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Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern Alps: bearing on Alpine orogenesis

by *Martin Thöni*[1] and *Emil Jagoutz*[2]

Abstract

Sm–Nd, Rb–Sr and Pb–Pb isotopic data on eclogite whole rocks and mineral assemblages and of their partly preserved protolithologies from the Austroalpine Koralpe and Saualpe basement in SE Austria point to production of young MORB-type oceanic crust material in the Early Permian. This is related to crustal fragmentation and early rifting processes in the westernmost Neotethys. According to sedimentological and paleontological results, closing of this oceanic domain started in Late Jurassic times. Subduction and high-pressure metamorphism of considerable portions of the crust along the frontal Adriatic microplate is inferred from data derived from metabasic high-P assemblages (garnet – omphacite – zoisite – kyanite – amphibole – rutile – phengite) which yield a maximum age of about 150 Ma and a minimum age of about 100 to 90 Ma for the eclogite metamorphism. Published geobarometric data are in the range of 11–18 kbar for the pressure peak of this subduction event. It is inferred from various literature sources that the southern Austroalpine units were probably involved in this subduction on a regional scale, over a distance of some hundreds of km.

During subsequent exhumation, high-P assemblages were thoroughly altered or completely overprinted by metamorphic fluid activity and thermal relaxation. These processes started before 90 Ma and extended to about 70 Ma. The post-high-P, eo-Alpine thermal peak is recorded by the recrystallized garnet-staurolite-kyanite metapelites which host the basic eclogites. These assemblages yield Sm–Nd and Rb–Sr mineral ages close to 90 Ma. Interruption of the prograde metamorphic evolution at about this time probably reflects detachment, emplacement and extensional exhumation of crustal slices. Rapid exhumation in Late Cretaceous time may be one main reason for the preservation of unaltered high-P assemblages of both Koralpe and Saualpe eclogites.

Keywords: isotopic dating, eclogite, high-pressure metamorphism, subduction, Adriatic plate, Tethys, Koralpe, Saualpe, Austria.

Zusammenfassung

Sm/Nd-, Rb/Sr- und Pb/Pb-Isotopendaten an basischen Eklogiten und deren teilweise noch erhaltenen Protolithen des Sau- und Koralpenkristallins in SE-Österreich belegen die Produktion ozeanischer Kruste vom MORB-Typ im Unterperm. Dies wird mit Rifting-Prozessen am westlichen Ende der sich öffnenden Neotethys in Verbindung gebracht. Nach sedimentologischen und paläontologischen Ergebnissen setzte die Schliessung dieses Ozeans bereits im Oberjura ein. Entlang der Front der Adriatischen Mikroplatte kam es nachfolgend zu Subduktion und Hochdruckmetamorphose in beachtlichen Teilen der kontinentalen Kruste. Hochdruckparagenesen der untersuchten basischen Eklogite (Granat – Omphazit – Zoisit – Disthen – Amphibol – Rutil – Phengit) geben Hinweise auf eine zeitliche Obergrenze dieser Metamorphose bei ca. 150 Ma und ein Mindestalter von 100 bis 90 Ma. Publizierte geobarometrische Daten liegen bei 11–18 kbar für den Druckhöhepunkt bei der Subduktion. Nach Literaturdaten könnten die südlichen ostalpinen Decken in regionalem Massstab, über eine Distanz von mehreren Hunderten von Kilometern, in diese Subduktionsprozesse einbezogen worden sein.

Während der nachfolgenden Exhumierung ab rund 90 Ma wurden die Hochdruckparagenesen thermisch und durch Fluideinwirkung stark überprägt bis gänzlich umgewandelt. Der dem Druckmaximum folgende altalpidische

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Temperaturhöhepunkt ist am besten in statisch rekristallisierten Granat-Staurolith-Disthen-Paragenesen, den Hüllgesteinen der basischen Eklogite, erhalten. Diese Minerale geben Sm/Nd- und Rb/Sr-Isochronenalter um 90 Ma. Geodynamisch könnte diese Unterbrechung der prograden Metamorphose kontinentale Kollision und Abscherung obduzierter Krustenteile widerspiegeln. Ihre Exhumierung und schnelle Abkühlung beim Deckentransport in der Oberkreide mag ein Hauptgrund für die Erhaltung kaum umgewandelter Hochdruckparagenesen in den Gesteinen der Koralpe und der Saualpe sein.

1. Introduction

The Austroalpine thrust wedge of the Eastern Alps pre-Mesozoic *basement* and Permo-Mesozoic *cover* experienced a complex stacking history (e.g. Krohe, 1987; Eisbacher et al., 1990).

The basement consists of medium- to high-grade polymetamorphic rocks with a predominantly pelitic to psammitic composition and intercalations of acidic to intermediate orthogneisses, pegmatites, metacarbonates and metabasites. Up to the early 1970s these allochthonous basement units were essentially seen as pre-Alpine rock series that experienced only minor deformation and metamorphism during Alpine orogenesis. This view is reflected in the mapping term "Altkristallin", still widely used in Austrian geological terminology.

However, geochronologic and isotopic work showed that a considerable portion of this "Altkristallin" was intensly heated and structurally reworked during eo-Alpine (= Cretaceous) times (for review see Frank et al., 1987).

Major coherent parts of the amphibolite- to eclogite-facies metamorphic Austroalpine basement are exposed both west and east of the Penninic Tauern Window (T.W. in Fig. 1). In both areas, Alpine metamorphism increases from north to south, with inferred paleotemperatures reaching values in excess of 600 °C during the later stages of eo-Alpine evolution. Mineral cooling ages for this metamorphism range between 90

