MITT.ÖSTERR.MINER.GES. 150 (2005)

# ECLOGITES FROM THE KORALPE AND SAUALPE TYPE-LOCALITIES, EASTERN ALPS, AUSTRIA

by

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## 1. Geology of the Saualpe-Koralpe region

The area of interest is located in the Carinthia and Styria districts of Austria. Geographically it is dominated by two approximately N-S oriented mountain ridges: (i) the westerly ridge of the Saualpe and Seetaler Alps and (ii) the Koralpe and Stubalpe ridge that continues north-eastwards into the Gleinalpe and south-eastwards into the Pohorje Mountains. These two ridges are separated by the Lavant valley. The terrain morphology is characterized by valleys and basins at altitudes between 500 and 700 m, and by gently sloping mountains up to 2150 m high. Outcrops are few and restricted to rocky cliffs ("Öfen"). The area is bordered to the east by the Styrian basin, to the north by the Knittelfeld basin, to the southeast by the Klagenfurt basin and to the west by the Gurktaler Alps.

Tectonically the Saualpe-Koralpe region is an assembly of Austroalpine units (part of the Apulian microplate) with medium to high-grade metamorphic units, low-grade Paleozoic units with remnants of unmetamorphosed transgressive Permotriassic sediments in places, and unmetamorphosed Upper Cretaceous sediments. According to the nomenclature of SCHMID et al. (2004), this area forms part of the Upper Austroalpine unit and can be subdivided in several genetically linked nappe systems. These nappe systems are described below from north to south and from bottom to top with respect to their lithological content and their metamorphic history (Fig. 1, and Fig. 4 of SCHUSTER & KURZ, this volume).

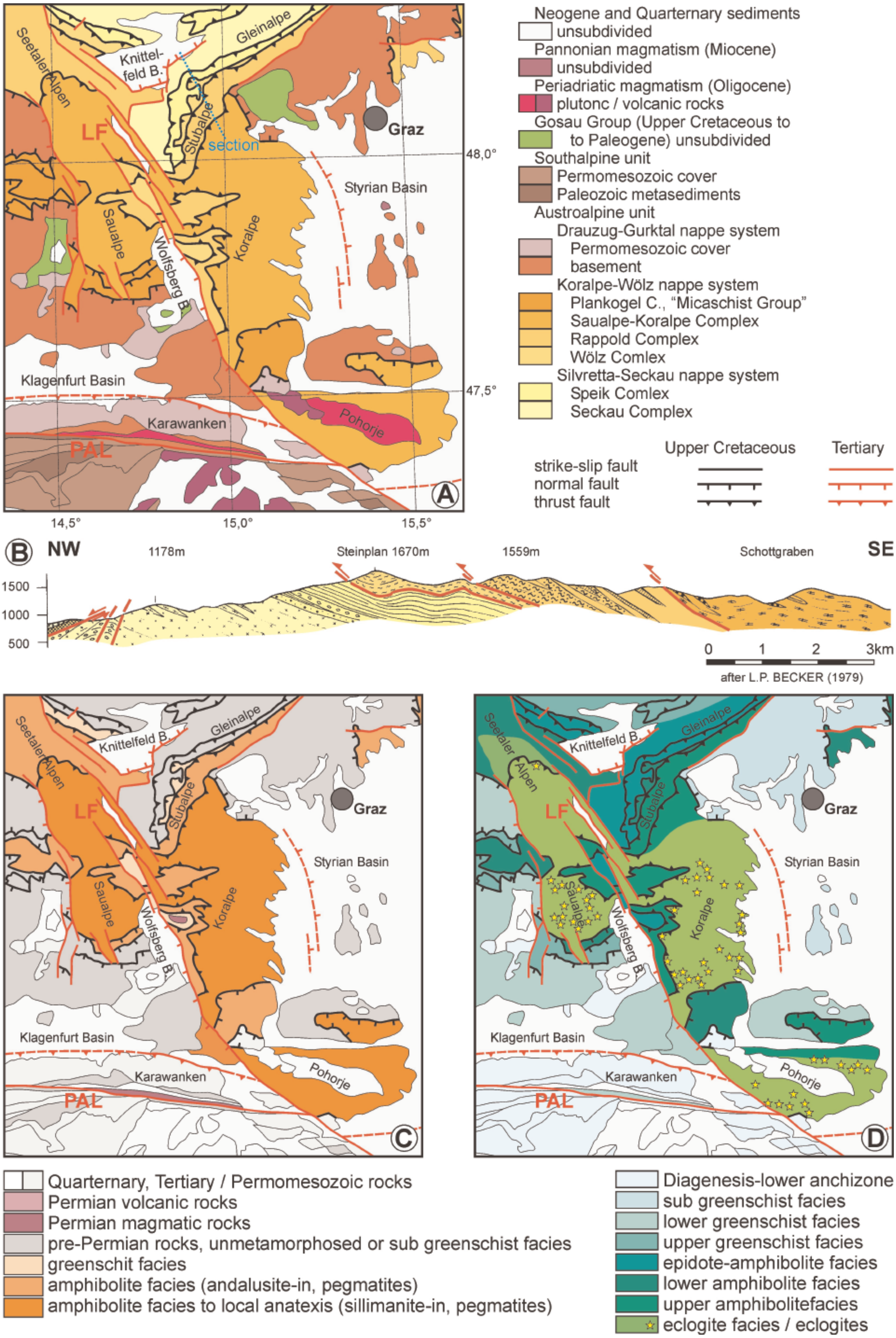

Seetaler Alpen
Knittel-feld B.
Gleinalpe
Stubalpe
section
LF
Graz
48,0°
Styrian Basin
Saualpe
Wolfsberg B.
Koralpe
Klagenfurt Basin
47,5°
Karawanken
Pohorje
PAL
A
14,5°
15,0°
15,5°
Neogene and Quarternary sediments
unsubdivided
Pannonian magmatism (Miocene)
unsubdivided
Periadriatic magmatism (Oligocene)
plutonc / volcanic rocks
Gosau Group (Upper Cretaceous to to Paleogene) unsubdivided
Southalpine unit
Permomesozoic cover
Paleozoic metasediments
Austroalpine unit
Drauzug-Gurktal nappe system
Permomesozoic cover
basement
Koralpe-Wölz nappe system
Plankogel C., "Micaschist Group"
Saualpe-Koralpe Complex
Rappold Complex
Wölz Comlex
Silvretta-Seckau nappe system
Speik Comlex
Seckau Complex
Upper Cretaceous
Tertiary
strike-slip fault
normal fault
thrust fault
B
NW
1178m
Steinplan 1670m
1559m
Schottgraben
SE
1500
1000
500
0
1
2
3km
after L.P. BECKER (1979)
Knittelfeld B.
Gleinalpe
Seetaler Alpen
LF
Stubalpe
Graz
Styrian Basin
Saualpe
Wolfsberg B.
Koralpe
Klagenfurt Basin
Karawanken
Pohorje
PAL
C
D
Quarternary, Tertiary / Permomesozoic rocks
Permian volcanic rocks
Permian magmatic rocks
pre-Permian rocks, unmetamorphosed or sub greenschist facies
greenschit facies
amphibolite facies (andalusite-in, pegmatites)
amphibolite facies to local anatexis (sillimanite-in, pegmatites)
Diagenesis-lower anchizone
sub greenschist facies
lower greenschist facies
upper greenschist facies
epidote-amphibolite facies
lower amphibolite facies
upper amphibolitefacies
eclogite facies / eclogites

*Fig. 1a, b*

*Tectonic map of the Saualpe-Koralpe-Pohorje area (a) and section in the northern part (b).*

*Fig. 1c, d*

*Maps showing the distribution of the Permotriassic (c) and eo-Alpine (d) metamorphic grades in the Saualpe-Koralpe-Pohorje area.*

## 1.1. Lithological content and metamorphic history

The *Silvretta Seckau nappe system* (Seckau and Speik Complexes) is composed of paragneisses, migmatic paragneises, hornblende gneisses and amphibolites, of partly metavolcanic origin. Up to kilometre sized ultramafic bodies are locally present and eclogites are known from the northernmost part of the system; granitic intrusions of pre-Variscan and Variscan age also occur (FLÜGEL & NEUBAUER, 1984; NEUBAUER, 2002). Permo-Scythian transgressive sediments are preserved along the northern margins. Geochronological ages of the medium to high-grade metamorphism are Variscan (Upper Devonian to Carboniferous) (SCHARBERT, 1981; FARYAD et al., 2002), and the eo-Alpine overprint reached upper greenschist facies.

The overlying *Koralpe-Wölz nappe system* (Wölz, Rappold, Saualpe-Koralpe, Plankogel Complex and "Micaschist Group") has garnet-bearing micaschists and mostly mylonitic, kyanite-bearing paragneisses as its major lithologies, with intercalations of marbles, amphibolites, eclogites (only in the Saualpe-Koralpe Complex) and quartzites. Pre-Variscan and Variscan magmatic rocks have not yet been documented but granitic gneisses, (meta)gabbros, and partly spodumene-bearing meta-pegmatites with Permian intrusion ages are known to occur (GÖD, 1989; MILLER & THÖNI, 1997; THÖNI & MILLER, 2000; SCHUSTER et al. 2001). Permo-mesozoic sediments are absent. The Koralpe-Wölz nappe system is polymetamorphic, with a Permotriassic low-P/T imprint and an eo-Alpine high-P/T overprint. A prior amphibolite facies regional metamorphism of Variscan age is proven, at least for the Rappold Complex. Permo-triassic as well as eo-Alpine P-T conditions increase upwards in the lower part of the nappe system and then decrease again (GREGUREK et al., 1997; SCHUSTER et al., 2004). Upper amphibolite facies conditions have been reached within the central Saualpe-Koralpe Complex in Permian times (0.38 GPa and 590 °C at 250-270 Ma; HABLER & THÖNI, 2001), and eclogite facies (2.4 GPa and 650-730°C at approximately 90-95 Ma; MILLER, 1990; MILLER et al., this volume) as well as subsequent amphibolite facies conditions have been determined for the eo-Alpine event.

Some types of paragneisses contain kyanite aggregates which can, within the less deformed rocks, be identified as pseudomorphs after (Permian) andalusite and sillimanite. The most spectacular rocks of this type, called "Paramorphoseschiefer", exhibit large idioblastic pseudomorphs after chiastolitic andalusite measuring up to 50 cm. The mylonitic, kyanite-bearing gneisses of the Saualpe region are called "Disthenflasergneisses". The "Plattengneiss", a blastomylonite of up to 700 m thickness, is a major element in the Koralpe and is composed of kyanite-bearing paragneisses and interlayered pegmatite gneisses. Meter to kilometre-sized lenses of eclogite, eclogite-amphibolite and (meta)gabbros occur within the paragneisses.

Discordant pegmatoids formed preferentially adjacent to this rigid rock type (NEUBAUER, 1991) during decompression after the eo-Alpine pressure peak.

The *Drauzug Gurktal nappe system* (Gurktal Nappe, Graz Paleozoic, North Karawanken) is mainly formed by anchizonal to greenschist facies Paleozoic metasedimentary sequences and by unmetamorphosed Permotriassic sediments (RANTITSCH, G. & RUSSEGGER, B., 2000).

The Southalpine unit follows to the south of the Periadriatic Lineament and is composed of anchizonal to greenschist facies Paleozoic metasediments and unmetamorphosed Permotriassic sediments.

The eo-Alpine nappe stack is discordantly overlain by Cretaceous, mostly clastic sediments of the Upper Cretaceous Gosau Group (Krappfeld, St. Paul and Kainach Gosau). Oligocene plutonic and volcanic rocks related to the Periadriatic magmatism occur in the Pohorje area.

## 1.2. Geodynamic and tectonic evolution

The *Silvretta-Seckau nappe system* is an external part of the Austroalpine unit with respect to the eo-Alpine subduction zone (SCHUSTER & KURZ, this volume). As a result of only greenschist facies metamorphic overprinting, pre-Alpine structures are well preserved in the northern part of this system whereas a penetrative ductile eo-Alpine deformation prevails in the southern part (FRANK, 1987).

The *Koralpe-Wölz nappe system* is interpreted as an extrusion wedge (SCHMID et al. 2004) that developed during the E-SE directed subduction (RATSCHBACHER, et al. ,1989) until 9095 Ma (THÖNI, 2002) and the subsequent exhumation from the internal part of the Austroalpine unit. Exhumation was characterised by  penetrative deformation of the whole nappe system by NW-directed thrusting in the lower part of the wedge (KROHE, 1987) and SE-E directed extensional deformation in its upper part (KURZ et al., 2002). These post-peak metamorphic tectonics caused an inversion of the metamorphic grade in the lower part of the nappe system (Fig. 4, SCHUSTER & KURZ, this volume).

Sm-Nd garnet ages on eclogites from the Saualpe, Koralpe and Pohorje areas are in the range of 108-87 Ma (THÖNI, 2002). K-Ar and Ar-Ar muscovite ages are 85-90 Ma in the northern part of the nappe system (Gleinalpe-Stubalpe region), about 75 Ma in the central part (Saualpe-Koralpe region) and around 18 Ma in the Pohorje area to the south (MORAUF, 1982; SCHUSTER et al., 1999; FODOR et al., 2002). The same trend, with somewhat younger ages, is also shown by Rb-Sr data on biotites. Apatite fission track data from the Koralpe region are in the range of 35 to 40 Ma (HEJL, 1997), whereas about 11 Ma was measured from Pohorje (FODOR et al., 2002). These geochronological data indicate a maximum burial of the Saualpe-Koralpe Complex in the Cenomanian and Turonian, followed by rapid exhumation in the Coniacian and Senonian. From the Campanian to the middle Eocene the Koralpe area was affected by slow exhumation and cooling whereas the Pohorje area remained at much greater depths until the Miocene, when it was rapidly exhumed.

The history of the Drauzug-Gurktal nappe system indicates that it was part of the eo-Alpine tectonic upper plate (SCHMID et al., 2004). It shows an upward decrease of the eo-Alpine metamorphic grade until reaching diagenetic conditions in the Permomesozoic sediments at the top, indicating that it has not been buried since Permian times. It was affected by thrusting in the Lower Cretaceous (FRITZ, 1988; DALLMEYER et al., 1998), whereas in the Upper Cretaceous it was affected by ductile extensional deformation and normal faulting (NEUBAUER et al., 1995), as for the upper part of the Koralpe-Wölz nappe system. The extensional deformation led to the formation of basins and the deposition of the Gosau Group sediments, which are Santonian to Paleogene in age (e.g. EBNER & RANTITSCH, 2000). The formation of these sedimentary basins is also linked to the rapid exhumation of the eclogite bearing unit (KURZ & FRITZ, 2003).

Subsequent exhumation of the underlying Penninic and Sub-Penninic nappes within windows (GENSER & NEUBAUER, 1989; FÜGENSCHUH et al., 1997) and lateral extrusion of the orogene in the Miocene (RATSCHBACHER et al., 1989) generated a system of normal and strike slip faults. These faults have a major influence on the recent morphology and are responsible for the exhumation of the Saualpe-Koralpe Complex in the Pohorje region. The Styrian, Knittelfeld and Klagenfurt basin developed along these faults. The major strike-slip faults are the Periadriatic line or the Lavanttal fault.

## 2. Petrological characteristics of the eclogites

### 2.1. Mineral assemblages

The Koralpe, Saualpe and Pohorje eclogites are either quartz- or kyanite-rich and contain garnet, omphacite, quartz, kyanite, zoisite/clinozoisite, rutile, apatite, zircon, phengite, calcic-subcalcic amphiboles, paragonite, dolomite and sulfides (MILLER, 1990; MILLER & THÖNI, 1997; JANÁK et al., 2004; SASSI et al., 2004). Amphiboles may be in textural equilibrium with omphacite and garnet, but more frequently form poikiloblasts overgrowing the foliation defined by omphacite ± kyanite and zoisite. Retrogression is documented by (1) omphacite rimmed by symplectites of Na-poor clinopyroxene ± calcic amphibole and sodic plagioclase, (2) kyanite mantled by complex symplectites of corundum + anorthite ± spinel ± sapphirine ± Mg-staurolite, (3) symplectites of biotite + plagioclase after phengite, and (4) garnet replaced by a kelyphitic intergrowth of amphibole ± plagioclase ± epidote.
At the Bärofen and Gressenberg localities in the Koralpe the transition from gabbro to eclogite can be studied in situ. The gabbros are generally isotropic and medium to coarse-grained, but modal layering on a cm-scale is locally present. They are mainly composed of calcic plagioclase and clinopyroxene ± orthopyroxene ± olivine (HERITSCH, 1973; THÖNI & JAGOUTZ, 1992; MILLER & THÖNI, 1997).

### 2.2. Major and trace element whole rock composition

The Koralpe-Saualpe-Pohorje eclogites have a wide compositional range and can be subdivided into cumulate and basaltic types on the basis of the PEARCE (1983) $Al_2O_3$-$TiO_2$ discrimination diagram (Fig. 2).

