# Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria

Autor(en): **Miller, Christine**

Objekttyp: **Article**

Zeitschrift: **Schweizerische mineralogische und petrographische Mitteilungen = Bulletin suisse de minéralogie et pétrographie**

Band (Jahr): **70 (1990)**

Heft 2

PDF erstellt am: **21.09.2024**

Persistenter Link: https://doi.org/10.5169/seals-53619

**Nutzungsbedingungen**

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

**Haftungsausschluss**

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

**http://www.e-periodica.ch**

*SCHWEIZ. MINERAL. PETROGR. MITT. 70, 287–300, 1990*

# Petrology of the type locality eclogites from the Koralpe and Saualpe (Eastern Alps), Austria

by *Christine Miller*[1]

## Abstract

The type-locality eclogites were derived from basic igneous and volcanic protoliths. Two types can be distinguished: the kyanite-eclogites appear to have formed by metamorphism of gabbroic cumulates, whereas the kyanite-free eclogites have geochemical affinities with MORB basalts. All eclogites contain abundant hydrous phases.

In several outcrops the gabbroic precursor rocks have incompletely reacted to eclogite suggesting water-deficient conditions. For most eclogites, however, phase relationships of anhydrous and hydrous silicates, mineral textures and syn-high-pressure veins suggest eclogite crystallization under conditions of high water activity. For the eclogite event, PT estimates derived from mineral compositions and oxygen isotope studies are about 18 kbar and 580–630°C. These conditions are similar to those for subduction-related eclogites from the Alps and Caledonides. The PTt-history, however, is still problematic. Although there is evidence for a pre-Alpine eclogite-forming event, Sm/Nd isotope work in progress yielded early Alpine mineral isochrons for some type-locality eclogites.

*Keywords:* Eclogite, PTt-history, oxygen isotopes, Sm/Nd Alpine isochrone, Austroalpine, Saualpe, Austria.

## Introduction

Eclogite as first defined by HAÜY (1822) on samples from the Koralpe and Saualpe is a rock principally composed of garnet, omphacite ("green diallage"), kyanite and also containing quartz, zoisite and amphibole ("carinthine"). However, the concept that orogenic eclogites formed under dry conditions (e.g. YODER and TILLEY, 1962; FRY and FYFE, 1969; AHRENS and SCHUBERT, 1975; BEST, 1982) has ignored the fact already stated in this early definition that hydrous silicates form an essential part in most group B and C eclogites (COLEMAN et al., 1965). This paper discusses the evidence for the presence of an aqueous fluid phase during eclogite formation and provides new estimates of the high-pressure metamorphic conditions of the type-locality eclogites.

## Outline of geological setting

The Koralpe and Saualpe crystalline complex is a part of the Austroalpine nappe system (Fig. 1). It consists predominantly of metapelitic gneisses and schists of a pre-Mesozoic continental basement. Three metamorphic events have been established (FRANK et al., 1983). The first metamorphic event (K1) is characterized by the stability of orthoclase and andalusite or sillimanite rather than muscovite and quartz. The high temperature during this event was also responsible for the development of a segregation banding in the gneisses and, possibly, for incipient migmatization (WIMMER-FREY, 1984, cum lit.). The second, high-pressure event (K2) caused the transformation of andalusite/sillimanite to kyanite, the incomplete back-reaction of alkali-feldspar and aluminum-silicate to muscovite and quartz, the growth of garnet I and staurolite I (FRANK et al., 1983; WIMMER-FREY, 1984). In the northern Koralpe and Saualpe evidence of a prograde breakdown of staurolite I to garnet and kyanite has been preserved. Crystallization generally outlasted deformation. Towards the end of this event pegmatites were intruded, some of which are preserved undeformed in areas that escaped later overprints.

---

[1] Institut für Mineralogie und Petrographie, Innrain 52, A-6020 Innsbruck.

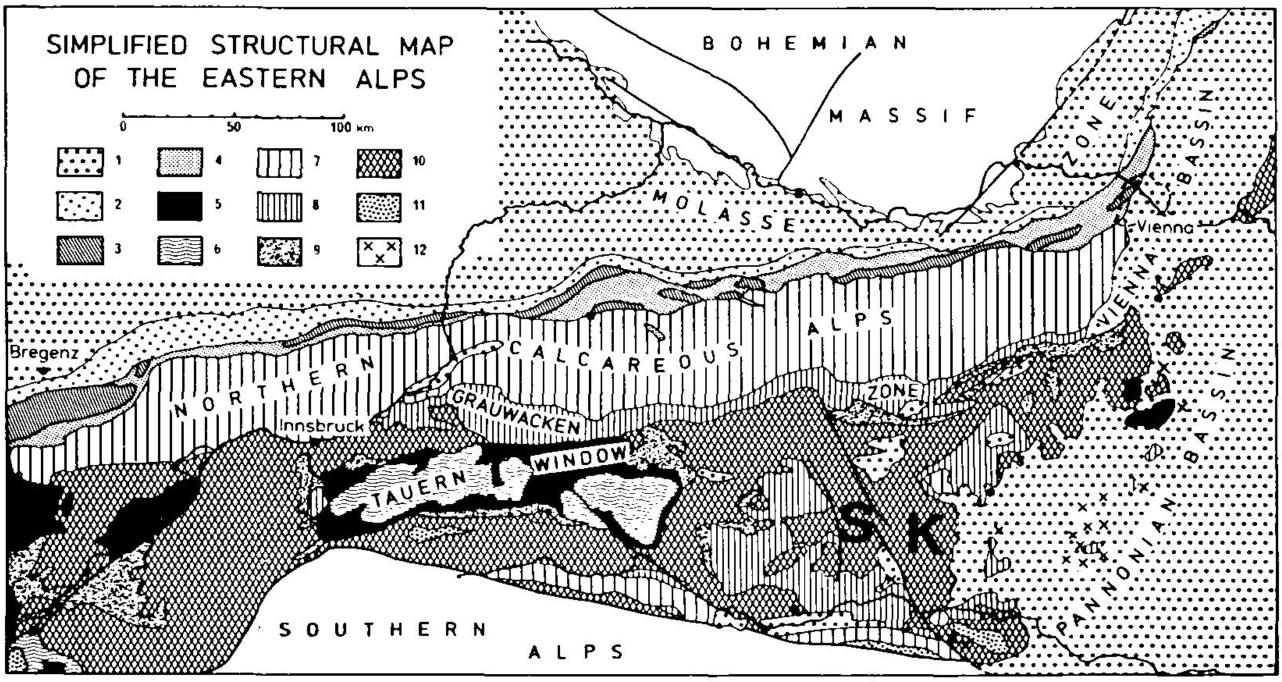

*Fig. 1* Tectonic sketch map of the Eastern Alps showing the location of the investigated area. 1 = Molasse Zone and Tertiary Basins; 2 = Subalpine Molasse; 3 = Helvetic and Klippen Zone; 4 = Flysch Zone; 5 = Pennine Permo-mesozoic metasediments and ophiolites; 6 = Pennine Basement complex; 7–10 = Austroalpine nappes; 11 = Periadriatic intrusives; 12 = Tertiary volcanics; K = Koralpe; S = Saualpe.

The overprint of the third and last metamorphic and structural event (K3) varies with the intensity of deformation and the availability of a fluid phase. During this event, the intracrustal "Plattengneis" shear-zones characterized by a layered appearance and a prominent stretching lineation developed in the Koralpe gneiss complex under high PT conditions (Frank et al., 1983; Wimmer-Frey, 1984; Krohe, 1987). The somewhat less deformed equivalents in the Saualpe are known as kyanite-flasergneisses (Weissenbach, 1965). In these rocks, syn- to postkinematic growth or recrystallization is documented for garnet (II), kyanite, staurolite (II), plagioclase, muscovite, biotite and quartz. The same intense mineral growth (including staurolite II ± chloritoid) also occurred in horizons above and below the Plattengneiss shear-zone in the central Koralpe and in the mica-schist series, originally overlying the high-grade gneiss group in both Koralpe and Saualpe but now involved in large-scale recumbent fold structures (Frank et al., 1983).

Rb/Sr and $^{87}$Sr/$^{86}$Sr data suggest a late Proterozoic to Cambrian model age for the metasediment protoliths (Frank et al., 1983). The metamorphic event K1 is still undated, it could be early Hercynian or pre-Hercynian. K2 is documented by a few Rb/Sr whole rock ages of 391 ± 16 Ma (Morauf, 1982) and by Rb/Sr mineral ages of 265–240 Ma (Morauf, 1982; Jung, 1982). These, however, may reflect a cooling process in areas with pegmatitic activity post-dating the cooling event in the main basement. Rb/Sr muscovite model ages in the range 117–81 Ma (Morauf, 1982; Frank et al., 1983) reflect regional cooling after the Cretaceous event (K3).

High-pressure assemblages are mainly preserved in structurally incoherent mafic lenses and layers enclosed in kyanite-garnet-bearing gneisses and schists. Mineral-fabric relations between eclogites and country rocks can only be correlated for a few occurrences within the Cretaceous "Plattengneis" shear zones. Known since Haüy (1822) they have been discussed by number of authors, e.g. Kieslinger (1928), Wieseneder (1934), Heritsch (1966, 1973, 1980 cum lit.), Weissenbach (1965), Mottana et al., (1968), Richter (1973).

## Petrography

The eclogite bodies occur as small pods or as sheet-like bodies within kyanite-garnet-bearing gneisses and schists. Stratigraphic relationships with these country rocks are obscured because of poor exposure and polyphase tectonometamorphism. Some occurrences, however, suggest disruption of originally larger bodies. Field evidence indicates that the eclogites and related metabasites are volumetrically insignificant relative to the country rocks.

On a textural basis four types may be distinguished among the eclogites although later metamorphic overprints make the more altered specimens hard to classify.

*(1) Pale, gabbroic-textured eclogites:* Compositional layering and a wide range of grain size and textures is characteristic. An example is H8 where the magmatic pyroxenes have been replaced by a polygonal aggregate of omphacite ± coexisting amphibole. Inclusion-rich garnet either mimics the original plagioclase or forms coronas separating the omphacite ± amphibole domains and the pseudomorphs after igneous plagioclase consisting of zoisite, kyanite and quartz. Rutile, apatite and sulfides are minor accessories.