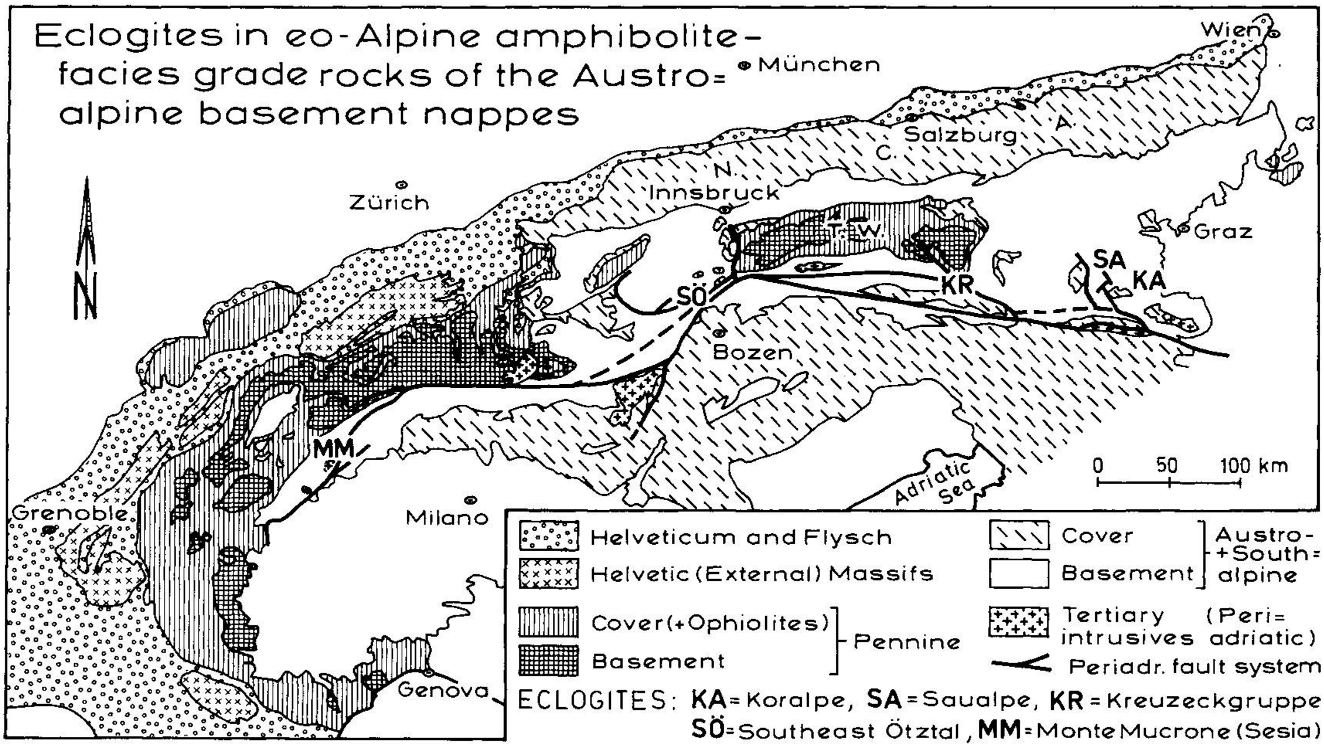

Fig. 1 Simplified geologic-tectonic map of the Alps, showing the location of eclogite facies rocks of definite or probable eo-Alpine age from the southern parts of the Austroalpine basement nappe sheet. A high-P-zone is expected to extend from the Saualpe and Koralpe (SA, KA) in the east to the Sesia zone (MM) in the far west, tracing eo-Alpine subduction of continental crust. T.W. = Tauern Window, N.C.A. = Northern Calcareous Alps.

and 70 Ma (FRANK et al., 1987). In the west a considerable part of the Austroalpine basement is relatively unaltered pre-Alpine crust, while east of the Tauern Window penetrative Alpine deformation is much more widespread.

The present discussion is based mainly on new data from the southeastern parts of the Austroalpine basement units, the Saualpe (SA) and the Koralpe (KA) regions (Fig. 1) in southeastern Austria. A rather intense, probably pressure-dominated Alpine metamorphic overprint in this area was first postulated by MORAUF (1980, 1982). Further detailed structural, petrological and geochronological studies revealed amphibolite grade eo-Alpine metamorphic conditions over large parts of the Saualpe and the Koralpe (FRANK et al., 1983; FRANK, 1983, 1987; KROHE, 1987).

Associated with the polyphase metamorphics of the Saualpe and Koralpe basement are abundant basic eclogites (e.g. HERITSCH, 1973). Some of these well-preserved garnet-omphacite-zoisite-kyanite-amphibole-rutile-quartz-phengite assemblages were first described by the French mineralogist HAÜY in 1822. He created the term "eclogite" for this type of rock in this particular area. The petrology, geochemistry and structures of the Saualpe and Koralpe eclogites have recently been studied in detail (MILLER et al., 1988; MANBY and THIEDIG, 1988; MILLER, 1990; NEUBAUER, 1991). The P-T conditions at the peak of eclogite metamorphism are given as 18 kbar / 580–630 °C (MILLER, 1990). However, published interpretations for the timing of the eclogite metamorphism disagree strongly and its age so far has been poorly constrained. One example for the existence of probably pre-Alpine eclogites in the Koralpe was cited by GÖD (1989). In general, a traditional pre-Alpine age for "Altkristallin" rocks and lack of convincing geochronological data has led most authors to infer a pre-Mesozoic age for the eclogites as well (see DROOP et al., 1990, for a review). In contrast, MILLER and FRANK (1983) postulated an Alpine age for some of the Koralpe eclogites, on the basis of structural and petrological criteria.

We therefore review some recently obtained isotopic data for type-locality eclogites and their host rocks from the Saualpe and Koralpe and then discuss their significance for Alpine geodynamics.

2. New isotopic data from the Austroalpine basement in the Saualpe and Koralpe regions, southeastern Austria

Given the contrasting views concerning the timing of the polyphase metamorphism in the Saualpe and Koralpe regions (e.g. MILLER and FRANK, 1983; MANBY and THIEDIG, 1988), Sm–Nd and Rb–Sr studies were undertaken recently in order to contribute more convincing geochronological information to this problem (THÖNI and JAGOUTZ, 1992 and THÖNI, 1992, unpubl. data). The most important results are summarized on figures 2 to 4.

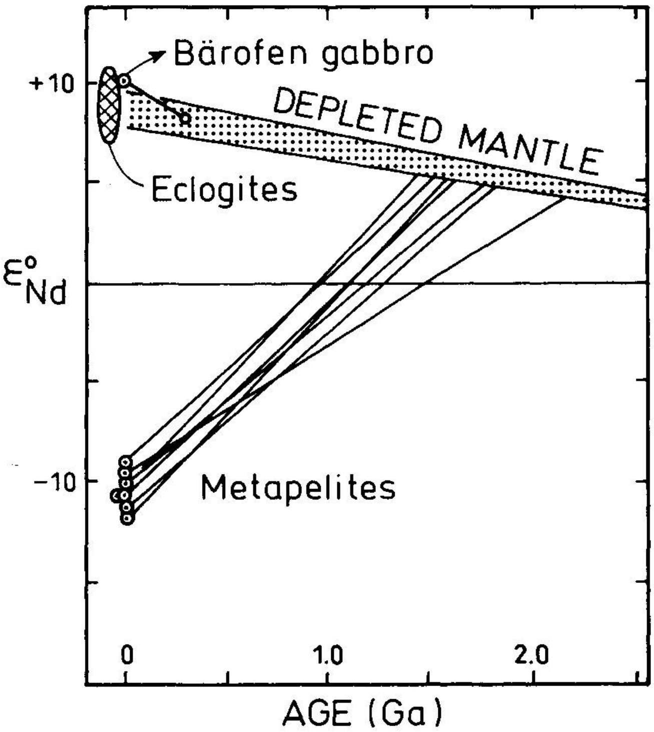

Fig. 2 ε^0_{Nd} vs time diagram showing the fundamental difference between the evolution of the metabasic eclogites and the metapelitic eclogite host rocks. Whereas for the Bärofen gabbro a young t^{Nd}_{DM} age of ca. 250 Ma may be calculated, the model ages for the metapelites are uniformly Proterozoic.