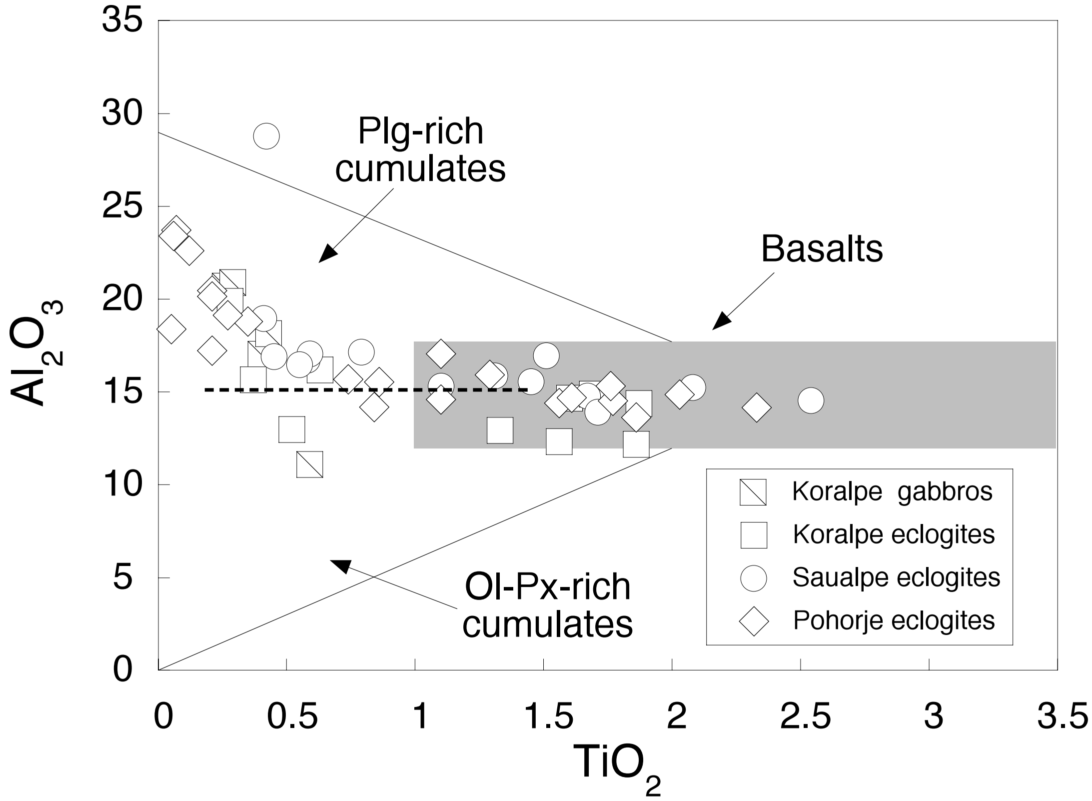



*Fig. 2*

*$Al_2O_3$ - $TiO_2$ variation of the Koralpe, Saualpe and Pohorje eclogites, plotted on the discrimination diagram of Pearce (1983). Dashed line separates kyanite-bearing and kyanite-free eclogites. Data are from MILLER et al. (1988), MILLER & THÖNI (1997), SASSI et al. (2004) and unpublished data.*

The cumulate eclogite types are Mg-rich and characterized by low $TiO_2$ (0.06 - 0.79 wt. %), generally high $Al_2O_3$ (up to 28.8 wt. %), and Cr contents ranging from 400 to 1240 ppm, resulting in a low modal abundance of rutile and quartz and in Mg-rich garnet and omphacite. The basaltic eclogite types, on the other hand, are quartz-rich and characterized by distinctly higher FeO and $TiO_2$ (1.10 - 2.70 wt.%), but a lower $Cr_2O_3$ content of 160-260 ppm. Kyanite is present in Al-rich compositions of both eclogite types, but modally much more abundant in the cumulate-type eclogites thought to be derived from plagioclase-rich cumulates (kyanite-rich eclogites, Fig. 2). The low-K characteristics indicate a tholeiitic affinity for all investigated samples. Highly variable Cr and Ni contents and the wide range in Mg-ratios [Mg# = Mg/(Mg + ΣFe)] of 0.54-0.84 clearly point to igneous fractionation during protolith generation.

In terms of immobile trace element concentrations and Nd isotopic compositions, the Koralpe-Saualpe-Pohorje eclogites and their gabbroic protoliths are comparable to N-MORBs. Sr and oxygen isotope systematics (MILLER et al., 1988) are best explained by variable, but mostly minor, seawater alteration (Fig. 3). All samples are light rare earth element (LREE)-depleted ($La_N/Yb_N$ = 0.35 - 0.69). Some of the analysed metagabbros and cumulate-type kyanite-rich eclogites have lower and more variable incompatible trace element contents compared to basaltic-type quartz-rich eclogites (Fig. 4a) as well as positive Sr and Eu-anomalies (Eu/Eu*= 1.12-1.53). As argued by MILLER et al. (1988), THÖNI & JAGOUTZ (1992), MILLER & THÖNI (1997), SASSI et al. (2004) and MILLER et al. (2005), the eclogite precursor rocks represent a Permian (247 - 275 Ma) N-MORB-type gabbroic rock-suite evolving through fractional crystallization of olivine, clinopyroxene, orthopyroxene and plagioclase.

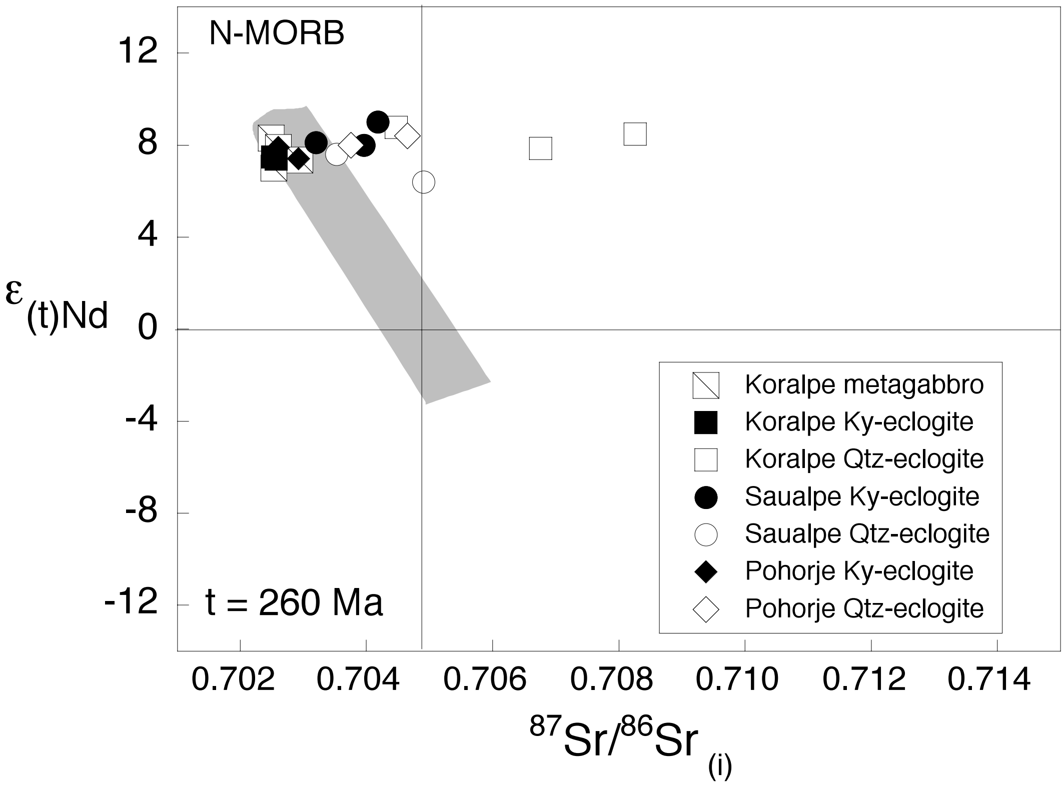



*Fig. 3*

*Nd vs. Sr isotope correlation diagram of the Koralpe, Saualpe and Pohorje eclogites (data from THÖNI & JAGOUTZ 1992; MILLER & THÖNI 1997, SASSI et al. 2004). The gabbroic protoliths and most of the kyanite-rich eclogites plot on the Mantle array. The Sr isotopic composition of eclogites that plot to the right of the Mantle array could have been altered by reactions with seawater (e.g. MUEHLENBACHS 1986).*

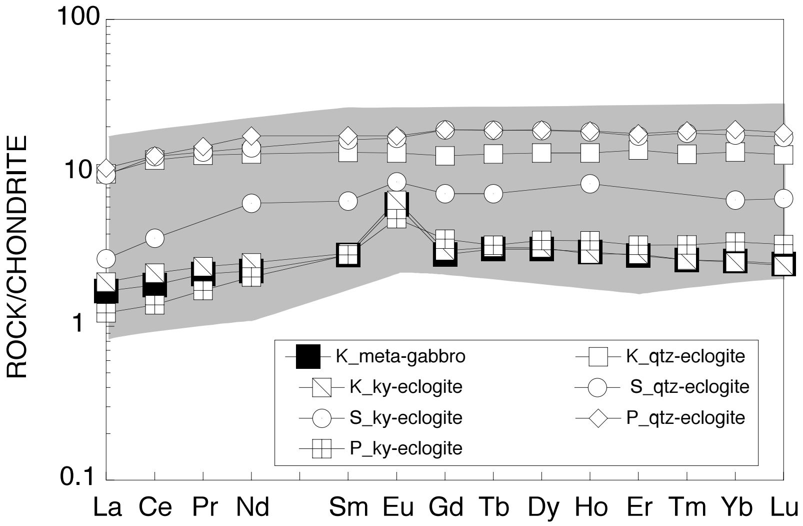



*Fig. 4a*

*Chondrite-normalized (BOYNTON, 1984) rare earth element plot showing representative patterns of a Koralpe meta-gabbro, kyanite- and quartz-rich eclogites form the Koralpe (K), Saualpe (S) and Pohorje (P). The shaded area represents the range of all compositions reported for these eclogites and their gabbroic protoliths by MILLER et al. (1988), MILLER & THÖNI (1997), SASSI et al. (2004) and unpublished data.*

## 2.3. Geothermobarometry

Despite recent advances in high pressure/ultrahigh pressure (HP/UHP) geothermometry, the precise determination of eclogite peak metamorphic conditions remains difficult. Geothermobarometric calculations are critically dependent on thermodynamic data sets, activity models and the quality of mineral chemical data, and do not yet permit an unambiguous determination of pressure and temperature. The thermometric evaluation of the temperature-dependent $Fe^{2+}$-$Mg^{2+}$ partitioning between garnet and omphacite is based on the calibrations of KROGH RAVNA (2000) and POWELL (1985). A familiar problem with this exchange equilibrium is the absence of data on the $Fe^{3+}/Fe^{2+}$ ratios in microprobe analyses of garnet and omphacite. The temperatures listed in Table 1 were calculated using stoichiometric charge balance for both minerals and indicate temperatures between 626-665°C according to the calibration of KROGH RAVNA (2000) and between 695-746°C according to that of POWELL (1985), at a nominal pressure of 2.4 GPa. Temperatures based on the Zr content of rutile coexisting with zircon (ZACK et al., 2004) range from 651-733°C.

KROGH RAVNA & TERRY (2004) and BRANDELIK & MASSONNE (2004) have formulated sets of internally consistent geothermobarometric expressions for reactions between the garnet-clinopyroxene-kyanite-phengite-quartz/coesite mineral assemblages where net transfer reactions involving the endmenbers grossular, diopside, muscovite, celadonite, kyanite, quartz/coesite define equilibrium pressure and temperature for kyanite-phengite-quartz/coesite-bearing eclogites. The results listed in Table 1 show that these invariant points range from 2.2 to 2.4 GPa when calculated according to BRANDELIK & MASSONNE (2004), and from 2.4 to 2.8 when using the geothermometric expressions of KROGH RAVNA & TERRY (2004). The results also show that all samples plot within the stability field of quartz.

Despite the absence of coesite and micro-diamond, JANÁK et al. (2004) claimed an UHP origin for the Pohorje eclogites based on mineral compositions and micro-textures such as quartz "exsolutions" in omphacite and quartz inclusions in garnet, omphacite and kyanite that are surrounded by radial fractures. As discussed by MILLER & KONZETT (in press), similar micro-textures are also present in Koralpe and Saualpe eclogites. However, these micro-textures cannot be taken as unambiguous evidence of former UHP conditions. In our opinion it is exclusively the presence of coesite and/or diamond identified by microbeam techniques that documents UHP conditions beyond any doubt. The metastable persistence of coesite and/or diamond up to surface conditions is frequently the result of their inclusion in mechanically strong host minerals, such as garnet and zircon, that act as pressure vessels around inclusions (e.g. PARKINSON, 2000). Because zircon is considered to be the closest analogue to diamond in its mechanical resistivity (CHOPIN & SOBOLEV, 1995) we selected this mineral in our attempt to find coesite in the Pohorje, Koralpe and Saualpe eclogites. Out of 252 zircon crystals so far investigated in polished thin sections or mounted in epoxy, fifteen contained inclusions of rutile, apatite, omphacite, garnet or magnesio-hornblende (Fig. 5). Only two zircons (Pohorje eclogite sample CM27/03 and Saualpe eclogite sample SKP17) contained quartz that was identified by micro-Raman spectroscopy (Fig. 6). Because zircon CM27/03 contains omphacite in addition to quartz and both zircon grains are unfractured we take this to indicate zircon growth during HP metamorphism in the stability field of quartz.

*Table 1*

*Estimated PT conditions of Saualpe, Koralpe and Pohorje eclogites.*

| sample | locality | type | T1°C *2.4 GPa* | T2°C *2.4 GPa* | T3°C Zr (Rt) | T4°C P(GPa) | T5°C P(GPa) |
|---|---|---|---|---|---|---|---|
| **SAUALPE** | | | | | | | |
| GE2 | Gertrusk | qtz | 655 | 695 | 651 | | |
| SJ1 | Jurkikogel | kya | 635 | 716 | | 693/2.25 | 724/2.49 |
| SJ4 TS | Jurkikogel | qtz | 626 | 688 | | | |
| SK20 | Kirchberg | kya | 664 | 744 | | | |
| SK 30TS | Kirchberg | kya | 651 | 723 | | | |
| SKP2 | Kupplerbrunn | qtz | 655 | 711 | 721 | | |
| CM06/03 | Kupplerbrunn | kya | 641 | 724 | | | |
| 88T35 | Kupplerbrunn | kya | 654 | 731 | | 721/2.23 | 744/2.52 |
| 04T30 | Kupplerbrunn | qtz | 659 | 740 | | | |
| 04T31 | Kupplerbrunn | kya | 648 | 730 | | | |
| SKP17 | Prickler Halt | qtz | 648 | 713 | | | |
| SKP23 | Prickler Halt | kya | 639 | 717 | | 705/2.22 | 729/2.47 |
| SKP26 | Prickler Halt | kya | 639 | 719 | | | |
| CM11/03 | Grünburg | qtz | 629 | 698 | | | |
| CM12/03 | Grünburg | qtz | 647 | 717 | | | |
| **KORALPE** | | | | | | | |
| 94T44KH | Hohl | kya | 630 | 708 | | | |
| H42 | Hohl | qtz | 657 | 704 | | | |
| H8 | Hohl | kya | 665 | 732 | | | |
| CM5/04 | Hohl | kya | 642 | 722 | | | |
| KBE | Bärofen | kya | 624 | 698 | | | |
| KK3 | SE Kleinalpl | qtz | 639 | 688 | | | |
| KM10 | Mauthner Eck | qtz | 661 | 700 | 681 | | |
| CM1/04 | Krumbach | qtz | 660 | 708 | | | |
| **POHORJE** | | | | | | | |
| CM15/01 | Kebelj | qtz | 644 | 703 | 701 | 696/2.21 | 707/2.47 |
| CM16/01 | Kebelj | qtz | 647 | 702 | | | |
| CM20/01 | Kebelj | qtz | 658 | 722 | 697 | 666/2.19 | 696/2.38 |
| CM23/01 | W Visole | kya | 660 | 731 | | | |
| CM25/01 | W Visole | kya | 636 | 747 | | | |
| CM42/01 | Turiska Vas | kya | 648 | 741 | | | |
| CM46/01 | Jurisna Vas | kya | 643 | 740 | | | |
| RS03/01 | N Visole | kya | 653 | 746 | | | |
| CM24/03 | E Vranjek | kya | 635 | 711 | | 704/2.42 | 732/2.61 |
| CM27/03 | E Vranjek | kya | 637 | 721 | 733 | 745/2.41 | 773/2.67 |
| CM31/03 | Visole | kya | 665 | 758 | | 760/2.43 | 785/2.80 |
| CM40/03 | Sv. Lenhart | qtz | 651 | 699 | 713 | | |

T1= Krogh Ravna (2000); T2 = Powell (1985)

T3= Zack et al. 2004; Zr in rutile determined by LA-ICP-MS

T4/P= Brandelik and Massonne (2004)

T5/P= Krogh Ravna and Terry (2004)

The exhumation path is not well constrained with respect to P and T. The onset of lower-grade transformation is marked by the breakdown of omphacite to Na-augite ± Ca-amphibole + sodic plagioclase symplectites, by biotite-plagioclase symplectites that replace phengite and by plagioclase-corundum ± spinel symplectites formed at the expense of kyanite. The only mineral reactions that can be attributed to the intervening stage are texturally late amphibole poikiloblasts that coexist with garnet and omphacite. Model calculations show that this could have happened as the pressure dropped to approximately 2 GPa.

