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Petrology of eclogites from the Saualpe, Austria

by *G. M. Manby*[1] and *F. Thiedig*[2]

Abstract

The eclogite bearing crystalline rocks of the Saualpe form the lower part of the Koriden unit which belongs to the Austroalpine nappe system. Major, trace and RE element chemistry of the eclogites confirms the evolved tholeiitic character of their protoliths and suggests that they were derived from a common but fractionated magma source of N-MORB affinity. εNd(t) values of +5 to +6.1 by comparison with modern examples are however within the range of ocean island or island arc basalts. A back-arc basin environment of formation would reconcile these differences and be consistent with the terrigenous character of the associated schists and gneisses. Sm/Nd isotopic age determinations of ca. 700 Ma coincide with the isothermal decompression of the eclogites from a maximum of 18 kb/840 °C down to 10 kb followed by equally declining PT to 5,5 kb/500 °C. The extensive preservation of symplectite textures in the eclogites suggests that the decompression took place with little directed stress. Hercynian amphibolite facies metamorphism was accompanied by pegmatoid injection into both the country rocks and the eclogites. Although Alpine nappe stacking gave rise to extensive mylonitization of the country rocks and largely reset K/Ar and Rb/Sr isotope systems the eclogites escaped penetrative deformation. Where post pegmatoid shearing and retrogression of the eclogites has occurred textures and mineralogies are typically greenschist facies in character. The PTt history of the eclogites cannot therefore be represented by a single continuous loop. Rather it is marked by a series of discontinuous and unrelated events separated by large intervals of time.

Keywords: Eclogites, geochemistry, Sm/Nd age determination, PTt-history, Saualpe, Austria.

Zusammenfassung

Die Eklogit-führenden Gesteine des Saualpenkristallins bilden den unteren Teil der Korideneinheit, die zum Mittelostalpinen Deckensystem gehört. Untersuchungen der Haupt-, Spuren- und Seltenerdenelement-Chemie belegen den ausgeprägt tholeiitischen Charakter der Ausgangsgesteine und legen den Schluss nahe, dass diese sich aus einem gewöhnlichen, aber fraktionierten Magma mit N-MORB-Charakter entwickelt haben. Nd(t)-Werte von +5 bis +6,1 entsprechen hingegen den Werten von rezenten ocean-island- oder island-arc-Basalten. Die Annahme einer Entstehung der Ausganggesteine im back-arc-basin-Milieu umgeht diese Differenzen und lässt sich mit dem terrigenen Charakter der umgebenden Glimmerschiefer und Gneise gut vereinbaren. Gesamtgesteins- und Granatmineral-Sm/Nd-Alter von ca. 700 Mio. Jahren entsprechen der isothermalen Druckentlastung der Eklogite von max. 17 Kb/840°C auf ca. 10 Kb, gefolgt von einem Druck-Temperaturabfall auf 5,5 Kb/500°C. Die weitgehende Erhaltung von symplektitischen Strukturen in den Eklogiten spricht für eine Druckentlastung bei geringem gerichtetem Stress. Eine variskische amphibolitfazielle Metamorphose war begleitet von pegmatoiden Injektionen in den Eklogiten und den umgebenden Gesteinen. Obwohl die alpine Deckenstapelung eine ausgedehnte Mylonitisierung der Nebengesteine und eine Neueinstellung der Rb/Sr-Isotopenverhältnise bewirkte, blieben die grösseren Eklogitkörper von einer durchdringenden Deformation verschont. In Bereichen postpegmatoider Zerscherung und retrograder Umwandlung der Eklogite entsprechen die Texturen und Mineralisationen den Bedingungen einer typischen Grünschieferfazies. Der Druck-Temperatur-Pfad der Eklogite kann aus diesem Grund nicht als einfache Schleife beschrieben werden, sondern besteht eher aus einer Folge von mehreren, nicht zusammenhängenden Ereignissen mit grossem zeitlichen Abstand.