*(2) Pale, medium-to coarse-grained eclogites:* These rocks, typified by SK 1 or SKP 12, are characterized by an irregular compositional layering on a 1–10 cm scale. In most samples omphacite crystals define a strong planar fabric within which zoisite, kyanite and amphibole are aligned. Inclusion-poor garnet forms anhedral porphyroblasts. Rutile, apatite and pyrite are accessories. Subordinate amounts of quartz, paragonite, phengite and carbonates (dolomite, calcite) may also be a part of the primary eclogite assemblages. Type (2) eclogites are characterized texturally by sharp grain boundaries of hydrous and anhydrous silicates. Amphibole poikiloblasts appear to overgrow the foliation in some eclogites. Mutual inclusions, however, indicate a largely contemporaneous crystallization of anhydrous and hydrous phases.

In many of these kyanite-eclogites quartz-rich veins occur, 1–5 cm in width, containing high pressure minerals (kyanite, omphacite, rutile) ± hydrous silicates (zoisite, amphibole). Kyanite may form blades up to 20 cm in length. Vein walls show no alteration of the host eclogites. As textural relations indicate that the vein minerals have crystallized from a fluid in equilibrium with the adjacent kyanite-eclogite these veins could document fluid escape at the stage of high-pressure metamorphism.

*(3) Dark, heteroblastic eclogites:* GE 2, H12, are typical examples of this category. Usually these rocks are medium-grained, with or without a planar fabric and consist of garnet, omphacite, clinozoisite and quartz. Kyanite is always absent. Apatite, rutile, pyrite and zircon are accessories. In many samples amphibole and phengite seem to be in textural equilibrium with both garnet and omphacite, but commonly the amphibole is poikiloblastic. These poikiloblasts are up to 20 mm in diameter and contain numerous inclusions of garnet, clinozoisite, omphacite ± diopside-oligoclase-symplectite, quartz, rutile as well as highly irregular quartz-blebs. These quartz-blebs are sometimes characterized by an internal reaction rim consisting of an albite-rich plagioclase and diopside and/or a central grain of omphacite ± symplectite. Irregular segregations containing quartz and phengite are quite common.

*(4) Fine-grained, banded, strongly foliated eclogites:* These rocks, typified by FYK 236, form layers within the Plattengneis shear-zones. The compositional banding is due to modal variations of the amphibole content. Subhedral garnets are set in a fine-grained planar omphacite + amphibole + clinozoisite fabric. Quartz, sphene ± rutile, apatite and graphite are minor, respectively accessory constituents.

## PROTOLITHS

The major- and trace-element chemistry of the eclogites is consistent with an origin of their protoliths at a constructive plate margin (MILLER et al., 1988). These data indicate that the precursor rocks of the kyanite-bearing type (1) and (2) eclogites are Ti-poor and formed as cumulates of clinopyroxene, ± olivine and plagioclase at $P < 8$ kb from a mafic magma. In contrast, the protoliths of the high-Ti and kyanite-absent type (3) and (4) eclogites appear to be basalts with N- to E-type MORB affinities. Shallow-depth fractionation of plagioclase is indicated by small negative Eu-anomalies.

## Mineral Chemistry

*Garnets* constitute up to 45 vol % of the eclogites. Garnets from metagabbroic eclogites (1) ei-

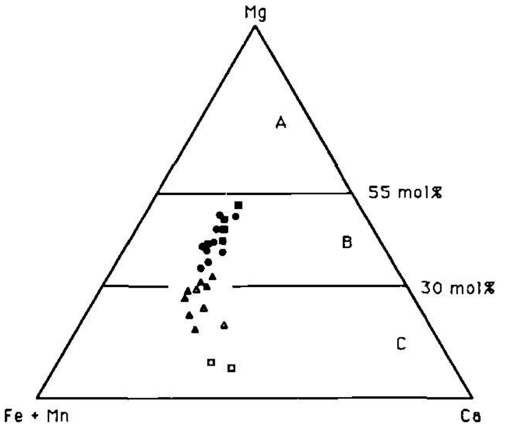

*Fig. 2* Plot of garnet rim compositions from the Koralpe and Saualpe eclogites. Boundaries separating type A, B and C eclogites are from COLEMAN et al. (1965). Symbols: black squares: E1, dots: E2, black triangles: E3, open triangles: E4, open squares: garnet II (E3).

ther have a highly irregular morphology or they form coronite textures surrounding cores of omphacite ± amphibole. They contain numerous inclusions (quartz, zoisite, kyanite). Garnets from other eclogites occur as aggregates of subhedral grains, as dodecahedrons (0.3–8 mm in diameter) or as rounded grains. Inclusions, if present, are concentrated in the core. Most garnets contain quartz and rutile only. In addition, omphacite, kyanite, zoisite, phengite, paragonite, amphibole have been observed in type (2) kyanite-eclogites and omphacite, albite, amphibole, chlorite, apatite, zircon in kyanite-absent type (3) and (4) eclogites.

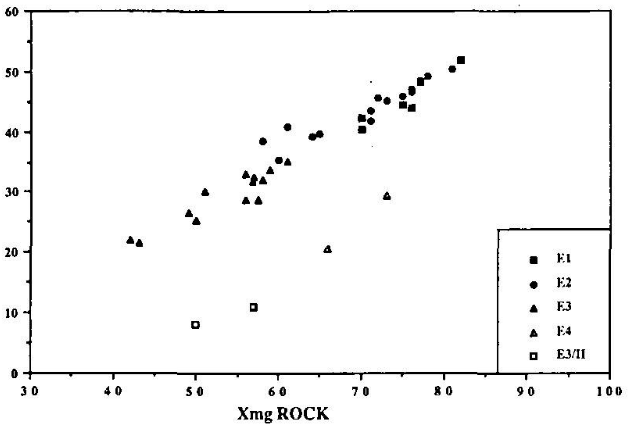

*Fig. 3* Plot of mol% pyrope in eclogite garnets versus mg-numbers of bulk rocks (Miller et al., 1988). Only type (4) eclogites plot of the correlation trend. Note the marked decrease in pyrope content for garnet II in strongly overprinted type (3) eclogites.

The garnet compositions are highly variable (Tab. 1, Fig. 2) being a function of bulk rock composition (Fig. 3) and of metamorphic grade. Thus the range of pyrope contents of the garnet rims from type (1) and (2) kyanite eclogites, 37–52 mole %, is clearly higher than that for the kyanite-absent type (3) and (4) eclogites (18–33 mole %).

Although unzoned garnets do occur in some type (2) kyanite-eclogites, compositional zoning is common. As shown in Fig. 4, the zoning patterns are not always simple. Asymmetric zoning is ubiquitous in corona garnets of type (1) rocks and was also observed in some type (2) eclogites. In general, the zonation pattern is one of decreasing grossular and spessartine contents from core to rim accompanied by increasing pyrope contents and increasing Mg/Fe$^{2+}$. A reversal in Mg/Fe$^{2+}$ ± Mg/Ca zoning occurs in some samples at the outermost edges.

*Tab. 1* Representative microprobe analyses of garnet; formulae calculated on the basis of 24 oxygens.

| | (E1) | (E2) | (E2) | (E2) | (E3) | (E3) | (E3) | (E3) | (E4) | (E4) | gar II |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | H8r | SKP12c | SKP12r | SK1r | H12r | GE1c | GE1r | KM4r | FYK236c | FYK236r | KM1 (E3) |
| SiO2 | 40,12 | 40,10 | 40,72 | 39,95 | 39,13 | 38,47 | 39,07 | 39,00 | 38,39 | 38,82 | 38,16 |
| TiO2 | 0,02 | 0,02 | - | 0,05 | - | 0,04 | - | 0,03 | 0,21 | 0,04 | 0,08 |
| Al2O3 | 22,64 | 22,57 | 22,85 | 22,55 | 22,10 | 21,52 | 22,08 | 21,96 | 21,52 | 21,82 | 21,61 |
| Cr2O3 | 0,03 | 0,06 | 0,16 | 0,03 | - | 0,09 | 0,04 | 0,02 | - | 0,19 | - |
| FeOtot | 17,32 | 18,11 | 16,19 | 19,58 | 23,41 | 24,64 | 23,78 | 23,96 | 21,67 | 20,83 | 22,85 |
| MnO | 0,44 | 0,60 | 0,19 | 0,45 | 0,61 | 0,94 | 0,78 | 0,71 | 2,16 | 0,69 | 0,72 |
| MgO | 11,33 | 11,26 | 13,41 | 10,96 | 7,47 | 5,67 | 7,08 | 6,82 | 3,70 | 5,12 | 2,10 |
| CaO | 8,02 | 7,44 | 6,80 | 6,64 | 7,42 | 8,62 | 7,54 | 7,74 | 12,38 | 12,26 | 14,41 |
| Σ | 99,92 | 100,16 | 100,32 | 100,21 | 100,14 | 99,99 | 100,37 | 100,24 | 100,03 | 99,77 | 99,93 |
| Si | 5,992 | 5,992 | 5,995 | 5,989 | 6,000 | 5,986 | 5,995 | 6,000 | 5,988 | 6,000 | 5,988 |
| Ti | 0,002 | 0,002 | - | 0,006 | - | 0,005 | - | 0,003 | 0,025 | 0,005 | 0,009 |
| Al | 3,986 | 3,975 | 3,965 | 3,985 | 3,994 | 3,947 | 3,994 | 3,982 | 3,956 | 3,975 | 3,997 |
| Cr | 0,004 | 0,007 | 0,019 | 0,004 | - | 0,011 | 0,005 | 0,002 | - | 0,023 | - |
| Fe2+ | 2,164 | 2,263 | 1,994 | 2,455 | 3,002 | 3,206 | 3,052 | 3,083 | 2,827 | 2,693 | 2,999 |
| Mn | 0,056 | 0,076 | 0,024 | 0,057 | 0,079 | 0,124 | 0,101 | 0,093 | 0,285 | 0,090 | 0,096 |
| Mg | 2,522 | 2,508 | 2,943 | 2,449 | 1,708 | 1,315 | 1,619 | 1,564 | 0,860 | 1,180 | 0,491 |
| Ca | 1,284 | 1,191 | 1,073 | 1,067 | 1,219 | 1,437 | 1,240 | 1,276 | 2,069 | 2,030 | 2,423 |
| Σ | 16,010 | 16,014 | 16,013 | 16,011 | 16,003 | 16,031 | 16,001 | 16,004 | 16,010 | 15,996 | 16,004 |
| Pyr | 42,16 | 41,99 | 49,25 | 40,94 | 28,50 | 22,15 | 27,01 | 26,17 | 14,50 | 19,68 | 8,20 |
| Alm | 35,46 | 36,80 | 32,40 | 40,27 | 49,83 | 51,55 | 50,62 | 50,94 | 45,83 | 44,93 | 49,74 |
| Gro | 21,36 | 19,76 | 17,48 | 17,74 | 20,35 | 23,93 | 20,56 | 21,29 | 34,86 | 33,30 | 40,46 |
| Spe | 0,93 | 1,27 | 0,40 | 0,96 | 1,32 | 2,09 | 1,69 | 1,55 | 4,81 | 1,51 | 1,60 |
| Uva | 0,09 | 0,18 | 0,47 | 0,09 | - | 0,28 | 0,12 | 0,06 | - | 0,58 | - |