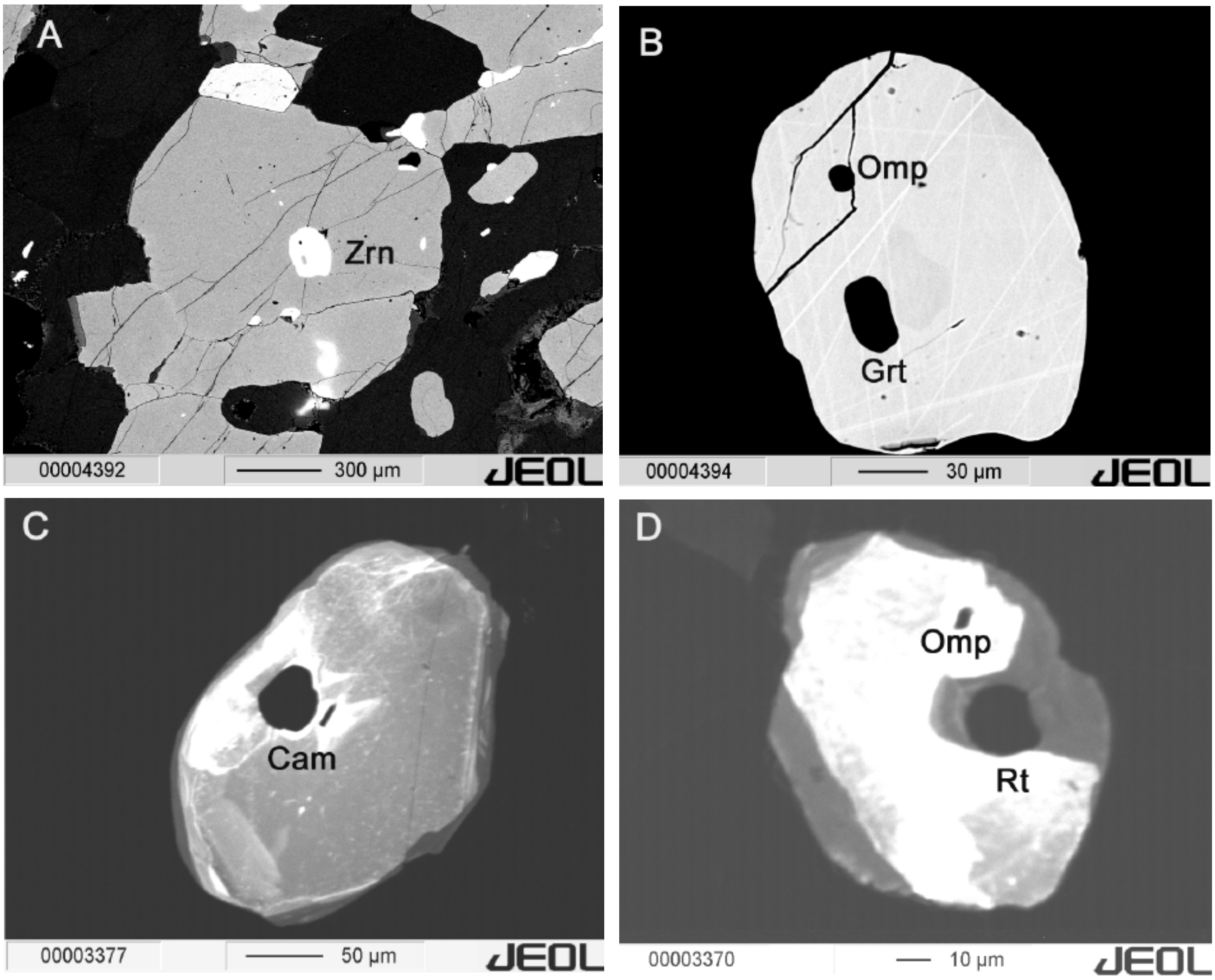
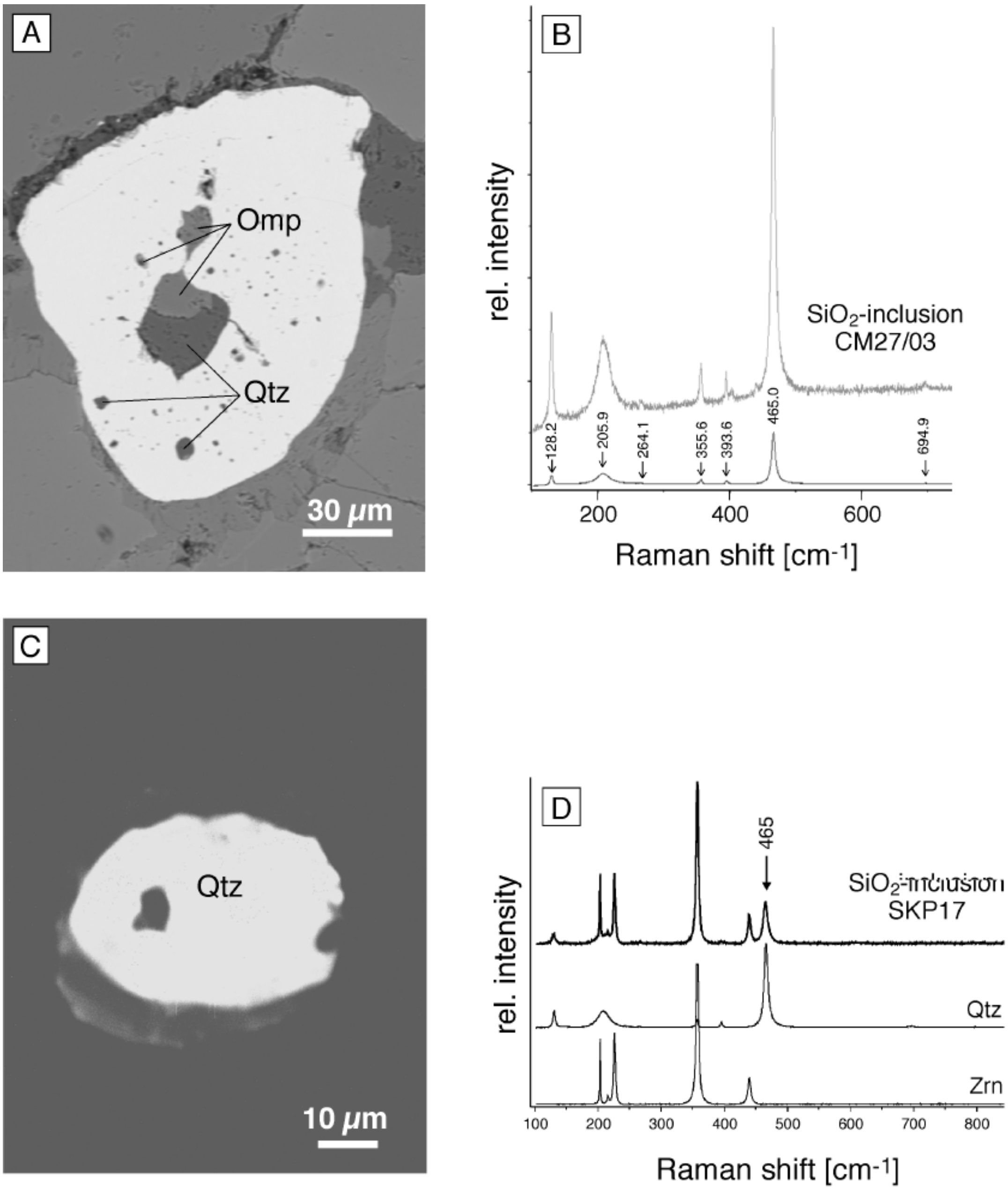



*Fig. 5*

*Backscattered electron (BSE) and cathodoluminescence (CL) images showing (a) a zircon inclusion in garnet of sample SKP2 (Kupplerbrunn, Saualpe) containing inclusions of garnet and omphacite depicted in enlargement (b); (c) matrix zircon with inclusions of magnesio-hornblende, sample SKP23 (Prickler Halt, Saualpe); (d) matrix zircon with inclusions of omphacite and rutile, sample CM1/04 (Krumbach Graben, Koralpe).*

*Fig. 6*

*(a) BSE image of quartz and omphacite inclusions within unfractured zircon in kyanite-rich eclogite CM27/03 (E Vranjek, Pohorje). (b) Raman spectrum of the large quartz inclusion showing Raman bands at 465 cm$^{-1}$ diagnostic of quartz. (c) CL image of matrix zircon in quartz-rich eclogite SKP17 (Prickler Halt, Saualpe) containing an inclusion of quartz. (d) Raman spectrum of this inclusion showing Raman bands diagnostic of zircon and quartz. Raman spectra of zircon and standard quartz are shown for comparison.*




## 2.4. Geochronology

In HP assemblages, especially those derived from mafic precursor rocks, the interpretation of geochronological results is a major challenge and requires a close link between isotope data and data from petrology and micro-textures. Conventionally, geochronometers are linked to the thermal evolution (via the “closure temperature”, $T_c$) of a “system”, and the data give little information about pressure. In HP rocks, however, knowledge of the time at which peak pressure conditions and maximum burial were effective is essential. Therefore, the main question for eclogite geochronology is: which point is dated along a pressure-dominated PT path? This includes the crucial point of linking trace element and radiogenic isotope diffusion behaviour with thermometric results inferred from major element distribution.

In meta-gabbroic eclogites whose protolith is derived from a LILE depleted source, several additional problems arise for geochronology, such as (1) very low (< 0.1 ppm) abundances of trace elements, such as Nd and Hf whose radiogenic isotope ratio must be determined precisely, or those which control the net radiogenic ingrowth (such as low U concentrations in zircon) (PAQUETTE & GEBAUER, 1991; THÖNI & JAGOUTZ, 1992); (2) isotopic disequilibrium between different HP phases, in particular between garnet and omphacite (MØRK & MEARNS, 1986; THÖNI & JAGOUTZ, 1992), resulting in spurious, and mostly too young "ages". These problems also represent a major limitation for geochronology in the Koralpe-Saualpe metabasic suite and will be addressed below.
Over the past two decades, it has been shown that eclogites can be dated, though with variable success, using the so-called "robust" isotope systems Sm-Nd, Lu-Hf (for garnet) and U-Pb (in zircon) (e.g., GRIFFIN & BRUECKNER, 1985; BECKER, 1993; DUCHÊNE et al., 1997; RUBATTO et al., 1999; MILLER et al., 2005). It seems that these isotopic systems are able to record mineral formation ages up to very high temperatures; cooling, on the other hand, can be dated by using the Rb-Sr and/or the $^{40}Ar$-$^{39}Ar$ technique for phengite.
At present, the age results for both protolith source and the subsequent evolution in time of the Koralpe-Saualpe type-locality eclogites can be summarized as follows: (1) The protoliths of the investigated eclogites were emplaced in Permian time within thinned continental crust, either as gabbros or basalts of MORB-type affinity; (2) Cretaceous HP conditions were effective in the Koralpe-Saualpe region up to 90-88 Ma B.P.; (3) fast exhumation, with exhumation rates in the range of 3-5 km/Ma, was operating in the time interval c. 90-80 Ma B.P., with a clear decrease in cooling rates after that time.

## 3. KORALPE EXCURSION

### Location K1: Hohl (N46°43´32 E15°08´44)
### Österreichische Karte 1:50.000, sheet 206 Eibiswald

Hidden in the forest is a residual hill consisting of coronitic kyanite-rich eclogite. The base of the hill is comprised of foliated quartz-rich eclogite with an intercalation of kyanite-garnet-phengite schist. Locally developed eclogite-facies shear zones show no evidence of large-scale displacements. Metamorphic textures and mineral compositions of the kyanite-rich eclogite are quite variable. Igneous relics have not been preserved, but the chemical composition and positive Eu anomalies clearly indicate a cumulate precursor rock (Fig 4b: samples H8 and 94T44KH). In addition, igneous textures have been locally preserved (Plate 1a): igneous clinopyroxene is frequently replaced by magnesio-hornblende or by an aggregate of fine-grained omphacite ($X_{Jd}$ = 0.32-0.39). Inclusion-rich garnet ($Prp_{40-48}Alm_{33-37}Grs_{14-24}Sps_{0.7-1.2}$) forms porphyroblasts or aggregates aligned along former clinopyroxene-plagioclase boundaries. Former plagioclase domains consist of kyanite + zoisite ± quartz ± garnet. Rutile, apatite and Fe-sulfides are accessories.

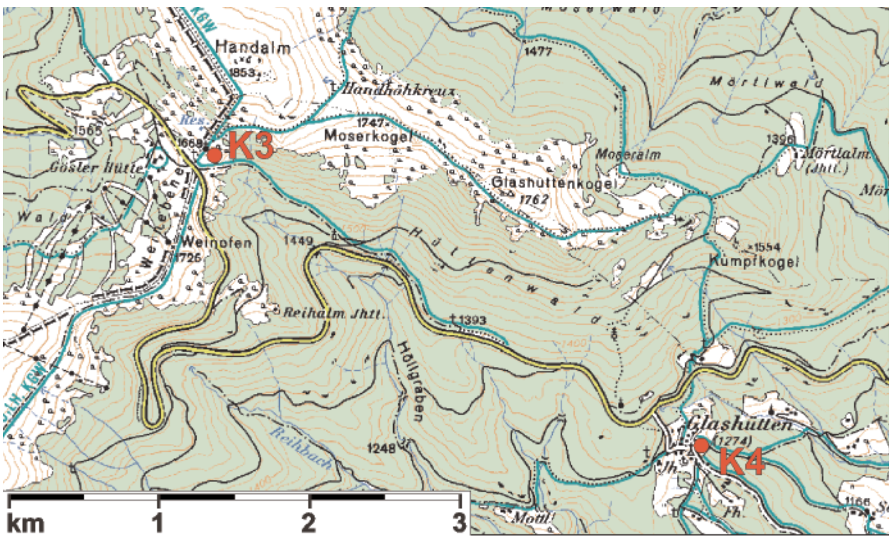




*Fig. 7a*
*Locations Hohl (K1) and Bärofen (K2)*

*and*

*Fig. 7b*
*Weinebene (K3) and Glashütten (K4)*

*visited on the Koralpe excursion.*

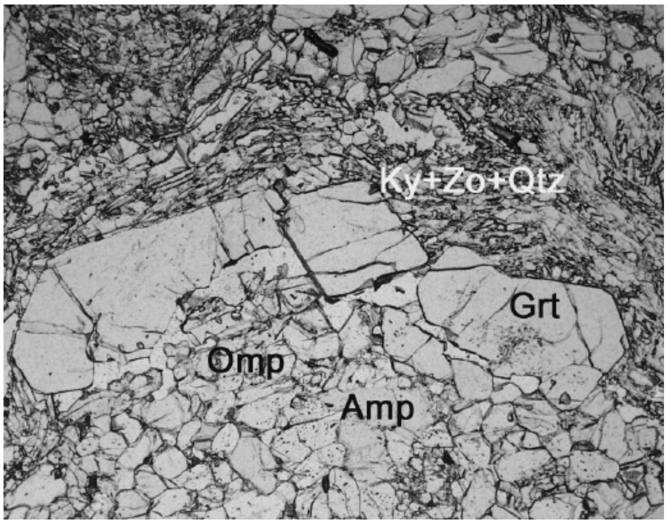



*Plate 1a*
*Photomicrograph of coronitic Ky-rich eclogite CM5/03 from Hohl, Koralpe. A string of garnet separates former plagioclase and clinopyroxene domains that now consist of kyanite + zoisite + quartz and omphacite + magnesiohornblende + quartz, respectively.*

The quartz-rich eclogite at the base of the hill is medium-grained, foliated and layered due to variable proportions of garnet ($Prp_{22\text{-}29}Alm_{46\text{-}49}Grs_{22\text{-}28}Sps_{0.8\text{-}1.0}$), omphacite ($X_{Jd}$ = 0.38-0.40), Ca-amphibole (magnesio-hornblende) and clinozoisite. These minerals coexist with quartz, minor phengite, rutile, apatite, zircon and pyrite. Bulk rock compositions are clearly enriched in incompatible elements relative to the overlying cumulate-type kyanite-rich eclogites of the same outcrop (Fig. 4b: samples H12 and 87T28).