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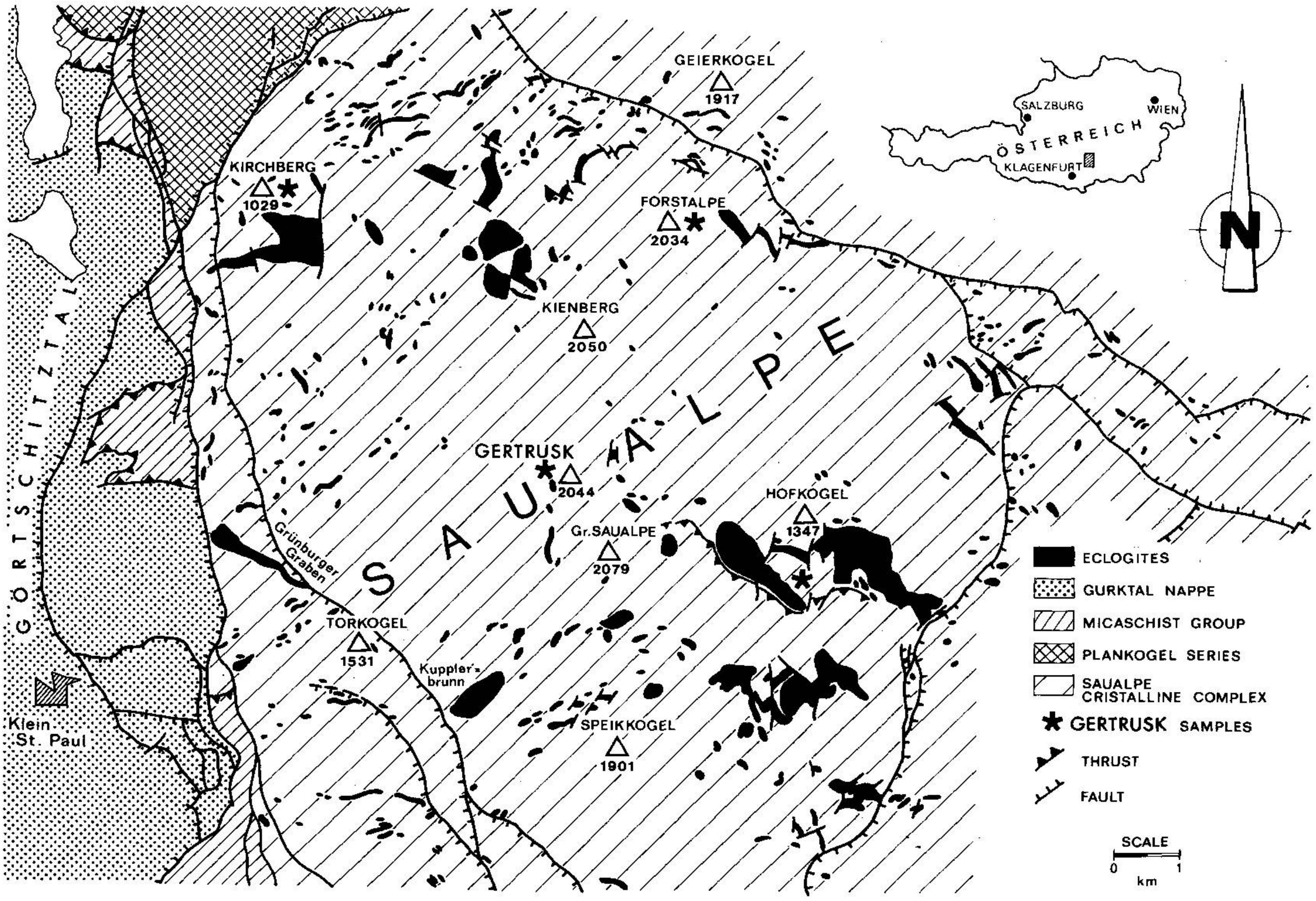
1. Introduction

The region of the Saualpe has been the subject of considerable geological and mineralogical research in the last thirty years (CLAR, 1953, 1975; MEIXNER and CLAR, 1981; FRITSCH, 1962; PILGER and SCHÖNENBERG, 1975; WEISSENBACH, 1971, 1975). These activities are summarised in "Geologie der Saualpe" edited by PILGER and SCHÖNENBERG (1975) and the geological map (1:25000) compiled by WEISSENBACH and published by the Austrian Geological Survey (1978). More recent published accounts on the Saualpe rocks have tended to concentrate on the chemistry of the eclogites (MOTTANA et al., 1968; LODEMANN, 1970; RICHTER, 1973; SCHMEROLD, 1988; MILLER et al., 1988) or alternatively restricted to isotopic age determinations (MORAUF, 1981; MILLER and FRANK, 1983; RITTMANN, 1984) of the eclogites and associated rocks.