Figure 2 concerns derivation and evolution of the eclogite and metapelite protolith material. The eclogites exhibit ε^0_{Nd} signatures typical for modern depleted mantle (D.M.), in line with the Sr, Nd and Pb isotope characteristics and other geochemical data (MILLER et al., 1988) which point to a derivation of this material from a MORB-type source. Two gabbro samples and one eclogitized gabbro ("Bärofen gabbro" on Fig. 2) yield t^{Nd}_{DM} ages of 253, 225 and 216 Ma, respectively.

In contrast, the metapelite host rocks of the eclogites show strongly diverging, negative ε^0_{Nd} notations and result in t^{Nd}_{DM} ages between 1.5 and 2.2 Ga, pointing to a Proterozoic age for the source material.

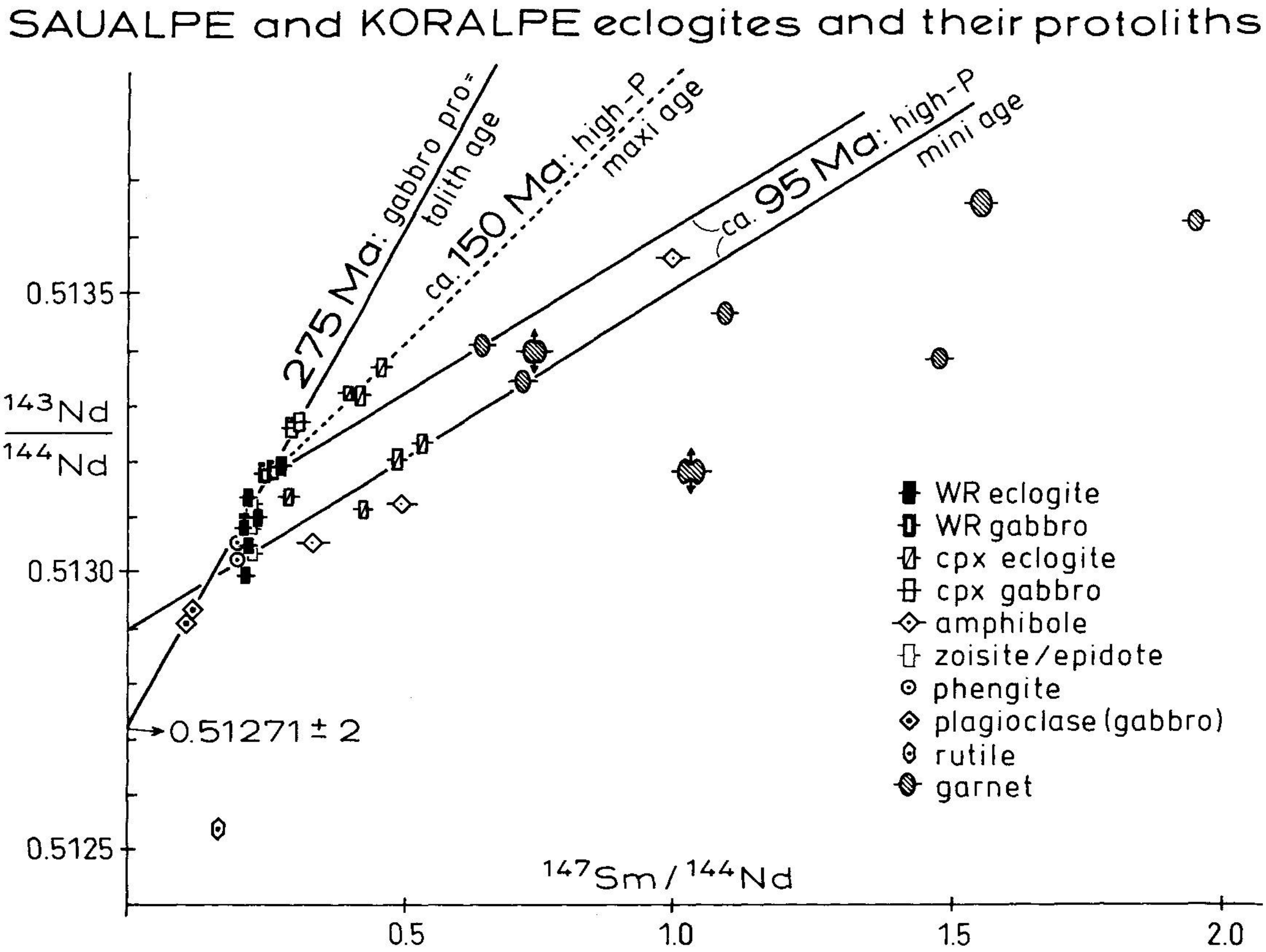

Fig. 3 Isochron plot of whole rock (WR) and mineral Sm–Nd data for eclogites and metagabbros from the Saualpe and Koralpe basement.
Three age reference lines are shown:
a) The 275 Ma "protolith age" gives a hint that at least some eclogites are post-Hercynian.
b) The 150 Ma figure is understood as uppermost time limit for the eo-Alpine pressure peak in the Koralpe.
c) The 95 Ma age sets a lower time limit for this metamorphism.
Data points lying to the right of the 95 Ma reference line are explained by a combination of (1) incomplete isotopic resetting during eclogitization and (2) post-pressure peak crystallization as well as metasomatic alteration and introduction of extraneous isotopic compositions.

Figure 3 is a plot showing all Sm-Nd data for basic eclogites and metagabbros of the Saualpe and Koralpe basement (THÖNI and JAGOUTZ, 1992). It is evident from figure 3 that the low spread in Sm/Nd precludes any time information to be derived for the eclogite protolith formation. However, the above mentioned unaltered gabbro relic from the Koralpe at Bärofen (Fig. 2) that shows step-wise eclogitization on the outcrop scale yielded two Sm–Nd isochrons for plagioclase, clinopyroxene and whole rock of 275 ± 18 Ma and 261 ± 10 Ma, respectively. The ages are similar to the t_{DM}^{Nd} ages of the same rock suite and are interpreted to date magmatic crystallization of the eclogite protolith material. Because the geochemical signatures of the metabasites are relatively uniform (MILLER et al., 1988), the Bärofen is tentatively used as a model and may, hence, set an uppermost time limit for eclogite metamorphism in the study area in general. The 275 Ma figure is labelled "gabbro protolith age" on figure 3.