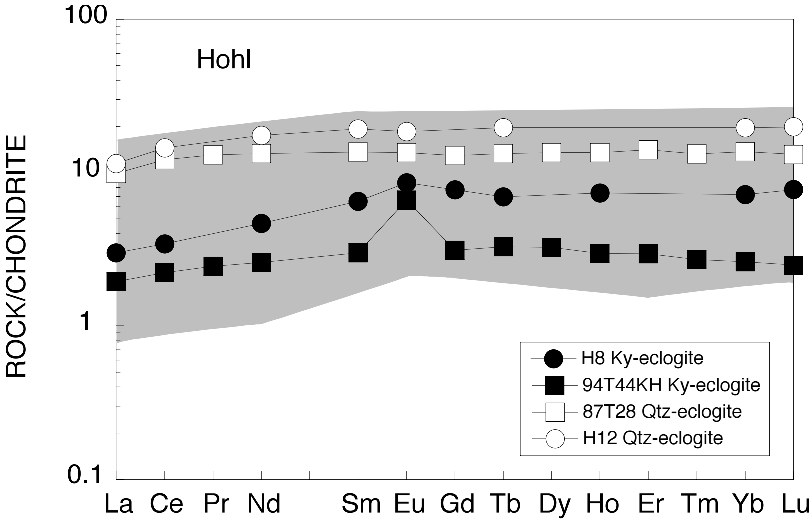
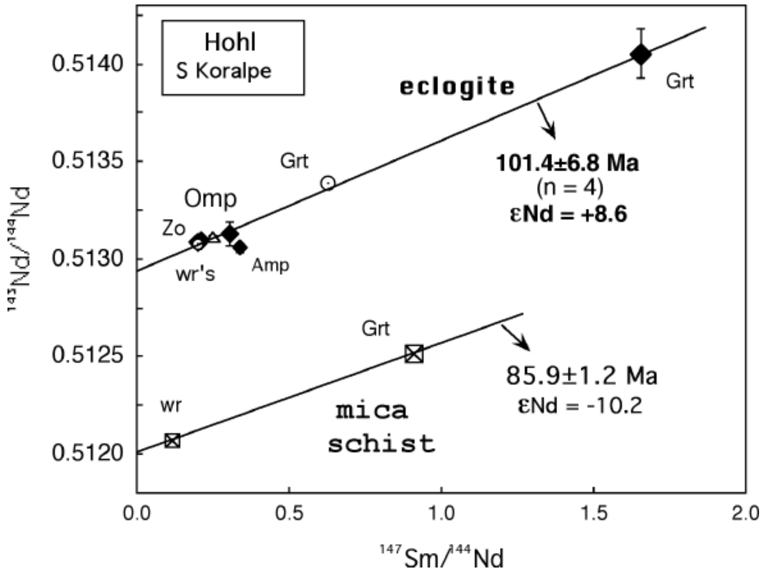



*Fig. 4b*
*Chondrite-normalized (BOYNTON, 1984) rare earth element plot for Ky- and Qtz-rich eclogites from Hohl, Koralpe. Mineral abbreviations after KRETZ (1983).*

The precise Nd isotope analysis of eclogite minerals from this outcrop is hampered by the low to very low Nd concentrations. Thus, Nd and Sm contents in garnet of quartz-rich eclogite 87T28 are only 0.022 and 0.059 ppm respectively (MILLER & THÖNI, 1997). Regression of whole rock + Zo + Omp + Grt data points of sample 87T28 yields an isochron age of 101.4 ± 6.8 Ma, but the Amp data point (Fig. 8) plots away from the regression. For three samples, initial $\varepsilon_{Nd}$ values range between +7.5 and +8.8, indicating derivation of the magmatic protolith from a depleted mantle source.

The Sm-Nd whole rock-Grt age of the kyanite-garnet-phengite schist 94T47KH, sampled from a c. 0.30 cm layer within the quartz-rich eclogite, is 85.9 ± 1.2 Ma, $\varepsilon_{Nd}$ = -10.1. Its Nd model age of 1.5 Ga is similar to model ages from other Koralpe metapelites (MILLER & THÖNI, 1997), indicating a Proterozoic mean crustal residence age for this material.

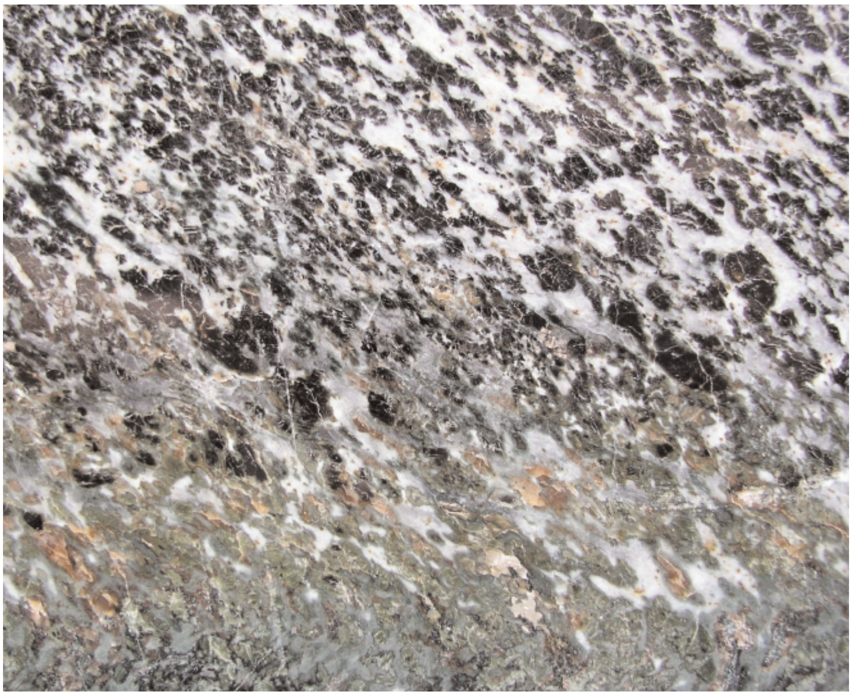
*Fig. 8*
*Isochron plot of whole rock and mineral Sm-Nd data of three eclogite samples (upper part) and an intercalated Grt-Ky-Phe-schist (lower part) from Hohl locality, southern Koralpe. Full symbols depict eclogite 87T28 (see text): wr, Zo, Omp and Grt of this sample define an age of 101.4 ± 6.8 Ma ($\varepsilon_{Nd}$ = +8.6; MSWD = 0.32), but overall uncertainties are high due to the extremely low Nd concentrations (Grt: 22 ppb Nd). Data from MILLER AND THÖNI (1997).*




**Location K2: Bärofen (N46°47´06 E15°05´13)**
**Österreichische Karte 1:50.000, sheet 189 Deutschlandsberg**

In this spectacular outcrop, the gabbroic eclogite protoliths and the transition from gabbro to eclogite (Plate 1b) can be studied in situ (if one is lucky and somebody has provided a fresh outcrop by blasting) because partial preservation of igneous minerals and textures is ubiquitous.

*Plate 1b*
*Photograph showing the transition of gabbro to eclogite to eclogite-amphibolite within a single block. Bärofen, Koralpe.*



Bulk geochemistry and normative mineralogy of the gabbros are consistent with gabbro-norites, leuco-gabbronorites and olivine gabbros. Although most analysed samples have an isotropic, medium to coarse-grained igneous texture composed of plagioclase, clinopyroxene ± orthopyroxene ± olivine, distinct layering (Fig. 9) may also be observed.

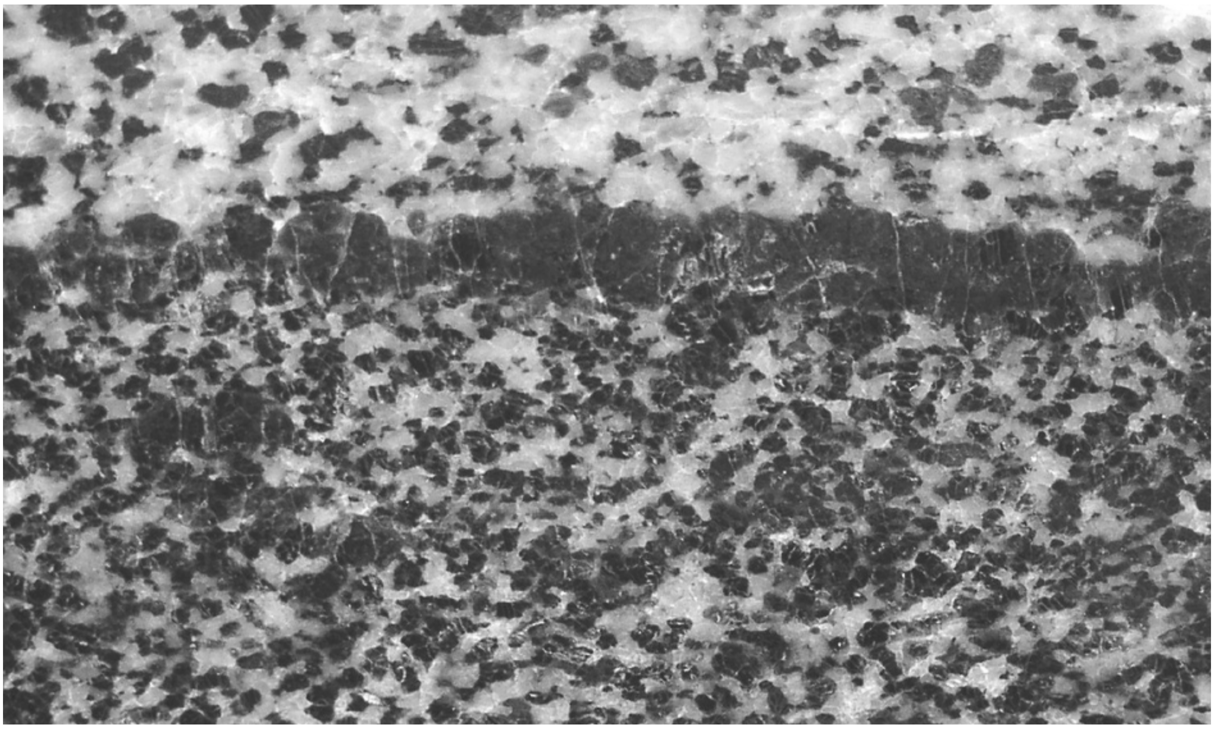
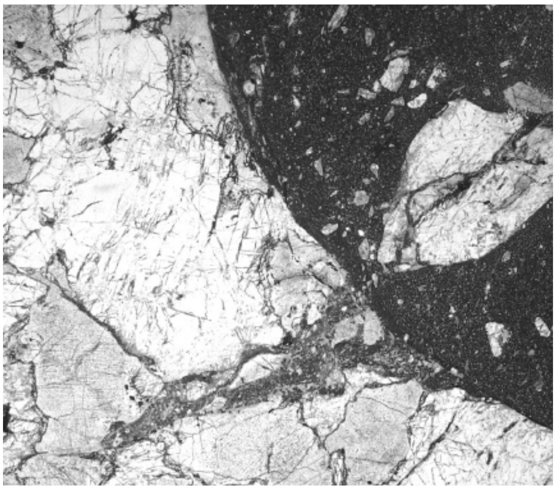


*Fig. 9*
*Photograph of igneous layering resulting from differing proportions of plagioclase, olivine, ortho- and clinopyroxene preserved in the Bärofen gabbro, Koralpe.*



Another interesting feature is the presence of pseudotachylite veins (Fig. 10) within the metagabbro. Whole rock chemical data show a good match between HFSE and REE of the kyanite-rich Bärofen eclogites with their protoliths (Fig. 4c), suggesting that these elements were immobile during HP metamorphism.

*Fig. 10*
*Photomicrograph showing contact of gabbro with pseudotachylite/cataclasite. Bärofen, Koralpe.*

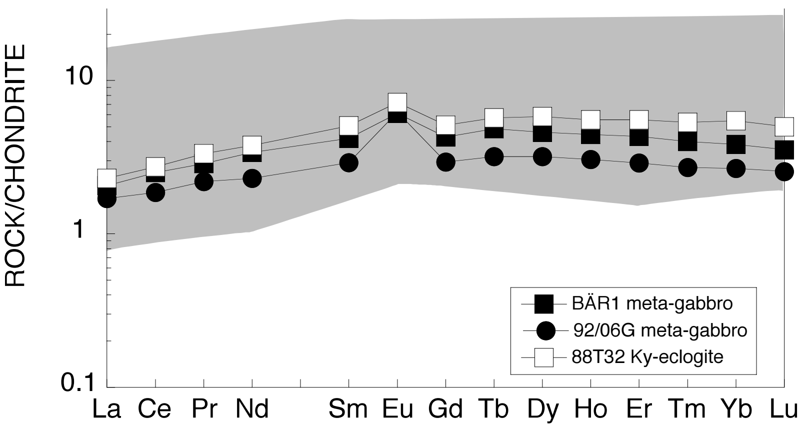



*Fig. 4c*
*Chondrite-normalized (BOYNTON, 1984) rare earth element plot for two meta-gabbros and a coronitic Ky-rich eclogite from Bärofen, Koralpe.*

Three gabbro samples from this locality were analysed by the Sm-Nd method (THÖNI & JAGOUTZ, 1992; MILLER & THÖNI, 1997). Whole rock (wr), plagioclase (Pl), and clinopyroxene (Cpx) analyses of sample Bär1 define an isochron corresponding to an age of 275 ± 18 Ma (MSWD = 0.12), resulting in an initial $\varepsilon_{Nd}$ = +8.4 (THÖNI & JAGOUTZ 1992). The Depleted Mantle model age for this rock is 253 Ma. Plagioclase-clinopyroxene two-point regression for another two gabbro samples (MILLER & THÖNI, 1997) yielded 247.2 ± 14.4 Ma (sample Bär2) and 254.4 ± 8.7 Ma (sample 92T11B). Within analytical uncertainties, these ages and the corresponding initial $\varepsilon_{Nd}$ values of +8.8 and +8.2 are identical with the results obtained on sample Bär1. Inclusion of all Bärofen wr, Pl and Cpx fractions (n = 9) in a single regression calculation results in: t = 257 ± 21 Ma; $\varepsilon_{Nd}$ = +8.4, MSWD = 4.1 (Fig. 11). The initial $^{87}Sr/^{86}Sr$ ratios range between 0.70249 and 0.70278 when calculated for an age of 260 Ma, suggesting that the gabbro has more or less preserved its primary magmatic isotopic signature.

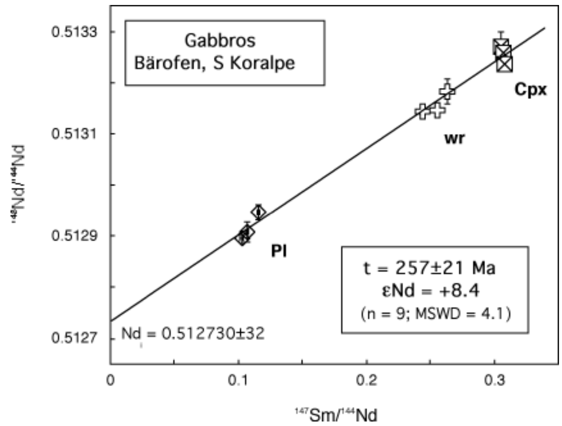



*Fig. 11*
*Sm-Nd isochron plot showing results for handpicked plagioclase (Pl) and clinopyroxene (Cpx) fractions, and the whole rock (wr) for the three gabbro samples Bär1, Bär2 and 92T11B from Bärofen locality, Koralpe The mean regression age of 257±21 Ma (Upper Permian) is taken to indicate the time of crystallisation of the gabbro that was derived from a depleted N-MORB-type source (mean $\varepsilon_{Nd}$ = +8.4).*

In addition, a coronitic eclogite (88T32) was analysed from this outcrop. This sample yields an $\varepsilon_{Nd}$ (260 Ma) of +8.4 and a corresponding $^{87}Sr/^{86}Sr$ ratio of 0.70258. As discussed by THÖNI & JAGOUTZ (1992), the Sm-Nd data of wr, garnet, clinopyroxene and amphibole show isotopic disequilibrium (Fig. 12), although wr and Grt yield a regression date of 93 ± 13 Ma (or of 88 ± 9 Ma if the data point for Zo is included; THÖNI & MILLER, 1997) that is close to new results obtained for well-equilibrated eclogites from the Saualpe and Pohorje (MILLER et al., 2005; THÖNI et al., in preparation).

A Ky-St-bearing Grt-mica schist sampled some 70 m away from the Bärofen eclogite outcrop yielded a Grt-wr Sm-Nd age of 88.7 Ma (MILLER & THÖNI, 1997). Inclusion of an impure garnet fraction in the regression (Fig. 12) results in an age of 89.5 ± 2.7 Ma (MSWD = 1.6; $\varepsilon_{Nd}$ = 10.1).

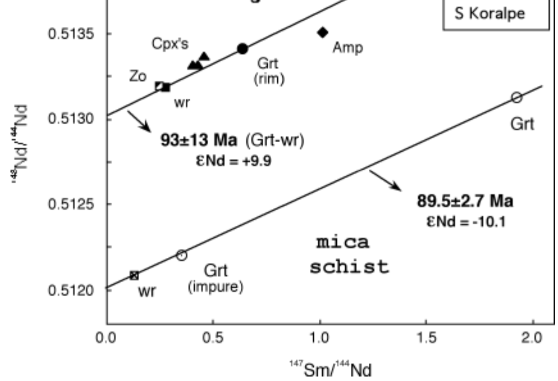



*Fig. 12*
*Sm-Nd isochron plot showing mineral and whole rock data points for metagabbroic, coronitic eclogite 88T32 (upper part of the diagram; data from THÖNI & JAGOUTZ, 1992) and metapelite 90T11B (lower part of the diagram; MILLER & THÖNI, 1997) from Bärofen locality. Note the strong Nd isotope disequilibrium among the high-P minerals of the gabbro. The Grt fraction was handpicked from the largely inclusion-free rims only. The age result of 89.5 ± 2.7 Ma for the metapelite garnet (n = 3; MSWD = 1.6) is very similar those of other metapelite garnets from the Saualpe-Koralpe-Pohorje crystalline.*

*Mineral chemistry of precursor gabbros*

Plagioclase compositions range from to $An_{60}$ to $An_{76}$ in unaltered domains of different samples. Incipient alteration results in cloudy areas consisting of extremely fine-grained kyanite, zoisite ± Ca-rich garnet ± sodic clinopyroxene. Clinopyroxene appears dark and cloudy due to exsolution of very fine-grained ilmenite in addition to exsolution of orthopyroxene (Fig. 13). The original composition prior to exsolution is not known; all analysed clinopyroxene grains are diopside ($Wo_{46-49}En_{43-46}Fs_{6-10}$) containing 4.1-4.6 wt% $Al_2O_3$, 0.2-0.4 wt% $Cr_2O_3$ and 0.7-0.9 wt% $Na_2O$. Orthopyroxene is relatively homogeneous bronzite ($En_{71-76}$) with 2.2-2.9 wt% $Al_2O_3$. Olivine has been replaced in most samples by Opx and spinel, but when still present its composition ranges between $Fo_{76}$ and $Fo_{79}$.