Of all the rocks comprising the Saualpe the eclogites are relatively well exposed and, in common with their counterparts in other terraines, they retain evidence of much of their metamorphic and tectonic history. However there have been no recent attempts to decipher the evolutionary history of the eclogites and accounts of their tectonic significance give only scant attention to microstructural evidence.

In this paper we examine the chemistry, K/Ar, Ar/Ar, Rb/Sr and Sm/Nd isotope systematics and mineral fabric relations in an attempt to deduce the PTt path of the eclogites since their formation. Our study is restricted to the larger exposed eclogite bodies of Grünburger Bach, Gertrusk, Kupplerbrunn and the Jurkikogel/Beilstein complex and some of the pegmatoids found cross-cutting them. Each of these bodies although showing textural and mineralogical similarities are chemically distinct in some respects.

Major and trace element contents were determined by XRF techniques at the University of Southampton and REE analyses were carried out in the Earth Sciences Department at Goldsmiths. Garnet - whole rock Sm/Nd and K/Ar mica age determinations were performed at the British Geological Survey Isotope Laboratories, London.



2. Structural setting

The Saualpe is a N-S trending horst-like block bounded by the Görtschitztal and Lavantal fault systems (Fig. 1). The horst consists of an 8 km thick sequence of metasediments found in a series of thrust nappes which for the most part are stacked in order of decreasing metamorphic grade. Earlier workers (Clar, 1975; Weissenbach, 1971, 1975, and Pilger and Schönenberg, 1975) considered the deformation and metamorphism of the Saualpe rocks to be largely Hercynian in age although they could not exclude the possibility of some Alpine reworking particularly in the lower nappes. Isotopic age determinations (Morauf, 1980, 1981, 1982; Miller and Frank, 1983 and Rittmann, 1984) have demonstrated extensive and intensive Hercynian reworking and have led to speculation that earlier Caledonian events may be recorded in these rocks. Importantly, these age determinations demonstrated beyond doubt the extensive nature of the Alpine overprinting in the region (Morauf, 1982).

Tectonically the sequence belongs to the Upper and Middle East Alpine segments of the Austroalpine nappe system. At the visible base of the nappe pile are the medium grade mica schists and amphibolites of the Kliening Series (Muriden Unit). These are overthrust by the Saualpe Crystalline Complex schists, mylonitic gneisses and eclogites. The Crystalline Complex, together with the overlying medium