The resulting conclusion, namely, that the metamophic assemblages of all the eclogites investigated are expected to be younger than

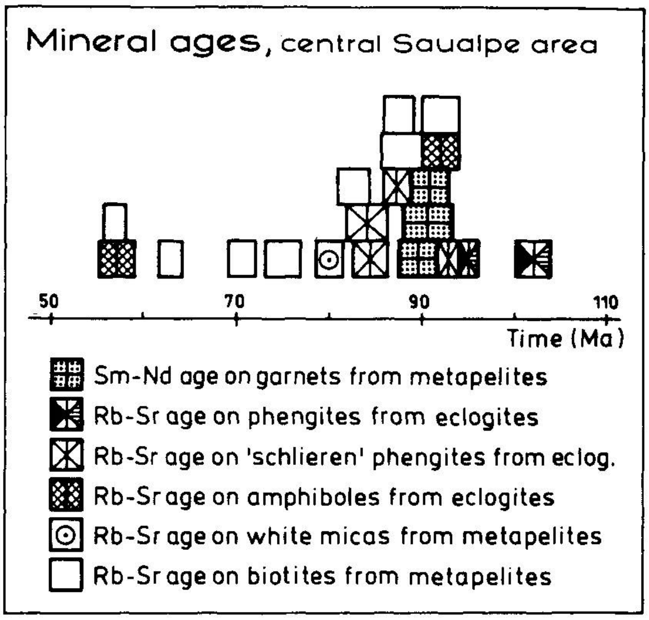

Fig. 4 Summary of Rb–Sr and Sm–Nd mineral ages from the central Saualpe area (Gertrusk – Große Saualpe). It is evident, that the eclogite metamorphism ended before 90 Ma (Rb–Sr ages on phengites). The last thermal peak was reached close to 90 Ma, as defined by concordant Sm–Nd data on garnets from coarsely-recrystallized metapelite assemblages.

275 Ma is readily inferred from figure 3 as well: all the mineral data points lie clearly to the right of the gabbro reference line. However, the detailed interpretation of the individual data sets is difficult to assess: figure 3 obviously reflects a complex metamorphic evolution of the eclogite assemblages. For purposes of simplification, two further trend lines that bracket the eo-Alpine metamorphic evolution, are also shown on figure 3 and interpreted in the following way. The 150 Ma regression "age" (broken line), called "high-P maxi age", was calculated using different clinopyroxene fractions from a gabbro-eclogite sample that experienced incomplete metamorphic resetting with respect to Sm–Nd isotope systematics (see detailed discussion in Thöni and Jagoutz, 1992). Hence, this figure would set an uppermost time limit for the eclogite metamorphism in the Koralpe; i.e. the metamorphism is younger than 150 Ma. The 95 Ma figure, labelled "high-P mini age", sets a lower time limit for the high-P event. It has been derived mainly from two moderatly well defined mineral isochrons of eclogite samples (one from the Koralpe and one from the Saualpe) with ages of 96 ± 10 and 93 ± 15 Ma, respectively. Some mineral data points on

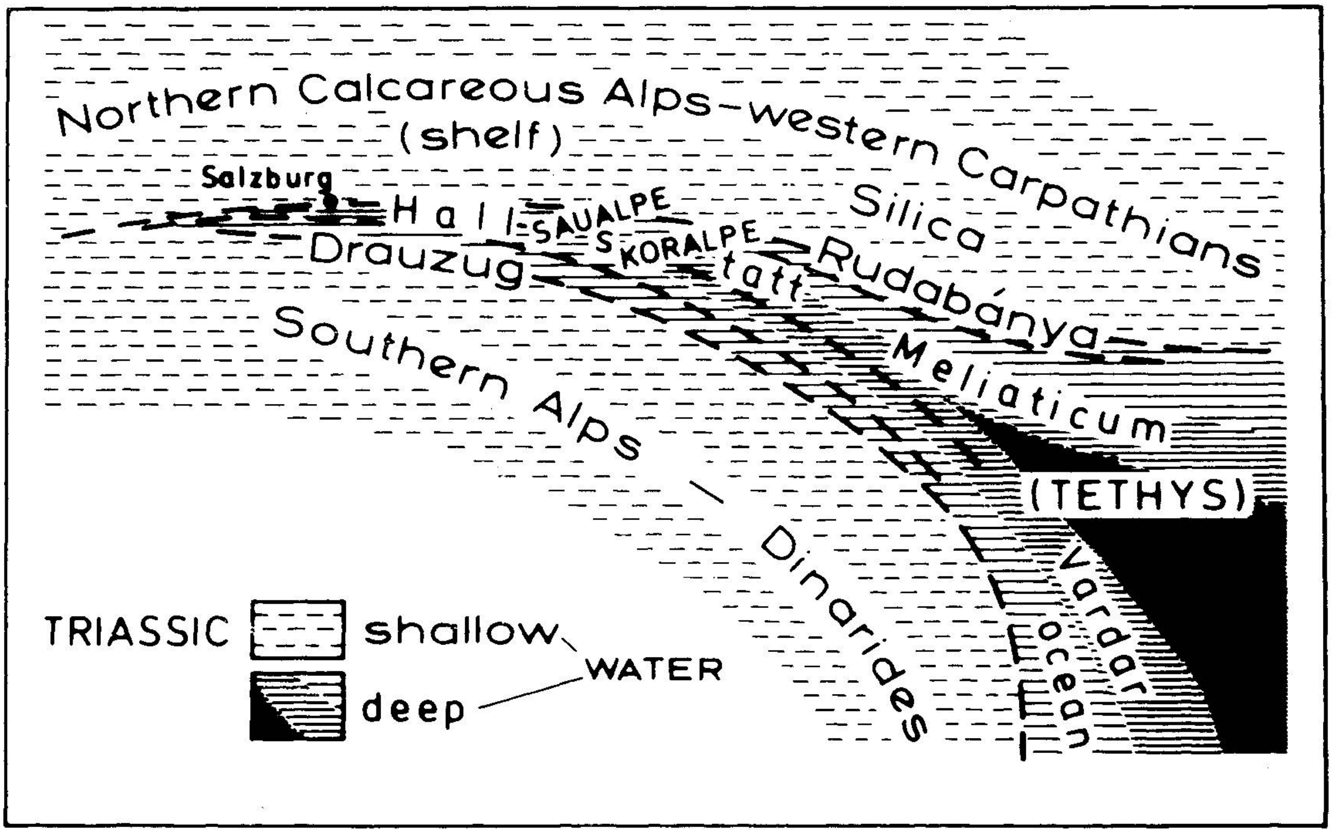

Fig. 5 Relative location of different stratigraphic-tectonic units mentioned in the text, for Triassic time. No attempt is undertaken here to further subdivide this wedge-shaped westernmost branch of the Tethys (Hallstatt-Meliata-Vardar domain). Not to scale.