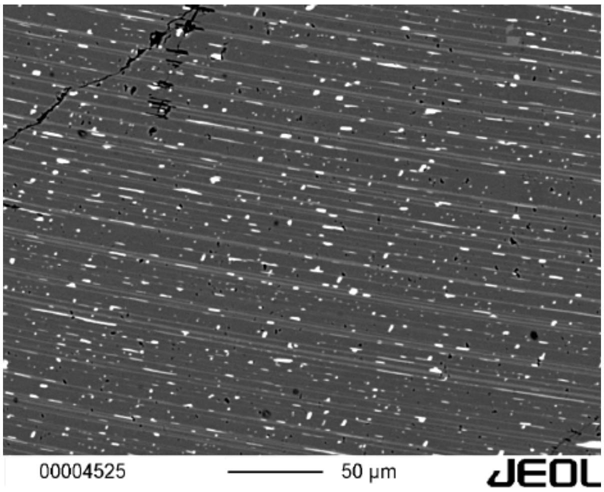



*Fig. 13*

*BSE image of igneous clinopyroxene containing exsolution lamellae of orthopyroxene and ilmenite exsolutions. Bärofen, Koralpe.*

*Coronitic stage of gabbro-eclogite transformation*

The breakdown of olivine to a complex aggregate of orthopyroxene ($En_{82}$), green spinel (50-64 mol% $MgAl_2O_4$) ± clinopyroxene ± garnet ($Prp_{43}Alm_{52}Grs_4Sps_1$) ± corundum (Fig. 14) starts along grain boundaries. The $SiO_2$, CaO and $Al_2O_3$ required for this reaction could have been released by the decomposition of plagioclase. Breakdown of plagioclase takes place along grain boundaries and at fractures and high-strain domains within the grains. Partly reacted plagioclase contains abundant kyanite and zoisite needles (Fig. 15), and small euhedral garnet or garnet aggregates strongly enriched in grossular (Grs = 53-91 mol%). In these altered domains, plagioclase composition becomes more sodic ($An_{36}$ - $An_{40}$) as reactions proceed.

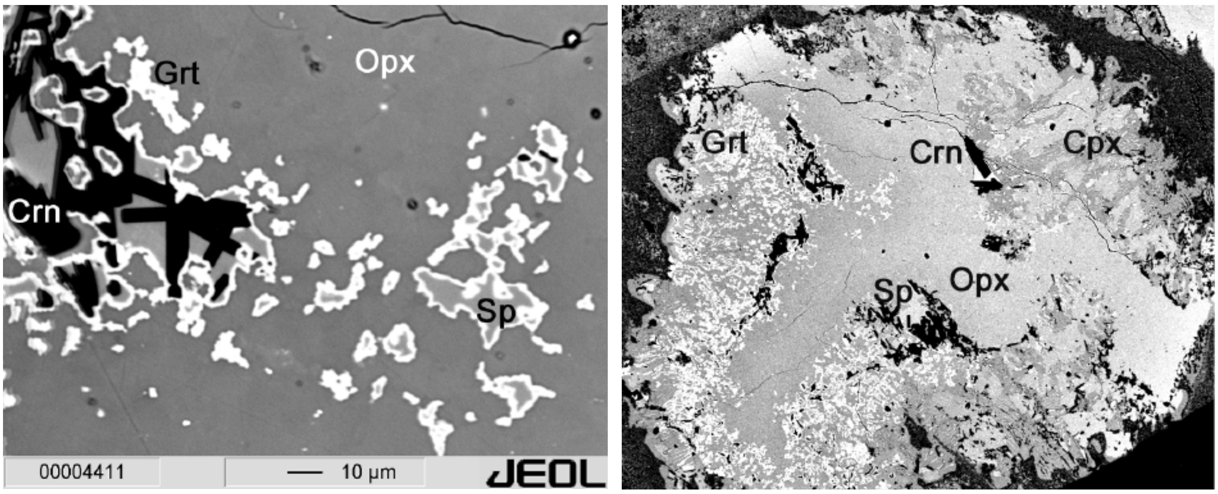



*Fig. 14*

*BSE images of olivine pseudomorph in meta-gabbro sample Bär1, Bärofen, Koralpe. Olivine is replaced by orthopyroxene (Opx), clinopyroxene (Cpx), spinel (Sp), garnet (Grt) and corundum (Crn).*

Igneous orthopyroxene has narrow coronas composed of sodic augite ($X_{Jd}$ = 0.10-0.14) when in contact with plagioclase. Igneous clinopyroxene has reacted with plagioclase forming garnet coronas along grain boundaries. Corona garnet is strongly zoned with higher values of grossular ($Grs_{75-81}$) and Fe/(Fe+Mg) and abundant inclusions of kyanite ± zoisite on the plagioclase side, and lower values of grossular ($Grs_{35-38}$) and Fe/(Fe+Mg) and inclusions of rutile towards clinopyroxene. This texture suggests that kyanite and zoisite nucleated at an early stage of plagioclase decomposition, probably by the continuous reaction proposed by GOLDSMITH (1982)

$$Pl + H_2O = Ky + Zo + Qtz + (NaSiCa_{-1}Al_{-1})_{Pl}$$

that proceeds to the right with increasing pressure. Reactions responsible for the final breakdown of the igneous phases and the formation of eclogite involve recrystallization and extensive diffusion between different chemical domains through a set of complex continuous reactions.

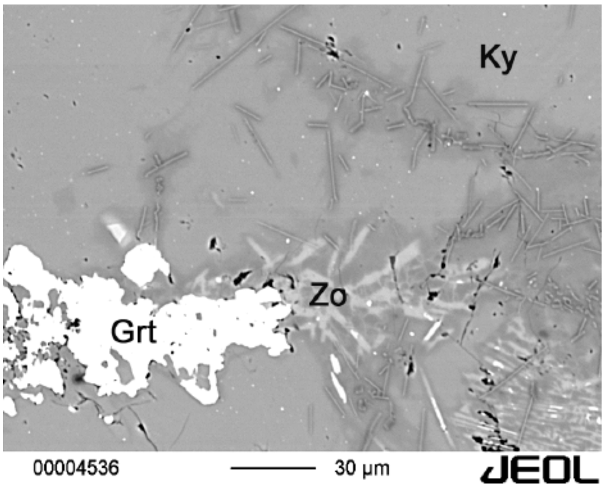



*Fig. 15*
*BSE image of altered plagioclase domain in metagabbro sample Bär2, Bärofen, Koralpe. Calcic plagioclase has partly reacted to grossular-rich garnet (Grt), kyanite (Ky), zoisite (Zo) and Na-rich plagioclase.*

*Eclogitic stage of gabbro-eclogite transformation*

Eclogite samples that preserve igneous textures still show string-like clusters of euhedral garnet separating former plagioclase and mafic mineral domains (Plate 2a). Plagioclase has been replaced by kyanite + zoisite ± garnet ± quartz, pyroxene and olivine domains have been replaced by fine-grained polygonal omphacite, quartz and magnesio-hornblende, with minor rutile. Garnet is often zoned, with decreasing $X_{Ca}$ and increasing Mg(Mg+Fe) from core to rim, and contains numerous micro-inclusions of kyanite, zoisite, quartz, rutile and omphacite. Further recrystallization results in a polygonal fabric, increasing grain size and a loss of igneous textures.

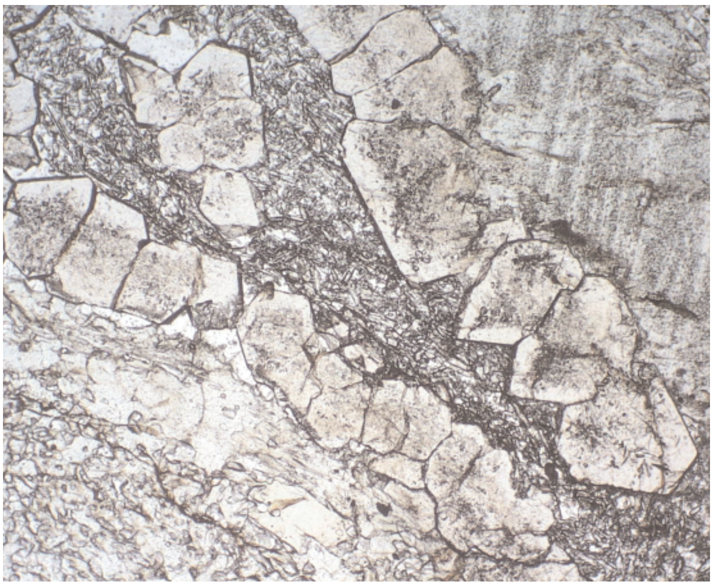


*Plate 2a*
*Photomicrograph of coronitic Ky-rich eclogite where strings of inclusion-rich garnet separate former plagioclase and pyroxene domains; Bärofen, Koralpe. Igneous plagioclase has reacted to Ky + Zo + Qtz, pyroxenes have been replaced by omphacite or recrystallized to a granular aggregate of omphacite + magnesiohornblende + quartz.*

The preservation of igneous minerals and textures and the coexistence of sodic plagioclase and eclogite in a single block of the same outcrop suggest sluggish reaction kinetics. As pointed out by AHRENS & SCHUBERT (1975a, b), the presence of an intergranular fluid is a pre-requisite for the transformation of gabbro into eclogite within geological timescales at T < 600-800°C. Although the formation of hydrous phases such as zoisite and amphibole in the coronitic eclogites documents the involvement of fluid, the metastable persistence of gabbroic assemblages indicates that fluid flow was not pervasive. The fact that coronitic eclogites partly preserve igneous textures whereas well-equilibrated eclogites are strongly foliated suggests that deformation also enhanced reaction kinetics and aided recrystallization by dislocation creep, grain-size reduction and allowing ingression of catalytic fluid.

*Eclogite microstructures and Crystallographic Preferred Orientations*

The eclogites of the Koralm area form layers and lenses of 0.1 to 100 meters thickness. Most eclogites show a strong schistosity and a mineral lineation at outcrop scale, due to a shape preferred orientation of omphacite, zoisite, kyanite, and amphibole, and a compositional layering at millimeter-scale. Coarse grained eclogites without shape preferred orientation occur as boudins within schistose fine-grained eclogite mylonites. On a microscale, the eclogites show a clear succession of mineral parageneses related to several phases of their metamorphic evolution. The transformation of gabbroic parageneses into coarse-grained eclogitic assemblages occurred without penetrative deformation at a meso-scale. The coarse-grained boudinaged eclogites show a weak foliation. However, omphacite (omph1) shows several features of plastic deformation. Coarse grains are twinned, kinked and bent. Fine grains of recrystallized omphacite (omph2) are arranged along twin lamellae, cleavage surfaces and the grain boundaries of the coarse omphacites; locally, core and mantle textures have been observed. Several stages from coarse-grained eclogites to the formation of fine-grained eclogite mylonites (due to dynamic recrystallisation and secondary grain size reduction) have been observed. These mylonites show a compositional layering with monomineralic layers of garnet, zoisite, and omphacite. The fine grained garnets are interpreted to represent dynamically recrystallized grains (KURZ et al., 2004).

Omphacite crystallographic preferred orientations (CPOs) from the Koralm-Saualm Complex may generally be described by S-type fabrics. Within coarse-grained samples WK17-98a, WK20-97, WK51-97 in Fig. 16 the {001} poles are distributed along a girdle parallel to the XY plane of the finite strain ellipsoid (foliation plane). These textures show {001} maxima near the Y axis of the finite strain ellipsoid, i.e. perpendicular to the lineation, but parallel to the foliation plane. The {010} poles, oriented parallel to the b [010] axes, show very well developed clusters centred within the Z; the {100} poles are distributed along a girdle within the XY plane (foliation), with maxima near X. This type of CPO fabric ({100} and {001} girdle within the XY plane, {010} poles with a cluster centred in Z) is formed within a deformation geometry of axial compression. The omphacite CPOs within fine-grained eclogite mylonites (WK7-97, WK8-97, WK3-99, WK-HF2 in Fig. 16) may be characterized as S to transitional S>L types with a {001} girdle within the XY plane (foliation); clusters of {010} poles are centred in Z. However, the {001} poles show a tendency to form weak maxima centred in X (WK8-97, and especially WK7-97); accordingly, the {010} poles show a tendency to form a girdle within YZ (normal to the foliation plane).

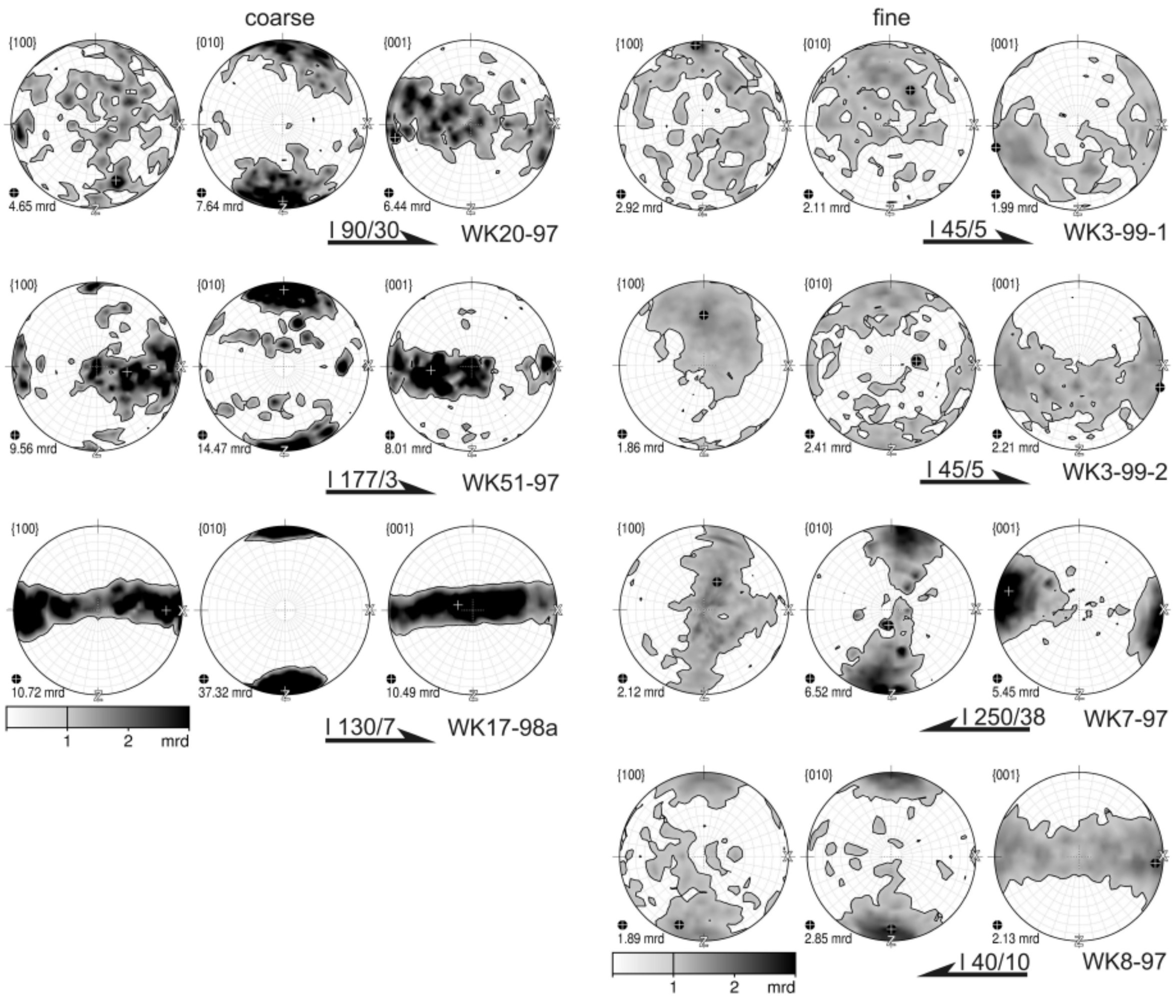



*Fig. 16*

*CPOs (textures) of omphacite in deformed eclogites from the Koralm-Saualm Complex obtained from neutron diffraction. The recalculated pole figures ({001}, {010} and {100}) describe the orientation of the poles to the (001), (010) and (100) planes, including the equivalent (00-1), (0-10) and (-100) poles. Trace of the foliation and lineation (X direction) is horizontal (east-west in the pole figures), Y direction is at the centre of the pole figure, and Z direction is vertical; equal area projection, lower hemisphere; mrd: Multiples of Random Distribution; ï marks the position of the maximum. The asymmetry of figures of WK3-99 is due to cutting slightly oblique to the foliation and lineation. The order of the pole figures corresponds to the decreasing grain size of the related samples.*

We assume that the deformation geometry from the pressure peak onwards is directly related to the mechanism of exhumation. Therefore, the evolution of CPOs depends on the tectonometamorphic evolution of these units, in particular the mode of exhumation. Hence, S-type fabrics predominantely occur within eclogites exhumed by crustal extension. This is associated with a flattening strain geometry and subvertical axial compression.