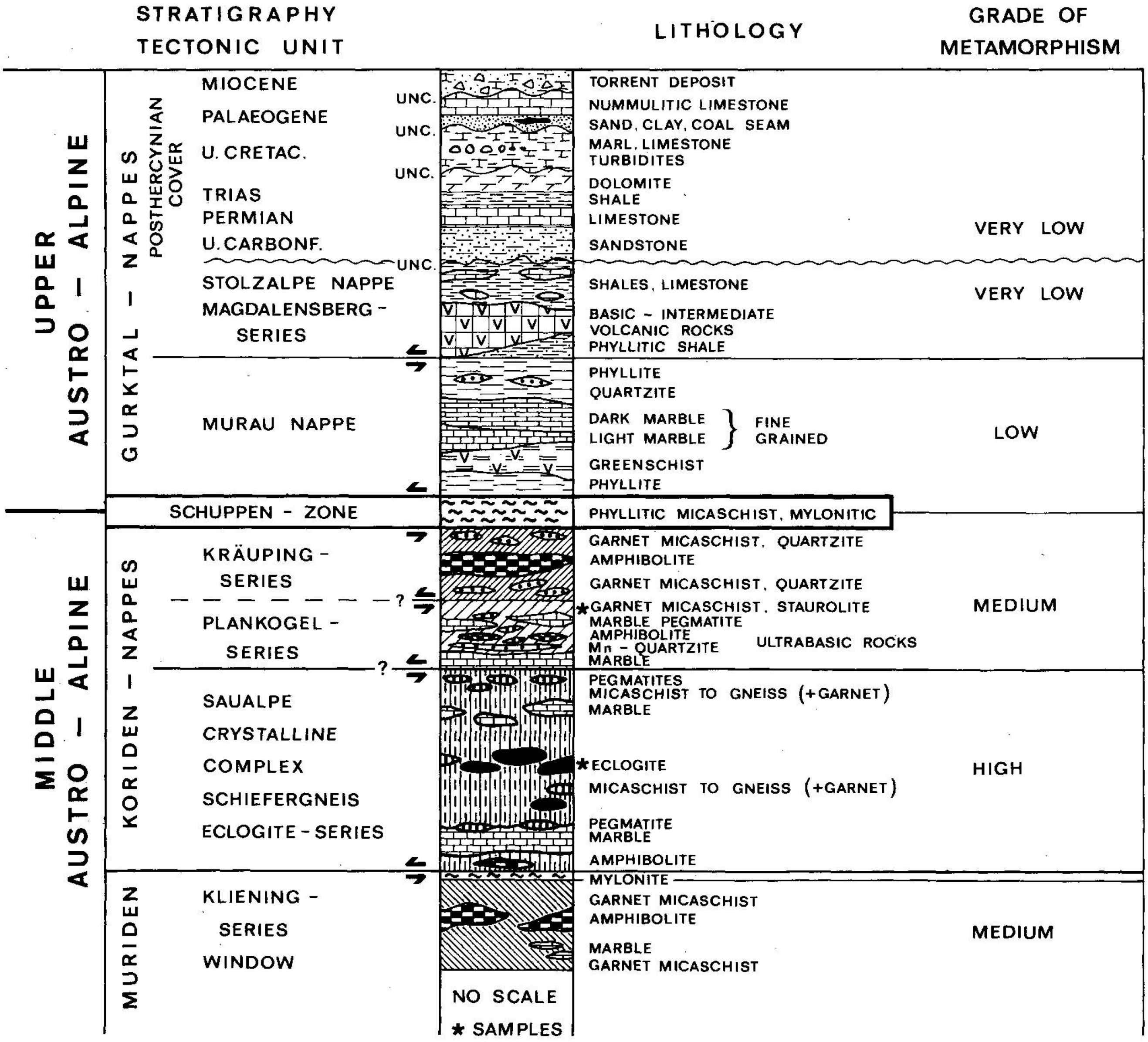


Fig. 1 General geology and tectonostratigraphy of the Saualpe.

grade schists, amphibolites, quartzites and marbles of the Mica Schist Group, constitute the Koriden nappe. The low grade Phyllite Group forms part of the overthrust Murau Nappe which is in turn overthrust by the Stolzalpen Nappe. This nappe carries an unconformable cover sequence of very low grade to unmetamorphosed Late Carboniferous to Late Cretaceous sediments.

The presence of Alpine nappe structures in this segment of the Eastern Alps was postulated by Tollmann (1963) and confirmed by detailed mapping in the adjacent Gurktal nappes by von Gosen (1982). Re-mapping of the Krappfeld area by Thiedig and co-workers (Thiedig, 1981; Wolter et al., 1982) in recent years has also led to the discovery of many previously unrecognised folds and thrusts in the post-Hercynian rocks. According to Frank etmetamorphism has affected the Crystalline complex rocks of the Koralpe and Saualpe. However other than the upward decrease in metamorphic grade through successively higher nappes in the Saualpe no major inversions of stratigraphy nor any mesoscale structures supporting this interpretation have been observed by us in the field.

3. Eclogite field relations

The eclogites occur as sheet-like bodies within the dominant foliation of the Crystalline Complex (Fig. 1). In the lower part of the Crystalline Complex nappe the eclogites are found as a series of thin sheets a metre or so in thickness and intimately interleaved with the schists and gneisses. Higher in the nappe the eclogite bodies are predominantly thick (up to 180 m) sheets. The precise field relations with the country rocks are difficult to determine because of poor exposure and the polyphasal nature of the deformation / metamorphism which has affected the whole package of rocks. Deformation has dismembered the eclogites and the block-like shapes of the bodies reflect the high viscosity contrast between the eclogites and the enclosing country rocks. The eclogites have therefore behaved as relatively rigid masses and have been less sensitive to deformation than the predominantly phyllosilicate-rich country rocks. The combined effect of these factors is that mineral-fabric relations in the eclogites and their country rocks are difficult to correlate.

All of the eclogite bodies described in this study display a marked compositional banding with granoblastic to strongly lineated fabrics. This foliated fabric is overprinted by discrete, conjugate, ductile to brittle, shear band foliations.