NOTE: r: margin to omphacite; c: core

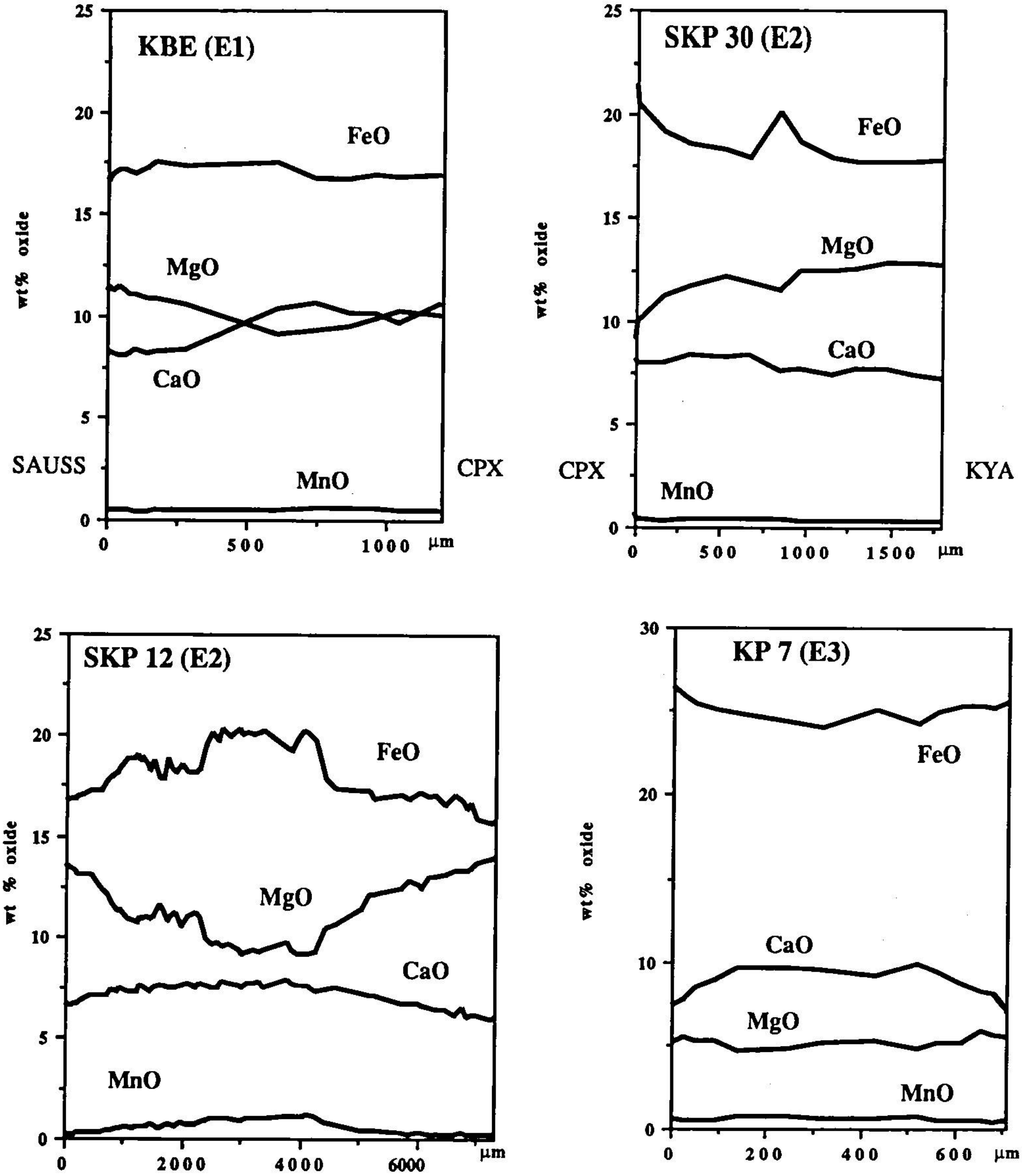

*Fig. 4* Asymmetric and symmetric compositional zoning of garnets from type (1), (2) and (3) eclogites. For the asymmetric zoning profiles the adjacent mineral phases are indicated (SAUSS = plagioclase breakdown assemblage consisting of kyanite, zoisite, quartz; CPX = omphacite; KYA = kyanite).

In a few, strongly overprinted eclogites (e.g. Schwaigberg, Koralpe) a second generation of subhedral garnets has formed. This garnet II (Tab. 1, Figs. 2, 3) coexists with amphibole III, diopside and plagioclase (An 10–13) and is strongly depleted in Mg and enriched in Ca when compared to eclogite garnets.

*Clinopyroxenes*

(Tab. 2) are main constituents (24–53 vol.%) and present in two generations. *Clinopyroxene I* ranges in composition from sodic augite to omphacite. It shows a nearly continuous series of compositions from Jd22 to Jd49 across the diopside-omphacite miscibility gap (CARPENTER, 1979). Clinopyroxene I has low acmite values (≤ 10 mole %, calculated according to the stoichiometric method of simultaneous normalization to 4.00 cations and 6.00 oxygens). A small but persistent deficiency of Na and Ca for the M2 sites possibly indicates the presence of some Mg, $Fe^{2+}$, Mn in the M2 sites. Consistency in calculations, however, suggests that garnet-clinopyroxene geothermometry is not significantly affected by these substitutions. In general, clinopyroxene I is unzoned. Inclusions of quartz and rutile are common, inclusions of garnet, kyanite, zoisite, phengite and amphibole also occur. According to the structural refinements reported by HERITSCH (1973) and WALITZI and WALTER (1980) Koralpe and Saualpe omphacites with $Na/(Na + Ca) \leq 0.33$ exhibit C2/c symmetry, while those with $Na/(Na + Ca) \geq 0.35–0.42$ exhibit P2/n space group symmetry. At low temperatures, two miscibility gaps exist between the two space groups. CARPENTER (1980) suggested that the size and the shape of these solvi vary inversely with the temperature and acmite content of the pyroxenes and that the maximum of the diopside-omphacite miscibility gap lies at temperatures of about 480–500 °C.

*Clinopyroxene II* commonly forms by grain boundary replacement of clinopyroxene I. The transformation of clinopyroxene I into symplectitic intergrowth of diopsidic clinopyroxene II and plagioclase (An 10–28) is characteristic of the first posteclogite alteration. A post-eclogitic clinopyroxene also occurs as discrete grains in a few strongly overprinted eclogites (E3), where it coexists with garnet II, amphibole, plagioclase, quartz and sphene. Clinopyroxene II is always more Fe-rich than clinopyroxene I. The jadeite molecule content is lower (1–17 mole%).

*Amphiboles* (Tab. 3) may be present in minor amounts (about 5 vol.%) or constitute up to 30 vol.% in some eclogites. Texturally, there are two types of amphiboles. *Amphibole I* is in apparent textural equilibrium with omphacite and garnet. Mutual inclusions involving this amphibole and garnet, omphacite, kyanite, zoisite also indicate a contemporaneous crystallization of hydrous and anhydrous silicates. *Amphibole II* forms large poikiloblasts which overgrow omphacite, garnet, zoisite ± kyanite, often discordant with respect to the foliation defined by these minerals and contains numerous vermicular inclusions of quartz. These conflicting amphibole textures and the regular Fe/Mg ratios of amphibole, garnet and omphacite could be explained by a buffering reaction of the sort

$$\mathrm{OMP + GAR \pm KYA + H_2O \rightarrow AMP + ZOI + QTZ}$$

during eclogite crystallization, where $\underline{a}H_2O$ is controlled by the mineral assemblage.