**Location K3: Weinebene (N46°50´29 E15°01´01)**
**Location: OEK 50, sheet 188, Wolfsberg**

At this location can be seen paragneiss with pseudomorphs of kyanite after andalusite, and Plattengneiss. Follow the road from Deutschlandsberg to the Weinebene, a saddle in the Koralm. From the Weinebene follow the footpath to the north, towards the Handalpe (N46°50´51 E15°01´16).

Along this path you may observe continuously increasing deformation of the gneisses and micaschists. The gneisses grade into mylonites (the so-called Plattengneiss) with a closely spaced schistosity, a N trending stretching lineation and secondary grain size reduction.
The Plattengneiss forms an important shear zone within the Austroalpine Nappe Complex of the Eastern Alps, which developed during the Lower Cretaceous collisional event (Eo-Alpine) within the Austroalpine unit. It has been investigated for regional tectonic reasons as well as in order to get general information about the evolution of microfabrics and the development of CPOs within high-grade shear zones.
The quarry exposes the typical, fine-grained mylonitic Plattengneis with a flat-lying foliation and a N-trending stretching lineation. The Plattengneis is composed of quartz, feldspar (K-feldspar and plagioclase), muscovite, biotite and kyanite. The feldspar is completely recrystallized during deformation and the quartz displays monomineralic layers with quartz shapes similar to those of granulites.

*Plattengneiss Microstructures (for details, see KURZ et al., 2002)*
Quartz typically forms layers and lenses within the Plattengneis (Fig. 17a). Within these layers and lenses, the quartz grains show an equant shape and are characterized by serrate and lobate grain boundaries typical of high temperature deformation (equigranular - interlobate fabric). The main mechanism of dynamic recrystallization is grain boundary migration recrystallisation. Subgrains commonly occur, and in many cases the subgrains show undulatory extinction. Some domains are characterised by uniformly sized quartz grains bordered by straight grain boundaries; these fabrics document partial annealing.
Feldspar (K- feldspar and plagioclase) occurs as single porphyroclasts within a fine grained matrix of quartz, white mica, biotite and plagioclase. The porphyroclasts are characterized by undulatory extinction and the development of subgrains (Fig. 17c). Very often large grains with undulatory extinction are surrounded by small, dynamically recrystallized grains (0.02 - 0.05 mm) forming core-and-mantle structures. The occurrence of subgrains and the development of core-and-mantle structures indicates medium to high-grade deformation conditions (above 500°C). The porphyroclasts are sometimes surrounded by asymmetrically arranged strain shadows; these kinematic indicators document a top-to-the-north sense of shear. The strain shadows are either filled with dynamically recrystallized feldspars, or with quartz grains.
In the paragneisses, garnet is partly boudinaged (Fig. 17d), which indicates strong extension in the X direction of the finite strain. The garnets are very often surrounded by biotite. In places, biotite crystallized in strain shadows is asymmetrically arranged around garnet cores. These fabrics also indicate a top-to-the-north sense of shear (Fig. 17d).
Crystallographic Preferred Orientations (CPO) of quartz have been investigated along a south-north oriented section across the Plattengneis of the Koralm Complex (Eastern Alps) (Fig. 18). The quartz c-axes form small circular distributions in the southernmost parts of the Koralm Complex, which represent the uppermost structural level of the Plattengneis (Fig. 19). Further to the north two maxima between the Y and Z directions of the finite strain can be interpreted in terms of preferred slip on the rhomb planes. These fabrics continuously grade into (type I and type II crossed) girdle distributions in a northward direction. A strong maximum near the Y axis with a tendency to be distributed along a single girdle and with three corresponding maxima of a-axes near the margin of the pole figure can be observed in the central and northern parts (Figs. 18, 19).

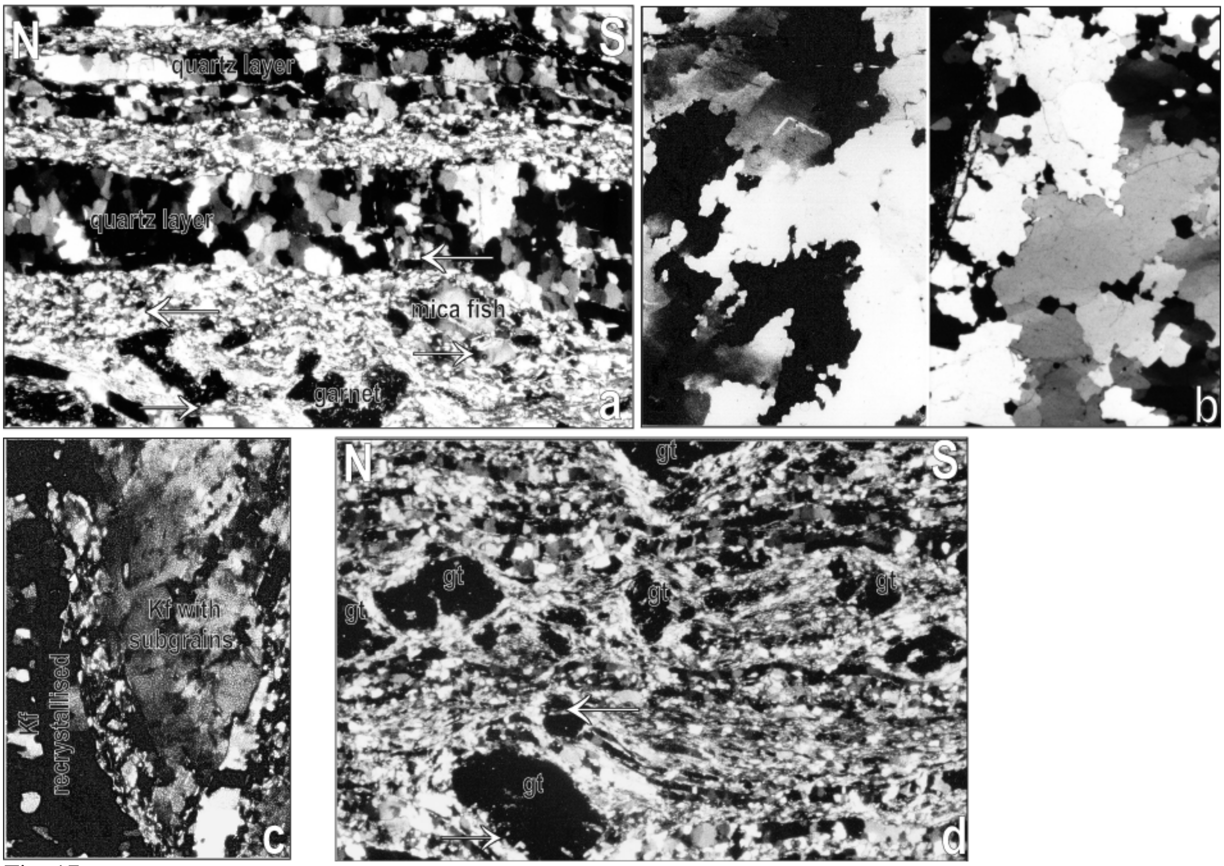



Fig. 17

Representative microstructures from the Plattengneis. a - Typical quartz layers parallel to the penetrative foliation showing HT microstructures. b - Quartz microstructures from transposed quartz vein; the quartz grains show typical lobate grain boundaries. c - K- feldspar (Kf) showing undulatory extiction and subgrain formation; dynamically recrystallized K- feldspar grains are developed along the margins of the host grain. d - Boudinaged garnets (gt) within metapelitic Plattengneis; asymmetric strain shadows around garnet indicate top-to-N sense of shear, and are filled with biotite; quartz within layer shows uniform grain size and partially straight grain boundaries.
a-d: crossed polarized Nicols. a, b, d: long axis of photograph about 4mm; c: long axis of photograph about 2mm.

Such CPO are characteristic of both high grade metamorphic conditions and high finite strain. The microstructures show that deformation within the Plattengneis shear zone was synmetamorphic. A continuous increase in peak temperatures from approximately 550°C to approximately 750°C, from the south to the central parts, can be inferred from geothermometric calculations. The temperatures then decrease again to approximately 650°C in the north. The corresponding pressures increase from 8 to 16 kbar, and then decrease to 10 kbar. The CPO changes that have been observed in the study area are best interpreted in terms of temperature dependence of the activation of glide systems within quartz aggregates. Together with the CPO-evolution, the temperature and pressure evolution indicates that exhumation rates for the central parts of the Koralm Complex were higher than for the northern and southern parts. We assume that the Plattengneis shear zone formed during the exhumation of the Koralm Complex, as a consequence of the strong exhumation of the eclogite-bearing high-pressure units in the footwall of this shear zone. Consequently, the kinematics of the Plattengneis shear zone is extensional rather than thrust-related.

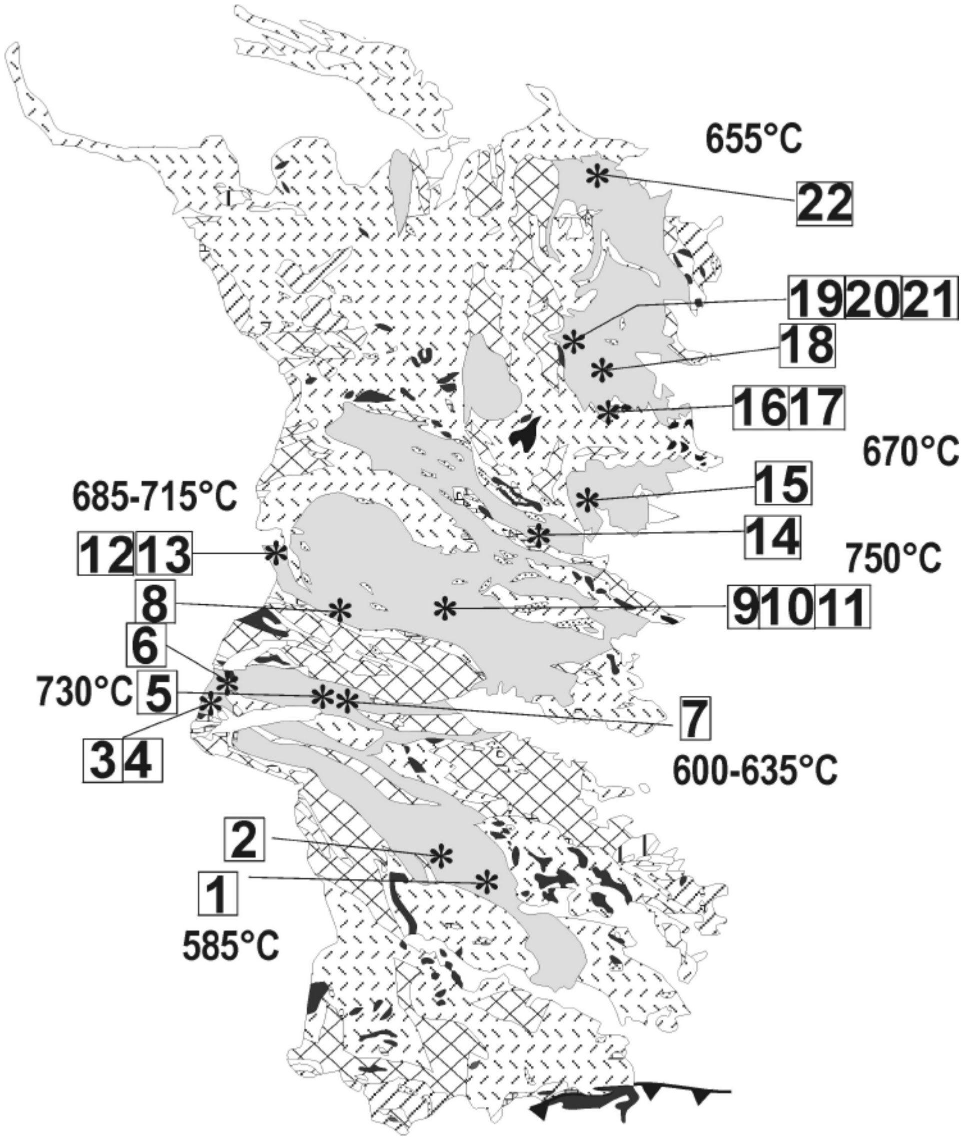



*Fig. 18*
*Geological map of the Koralm area including the sampling sites for texture measurements; numbering corresponds to the pole-figure-numbers in Fig. 19 (from KURZ et al., 2002).*

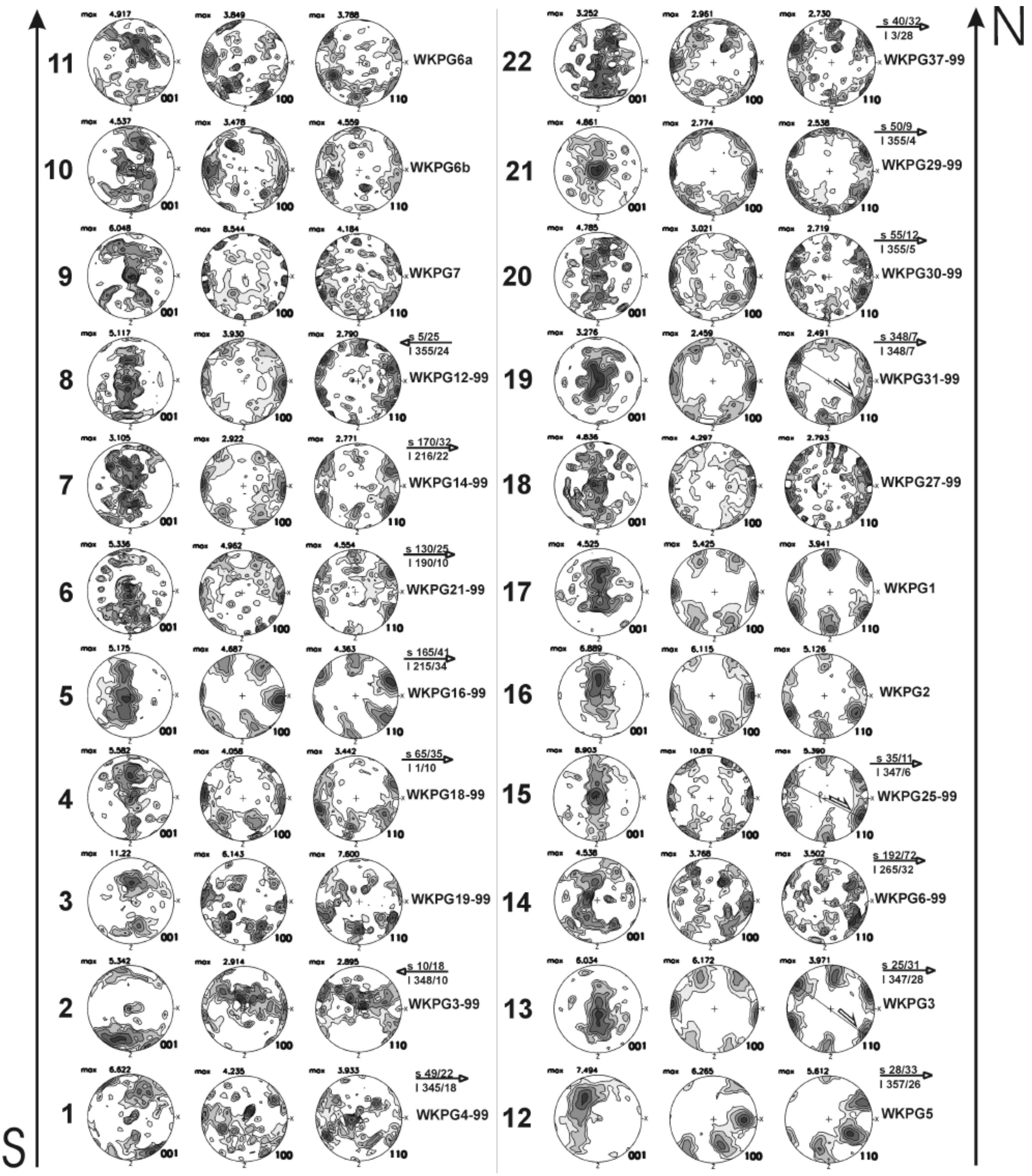


*Fig. 19*

*Pole figures of quartz CPO from the Plattengneis, arranged along the S-N- section presented in Fig. BB; the sampling sites are displayed in Fig. BB; (001): c-axes; (110): a-axes; (100): poles to prisms; X marks the direction of the stretching lineation and the strike of the shear zone boundary; line through the dominating a-axis maxima and arrows in pole figures 13, 15, 19 indicate the orientation of the dominant gliding plane for prism-a-slip. Stereographic projections, lower hemisphere; logarithmic gradation of isolines; first isoline: uniform distribution; fifth isoline: 85% of maximum; the arrows at the top right of the pole figures indicate the dip direction of the stretching lineation; s: penetrative foliation; l: stretching lineation. Lack of axis symmetry in pole figure 12 results from cutting slighty oblique to the foliation and lineation. For explanation see text.*

**Location K4: Geopark Glashütten**

The small, picturesque village of Glashütten, which was a booming centre for glass production ("Waldglas") in the 17th and 18th centuries, is today one of numerous tourist attractions in the area. The Geopark, situated in the centre of the village, has about 20 huge boulders (weighing up to 12 metric tons) on open-air display. These are hand-picked, often cut and polished, examples of typical rocks from the Koralpe, which include not only some rather spectacular eclogites from the main localities, but also "Plattengneis", marble, micaschist and pegmatite. The large polished surfaces allow an amazing insight into these rocks, even drawing the admiration of experienced scientists. A quartz-glass sculpture and a "geological mosaic" by artist Werner Schimpl add to the attraction and flair of the site.