4. Eclogite petrography and mineral chemistry

All of the eclogites show a pronounced compositional banding on the scale of a few to several tens of centimetres with alternations of omphacite-zoisite / clinozoisite and garnet rich layers. Some bands are fine to medium grained, granoblastic and lack any distinct foliation. In most eclogites however the omphacites and zoisites / clinozoisites have a strong dimensional preferred orientation and the garnets may be elongate or distributed in strings.

Garnet, omphacite, zoisite, quartz and, in some cases kyanite, assemblages form the bulk of the unaltered eclogites. Variations in the modal proportions of these phases give these rocks their banded character. Amphiboles, usually a few grains per thin section, also appear in textural equilibrium with the above minerals. In the eclogites the following, prograde equilibrium assemblages can be recognised;

1. gt + omp + qtz + rt
2. gt + omp + zo / czo + rt
3. gt + qtz + / - rt
4. gt + omp + zo / czo + ed / par + qtz + rt / ilm
5. gt+ omp + ky+ zo / czo + qtz + phe + / - rt

Mineral abbreviations largely follow Kretz (1983).

4.1. GARNETS

The garnets often contain fine grained inclusions of quartz, rutile and omphacite in the central region of the porphyroblasts whereas the rims are usually inclusion free (Fig. 2a). However where the garnets have enlarged during pegmatoid injection they may also partially enclose amphibole grains.

Garnet formulae were calculated on the basis of 12 oxygens (Tab. 1). Al was assigned to the tetrahedral site to bring the total to two and the proportion of ferric iron was determined by difference assuming trivalent cations totalled

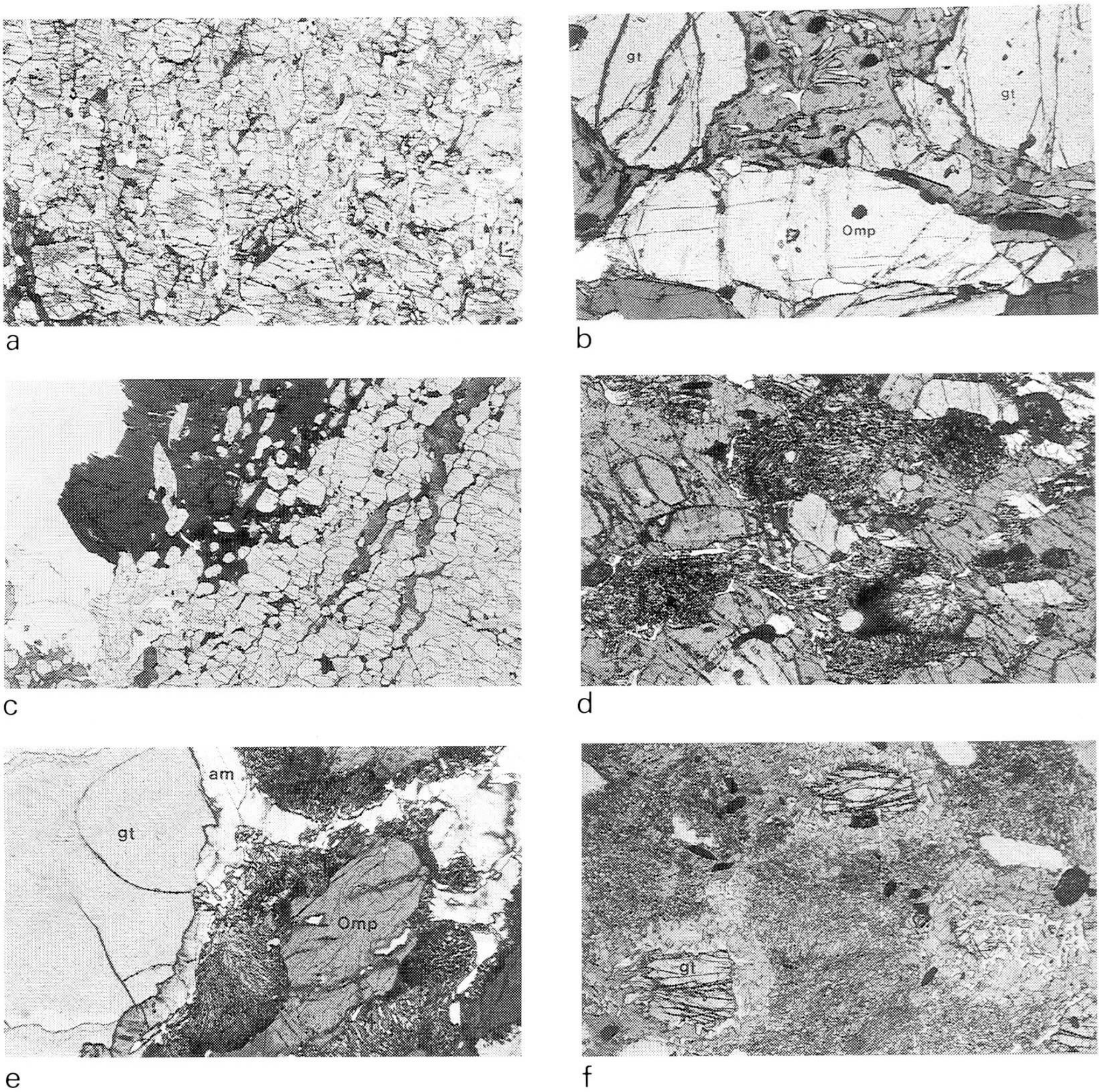
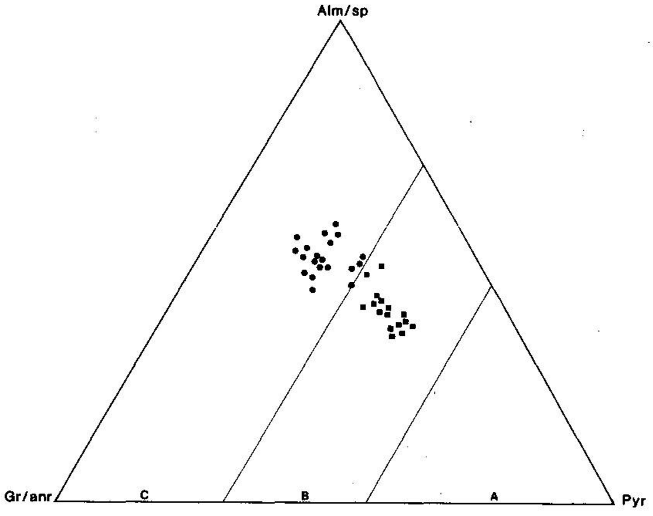