figure 3, however, and in particular the ones for garnets lie still further to the right of the 95 Ma trend line, resulting in isochron ages as young as 53 Ma. These figures probably have no real significance with respect to timing of metamorphism and could be due to

a) Nd isotope disequilibrium during eclogitization of the protoliths, leaving clinopyroxene, in part, as a closed system, which would result in a negative slope for the clinopyroxene-garnet pair at the time of eclogite metamorphism;

b) introduction of Nd with extraneous isotope composition of probable crustal (unradiogenic) origin into eclogite by infiltration of metasomatic fluids during later stages of crystallization.

Nevertheless, an Alpine age of eclogite metamorphism can clearly be inferred from the data and no memory of an older (pre-Alpine) eclogite event is found in the minerals analyzed.

In figure 4 we show data mainly for metapelitic host rocks of eclogite from the central Saualpe area. They also give valuable hints for the timing of eclogite metamorphism, the most conclusive of which are Sm–Nd analyses of garnets. These minerals grew, or recrystallized, within a coarse-grained mica-feldspar-quartz matrix with abundant staurolite and kyanite. Garnet, staurolite and kyanite are mostly inclusion-free. Random mineral orientation as well as lack of intragranular deformation structures point to a late- or post-kinematic growth of the coarse-grained mineral assemblage. Garnets from three metapelite samples collected over a distance of some 3 km yielded concordant Sm–Nd ages of 90 ± 3, 91 ± 4 and 89 ± 2 Ma, interpreted to date the thermal peak that followed the eo-Alpine high-P event. Unpublished data by MILLER (pers. comm. 1991) indicate that metamorphic temperatures at this stage probably exceeded 600 °C, at pressures ranging between 5 and 12 kbar. Also shown on figure 4 are some Rb–Sr data on coarse-grained phengites from eclogites. The two ages of 102 ± 2 and 95 ± 1 Ma are interpreted to mark the end of the high-P event, or some early stage during subsequent pressure release. However, the "schlieren" phengites stem from specific zones from within the mafic eclogite bodies that are interpreted to be the result of fluid escape and related extensional processes during later stages of, but still related to the same metamorphic evolution. Their ages, derived from four grain size/magnetic fractions separated from two samples, range between 84 and 93 Ma.

Rb–Sr biotite ages from the metapelitic host rocks range between 90 and less than 60 Ma. Though widely scattering, these data generally fall into the regional pattern of K–Ar and Rb–Sr mica ages (e.g. MORAUF, 1980; JUNG, 1982; FRANK et al., 1987; MANBY and THIEDIG, 1988) which signifies that eo-Alpine metamorphism in the basement ceased some 70–60 Ma ago.

Thus, isotopic information derived from eclogites and their host rocks permits the following conclusions:

– Eclogite metamorphism in the classic eclogite localities of the Koralpe and Saualpe regions is eo-Alpine in age, with an upper time limit for peak pressures at about 150 Ma and a lowermost time limit at about 90 Ma.

– The eo-Alpine temperature peak was reached close to 90 Ma.

– Regional cooling below 300 °C was completed at about 70 to 60 Ma.

3. Regional significance of eo-Alpine eclogite metamorphism in the southeastern Alps

From our data and those of others we infer an Alpine evolution for the southeastern Austroalpine domain as depicted schematically in figure 6.

3.1. LATE PALEOZOIC TO EARLY MESOZOIC

From Late Paleozoic times onward the wedge-shaped Tethys ocean developed between the two supercontinents Gondwana and Laurasia. According to ŞENGÖR (1984) this area comprises both the Paleotethys and the young Neotethys, where different crustal slices of Gondwana (called the "Cimmerian Continent", ŞENGÖR, l.c.) began to rift from the southern passive margin and to move northwards to be accreted to Laurasia (KAZMIN, 1991). Since the Austroalpine nappes are generally regarded as a frontal slice of the Adriatic (or Apulian) microplate they originally formed the northernmost part of the African continent (CHANNEL et al., 1979; DERCOURT et al., 1985).

Despite the strong structural reworking within and above the Alpine subduction zone, the metabasic rocks of the Koralpe-Saualpe discussed above still record the original geochemical environment of their protoliths rather well. The geochemical and isotopic signatures support the conclusion that most eclogite precursors originate from a MORB-type source. This evidence for the production of fairly juvenile oceanic crust material in Permian time suggests nucleation of a young ocean and crustal fragmentation and thinning of consolidated pre-Alpine basement along a rift zone.