## 4. SAUALPE EXCURSION

**Location S1: Kupplerbrunn (N46°49´53 E14°37´22), Prickler Halt (N46°50´04 E14°37´43) Österreichische Karte 1:50.000, sheet 187 Bad Sankt Leonhard im Lavanttal**

The granoblastic medium to coarse-grained eclogites are foliated and often banded on a dm-scale. Kyanite-bearing eclogites consisting of garnet + omphacite + kyanite + quartz + rutile + apatite ± phengite ± zoisite/clinozoisite ± amphibole ± dolomite ± zircon ± pyrite may be inter-layered with kyanite-free compositional bands. Veins of various kinds are widespread in the eclogites and were formed during different stages of the metamorphic evolution. The earliest veins are oriented subparallel to the foliation. They are filled with quartz and varying amounts of kyanite, omphacite and zoisite, indicating the presence of a vein fluid during HP metamorphism. Late coarse-grained pegmatoid veins are oriented at high angles to the foliation and contain zoisite/clinozoisite, quartz, ± plagioclase, ± green amphibole ± rutile and zircon. One of these veins that crosscut an eclogite at Prickler Halt is the type locality for zoisite, named after the Austrian mineral collector Siegmund von Zois (1747-1819).

Bulk rock compositions for the Kupplerbrunn and Prickler Halt eclogites are quite variable with bulk-rock Mg-numbers ranging between 0.54 and 0.79. Fig. 4e shows that plagioclase-rich gabbroic cumulates recrystallized to Ky-rich eclogites, whereas Qtz-rich eclogites were derived from protoliths that were enriched in FeO, $TiO_2$ and incompatible elements relative to the plagioclase-rich cumulates.

Garnet is almandine and pyrope-rich, and frequently contains inclusions of rutile, quartz, zoisite, ± kyanite, apatite and zircon. Garnet may be zoned, usually concentrically (Fig. 21), with $X_{Ca}$, $X_{Mn}$ and Fe/(Fe+Mg) decreasing from core to rim. Maximum pyrope contents in garnet rim domains vary from 30 to 57 mol% as a function of bulk-rock Mg-numbers between 0.54 and 0.79. Within a single sample, omphacite is unzoned and compositions vary only slightly, but there are distinct differences between samples. Most analyses are in the range $X_{Jd}$ = 0.29 - 0.40. Calcic amphibole is a minor phase in most of the samples studied, where it occurs in a number of textural and compositional varieties, such as (1) inclusions in garnet and zircon, (2) a phase apparently in equilibrium with omphacite and garnet, (3) texturally late bleb-textured poikiloblastic grains, (4) strongly coloured grains at garnet/omphacite contacts and (5) vermicular intergrowths in symplectite replacing omphacite.

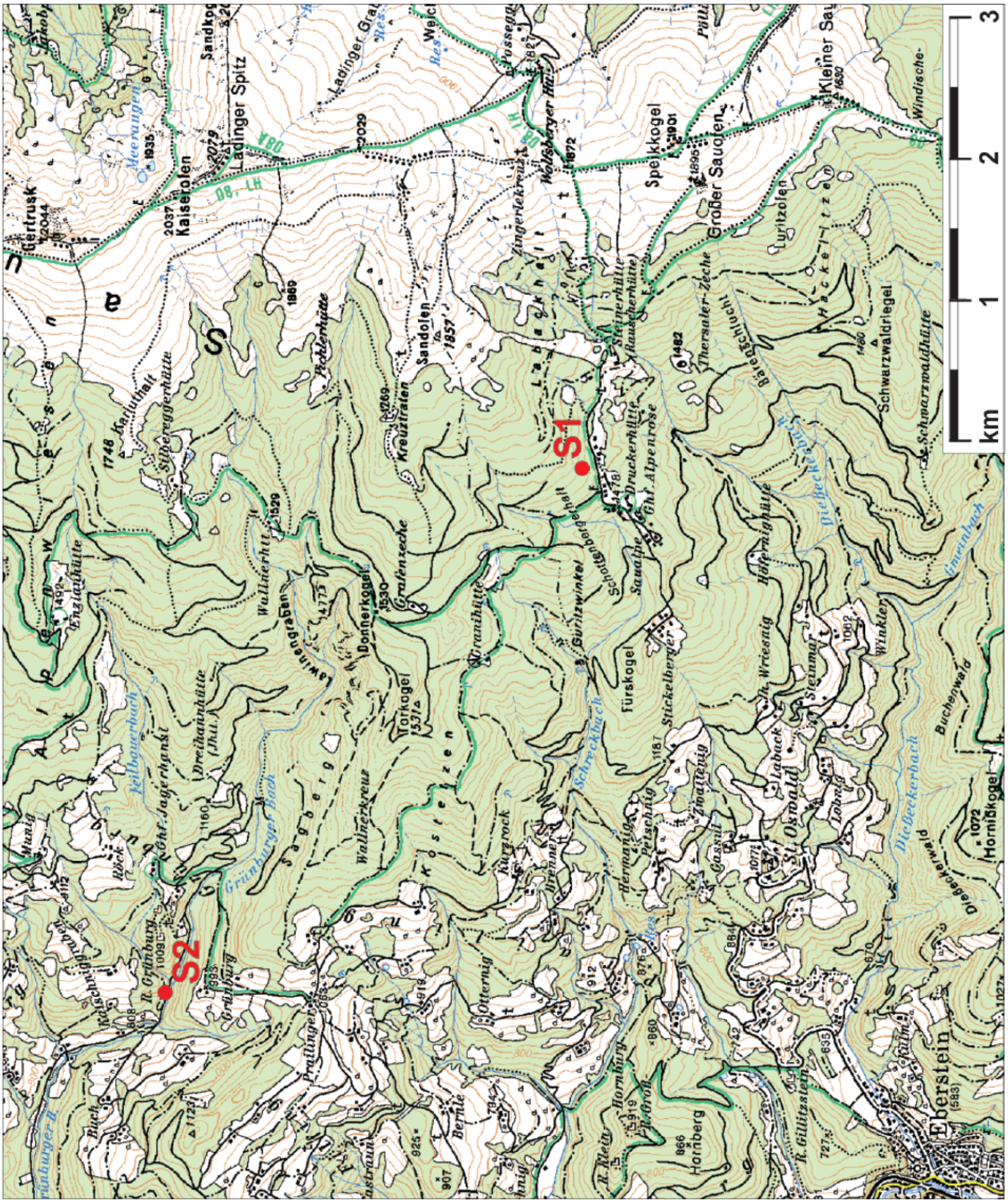



*Fig. 20a*
*Locations Kupplerbrunn (S1) and Grünburg Graben (S2) visited on the Saualpe excursion.*

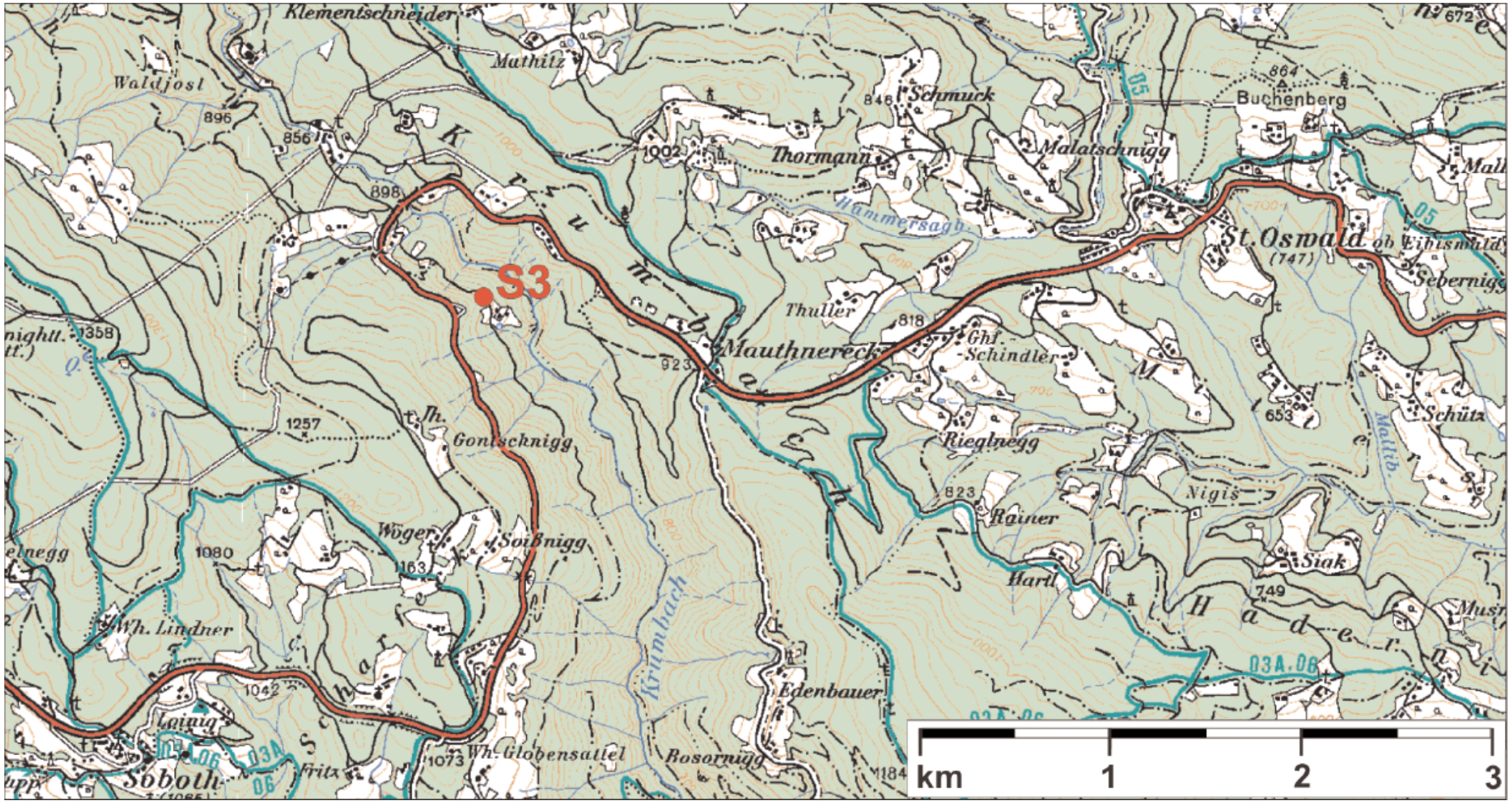



Fig. 20b
Location Krumbachgraben/Koralpe (S3) visited on the Saualpe excursion

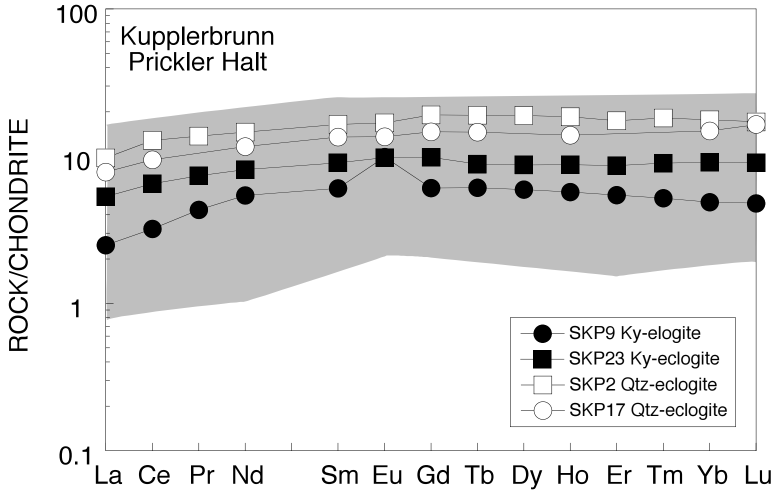



*Fig. 4e*
*Chondrite-normalized (BOYNTON, 1984) rare earth element plot for two Ky-rich and two Qtz-rich eclogites from Kupplerbrunn and Prickler Halt, Saualpe.*

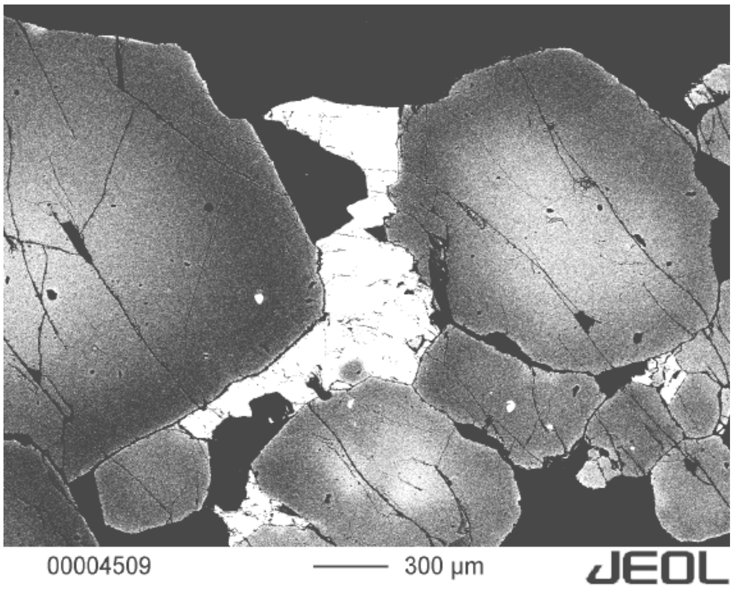



*Fig. 21*
*BSE image of garnet in a Ky-rich eclogite from Kupplerbrunn, Saualpe. The bright core domain of the garnet shown on the upper right side has a composition of* $Prp_{40.3}Alm_{38.2}Grs_{20.3}Sps_{0.9}Uv_{0.2}$*, the dark rim domain has a composition of* $Prp_{44.6}Alm_{34.8}Grs_{19.9}Sps_{0.6}Uv_{0.2}$*.*

Some chemical differences between these textural types are illustrated in Fig. 22. In general, the primary amphiboles are magnesio-hornblendes that contain less tetrahedral Al and have lower A-site alkalies than the poikiloblastic grains. These bleb-textured amphiboles are edenitic, pargasitic or magnesio-hornblendes with less T-site alumina than other secondary amphiboles. This is compatible with their early formation still at high pressures. Secondary amphiboles in contact with garnet are highly aluminous subsilicic-alumino-pargasite, ferrian-alumino-pargasite, sodian pargasite and pargasitic hornblende. Where amphibole is present in symplectites after omphacite, it is magnesio-hornblende or actinolitic hornblende with distinctly lower $Al^{VI}$ than all other amphiboles. Fe-poor zoisite with $X_{Fe}$ from 0.02 to 0.04 is common in kyanite-rich eclogites, whereas quartz-rich eclogites may contain clinozoisite with $X_{Fe}$ ranging from 0.11 to 0.13. Kyanite contains trace Cr (0.03 - 0.28 wt% $Cr_2O_3$) and Fe (0.18 - 0.39 wt% $Fe_2O_3$) as the main impurities. Phengite with 3.27 - 3.36 Si apfu is a minor phase and may be present in both eclogite-types.

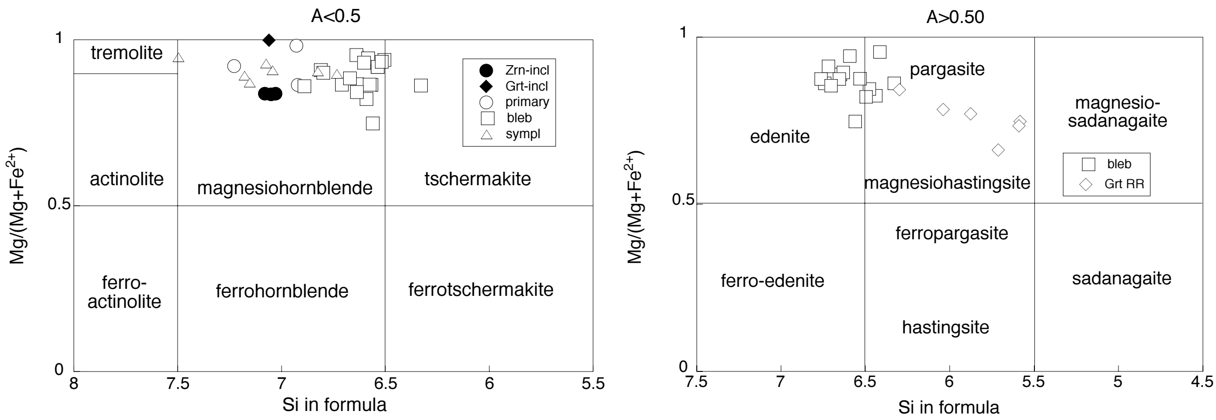



*Fig. 22*
*Mg/(Mg+Fe$^{2+}$) vs. Si diagrams for amphiboles from Kupplerbrunn and Prickler Halt (Saualpe) eclogites. The amphibole nomenclature is after LEAKE et al. (1997). See text for discussion.*

Attempts to date the HP metamorphism from both Kupplerbrunn and Prickler Halt localities by the Sm-Nd method, using the famous Ky-eclogite, are faced with even more problems than those discussed for some Koralpe eclogites: (1) extremely low Nd concentrations (< 100 ppb) in Omp, Amp and Grt, for example Nd concentrations in garnet from four different samples range between 11 and 38 ppb (data from THÖNI & JAGOUTZ, 1992; THÖNI et al., data in prep.). (2) Nd isotope disequilibrium among HP minerals, as well as (3) post-HP metamorphic mineral reactions that may also perturb the isotopic systems, resulting in spurious "ages" (e.g., mostly too young Sm-Nd Grt-wr tie lines; THÖNI & JAGOUTZ, 1992).
The $\varepsilon_{Nd}$ values for three whole rock samples, calculated for 260 Ma based on the Koralpe gabbro protolith age, are +7.3 (Prickler Halt), +8.1 and +9.0 (Kuppler Brunn); $^{87}Sr/^{86}Sr$ ratios are 0.70418 and 0.70316 (samples 88T35 and 86T09; THÖNI & JAGOUTZ, 1992). Rb-Sr dating of phengite separated from the massive eclogite resulted in a wr-phengite age of 102 ± 2 Ma, whereas wr-amphibole from the same sample (88T35) yielded a Rb-Sr age of 92.5 ± 1.6 Ma. Coarse-grained phengite from a late vein that crosscuts the eclogite-foliation discordantly gave ages of 84 ± 2.5 and 84.4 ± 2.1 Ma (THÖNI & JAGOUTZ, 1992).