Fig. 2
a. Typical foliated eclogite with inclusion and colour zoned garnets. Plate length is 2 cm.
b. Early pargasite with vermicular exsolved quartz. Plate length 3 mm.
c. Poikiloblastic pargasite overgrowing eclogite. Note vein-like amphibole and close spaced fractures cutting all phases. 3 cm × 1,5 cm.
d. Symplectite garnet and zoned epidote inclusions in pargasite. Symplectites are separated from pargasite by narrow feldspar rim. Plate length 3 mm.
e. Amphibole rimming garnet and partially enclosing symplectite. Plate length 2 mm.
f. Garnets with Mg–hb / plag rims set in fine-grained symplectite matrix. Plate length 3 mm.

two. The remaining iron was assumed to be divalent and assigned to the divalent (M2) cation site.

Garnet compositions plot in two distinct groupings on the COLEMAN et al. (1965) diagram (Fig. 3). Those frphase amphiboles are transitional into, or are, type C. Despite having inclusion or occasional colour zoning (Fig. 2a) most garnets from the least altered eclogites are chemically homogeneous. However in amphibolitised horizons garnets are often slightly zoned with higher almandine rim compositions indicating renewed growth during the amphibolite facies overprint.



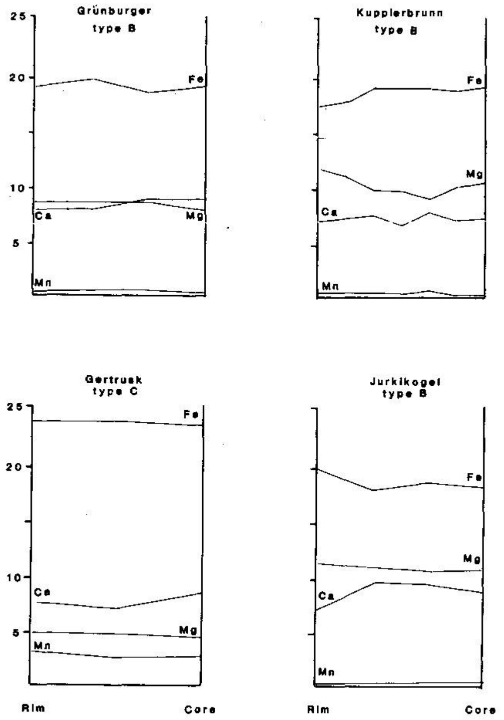


Fig. 3 Garnet compositions plotted after COLEMAN et al. (1965). Squares are unaltered and largely unzoned types. Circles are garnets which have enlarged or grown with pegmatoid related amphiboles. Core-rim traverses of some typical garnets. Variations are within limits of analytical error.

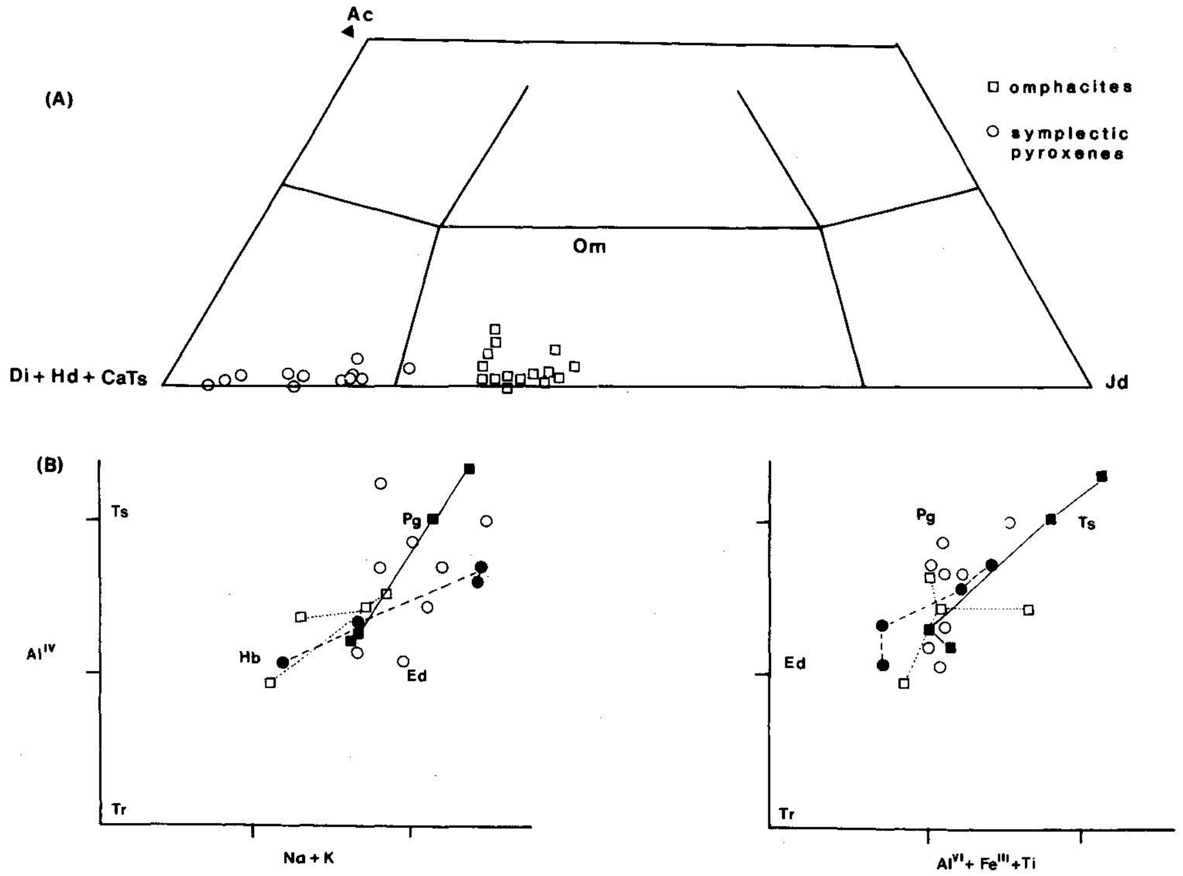


Fig. 4 (A) Pyroxene and (B) amphibole compositions. Tie lines on amphibole plots join compositions in same sample. Open circles represent compositions of different samples.