*Tab. 2* Representative microprobe analyses of clinopyroxene; formulae calculated on the basis 6 oxygens / 4 cations.

| | omp(E1) | omp(E2) | omp(E2) | omp(E3) | omp(E3) | omp(E3) | omp(E4) | cpx II | cpx II | cpx III |
|---|---|---|---|---|---|---|---|---|---|---|
| | H8 | SKP12 | SK1 | H12 | GE1 | KM4 | FYK236 | SK1 | KM4 | KM1 |
| SiO2 | 54,58 | 54,63 | 55,00 | 54,90 | 55,03 | 55,64 | . 54,30 | 53,19 | 53,64 | 51,86 |
| TiO2 | 0,13 | 0,15 | 0,11 | 0,15 | 0,11 | 0,13 | 0,13 | 0,19 | 0,17 | 0,16 |
| Al2O3 | 9,17 | 9,15 | 10,75 | 9,82 | 8,59 | 11,93 | 7,90 | 5,02 | 3,68 | 5,09 |
| Cr2O3 | 0,03 | 0,08 | 0,01 | 0,02 | - | 0,04 | 0,12 | 0,05 | 0,03 | - |
| FeOtot | 3,04 | 2,87 | 3,12 | 5,43 | 5,53 | 4,43 | 4,34 | 4,12 | 6,08 | 10,14 |
| MnO | - | - | 0,02 | 0,03 | 0,03 | 0,03 | 0,03 | 0,07 | 0,02 | 0,05 |
| MgO | 11,40 | 12,46 | 10,90 | 9,78 | 10,15 | 8,61 | 11,34 | 15,00 | 13,64 | 9,44 |
| CaO | 17,01 | 16,15 | 14,70 | 14,29 | 14,41 | 12,57 | 18,00 | 20,63 | 20,10 | 19,45 |
| Na2O | 4,71 | 4,51 | 5,72 | 5,59 | 5,54 | 6,82 | 4,06 | 1,62 | 2,09 | 3,05 |
| Σ | 100,07 | 100,00 | 100,33 | 100,01 | 99,39 | 100,20 | 100,22 | 99,89 | 99,45 | 99,24 |
| Si | 1,942 | 1,940 | 1,939 | 1,962 | 1,979 | 1,968 | 1,947 | 1,927 | 1,965 | 1,932 |
| Ti | 0,003 | 0,004 | 0,003 | 0,004 | 0,003 | 0,003 | 0,004 | 0,005 | 0,005 | 0,004 |
| Al | 0,385 | 0,383 | 0,447 | 0,414 | 0,364 | 0,497 | 0,334 | 0,214 | 0,159 | 0,224 |
| Cr | 0,001 | 0,002 | - | 0,001 | - | 0,001 | 0,003 | 0,001 | 0,001 | - |
| Fe3+ | 0,046 | 0,034 | 0,058 | 0,038 | 0,056 | 0,025 | 0,041 | 0,031 | 0,047 | 0,126 |
| Fe2+ | 0,044 | 0,051 | 0,034 | 0,124 | 0,110 | 0,106 | 0,089 | 0,094 | 0,140 | 0,190 |
| Mn | - | - | 0,001 | 0,001 | 0,001 | 0,001 | 0,001 | 0,002 | 0,001 | 0,002 |
| Mg | 0,605 | 0,660 | 0,573 | 0,521 | 0,544 | 0,454 | 0,606 | 0,810 | 0,745 | 0,524 |
| Ca | 0,649 | 0,615 | 0,555 | 0,547 | 0,555 | 0,476 | 0,692 | 0,801 | 0,789 | 0,776 |
| Na | 0,325 | 0,311 | 0,391 | 0,388 | 0,386 | 0,468 | 0,282 | 0,114 | 0,149 | 0,229 |
| Jad | 26,91 | 26,39 | 32,41 | 33,85 | 32,23 | 43,33 | 22,90 | 7,89 | 9,92 | 8.69 |
| Ac | 5,60 | 4,68 | 6,70 | 4,91 | 6,42 | 3,46 | 5,35 | 3,49 | 4,93 | 13.34 |

*Tab. 3* Representative microprobe analyses of amphibole; formulae calculated on the basis of total cations less (Ca + Na + K) normalized to 13.

| | amp (1)-E1 H8 | amp (1)-E2 SKP12/81 | amp (1)-E2 SKP12 | amp (1)-E2 SKP29/22 | amp(1)-E3 KM10 | amp(1)-E4 FYK-236 | amp(2)-E1 H4 | amp(2)-E2 SKP30 | amp(2)-E3 KM4 | amp(3)-E3 KM1 | amp(3)-E3 KGR 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SiO2 | 48,90 | 49,63 | 49,88 | 49,62 | 46,36 | 46,10 | 47,73 | 46,64 | 46,55 | 39,42 | 39,97 |
| TiO2 | 0,38 | 0,35 | 0,36 | 0,37 | 0,68 | 0,67 | 0,43 | 0,43 | 0,63 | 1,00 | 1,03 |
| Al2O3 | 12,33 | 11,06 | 11,86 | 12,74 | 13,89 | 13,31 | 11,73 | 13,56 | 13,91 | 15,41 | 13,76 |
| Cr2O3 | 0,19 | 0,15 | 0,13 | - | 0,04 | 0,13 | 0,26 | 0,12 | 0,03 | 0,01 | 0,02 |
| FeOtot | 5,71 | 4,42 | 4,84 | 6,02 | 10,51 | 10,04 | 6,27 | 6,98 | 10,42 | 18,51 | 15,66 |
| MnO | 0,03 | - | 0,06 | 0,04 | 0,03 | 0,06 | 0,03 | 0,01 | 0,06 | 0,11 | 0,23 |
| MgO | 16,78 | 17,88 | 17,09 | 16,36 | 13,50 | 13,86 | 16,76 | 16,08 | 13,45 | 7,44 | 10,80 |
| CaO | 10,39 | 10,30 | 9,86 | 10,07 | 8,72 | 9,78 | 10,40 | 9,42 | 8,33 | 10,98 | 10,91 |
| Na2O | 2,68 | 2,84 | 2,80 | 3,01 | 3,68 | 3,07 | 2,92 | 3,80 | 3,84 | 3,23 | 3,74 |
| K2O | 0,19 | 0,38 | 0,30 | 0,34 | 0,30 | 0,80 | 0,53 | 0,29 | 0,28 | 1,15 | 0,42 |
| Σ | 97,58 | 97,01 | 97,18 | 98,57 | 97,71 | 97,80 | 97,06 | 97,33 | 97,50 | 97,26 | 96,54 |
| Si | 6,786 | 6,907 | 6,904 | 6,831 | 6,533 | 6,555 | 6,732 | 6,528 | 6,557 | 6,020 | 6,013 |
| Aliv | 1,214 | 1,093 | 1,096 | 1,169 | 1,467 | 1,445 | 1,268 | 1,472 | 1,443 | 1,980 | 1,987 |
| Alvi | 0,804 | 0,721 | 0,842 | 0,898 | 0,835 | 0,785 | 0,682 | 0,766 | 0,867 | 0,792 | 0,455 |
| Ti | 0,042 | 0,033 | 0,042 | 0,041 | 0,076 | 0,068 | 0,042 | 0,042 | 0,068 | 0,119 | 0,118 |
| Cr | 0,025 | 0,017 | 0,017 | - | 0,008 | 0,017 | 0,025 | 0,017 | - | - | - |
| Fe3+ | 0,470 | 0,372 | 0,438 | 0,350 | 0,809 | 0,526 | 0,420 | 0,698 | 0,824 | 0,190 | 0,606 |
| Fe2+ | 0,189 | 0,146 | 0,120 | 0,345 | 0,426 | 0,670 | 0,317 | 0,118 | 0,403 | 2,178 | 1,365 |
| Mn | - | - | 0,008 | 0,008 | - | 0,009 | - | - | 0,008 | 0,018 | 0,027 |
| Mg | 3,468 | 3,713 | 3,527 | 3,358 | 2,835 | 2,932 | 3,527 | 3,357 | 2,826 | 1,697 | 2,423 |
| Ca | 1,543 | 1,538 | 1,464 | 1,489 | 1,312 | 1,487 | 1,569 | 1,414 | 1,261 | 1,798 | 1,763 |
| Na | 0,717 | 0,769 | 0,794 | 0,802 | 1,007 | 0,846 | 0,797 | 0,035 | 1,049 | 0,855 | 1,095 |
| K | 0,033 | 0,067 | 0,050 | 0,058 | 0,051 | 0,145 | 0,093 | 0,050 | 0,051 | 0,220 | 0,081 |
| (Na+K) A | 0,293 | 0,374 | 0,263 | 0,349 | 0,370 | 0,478 | 0,459 | 0,499 | 0,361 | 0,973 | 0,939 |

NOTE. SKP 12/81: inclusion in kyanite; SKP 29/22: inclusion in omphacite

On the other hand, where symplectite is observed in the center of the quartz-blebs, an amphibole + quartz + plagioclase + clinopyroxene II producing decompression reaction postdating the eclogite event seems indicated.

Although texturally varied, pale amphiboles (I) and (II) in most of the eclogites are (± subcalcic) magnesio-hornblendes or barroisites (LEAKE, 1978) with compositions (Fig. 5) similar to those of intermediate to high pressure facies series amphibolites (LAIRD and ALBEE, 1981). Amphibole compositions are highly variable, dependent on bulk composition and apparently correlated with the coexisting omphacite by the coupled exchange $Na(Al^{VI},Fe^{3+})Ca_{-1}(Mg,Fe^{2+})_{-1}$.

Continuous compositional zoning in euhedral amphiboles (I) and large amphibole (II) poikiloblasts generally involves an increase in $Al^{IV}$ and in the ratio $Na^A/Na^{M4}$ from core to rim. This records a trend of increasing $NaAl[]_{-1}Si_{-1}$ (edenite exchange vector). As discussed by HEINRICH (1985) the continuous net transfer reaction

| | | | |
|---|---|---|---|
| $NaAlCa_{-1}Mg_{-1}$ | + | $CaMgSi_2O_6$ | = |
| jadeite exchange in clinopyroxene | | diopside | |
| $NaAl[]_{-1}Si_{-1}$ | + | $3\ SiO_2$ | |
| edenite exchange in amphibole | | quartz | |

is quite sensitive to temperature. Therefore the observed zoning trend probably indicates an increase in temperature during amphibole growth.

In strongly overprinted eclogites still another type of amphiboles occurs. *Amphibole III* forms as a breakdown product in reaction zones between garnet and omphacite, as part of the plagioclase-clinopyroxene II-symplectites and also as poikiloblasts within these symplectite domains. These post-eclogite amphiboles (III) are strongly colored iron-rich pargasitic, hastingsitic or tschermakitic hornblendes. Compared to amphiboles (I) and (II) , amphiboles (III) are characterized by lower ($Al^{VI}$ + $Fe^{3+}$ + Ti + Cr) for a given value of $Al^{IV}$ and by lower NaM4 for given values of ($Na^A$+K) (Fig. 6) and ($Al^{VI}$+$Fe^{3+}$+Ti).

