAD, 1995; FARYAD and HENJES-KUNST, 1997). Previously reported peak P estimates of Cretaceous metamorphism in the Austroalpine units range from 10–20 kbar in the Western Alps (FROITZHEIM et al., 1996; SPALLA et al., 1996, and references cited therein) and 11–18 kbar in the Austroalpine domain of the Eastern Alps (MILLER, 1990; HOINKES et al., 1992; THÖNI and MILLER, 1996) which is explained by upward translation of previous subducted continental pieces in front of a crustal wedge during subduction of the Penninic ocean (e.g., HSÜ, 1991). This explanation may be excluded for the Eastern Alps because of interca-

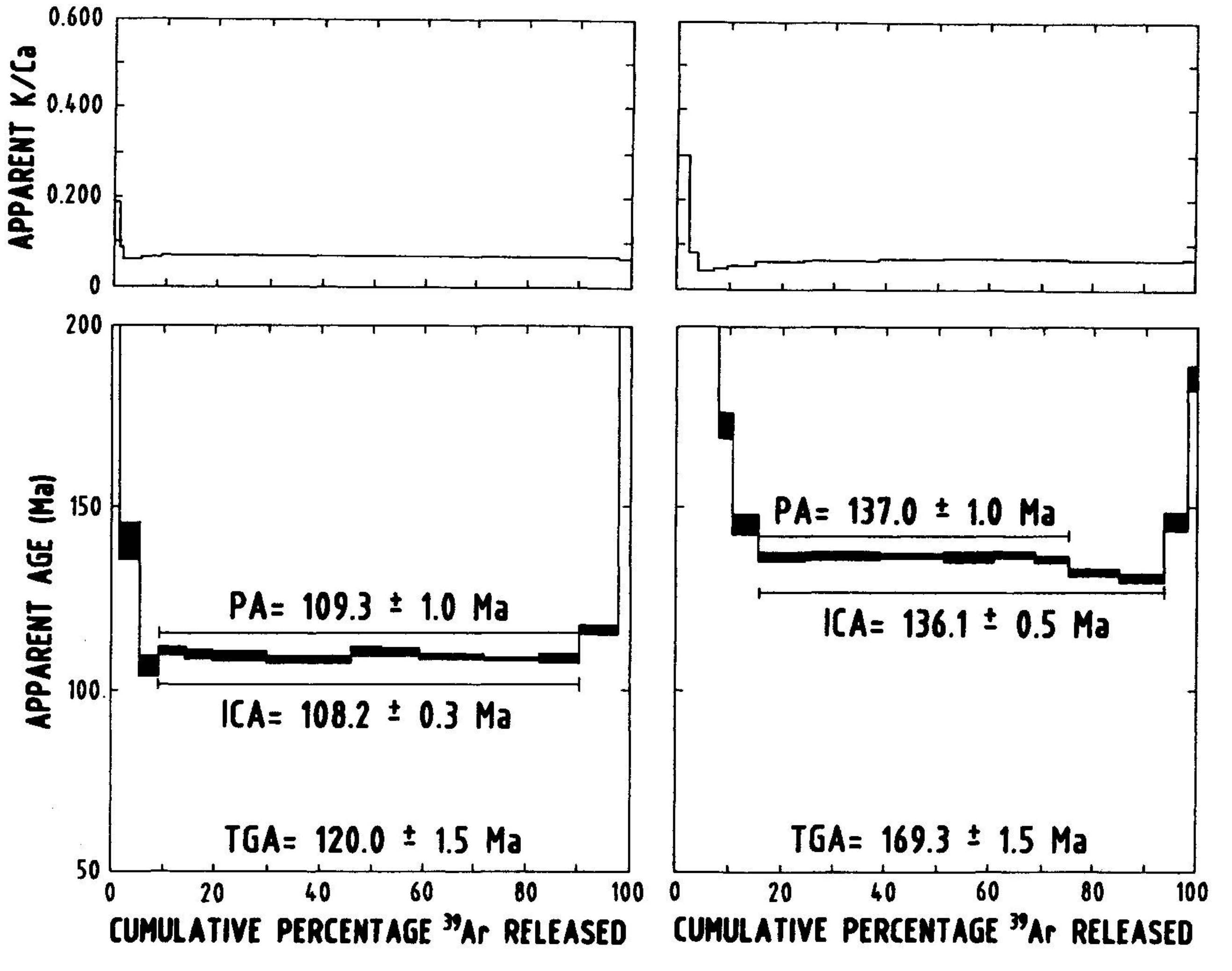

Fig. 5 $^{40}Ar/^{39}Ar$ age spectra and apparent K/Ca ratios of amphibole concentrates from two retrogressed eclogites, Sieggraben unit (Zöberndorf quarry; Schäffern klippe). Experimental temperature increases from left to right. Width of bars corresponds to analytical uncertainty. Legend: ICA – isotope correlation age; PA – plateau age; TGA – total gas age.