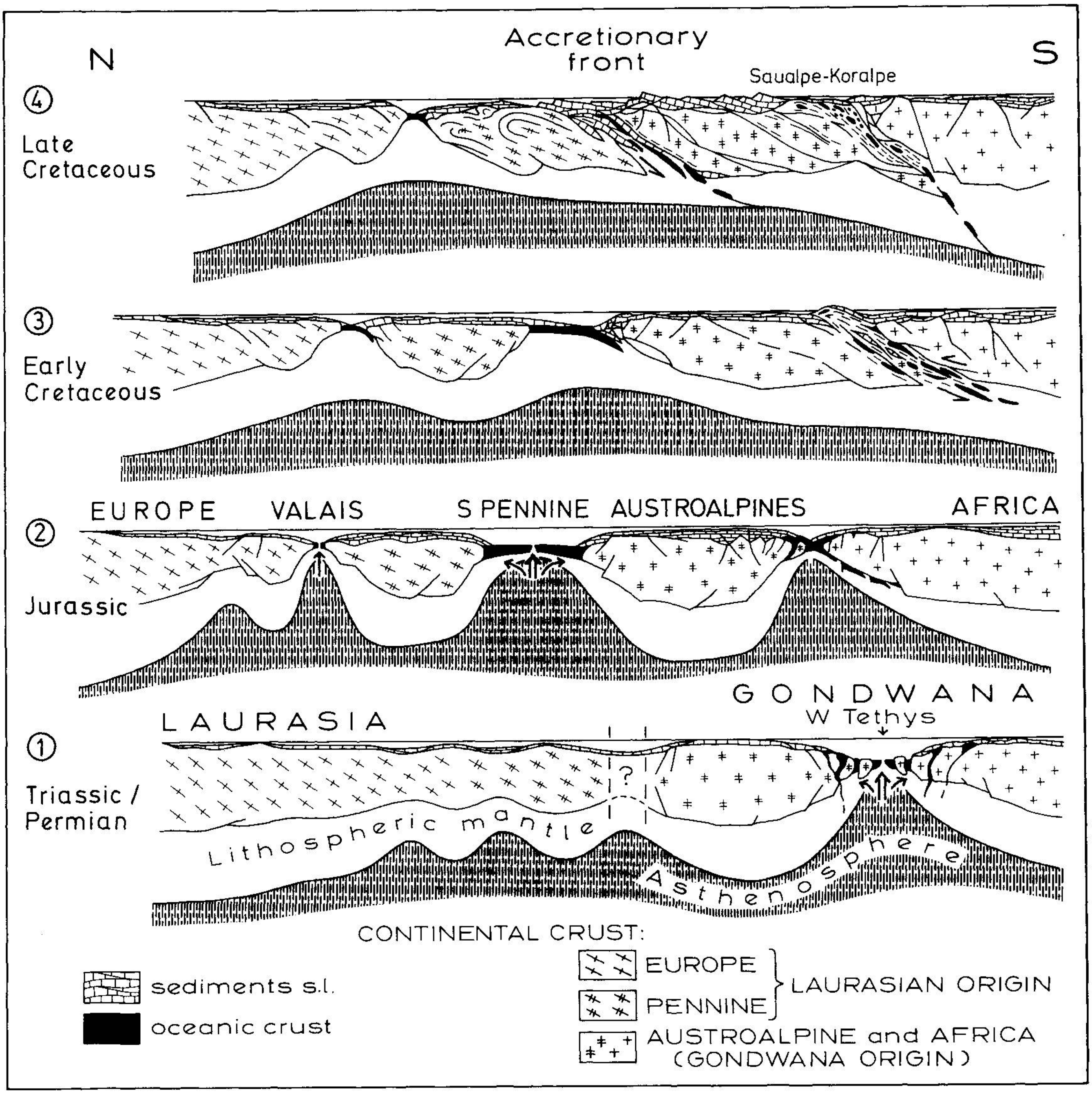

Fig. 6 Cartoon depicting the evolving Alpine orogen through Mesozoic time and showing the continuous progradation of subduction zones towards the European continent.
1) Continental fragmentation, extension and uprise of the asthenosphere result in the formation of a new oceanic environment at the western end of the early evolving Tethys: at least some of the Koralpe and Saualpe eclogite protoliths are derived from the mantle in Late Paleozoic to Early Mesozoic times.
2) During the Mesozoic, three oceanic domains existed in the Alpine region. Whereas in the south (Tethys ocean) subduction may have started during the Jurassic, oceanization goes on in the south Penninic trough.
3) and 4) In the Cretaceous the first and most important metamorphism during the Alpine cycle takes place in the Austroalpine units (eo-Alpine event). The southernmost parts are buried to some 50 km or more. Cooling sets on close to 90 Ma. Inspiration for this sketch stems from Prey (1978), Channel et al. (1979), Dercourt et al. (1985), Platt (1986), Decker et al. (1987), Frank (1987), Lein (1987), Pober and Faupl (1988), Trümpy (1988), Kozur (1991), among others.

The existence of such an old extensional realm is a rather new idea and still poorly constrained, since oceanization in the Alps is generally related to the evolution of the Piemontais-Penninic region during the Jurassic, which is itself clearly seen in connection with the opening of the N-Atlantic (e.g. FRISCH, 1981; TRÜMPY, 1988; HÖCK and KOLLER, 1989; HÖCK and SCHARBERT, 1989). One reason for this may be that in the Western Alps the Austroalpine units are only very rudimentarily preserved. Only in recent years and by taking into account the eastern continuation of the Alps into the Carpathians and Dinarides it became increasingly clear that for the Eastern Alps, three distinct oceanic domains may have existed during Mesozoic times (e.g. DECKER et al., 1987; cf. Fig. 6).

The autochthonous Permomesozoic cover of the Austroalpine realm is very rudimentarily preserved, but was largely tectonically removed from its basement. The Northern Calcareous Alps (NCA in Fig. 1) form a huge nappe pile of non- to anchimetamorphic, mainly calcareous strata between the western Carpathians and eastern Switzerland. Although different tectonic models exist for their derivation (see FRANK, 1987), these platformal to basinal strata are generally considered to have been deposited on extended continental basement very similar to the exposed Austroalpine basement ("Altkristallin", including Paleozoic rocks). In the earliest Mesozoic there was a clear connection with continental Europe such as during deposition of the Triassic Keuper facies. The most southerly parts of this shelf, however, point to deeper water conditions (BRANDNER, 1984). These parts form the highest tectonic elements within the eastern portion of the Northern Calcareous Alps, i.e. east of Salzburg and are referred to as the "Hallstatt zone". Based on sedimentological and faunistic elements, the Hallstatt zone recently has been interpreted to represent the link between a shelf and an open oceanic environment of large-scale dimension (LEIN, 1987), rather than a local deep water intra-shelf trough. An eastern continuation of the Hallstatt zone could be the Meliata-Hallstatt ocean of KOZUR (1991) and/or the Vardar ophiolite belt (KOVACS, 1982; PAMIC, 1984), thus representing the westernmost outliers of the early Tethys. The Meliata-Hallstatt ocean seems to have had a life-span ranging only from the Anisian to the Oxfordian (KOZUR, l.c.). No attempt is made to further clarify the detailed paleogeographic and plate tectonic situation here. Figure 5 gives just a very rough location of the different terms used in the text. However, the data on the eclogite precursors discussed above indicate that extension and oceanization in the southern Austroalpine region may have commenced as early as in the Upper Carboniferous to Lower Permian. The eclogite-bearing Saualpe and Koralpe rocks could thus be seen as the westernmost extensional domain to an open ocean that started to evolve soon after the Hercynian orogeny. Wide-spread Late Permian-Triassic basic to intermediate magmatic activity is documented for the Dinaridic part of the Tethys (PAMIC, 1984).