*Kyanite* (Tab. 4) is an important phase (up to 20 vol.%) in metagabbroic type (1) and in type (2) eclogites. The $Fe^{3+}Al_{-1}$ exchange never exceeds 0.5 mole %. In some samples up to 2 mole % chromium kyanite was detected. The inclusions are mainly quartz, but garnet, omphacite, amphibole (I), paragonite, zoisite and rutile were also observed. Based on quantitative IR spectroscopic microtechnique BERAN and GÖTZINGER (1987) have determined rather high amounts of structural OH groups in kyanite from the Kupplerbrunn type (2) eclogite (SKP 12: $H_2O^+$ = 0.075 wt%).

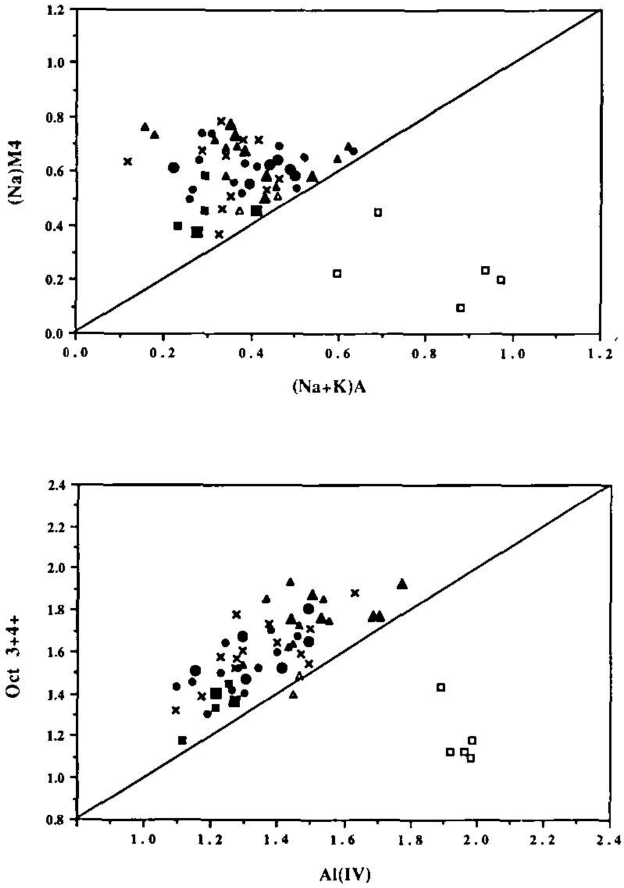

*Fig. 5* Formula proportion diagrams (LAIRD and ALBEE, 1981) of amphiboles from the Koralpe and Saualpe eclogites. Symbols as in Fig. 2 with smaller symbols representing amphiboles (I) and larger symbols denoting poikiloblastic amphiboles (II). Crosses represent amphibole inclusions in garnet, omphacite, kyanite and zoisite. Note that amphiboles (III) from strongly overprinted eclogites (open squares) clearly plot in the range of low pressure series mafic schists.

*Epidote-group minerals* (Tab. 4) are widespread as a primary phase in virtually all eclogites (2-34 % by volume). The type of epidote-group phase and its iron content are mainly determined by bulk rock composition. The $Fe^{3+}Al_{-1}$ exchange is also roughly correlated with that in the associated omphacites, as calculated according to stoichiometric requirements. Zoisite ($Fe^{3+}Al_{-1} < 0.15$ p.f.u.) is restricted to kyanite-eclogites, whereas the Fe-rich kyanite-absent eclogites contain clinozoisite and epidote ($Fe^{3+}Al_{-1} < 0.65$ p.f.u.). If zoned, the cores are always slightly more pistacitic than the rims. Although solid inclusions are not common, omphacite, garnet, kyanite and quartz were observed.

*Paragonite* was observed in kyanite-bearing type (2) eclogites only. It forms discrete grains or inclusions in garnet and kyanite. Its composition (Tab. 5) is displaced from the end-member $NaAl_3Si_3O_{10}(OH)_2$ by about 0.035 atom units of $CaNa_{-1}$ towards margarite and by 0.01–0.03 atom units of $KNa_{-1}$ towards muscovite. The displacement along the (negative) Tschermak's vector-$Al_2(Mg,Fe)_{-1}Si_{-1}$ is 0.06–0.1 atom units.

*Phengite* has been identified as discrete grains or as inclusions in omphacite and garnet of kyanite-bearing eclogites. In kyanite-absent type (3) eclogites phengite occurs as individual flakes and/or as coarse-grained aggregates. Analysed phengites (Tab. 5 ) are displaced from muscovite towards celadonite by 0.29–0.41 atom units of $-Al_2(Mg,Fe)_{-1}Si_{-1}$. The displacement towards paragonite varies between 0.01–0.13 atom units of $K_{-1}Na$. On a formula basis of 22 oxygens, Si values are 6.42–6.98, Ti values are < 0.003 for type (2) and 0.05–0.11 for type (3) eclogites.

*Biotite.* At the grain boundaries phengite has commonly been replaced by a symplectite consisting of biotite and plagioclase (An 22–47). Thus, biotite clearly postdates and overprints the high-pressure assemblages. These reaction rim biotites have compositions intermediate between phlogopite and eastonite with slightly less than 6.0 octahedrally coordinated cations, $Al^{IV} = 2.5$ to 2.8, $Al^{VI} = 0.5$ to 0.8 and $Mg/Fe^{2+}$ between 1.34 and 2.47 (Tab. 5).

The sporadic occurrence of *magnesian staurolite, sapphirine, spinell, chlorite, margarite* and the trioctahedral micas *K-eastonite, Na-eastonite, preiswerkite* (Tab. 6) in a variety of multiphase symplectites rimming kyanite and sometimes garnet is attributed to a decompression-induced retrogression of the parent eclogite. The composition of these phases is clearly controlled by the local chemical environment. Margarite, e.g., develops at kyanite-zoisite interfaces, whereas the preiswerkite- and eastonite-forming reactions always involve kyanite and amphibole.

*Plagioclase* was observed as rare inclusion in eclogite garnets (An-contents between 2 and 10 mole %) and as alteration product of the primary eclogite assemblages where it formed in (i) symplectites replacing omphacite (An 10–28), (ii) in reaction rims between phengite and garnet or omphacite (An 20–39), (iii) in reaction rims around kyanite (mostly An 11–17, rarely An 97–99 depending on the local environment) and (iv) in bleb-textures in amphibole (II) poikiloblasts (An 10–27). *Orthoclase* ($Or_{98}$) was observed only once as inclusion in garnet.

## Equilibration conditions

As shown by type (1) eclogites, high-pressure metamorphism of the gabbroic precursor rocks resulted in the reaction of plagioclase to zoisite +

*Tab. 4* Representative microprobe analyses of kyanite, epidote-group minerals and carbonates.

| | kya (E1)<br>H8 | kya (E2)<br>SKP 12 | zoi (E2)<br>H8 | zoi (E2)<br>SKP 12 | clz (E3)<br>KM4 | clz (E3)<br>GE1 | epi (E3)<br>KGR5 | dol (E2)<br>SKP29 | cal (E2)<br>SKP9 |
|---|---|---|---|---|---|---|---|---|---|
| SiO2 | 37,00 | 36,91 | 39,42 | 39,52 | 38,46 | 38,18 | 38,04 | - | - |
| TiO2 | 0,01 | - | 0,06 | 0,04 | 0,20 | 0,22 | 0,11 | - | - |
| Al2O3 | 62,30 | 62,03 | 32,28 | 32,61 | 27,94 | 27,26 | 25,24 | - | - |
| Cr2O3 | 0,02 | 0,62 | 0,02 | 0,12 | - | 0,04 | - | - | - |
| FeOtot | 0,31 | 0,30 | 1,49 | 1,23 | 6,57 | 7,35 | 10,00 | 3,08 | 0,51 |
| MnO | - | - | - | - | - | - | - | 0,02 | 0,10 |
| MgO | - | 0,02 | 0,06 | 0,12 | 0,23 | 0,13 | 0,04 | 23,16 | 0,71 |
| CaO | 0,03 | - | 24,49 | 24,38 | 23,80 | 23,70 | 23,65 | 26,23 | 54,76 |
| CO2 | - | - | - | - | - | - | - | 47,51 | 43,88 |
| Σ | 99,67 | 99,88 | 97,82 | 98,02 | 97,20 | 96,88 | 97,08 | 100,00 | 99,96 |

Cations on the basis of

| | 20(O) | 20(O) | 25(O) | 25(O) | 25(O) | 25(O) | 25(O) | 6(O) | 6(O) |
|---|---|---|---|---|---|---|---|---|---|
| Si | 4,008 | 3,999 | 6,000 | 5,997 | 5,982 | 5,975 | 5,988 | - | - |
| Ti | 0,001 | - | 0,007 | 0,005 | 0,023 | 0,026 | 0,013 | - | - |
| Al | 7,957 | 7,926 | 5,794 | 5,835 | 5,124 | 5,031 | 4,685 | - | - |
| Cr | 0,002 | 0,053 | 0,002 | 0,014 | - | 0,005 | - | - | - |
| Fe3+ | 0,028 | 0,024 | 0,190 | 0,157 | 0,855 | 0,963 | 1,317 | - | - |
| Fe2+ | - | - | - | - | - | - | - | 0,079 | 0,014 |
| Mn | - | - | - | - | - | - | - | 0,010 | 0,003 |
| Mg | - | 0,003 | 0,014 | 0,027 | 0,053 | 0,030 | 0,009 | 1,062 | 0,035 |
| Ca | 0,003 | - | 3,996 | 3,966 | 3,967 | 3,976 | 3,991 | 0,865 | 1,955 |
| C | - | - | - | - | - | - | - | 1,996 | 1,996 |
| Σ | 11,999 | 12,005 | 16,004 | 16,000 | 16,004 | 16,005 | 16,003 | 4,003 | 4,003 |

NOTE: CO2 content calculated by difference.

kyanite + quartz, in the replacement of magmatic clinopyroxene by omphacite + amphibole and in the growth of garnet as coronas at the clinopyroxene/plagioclase interface or as clots or small euhedra within the former plagioclase domains. Deformation could have been important in catalysing these eclogite-forming reactions (RUBIE, 1983) as indicated by the complete transition of gabbro to eclogite within distinct shear zones. This gabbro to eclogite transformation also requires the infiltration of a hydrous fluid. However, the limited range of equilibration and the metastable persistence of substantial volumes of igneous relics suggest fluid-deficient conditions for coronitic type (1) eclogites. Complete reaction to type (2) eclogites may have occurred only where enough fluid was available to react. In these rocks, infiltration of a hydrous fluid is also indicated by an increase in the whole rock water content, by an increase in $^{87}$Sr/$^{86}$Sr ratios and by a depletion in $\delta^{18}$O compared with type (1) eclogites (MILLER et al., 1988; THÖNI, in prep.) as well as by the structural OH content in kyanite (BERAN and GÖTZINGER, 1987) and by the formation of synmetamorphic veins. The presence of amphibole inclusions in some garnets of type (2) eclogites suggests hydration of the primary magmatic rocks before eclogite facies metamorphism.