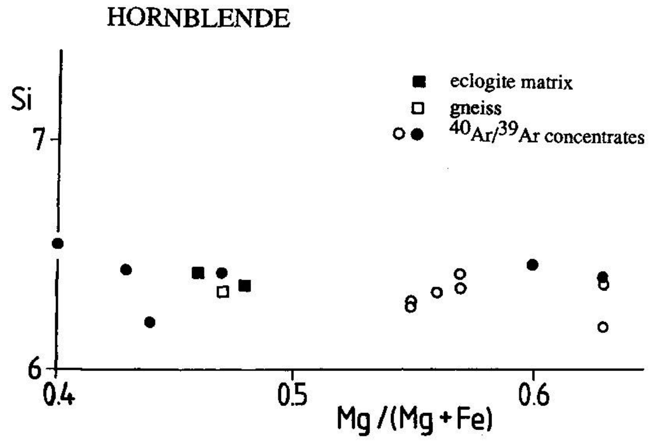

Fig. 6 Compositional variations of amphiboles from concentrates used for $^{40}Ar/^{39}Ar$ dating in comparison to amphibole from eclogite and gneiss matrix.

lation of high-pressure rocks within the Austroalpine nappe complex as also suggested by FROITZHEIM et al. (1996) and SPALLA et al. (1996).

Paleogeographic arguments show clear evidence for emplacement of a Middle Triassic ophiolite-bearing Meliata nappe. This was most probably derived from the Tethys at a structural level above the Austroalpine nappe complex within the Carpathian units in the northeastward continuation of the Alps (e.g., FARYAD and HENJES-KUNST, 1997). Furthermore, paleogeographic restoration of Austroalpine structural units in the Eastern Alps indicate the presence of similar Meliata-type deep sea sediments at a high structural level within the Northern Calcareous Alps (e.g., KOZUR, 1991) which originate from the present southeastern margin of the Austroalpine domain (TOLLMANN, 1987). Therefore, we conclude that the Austroalpine Cretaceous high pressure metamorphic belt is the result of A-subduction of a pre-Alpine basement unit which has been buried during emplacement of Tethyan ophiolite-bearing units (Fig. 7c). The new Ar–Ar amphibole and previously reported mica ages record Late