The Bärofen gabbro so far represents the only dated remnant of "post-Hercynian" MORB-derived gabbros within the Austroalpine basement, but numerous other magmatic bodies of largely the same age occur in the westerly continuation of this zone. Interestingly, these bodies lie to the north as well as to the south of the Periadriatic fault system (Fig. 1). The Eisenkappel granite (CLIFF et al., 1975), the Wolfsberg granite gneiss (MORAUF, 1980), the Brixen-Iffinger-Kreuzberg intrusives (BORSI et al., 1972) and the Monte Mucrone granite in the Sesia zone (PAQUETTE et al., 1989a) are some examples. This latter body has been involved in eo-Alpine high-P metamorphism (OBERHÄNSLI et al., 1985). Also to this age range belong some of the "Late Hercynian" pegmatites from the wider area in question (e.g. MORAUF, 1981; JUNG, 1982). The Permotriassic volcanism, as documented within the sedimentary sequences of the NCA (KIRCHNER, 1980) and the Southern Alps (e.g. STÄHLE et al., 1990), is further direct evidence for an active magmatism related with rifting processes and uprise of the asthenosphere at this time. Within such an extensional crustal environment a high geothermal gradient, crustal melting, and magma mixing are to be expected, producing probably unusual geochemical signatures. The Wolfsberg granite in the Koralpe, for example (MORAUF, 1980), shows a $^{87}Sr/^{86}Sr$ initial ratio typical for primitive magmas (0.7046), combined, however, with exceedingly high Rb/Sr and yielding a Rb–Sr isochron age of 258 ± 10 Ma (MORAUF, 1980). This "contradictory" feature could be explained by metasomatic alteration (Rb enrichment) of a primitive magma extracted from the mantle close to 260 Ma, a figure that is identical with the protolith age of the Bärofen eclogite (cf. Fig. 3).

3.2. EO-ALPINE SUBDUCTION AND THE TIMING OF ECLOGITE METAMORPHISM

Based on sedimentological and paleocurrent studies and the composition and distribution of heavy mineral spectra, POBER and FAUPL (1988) and FAUPL and POBER (1991) concluded that

Lower Cretaceous sequences within the NCA were fed essentially from source areas lying to the south of the Austroalpine domain. This has to be considered as a relatively early eo-Alpine feature, since the Roßfeld (FAUPL and TOLLMANN, 1979) and other Lower Cretaceous turbiditic series already show the above characteristics (see also ÁRGYELÁN, 1992). The outstanding diagnostic material is detrital chromian spinel, demonstrating that ophiolitic sequences could have been exposed for erosion along the southern margin of the Austroalpine domain as early as some 130 Ma ago. Based on the strongly divergent chemistry of the chromian spinels, POBER and FAUPL (1988) distinguish two different source areas of probably different age, i.e. a harzburgitic and a lherzolitic one; the latter, representing the source area for MORB-type magmas (as observed at Bärofen), was exposed to erosion somewhat later, i.e. only since mid-Cretaceous time (ca. 100 Ma). Hence, from the isotopic signatures for Pb, Nd and Sr the Bärofen gabbro and eclogites could be part of the lherzolitic subprovince of the Vardar ophiolite belt (FAUPL and POBER, 1991; PAMIC, 1983). Closure of the Meliata-Hallstatt ocean commenced in early Late Jurassic times (KOZUR, 1991), i.e. some 150 Ma ago. Just at the same time the well-known upper Jurassic "Gleittektonik" (nappe gliding) began in the Hallstatt zone (PLÖCHINGER, 1976). These very first steps of eo-Alpine tectonics may be explained by the same compression/collision events that eliminated oceanic environments and signal eo-Alpine subduction in the southern Austroalpine domain. Such an "eo-Alpine subduction" was first sketched by PREY (1978) for the Eastern Alps. The Vardar ocean was definitely closed during the Cretaceous.

The implications derived from the above observations are: a) The high-pressure metamorphism inferred for the study area could be the result of Late Mesozoic subduction of the southern Austroalpine units during partial closure of the Meliata-Hallstatt-Vardar ocean to depths of 50 km (MILLER, 1990). b) High-P parageneses crystallized during this event are expected to be younger than some 150 Ma.

This latter statement is well in line with the data discussed above: an upper age limit of 150 Ma is indicated by Rb–Sr and Sm–Nd results for the Bärofen eclogite, but a considerably younger age is more realistic (cf. Fig. 3). An age as young as 100 Ma for eclogite metamorphism in the Koralpe and Saualpe regions could be inferred from data presented in THÖNI and JAGOUTZ (1992). PAQUETTE and GEBAUER (1989b, 1991) presented U–Pb zircon data that support an Early Cretaceous high-P event for the Koralpe.

The closing of such a vast oceanic domain like the western Tethys is necessarily expected to have had serious effects for the adjoining continental crust. Roughly speaking, the zone following today's Periadriatic Lineament (PAL) to the north may represent that segment of "weakness" where large-scale crustal deformation took place as a consequence of consumption of an oceanic domain. Taking into account the western extension of the Hallstatt zone as a marker, open oceanic conditions may have ended somewhere to the east of the present Western-Eastern Alps boundary. However, taking also into account considerable dextral (and sinistral), strike slip in the order of some hundreds of kilometers (see TOLLMANN, 1978; KOVACS, 1982; SCHMID et al., 1989) along the PAL, the former position of the westernmost oceanic relics within the metamorphosed part of the basement could have been considerably changed. The opinions about the function of the PAL as an important geotectonic suture zone are strongly divergent in the literature (BÖGEL, 1975, with literature; EXNER, 1976). Young movements could have strongly masked, overprinted or even eliminated older structure elements, but a very early Alpine activity seems probable (e.g. GANSSER, 1968; CLIFF et al., 1975; PREY, 1978; HAGENGUTH, 1984). It is important to note, however, that in the Eastern Alps, over large distances a second (set of) lineament (s) exists that follows the Periadriatic lineament s.str. some kilometers to the north, within the Austroalpine basement (Fig. 1), and has considerable influence on the disturbance of the eo-Alpine metamorphic profile (Peio, Jaufen-Passeier, DAV, Mölltal and Lavanttal lines; BORSI et al., 1978; HOINKES et al., 1991; SCHMID et al., 1989, for references).

Recent field and petrological work has revealed other occurrences of metabasic eclogites and metapelite high-P assemblages in the western parts of the Austroalpine basement (OBERHÄNSLI et al., 1985; SCHIMANA, 1986; HOKE, 1990; HOINKES et al., 1991; KONZETT and HOINKES, 1991). Though thoroughly altered during uplift and thermal overprinting, the rocks point to crystallization at 11 to 15 kb (minimum pressures) and at temperatures of 500 to 600 °C. The conclusion drawn by the above authors is that the areas indicated in figure 1 were buried to depths of some 30–40 km during the Cretaceous. Typically, all these eclogites are hosted by metapelites that underwent amphibolite-grade metamorphism in the Cretaceous, in a position close to, but north of the Periadriatic Lineament. The westernmost occurrence is the Monte Mucrone eclogite in the Sesia zone. The Monte Mucrone granite is obviously of crustal origin but the analogy of these rocks with respect to both protolith age and eclogitization event, if compared to the Bärofen gabbro and eclogite, seems to be more than coincidental. Both eclogites originate from Lower Permian intrusives (PAQUETTE et al., 1989a; THÖNI and JAGOUTZ, 1992) and the conditions at the peak of eclogite metamorphism are very similar. For the Monte Mucrone eclogite a Rb–Sr age of 114 Ma for garnet and omphacite was published (OBERHÄNSLI et al., 1985). Further evidence for eo-Alpine high-pressure metamorphism in the rudimentarily preserved Austroalpine units of the Western Alps was given by COMPAGNONI (1977), RUBIE (1984), VOGLER (1984), STÖCKHERT et al. (1986). The recently published model of crustal extension and subsequent continental subduction for the Sesia zone by LARDEAUX and SPALLA (1991) resembles the above described scenario for the Eastern Alps in many respects (cf. Fig. 6).