Quartz, kyanite and zoisite of eclogites (2) contain fluid inclusions up to 10 μm in size. Most inclusions are $H_2O$-rich with a small gas bubble. In quartz saline (30–39 wt% NaCl) inclusions also occur. Preliminary microthermometric studies, however, showed that these salt-rich inclusions are clearly posteclogitic.

The typical maximum phase assemblage of the texturally equilibrated eclogites (2) is garnet + omphacite + kyanite + amphibole + zoisite + quartz + rutile + accessories. Subsets of this assemblage are common.

## GEOTHERMOMETRY

(1) The $Fe^{2+}$–Mg exchange between garnet and clinopyroxene can be used to estimate the temperature of eclogite formation. For omphacite, $Fe^{2+}$ was estimated from cation normalized stoichiometry, while for garnet minor ferric iron was neglected. Fig. 6a is a log-log plot showing the $Fe^{2+}$/Mg distribution between rims of garnet and omphacite in immediate contact for samples which escaped later hydration and deformation.

*Tab. 5* Representative microprobe analyses of micas; formulae calculated on the basis of 22 oxygens.

| | par (E2) | par (E2) | phe (E2) | phe (E2) | phe (E3) | phe (E3) | bio (E3) |
|---|---|---|---|---|---|---|---|
| | SK 12 | SKP 29 | SK 20/1 | SK 11 | H 42 | GE 3 | GE 3-80 |
| SiO | 46,29 | 45,82 | 50,71 | 50,62 | 49,16 | 49,56 | 35,29 |
| TiO2 | 0,02 | - | 0,02 | - | 0,51 | 0,89 | 1,76 |
| Al2O3 | 39,52 | 40,51 | 27,76 | 28,98 | 29,51 | 27,90 | 19,83 |
| Cr2O3 | 0,03 | 0,07 | 0,38 | 0,04 | - | 0,04 | 0,05 |
| FeOtot | 0,33 | 0,39 | 1,23 | 0,94 | 1,46 | 2,18 | 12,55 |
| MnO | - | - | - | - | 0,02 | - | 0,04 |
| MgO | 0,25 | 0,44 | 3,47 | 3,11 | 2,85 | 3,11 | 15,51 |
| CaO | 0,36 | 0,53 | 0,28 | 0,48 | 0,03 | 0,04 | 0,05 |
| Na2O | 7,26 | 7,34 | 0,23 | 0,35 | 0,91 | 0,66 | 0,18 |
| K2O | 0,75 | 0,45 | 1,832 | 10,86 | 10,23 | 10,44 | 10,23 |
| $\Sigma$ | 94,81 | 95,55 | 94,82 | 95,38 | 94,68 | 94,82 | 95,49 |
| Si | 5,953 | 5,850 | 6,780 | 6,720 | 6,587 | 6,663 | 5,401 |
| Al$^{IV}$ | 2,047 | 2,150 | 1,220 | 1,280 | 1,413 | 1,337 | 2,599 |
| AlVI | 3,947 | 3,950 | 3,157 | 3,257 | 3,250 | 3,087 | 0,614 |
| Cr | 0,003 | 0,007 | 0,040 | 0,004 | - | 0,004 | 0,006 |
| Ti | 0,002 | - | 0,002 | - | 0,051 | 0,090 | 0,196 |
| Mn | - | - | - | - | 0,002 | - | 0,005 |
| Mg | 0,048 | 0,084 | 0,692 | 0,615 | 0,569 | 0,623 | 3,419 |
| Fe2+ | 0,035 | 0,042 | 0,138 | 0,104 | 0,164 | 0,245 | 1,552 |
| $\Sigma$VI | 4,035 | 4,083 | 4,029 | 3,980 | 4,036 | 4,049 | 5,792 |
| Na | 1,810 | 1,817 | 0,060 | 0,090 | 0,236 | 0,172 | 0,052 |
| K | 0,123 | 0,073 | 1,832 | 1,839 | 1,749 | 1,791 | 1,943 |
| Ca | 0,050 | 0,073 | 0,040 | 0,068 | 0,004 | 0,006 | 0,006 |
| $\Sigma$ | 1,983 | 1,963 | 1,932 | 1,997 | 1,989 | 1,969 | 2,001 |

NOTE: SKP 29= inclusion in kyanite; SK 20/1 = inclusion in omphacite; GE3-80 = biotite in reaction rim

Fig. 6b shows that the Ellis and Green (1979) calibration of the garnet-clinopyroxene $K_D$ geothermometer corrects for compositional effects among the samples. Ln$K_D$ values for analyzed garnet-omphacite pairs from 36 different localities range from 2.13 to 2.85 with a concomitant increase of the mole fraction of grossular in the garnet $X_{Ca}^{Gar}$ from 0.177 to 0.352. These values indicate 648 ± 16 °C at a nominal pressure of 15 kbar. The effect of variable pressure is about 2.5 °C/kbar. In Fig. 6c, the same data as in Fig. 6a, b are corrected for $X_{Ca}^{Gar}$ after Krogh (1988) who proposed a curvilinear relationship between $K_D$ and $X_{Ca}^{Gar}$. Application of Krogh's expression for the garnet-clinopyroxene geothermometer results in temperatures of 598 ± 19 °C (15 kbar) and a pressure effect of about 2.9 °C/kbar.

(2) Oxygen isotope analyses reported by Vogel and Garlick (1969) for Rut, Qtz, Omp from sample WSR 25 A (Koralpe) and by Hoernes (pers. comm., 1987) for Gar, Rut, Omp from sample H12 (Koralpe) result in temperatures within the range of 580–600 °C and suggest that the fractionations among these minerals are approaching equilibrium. These temperatures compare well with the estimates based on Krogh's geothermometer whereas those based on Ellis and Green appear too high, also when compared to the calculated equilibria below.

## GEOBAROMETRY

For quartz eclogites minimum pressures can be estimated from the equilibrium:

$$\underset{\text{albite}}{NaAlSi_3O_8} = \underset{\text{jadeite}}{NaAlSi_2O_6} + \underset{\text{quartz}}{SiO_2} \qquad (1)$$

and the experimental data of Holland (1980), bearing in mind that effects due to ordering phe-

*Tab. 6* Microprobe analyses of minerals in kyanite and garnet reaction rims.

| | SKP26(E2) | SKP26(E2) | SKP25(E2) | A286(E1) | SK(E2) | SK(E2) | SK(E2) | SK111(E2) | SK111(E2) |
|---|---|---|---|---|---|---|---|---|---|
| | MG-STAU | SAPPH | SPINEL | SPINEL | Na-EAST | PREISW | MARG | EAST | PREISW |
| SiO2 | 29,24 | 13,59 | - | 0,11 | 34,10 | 29,38 | 31,82 | 34,62 | 29,12 |
| TiO2 | 0,09 | 0,08 | - | - | 0,09 | 0,04 | 0,02 | 0,42 | 0,03 |
| Al2O3 | 53,17 | 62,15 | 61,92 | 62,69 | 24,06 | 36,96 | 50,03 | 23,81 | 36,60 |
| Cr2O3 | 0,12 | 0,61 | 0,14 | 0,65 | 0,28 | 0,13 | 0,09 | 0,12 | 0,06 |
| FeOtot | 8,37 | 7,94 | 25,02 | 22,80 | 12,47 | 4,15 | 0,23 | 4,80 | 2,71 |
| MnO | 0,08 | 16,68 | 0,21 | 0,17 | 0,16 | - | - | - | - |
| MgO | 7,10 | - | 11,98 | 13,04 | 16,44 | 17,60 | 0,57 | 21,36 | 18,16 |
| CaO | - | - | - | – | 0,09 | 0,11 | 10,56 | 0,03 | 0,07 |
| Na2O | - | - | - | – | 6,78 | 7,34 | 1,73 | 1,31 | 7,07 |
| K2O | - | - | - | – | 0,35 | 0,23 | 0,02 | 8,81 | 0,62 |
| Σ | 98,17 | 101,05 | 99,27 | 99,46 | 94,82 | 95,94 | 95,07 | 95,28 | 94,44 |
| Cations on the basis of | | | | | | | | | |
| | 46(O) | 20(O) | 4(O) | 4(O) | 22(O) | 22(O) | 22(O) | 22(O) | 22(O) |
| Si | 7,893 | 1,604 | - | 0,003 | 4,898 | 4,004 | 4,210 | 4,917 | 4,011 |
| Ti | 0,018 | 0,007 | - | - | 0,010 | 0,004 | 0,002 | 0,045 | 0,003 |
| Al | 16,925 | 8,653 | 1,966 | 1,965 | 4,075 | 5,941 | 7,806 | 3,988 | 5,945 |
| Cr | 0,026 | 0,057 | 0,003 | 0,014 | 0,032 | 0,014 | 0,009 | 0,013 | 0,007 |
| Fe2+ | 1,890 | 0,784 | 0,563 | 0,507 | 1,498 | 0,473 | 0,025 | 0,570 | 0,312 |
| Mn | 0,018 | - | 0,005 | 0,004 | 0,019 | - | - | - | - |
| Mg | 2,857 | 2,935 | 0,481 | 0,517 | 3,520 | 3,576 | 0,112 | 4,523 | 3,729 |
| Ca | - | - | - | - | 0,014 | 0,016 | 1,498 | 0,005 | 0,010 |
| Na | - | - | - | - | 1,888 | 1,940 | 0,444 | 0,361 | 1,888 |
| K | - | - | - | - | 0,064 | 0,040 | 0,003 | 1,596 | 0,109 |
| Σ | 29,626 | 14,040 | 3,017 | 3,009 | 16,018 | 16,008 | 14,110 | 16,019 | 16,013 |