A more recent multi-isotopic approach to dating the Kupplerbrunn eclogites resulted in better constrained age estimates. Some of these results are shown in Fig. 23 and discussed below (THÖNI et al., 2005, data in prep.). Sm-Nd mineral whole-rock regression (n = 5) yields an age of 91.2 ± 2.6 Ma for Qtz-rich eclogite SKP2 ($\varepsilon_{Nd}$ = +8.2; MSWD = 4.9). Zircons from the same sample give a weighted mean $^{206}Pb/^{238}U$ SHRIMP age of 82.2 ± 3.8 Ma (n = 7; MSWD = 0.87) for the rims, whereas zircon cores show variable inheritance of radiogenic Pb (single spot ages up to 183 Ma). This is compatible with results from earlier studies on eclogite zircons from the Saualpe and Koralpe (HEEDE, 1997; PAQUETTE & GEBAUER, 1991). Lu-Hf isotope analysis of a meta-cumulate Ky-rich eclogite (sample 88T35) yields 88.4 ± 4.7 Ma for the garnet-omphacite pair. Inclusion of two whole rock analyses in the regression (n = 4) results in an age of 87.4 ± 11 Ma ($\varepsilon_{Hf}$ = +15.2; MSWD = 4.0). These new data suggest that eclogite-facies conditions prevailed at Kupplerbrunn up to 90-88 Ma.

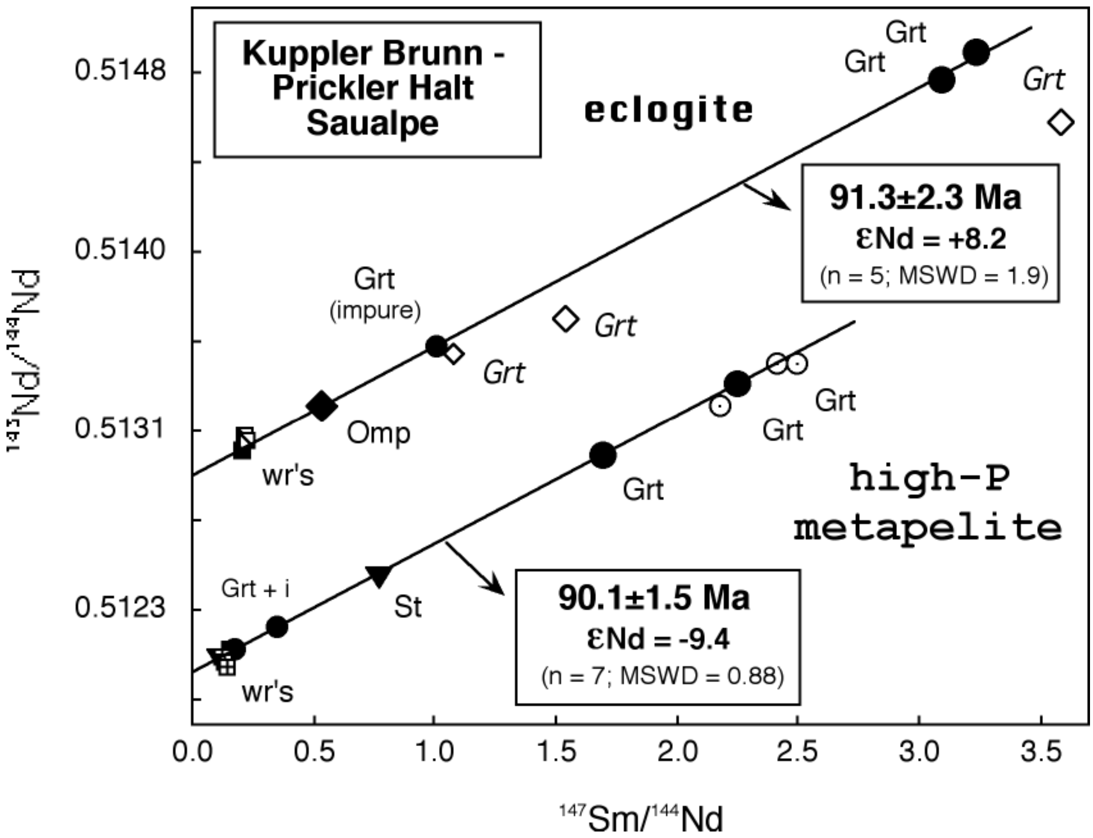



*Fig. 23*

*Isochron plot of mineral and whole rock Sm-Nd data of quartz-eclogite SKP2 (THÖNI et al., data in prep.) and metapelitic host rocks of the Kupplerbrunn-Prickler Halt localities, Saualpe. In the upper part of the diagram data points of two handpicked Grt fractions, one impure garnet, Omp and the wr (solid symbols) of quartz-eclogite SKP2 define a regression age of 91.2 ±2.6 Ma ($\varepsilon_{Nd}$ = +8.2). Open diamonds (Grt) and squares (wr) are from Ky-eclogites with Nd isotope disequilibrium (THÖNI & JAGOUTZ, 1992, and unpubl. data). The lower part of the graph shows mineral and whole rock Sm-Nd data of metapelitic eclogite host rocks, which suffered coeval high-P metamorphism. Sample 89T22 (solid symbols) defines an isochron age of 90.1 ± 1.5 Ma, based on handpicked garnet, leached handpicked garnet, its leachate, impure garnet, staurolite, w. mica and the whole rock (n = 7; MSWD = 0.88). Open symbols are from other Kupplerbrunn-Prickler Halt metapelite samples (THÖNI & MILLER 1996; THÖNI 2002).*

HEEDE (1997) showed that the Prickler Halt zoisite pegmatoid contains two zircon populations, (i) extremely U-rich (6800-21600 ppm U) metamict zircons and (ii) low-U (100-300 ppm U) unaltered colourless, pink or yellow zircons. Although most of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ analyses of these zircons are analytically slightly discordant, they indicate ages of 92-94 Ma for the metamict group and 88-92 Ma for the U-poor zircons (HEEDE, 1997).

The HP metapelites (Pl-Ky-St-bearing garnet-mica schists and gneisses) that form the eclogite country rocks at Kupplerbrunn-Prickler Halt consistently yielded Grt-wr and/or mineral-mineral isochron Sm-Nd ages between 88.5 ± 1.7 and 90.9±0.7 Ma (THÖNI & MILLER, 1996) (Fig. 23), also suggesting that high PT conditions persisted at Kupplerbrunn up to 88 Ma B.P.

**Location S2 (conditional): Grünburger Graben (N46°51´21 E14°33´30)**
**Österreichische Karte 1:50.000, sheet 186 Sankt Veit an der Glan**

This outcrop is part of an eclogite lens with a length of about 1500 m and about 150 m wide, intercalated with country rock mica-schists and gneisses. Near the base of the outcrop a pegmatoid vein containing muscovite, plagioclase and quartz is seen to intrude this eclogite parallel to the foliation. The fine to medium-grained eclogites are of the Fe- and quartz-rich "metabasaltic" variety (Fig. 4f) and consist of garnet + omphacite + quartz + rutile + apatite ± amphibole ± phengite ± clinozoisite ± zircon ± pyrite. Garnet is slightly zoned with rim compositions of $Prp_{35-37}Alm_{39-40}Grs_{22-24}Sps_{0.5-0.6}$ and contains inclusions of Rt, Qtz, Czo, Ap and zircon. Omphacite is unzoned with 0.34-0.35 mol% jadeite and, together with clinozoisite, defines a foliation. Subcalcic magnesiohornblende is present as texturally late poikiloblastic grains overgrowing garnet, clinozoisite, quartz and rutile.

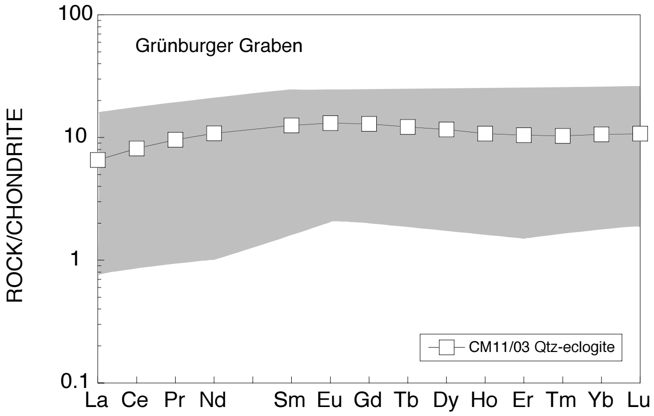



*Fig. 4f*
*Chondrite-normalized (BOYNTON, 1984) rare earth element plot for a Qtz-rich eclogite from Grünburger Graben, Saualpe.*

HEEDE (1997) attempted to date zircon (multigrain) separates from this eclogite, but without success due to their extremely low U contents (3.6-4.6 ppm) and Pb contamination problems. Sm-Nd studies are in progress (MILLER et al.). The Rb-Sr age of the muscovite from the pegmatoid is 81.1 ± 1.5 Ma, with an initial Sr isotope ratio of 0.71127 ± 8 (HEEDE 1997).

**Location S3: Krumbach Graben - Koralpe (N46°42´29 E15°05´36)**
**Österreichische Karte 1:50.000, sheet 206 Eibiswald**

A road cutting on the east-facing slope of the Krumbach Graben west of Mauthnereck provides a good exposure of a quartz-rich eclogite. The analysed whole rock sample plots in the basaltic field of the $Al_2O_3$-$TiO_2$ discrimination diagram (Fig. 2). Its trace element and LREE-depleted (Fig. 4d) signatures are similar to those of N-MORB. Primary phases observed in this quartz-rich eclogite are garnet, omphacite, clinozoisite, quartz, rutile, apatite, zircon and pyrite. Garnet is slightly zoned with core and rim compositions of $Prp_{35}Alm_{40}Grs_{24}Sps_1$ and $Prp_{39}Alm_{39.5}Grs_{21}Sps_{0.5}$ respectively, and may contain inclusions of quartz, rutile, apatite and zircon. Parallel oriented omphacite ($X_{Jd}$ = 0.39) and clinozoisite (11-14 mol% pistacite) define an early foliation. Zircon was observed as inclusions in garnet, omphacite, clinozoisite and in the matrix. Grain size is highly variable, with longest dimensions ranging from approximately 20 to 160 µm. In cross section, zircon grains have ovoid or rounded shapes, irrespective of size.

One zircon grain contains inclusions of rutile and omphacite, suggesting zircon growth under eclogite-facies conditions (Fig. 5d). Growth of amphibole (magnesio-hornblende) seems to postdate all other primary phases, but it still appears to be part of the stable eclogite facies assemblage (Plate 2b). Post-eclogite alterations are restricted to narrow symplectite rims consisting of Na-poor clinopyroxene and plagioclase at omphacite grain boundaries.

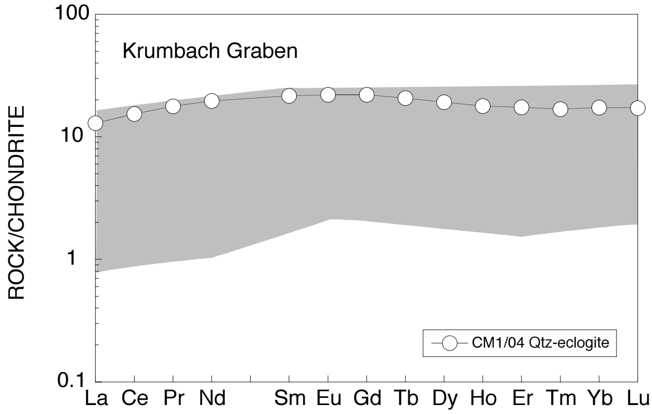



*Fig. 4d*
*Chondrite-normalized (BOYNTON, 1984) rare earth element plot for quartz-rich eclogite, Krumbach, Koralpe.*

Sm-Nd analysis of Grt and whole rock of an eclogite from this outcrop (sample DG92; GREGUREK, 1995, unpublished data) resulted in an age of 91.4 ± 6.7 Ma and an $\varepsilon_{Nd}$ (calculated for 260 Ma) of +7.5.

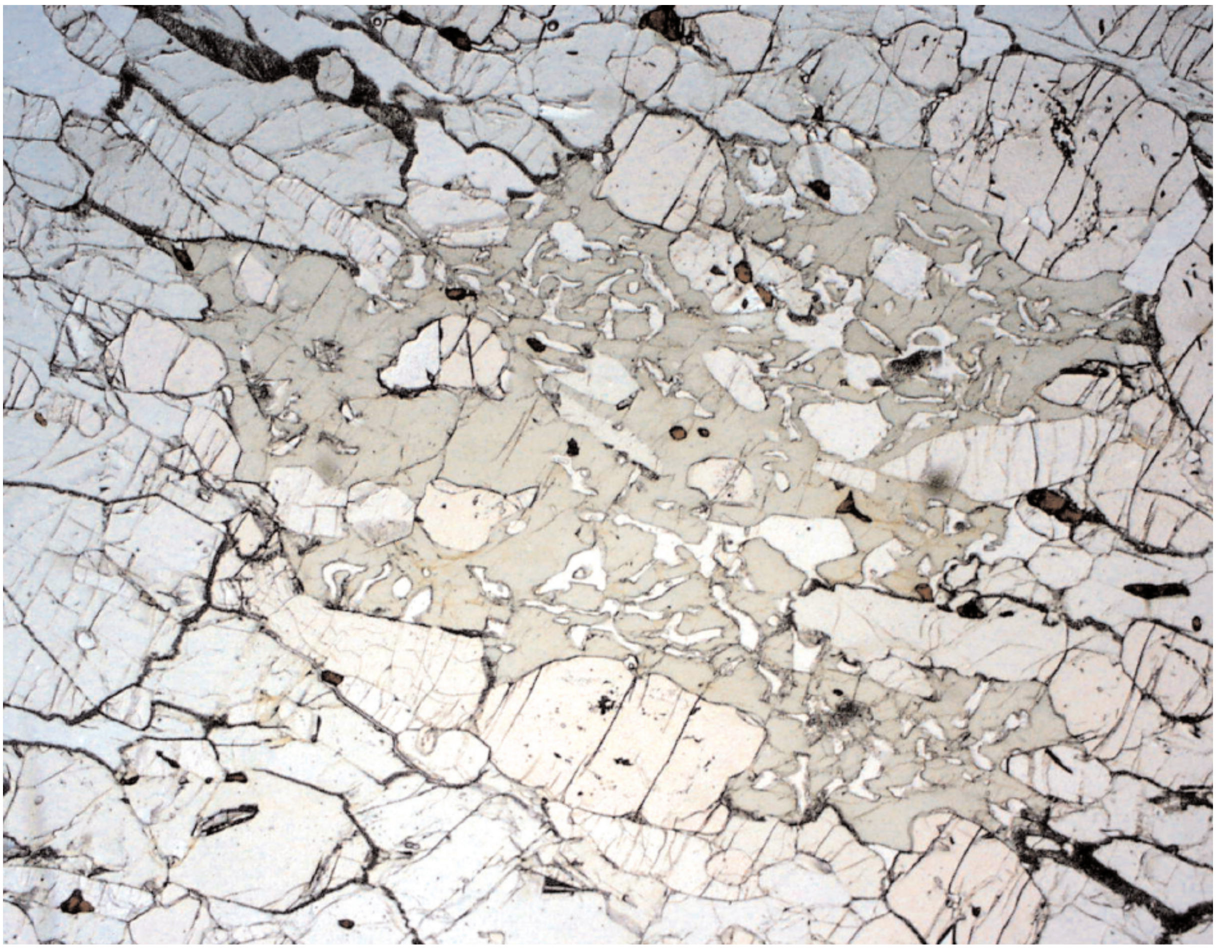


*Plate 2b*
*Photomicrograph of a quartz-rich eclogite where a texturally late edenitic amphibole poikiloblast overgrows an earlier foliation defined by omphacite and clinozoisite. Krumbach, Koralpe.*

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