The comparison of the eo-Alpine evolution in the Sesia zone with the one of the southern Austroalpine units of the Eastern Alps is speculative, since the Sesia zone is generally said to be of Lower Austroalpine (i.e. continental margin) affinity. However, considering a strongly narrowing Austroalpine nappe system towards the western end of the Alps, the Sesia zone could probably represent a thin crustal slice that experienced eo-Alpine intracontinental subduction fairly close to the Pennine-Piemontais subduction zone.

3.3. TECTONIC EMPLACEMENT AND COOLING HISTORY OF ECLOGITES

Because of strong retrograde metamorphism of eclogites in the westerly parts of the Austroalpine basement, the history of exhumation and cooling is poorly constrained. The metapelite eclogite host rocks have been largely adjusted to intermediate P-T-conditions during their return to the surface. This may be due to the strong competency contrasts between metabasic eclogites and metapelites during post-high-P deformation: the less competent acidic rocks may have lost largely their high-P memory in response to ongoing deformation-induced recrystallization. Using different minerals and isotopic systems in both Alpine low- and amphibolite-grade metamorphic parts of the western Austroalpine nappes, the onset of regional cooling was estimated at close to 90 Ma (THÖNI, 1988). Looking at the metapelite data from the Saualpe (Fig. 4), this seems to represent a fairly consistent chronological date over the whole Eastern Alps. This age pattern demonstrates that cooling of the nappes from about 600 to less than 300 °C was accomplished within some 10 to 20 Ma between 90 to 70 Ma. Mylonite ages in the same range document large-scale crustal thrusting (THÖNI, 1988; SCHMID and HAAS, 1989), contemporeaneous with fold-thrust imbrication in the frontal Northern Calcareous Alps (EISBACHER et al., 1990).

The 90 Ma age thus marks an interruption of prograde metamorphic conditions. Geodynamically, this date is best interpreted as the time of initial stacking of crustal slivers within the southeastern Austroalpine domain.

As a whole, the Alpine evolution is described as a successive northwards migration of subduction zones (DECKER et al., 1987), resulting in the consumption of three different oceanic domains, i.e. the NW Tethys, Piemontais = S Pennine, and Valais troughs (Fig. 6). Structural considerations, however, point to west-/northwest-directed motion of the Austroalpine thrust sheets during early eo-Alpine nappe tectonics, consistent with a counterclockwise rotation and dextral transpression within the Adriatic microplate (DERCOURT et al., 1986; RATSCHBACHER, 1986).

Cretaceous subduction of rather extensive south Penninic realms resulted in very high to ultrahigh pressure parageneses in the foot wall, the nature of which has been studied by MILLER (1974, 1986), SELVERSTONE et al. (1984), CHOPIN (1987), GOFFÉ and CHOPIN (1986), DAL PIAZ and LOMBARDO (1986), TILTON et al. (1989, 1991). Chronologically, however, this high-pressure event is not well defined, because of a generally intense Tertiary thermal overprint. Following TROMMSDORFF et al. (1990) and EISBACHER et al. (1990), nappe stacking within the frontal Austroalpine cover and hence Penninic subduction in the central parts of the Alps is younger than 100 Ma (though the beginning of this subduction process is clearly older). This is in accordance with our data that show that effective obduction of southern Austroalpine eclogite facies rocks may be as young or even younger than 100 Ma, requiring rapid tectonometamorphic evolution for Cenomanian-Turonian times.

The mechanism of accretion of orogenic wedges by underplating, leading to rapid uplift and exhumation of high-pressure metamorphic rocks in the rear of the wedge have been modelled by PLATT (1986). Following this model, high-P/low-T metamorphism develops mainly as a consequence of wedge thickening by inflow of thick competent layers at the front of the prism. Such a situation could lead to a fairly long lasting and complicated metamorphic evolution, with much time available for thermal re-equilibration and overprinting of high-P parageneses during uplift.

Applied to the Alps, this could explain the near-contemporaneity of P and T peaks of metamorphism, as well as immediate succession of high-P stages both within the Austroalpines and the Pennines (e.g. HUNZIKER, 1974) during the Cretaceous. Continuing tectonic underplating, however, led to faulting and extension of the underplated material, and large-scale detachment of nappes with older and higher-grade rocks having been emplaced over more-recently accreted, lower-grade rocks.

4. Conclusions

The isotope signatures of Sr, Nd and Pb for gabbroid rocks indicate production of depleted mantle material close to the SE border of the Austroalpine basement in Early Permian times. The MORB-type source magma was possibly produced along a narrow rift zone marking a branch of the western Tethys.

Closure of an ocean during Late Jurassic to Early Cretaceous times resulted in subduction and high-pressure metamorphism of dismembered oceanic and continental basement fragments along the northern Adriatic microplate. Overall P-T-conditions for this high-P stage are 11 to 18 kb and 500 to 630 °C. Eclogite metamorphism of mafic rocks caused – partly incomplete – transformation of the primary mineral assemblages into garnet + omphacite + zoisite + kyanite + quartz + amphibole + phengite + rutile parageneses. During this metamorphism the Sm–Nd mother-daughter pair behaved as a partly closed system on the grain scale, resulting in unrealistically young isochron ages for omphacite-garnet pairs that have no time significance in a strict sense. Metamorphic fluid activity and isotopic mobilization during a subsequent thermal overprint further complicate evaluation of timing of metamorphism. The exact age of the related eo-Alpine subduction event in the southern Austroalpine units is therefore difficult to assess. It is probably as young as 100 to 90 Ma, but is in any case younger than 150 Ma.

Tectonic underplating along the northern Adriatic continental margin during the Later Cretaceous caused crustal stacking resulting in west- to northwest-directed thrusting and related extension of formerly deeply buried crustal slices. Cooling within the Austroalpine nappes down to 300 °C was accomplished in the Late Cretaceous, around 70 ± 10 Ma ago.

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