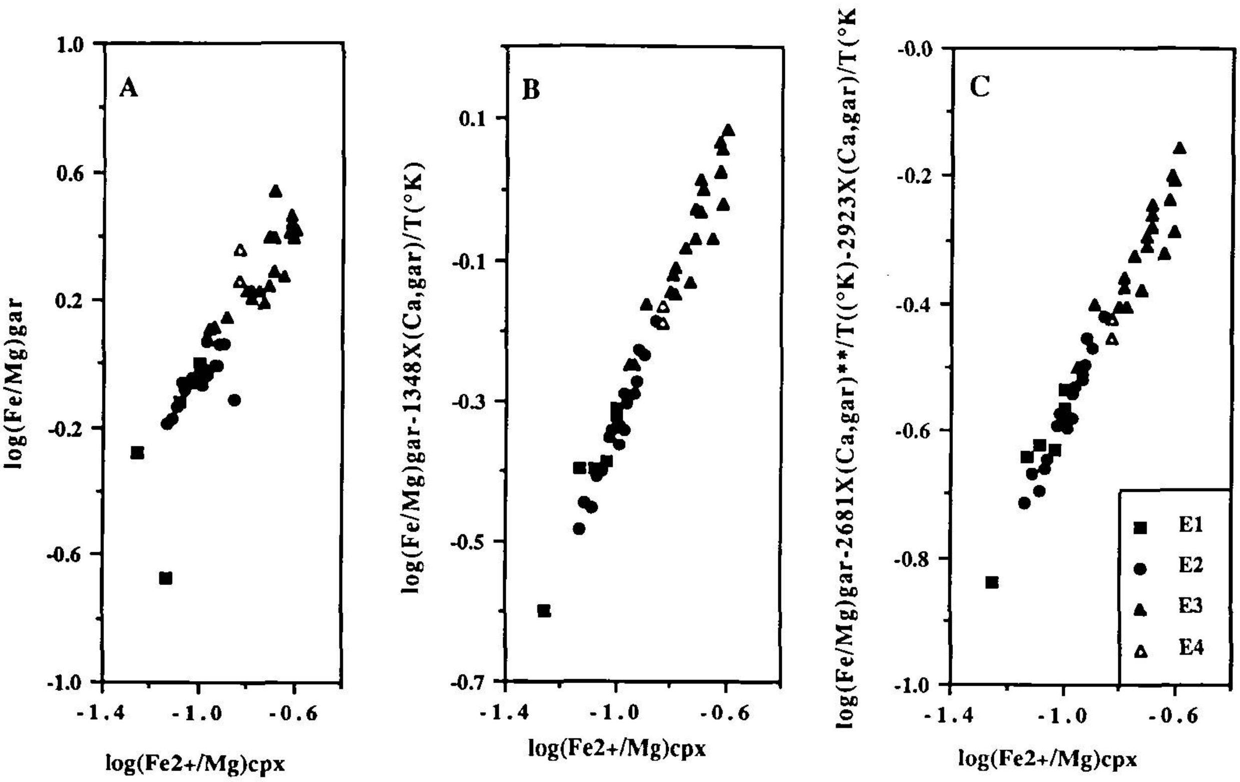

*Fig. 6* (A) Logarithmic distribution of $Fe^{2+}$/Mg between garnets and clinopyroxenes from the Koralpe and Saualpe eclogites (B). The same data as in (A), corrected for $X_{Ca}^{Gar}$ (B) after Ellis and Green (1979), resp. (C) after Krogh (1988). Asteriks denote power of two.

nomena in omphacite and albite are not yet quantitatively understood. Using the maximum amounts of Na in omphacite and the relation $a_{Jad}^{cpx} = X_{Na}^{M2}$ (NEWTON, 1983), equilibrium (1) yields a minimum pressure of about 13 kb for the temperature range of interest.

Additional information on the equilibration pressure can be obtained from experimental work on the stabilities of minor eclogite phases. According to the equilibrium

$8\ CaAl_2Si_2O_7(OH)_2 \cdot H_2O + 2\ NaAlSi_2O_6 =$
lawsonite jadeite

$2\ NaAl_3Si_3O_{10}(OH)_2 + 4\ Ca_2Al_3Si_3O_{12}(OH) +$
paragonite zoisite

$2\ SiO_2 + 12\ H_2O$ (2)
quartz vapor

the presence of zoisite and paragonite and the absence of lawsonite suggest upper pressure limits of about 22 kbars at a temperature of 600 °C and $\underline{a}H_2O = 1.0$. The equilibrium between paragonite, omphacite, kyanite and a vapor phase

$NaAl_3Si_3O_{10}(OH)_2 = NaAlSi_2O_6 +$
paragonite jadeite

$Al_2SiO_5 + H_2O$ (3)
kyanite vapor

was investigated by HOLLAND (1979). This reaction intersects the equilibrium

$6\ Ca_2Al_3Si_3O_{12}(OH) = 4\ Ca_3Al_2Si_3O_{12} +$
zoisite grossular

$5\ Al_2SiO_5 + SiO_2 + 3\ H_2O$ (4)
kyanite quartz vapor

Using the pertinent mineral data and the thermodynamic calculation methods of POWELL and HOLLAND (1988) this intersection (Fig. 7) indicates equilibration conditions near 600 °C (as suggested by the garnet-omphacite geothermometer) and 18 kbar for those low-variance type (2) eclogites where the stable coexistence of omphacite – garnet – kyanite – paragonite – zoisite and quartz has been observed only if $\underline{a}H_2O$ was close to 1.0. If the assemblage omphacite – paragonite – dolomite – quartz (e.g. SKP 29) also equilibrated at the same time at 600 °C the calculated fluid composition is water-rich ($X_{H_2O} > 0.96$).

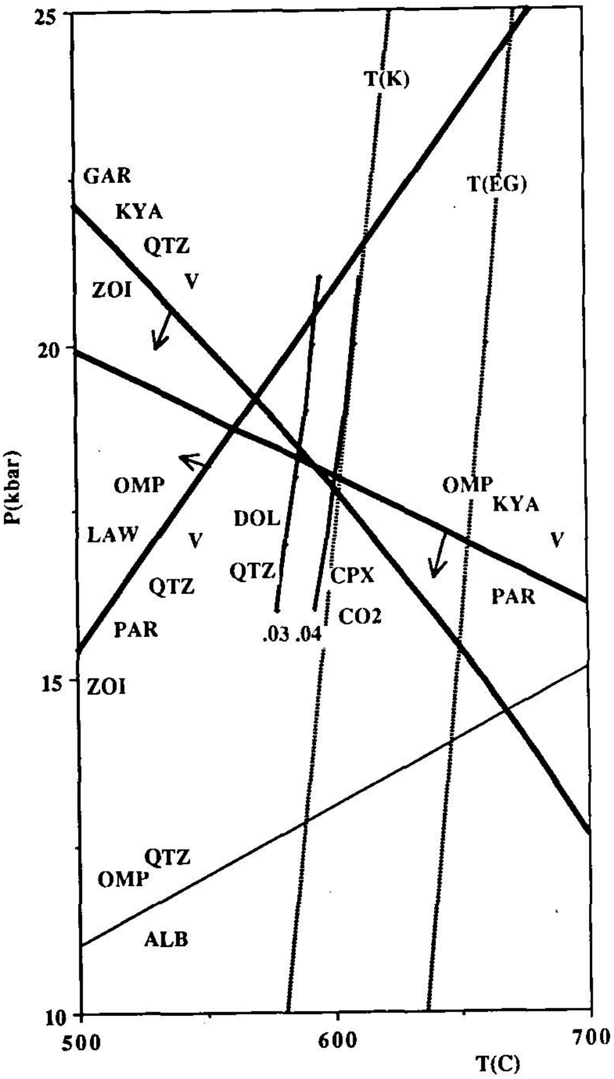

*Fig. 7* Estimated peak metamorphic conditions for Koralpe and Saualpe type (2) eclogites. Mineral equilibria calculated from data of POWELL and HOLLAND (1988) using the following activities: $a_{jad} = 0.310$, $a_{gross} = 0.020$, $a_{par} = 0.820$, $a_{zoi} = 0.900$, $a_{dio} = 0.610$, $a_{dol} = 0.900$. Iso-$K_D$-lines T(EG) and T(K) for $Fe^{2+}/Mg$ distribution between garnet and clinopyroxene calculated after ELLIS and GREEN (1979), resp. after KROGH (1988). Arrows indicate displacement due to $\underline{a}H_2O < 1.0$.

## Discussion

Pressures of 18 kbar imply metamorphism at depths of about 55 km. As the Koralpe and Saualpe eclogites were evidently derived from upper crustal protoliths, they require subduction models to explain them.

Subsequent uplift at relatively high temperature conditions (~600 °C) resulted partly in amphibolite facies assemblages, locally consisting of amphibole III + garnet II + plagioclase + quartz ± diopside + epidote + sphene + magnetite. Sapphirine, spinel and magnesian staurolite are rare retrograde products. Their occurrence is restricted to peraluminous subdomains of the eclogites where they formed along garnet-kyanite boundaries. Other post-eclogitic phases include margarite, chlorite and the tri-octahedral micas preiswerkite, eastonite and Na-eastonite which also formed in garnet or kyanite reaction rims.