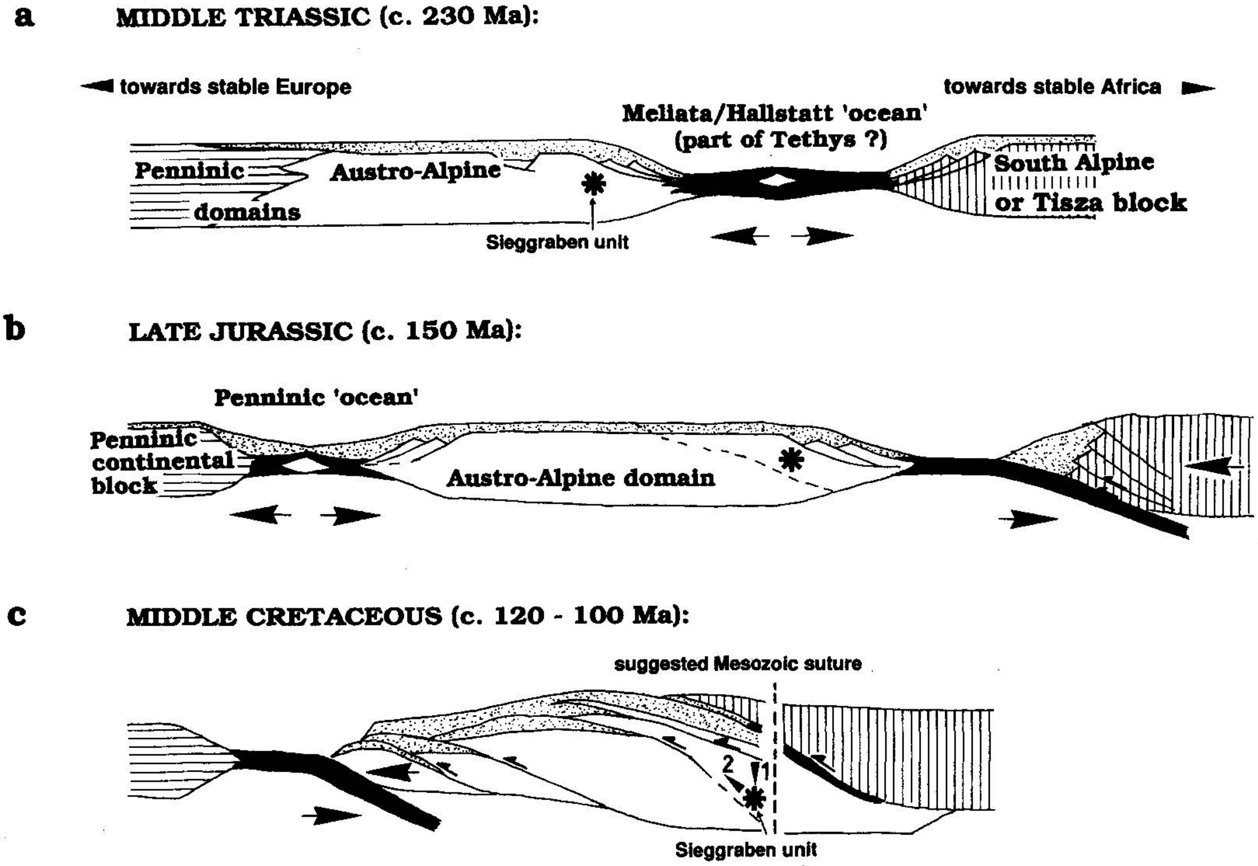

Fig. 7 Suggested tectonic evolution of Austroalpine segments of the Alps and Carpathians. Star locates the Sieggraben unit assuming a pre-Alpine continental origin of it. (a) Middle Triassic extension which resulted in the opening of an oceanic domain (Meliata/Hallstatt oceanic element). (b) Late Jurassic opening of the Penninic oceanic domain and closure of the Meliata/Hallstatt oceanic element. (c) Collision of the Austroalpine domain with the South Alpine or Tisza blocks (for present location of the Tisza block, see Fig. 1) resulting in the formation of the Austroalpine nappe complex, the burial of Austroalpine units (stage 1) and subsequent decompression by out-of-sequence thrusting (stage 2). Vertical broken line locates major Cenozoic strike-slip faults along which right-hand portion of the section with the upper continental plate removed.

Cretaceous exhumation of metamorphic sequences similar to other Middle Austroalpine units further to the west (e.g., NEUBAUER et al., 1995).

Field, P-T and geochronological data of the Sieggraben unit and previously reported P-T data suggest a new model for the tectonic evolution of Austroalpine structural units in comparison with Inner Western Carpathians where the structural relationships are more obvious (NEUBAUER, 1994; DAL PIAZ et al., 1995; FARYAD and HENJES-KUNST, 1997). Paleogeographic data recorded in sedimentary sequences suggest a Permo-Triassic extension resulting in the opening of a Triassic oceanic domain southeast of the present Austroalpine domain (Fig. 7a). Permian extension is recorded by: tectonic subsidence forming horst- and graben structures; emplacement of gabbros (e.g., THÖNI and JAGOUTZ, 1992); and possible low-pressure metamorphism with a Permian age (for geochronological ages, see FRANK et al., 1987; DALLMEYER et al., 1996; NEUBAUER et al., 1999). Paleogeography significantly changed with the opening of the Penninic oceanic domain in the Jurassic, which separated Austroalpine tectonic elements from the European plate (Fig. 7b). The Tethys closed during the Late Jurassic/Early Cretaceous and resulted in collision of the Austroalpine microplate with another tectonic element (Fig. 7c). This plate is not preserved within central sectors of the Eastern Alps because all units display lower plate tectonothermal characteristics. Uniform Permo-Mesozoic facies precludes separation of the Austroalpine units into two continental plates. A possible candidate of the upper continental plate is the Southalpine unit (CHANNELL et al., 1992) or more reliably the Tisza unit of the Pannonian basin. The Penninic oceanic domain was consumed during the Cretaceous and early Paleogene subduction, and final continent-continent collision between the European foreland with the Austroalpine units occurred during the Oligocene. Sinistral Cretaceous, Oligocene and Neogene displacement within the Austroalpine nappe complex, and Miocene dextral displacement along the Periadriatic Lineament dispersed the Cretaceous collisional belt (BALLA, 1985; RATSCHBACHER et al., 1989, 1991).

Acknowledgements

We appreciate discussions with Wolfgang Frank, Harry Fritz, Fritz Koller and Martin Thöni. We also appreciate suggestions by journal reviewers Marian Janák, Christian Meyre and Dusan Plasienka which helped to clarify the text. Callum Hetherington polished the English. The work was supported by the Austrian Research Funds to F.N. (grant P8652-GEO) and by the US NSF Tectonics Program to R.D.D. (grant EAR-9316042).

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Manuscript received June 11, 1998; revision accepted February 18, 1999.