The timing of these events is still poorly known, but there is evidence for two eclogite-forming events. The fact that some eclogite bodies are crosscut by variably deformed Hercynian pegmatites argues for a pre-Alpine age of high-pressure metamorphism. Thus, at Weinebene (Koralpe) undeformed pegmatites are intercalated with or crosscut an already deformed eclogite-amphibolite. The pegmatite Rb–Sr whole rock errorchrone of 270 Ma (FRANK, pers. comm.) suggests at least a Hercynian age for some of the Koralpe eclogites. The geological significance of the Sm/Nd isochron age of 700 Ma for the isothermal decompression of the eclogites (MANBY and THIEDIG, 1988) is not at all clear, esp. since more recent isotope work (THÖNI and JAGOUTZ, in prep.) yielded a Sm–Nd isochron of 275 ± 18 Ma for the magmatic crystallization of the gabbro protolith of the Bärofen type (1) eclogite.

An eo-Alpine "eclogite event" was postulated by MILLER and FRANK (1983) based on the occurrence of eclogites as concordant layers within the "Plattengneis" shear zone. According to WIMMER-FREY (1984), omphacite and amphibole define a crystallographic fabric characterized by a strong preferred orientation of [001] parallel to the "Plattengneiss" stretching lineation. As the inferred equilibration conditions (580 °C, 14 kbar) for the Cretaceous "Plattengneis" assemblage (K3) are compatible with the lower stability limit of these eclogites, this seems to indicate eclogite deformation and recrystallization during the Cretaceous.

K/Ar and $^{40}Ar/^{39}Ar$ model ages of most eclogite minerals reported by MILLER and FRANK (1983) and by RITTMANN (1984) are inconclusive because of excess $^{40}Ar$. The fact, however, that the amphibole Z2 from the Prickler Halt type (2) eclogite (Saualpe) is characterized by an undisturbed $^{40}Ar/^{39}Ar$ release spectrum and a concordant plateau (158.5 Ma) and isochron (155.8 Ma) age is interpreted by RITTMANN (1984) to date the eclogite formation. Even if this is still open to discussion, the amphibole K/Ar ages of 181–187 Ma for Koralpe eclogites, the $^{40}Ar/^{39}Ar$ plateau and isochron ages of 82.3–88.4 Ma for phengite from phengite-quartz segregations of the Prickler Halt eclogite (RITTMANN, 1984) and new internal Sm–Nd and Rb–Sr mineral isochron ages in the range of 60–100 Ma (THÖNI and JAGOUTZ, in prep.) indeed indicate Alpine mineral forming events for the mafic high-pressure rocks.

## Acknowledgements

This work was carried out in part under grant S 15/05 from the Fonds zur Förderung der wissenschaftlichen Forschung. Discussions and critical comments on an earlier draft by M. Schliestedt, M. Thöni and W. Frank are gratefully acknowledged. I would also like to thank J. Ganguin and B. Messiga for their helpful reviews and A. Mair for patiently typing the paper.

## References

AHRENS, T.J. and SCHUBERT, G. (1975): Rapid formation of eclogites in a slightly wet mantle. Earth Planet. Sci. Lett., 27, 90–94.

BERAN, A. and GÖTZINGER, M.A. (1987): The quantitative IR spectroscopic determination of structural OH groups in kyanites. Mineral. Petrol., 36, 41–49.

BEST, M.G. (1982): Igneous and metamorphic petrology. W.H. Freeman and Company, New York.

CARPENTER, M.A. (1979): Omphacites from Greece, Turkey and Guatemala: composition limits of cation ordering. Am. Mineral., 64, 102–108.

CARPENTER, M.A. (1980): Mechanisms of exsolution in sodic pyroxenes. Contrib. Mineral. Petrol., 71, 289–300.

COLEMAN, R.G., LEE, D.E., BEATTY, L.B. and BRANNOCK, W.W. (1965): Eclogites and eclogites: their differences and similarities. Geol. Soc. Amer. Bull., 76, 483–503.

ELLIS, D.J. and GREEN, D.H. (1979): An experimental study of the effect of Ca upon garnet-clinopyroxene Fe–Mg exchange equilibria. Contrib. Mineral. Petrol., 71, 13–22.

FRANK, W., ESTERLUS, M., FREY, I., JUNG, G., KROHE, A. and WEBER, J. (1983): Die Entwicklungsgeschichte von Stub- und Koralpenkristallin und die Beziehung zum Grazer Paläozoikum. Jahresbericht Hochschulschwerpunkt S. 15, 263–293.

FRY, N. and FYFE, W.S. (1969): Eclogites and water pressure. Contrib. Mineral. Petrol., 24, 1–6.

HAÜY, R.J. (1822): Traité de Minéralogie. II. Ed., Bachelier, Paris.

HEINRICH, CH. A. (1985): Eclogite facies regional metamorphism of hydrous mafic rocks in the central Alpine Adula Nappe. J. Petrol., 27, 123–154.

HERITSCH, H. (1966): Bericht über Untersuchungen an eklogitischen Gesteinen der Koralpe. Österreichische Akademie der Wissenschaften, Math. naturwiss. Kl. Anzeiger, 1966, 268–271.

HERITSCH, H. (1973): Die Bildungsbedingungen von alpinotypem Eklogitamphibolit und Metagabbro, erläutert an Gesteinen der Koralpe, Steiermark. Tschermaks Mineral. Petrograph. Mitt., 19, 213–271.

HERITSCH, H. (1980): Einführung zu Problemen der Petrologie der Koralpe. Mitt. Abt. Geol. Landesmus. Joanneum, 41, 9–44.

HOLLAND, T.J.B. (1979): Experimental determination of the reaction paragonite = jadeite + kyanite + $H_2O$, and internally consistent thermodynamic data for part of the system $Na_2O$–$Al_2O_3$–$SiO_2$–$H_2O$ with applications to eclogites and blueschists. Contrib. Mineral. Petrol., 68, 293–301.

HOLLAND, T.J.B. (1980): The reaction albite = jadeite + quartz determined experimentally in the range 600–1200 °C. Am. Mineral., 65, 129–134.

JUNG, G. (1982): Geologische und geochronologische Untersuchungen des Metamorphoseablaufes in Glein-, Stub- und Koralpe. Thesis, Univ. Wien.

KIESLINGER, A. (1928): Geologie und Petrographie der Koralpe, VII, Eklogite und Amphibolite. Akademie der Wissenschaften Wien, Mathematisch-naturwiss. Klasse I, 137, 401–454.

KROGH, E.J. (1988): The garnet-clinopyroxene Fe–Mg geothermometer – a reinterpretation of existing experimental data. Contrib. Mineral. Petrol., 99, 44–48.

KROHE, A. (1987): Kinematics of Cretaceous nappe tectonics in the Austroalpine basement of the Koralpe region (eastern Austria). Tectonophysics 136, 171–196.

LAIRD, J. and ALBEE, A.L. (1981): Pressure, temperature and time indicators in mafic schist: their application to reconstructing the polymetamorphic history of Vermont. Am. J. Sci., 281, 127–175.

LEAKE, B.A. (1978): Nomenclature of amphiboles. Am. Mineral., 63, 1023–1052.

MANBY, G.M. and THIEDIG, F. (1988): Petrology of eclogites from the Saualpe, Austria. Schweiz. mineral. petrogr. Mitt., 68, 441–466.

MILLER, CH. and FRANK, W. (1983): Das Alter der Metamorphose von Metabasiten und Eklogiten in Kor- und Saualpe. Jahresbericht Hochschulforschungsschwerpunkt S 15, 4, 229–236.

MILLER, CH., STOSCH, H.G. and HOERNES, ST. (1988): Geochemistry and origin of eclogites from the type locality Koralpe and Saualpe, Eastern Alps, Austria. Chem. Geol., 67, 103–118.

MORAUF, W. (1982): Rb- und K-Ar-Evidenz für eine intensive alpidische Beeinflussung der Paragesteine in Kor- und Saualpe, SE-Ostalpen, Österreich. Tschermaks Mineral. Petrograph. Mitt., 29, 255–282.

MOTTANA, A., CHURCH, W.R. and EDGAR, A.D. (1968): Chemistry, mineralogy and petrology of an eclogite from the type locality/Saualpe, Austria. Contrib. Mineral. Petrol., 18, 338-346.

NEWTON, R.C. (1983): Geobarometry of highgrade metamorphic rocks. Am. J. Sci., 283-A, 1–28.

POWELL, R. and HOLLAND, T.J.B. (1988): An internally consistent dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. J. Metam. Geol., 6, 173–204.

RICHTER, W. (1973): Vergleichende Untersuchungen an ostalpinen Eklogiten. Tschermaks Mineral. Petrograph. Mitt., 19, 1–50.

RITTMANN, K.L. (1984): Argon in Hornblende, Biotit und Muskovit bei der geologischen Abkühlung $^{40}$Ar/$^{39}$Ar-Untersuchungen. Thesis, Univ. Heidelberg.

RUBIE, D.C. (1983): Reaction-enhanced ductility: the role of solid-solid univariant reactions in deformation of the crust and mantle. Tectonophysics, 96, 331-352.

VOGEL, D.E., GARLICK, G.D. (1970): Oxygen-isotope ratios in metamorphic eclogites. Contrib. Mineral. Petrol., 28, 183–191.

WALITZI, M.A. and WALTER, F. (1980): Über die Raumgruppen-Symmetrie von Omphaziten aus eklogitischen Gesteinen der Kor- und Saualpe (Steiermark, Kärnten), Österreich. N. Jahrb. Mineral. Monatshefte, 449–460.

WEISSENBACH, M. (1965): Geologie und Petrographie der eklogitführenden hochkristallinen Serien im zentralen Teil der Saualpe, Kärnten. Thesis, Bergakademie Clausthal.

WIESENEDER, H. (1934): Beiträge zur Kenntnis der ostalpinen Eklogite. Tschermaks Mineral. Petrogr. Mitt., 46., 174–211.

WIMMER-FREY (1984): Gefüge- und Metamorphoseuntersuchungen am Plattengneis der zentralen Koralm, W-Steiermark, Thesis, Univ Wien.

YODER, H.S. Jr. and TILLEY, C.E. (1962): Origin of basalt magmas: an experimental study of natural and synthetic rock systems. J. Petrol., 3, 342–532.

Manuscript received February 2, 1990; revised manuscript accepted April 4, 1990.