4.2. PYROXENES

Whilst they are largely inclusion free the pyroxenes may enclose or be enclosed by the zoisites. In thin section they may be colourless or exhibit a characteristic pale green colour in plane-polarised light. In defining the dominant foliation these grains may show slight bending around the garnets but with little evidence of internal strain.

In calculating the formulae it was assumed that Al in the tetrahedral site is negligible in high pressure sodic pyroxenes. Because cation deficiencies are common in such pyroxenes normalisation to four cations has not been attempted. Ferric iron was determined as being equal to Na minus Al. The remaining iron was assumed to be ferrous and the cations normalised to six (Tab. 1).

Acmite contents are low and all prograde pyroxenes are omphacitic with Jd contents of ca. 37–43% (Fig. 4a). Pyroxenes growing in symplectic associations with feldspars around the omphacites show a range of compositions with decreasing Jd contents down to 7%. None of the pyroxenes have been found to be chemically zoned.

4.3. AMPHIBOLES

Amphiboles are found in a variety of textural associations. Amphibole compositions were calculated assuming 23 oxygens and the cations (excluding Ca, Na and K) were normalised to 13 (Tab. 1). The nomenclature employed follows LEAKE (1978a and b). Amphiboles from the various textural modes are plotted in Fig. 4b.

Those amphiboles which are found with vermicular intergrowths of quartz/feldspar (Fig. 2b) and in apparent equilibrium with the garnet-omphacite eclogite assemblage are invariably pargasitic in composition. The more abundant and often larger pegmatoid-related poikiloblastic amphiboles replacing the pyroxenes and enclosing the garnet zoisite/clinozoisite (Fig. 2c) range from pargasite towards the edenite or magnesio-hornblende compositions (Fig. 4b). Occasionally the poikiloblastic amphiboles may be zoned within this compositional range and it is not uncommon to find more than one variety of amphibole in the same section. Symplectic pyroxene-feldspar (Fig. 2d) intergrowths are also found as inclusions in the pegmatoid related amphiboles and they are often surrounded and separated from the host amphibole by feldspar rims. Garnets may be rimmed by pargasitic to magnesio-hornblende amphiboles with qtz or plag intergrowths respectively (Figs. 2e and 2f) which may also enclose the pyroxene symplectites or appear to overgrow them (Fig. 2e). In some strongly sheared and retrograded zones bordering or cutting through the eclogites actinolitic amphiboles may be found replacing or overgrowing the earlier pargasitic varieties.

4.4. PHENGITE

In the Gertrusk and Kupplerbrunn eclogites phengites which are undoubtedly part of the ec-

Tab. 1 Garnet, pyroxene and amphibole analyses from the Saualpe eclogites.

Sample no.	GARNETS					PYROXENE					AMPHIBOLES				
Element oxide %	B198	GK244	K25	$Gb3^R$	$Gb3^C$	GK244	$GK244^S$	K25	$K25^S$	Gb3	GK244	K25	Gb3	J194	
SiO_2	39.35	38.56	40.12	39.59	39.46	54.09	52.36	52.94	52.82	54.20	41.66	44.51	46.83	42.9	47.05
TiO_2	-	0.12	0.16	0.03	-	0.122	0.176	0.121	0.34	0.08	0.16	0.30	o.52	0.80	0.46
Al_2O_3	22.21	21.30	21.89	21.70	21.39	9.21	4.64	9.49	6.19	10.42	14.82	16.23	13.73	13.30	15.21
FeO_T	23.37	23.56	17.98	20.14	20.38	6.18	7.34	3.28	3.94	3.93	15.95	9.70	7.58	15.99	7.39
MnO	0.42	0.40	0.24	0.27	0.39	-	-	0.06	0.01	-	0.14	0.11	-	-	-
MgO	7.27	5.63	11.68	8.65	8.72	8.67	10.95	9.92	12.33	9.997	10.08	12.10	14.51	10.30	14.56
CaO	8.70	9:9	7.35	8.02	9.45	15.68	19.94	16.13	21.04	16.23	11.25	10.01	10.19	10.70	9.55
Na_2O	0.52	0.32	0.12	0.25	0.06	5.56	2.78	5.28	3.05	5.31	2.81	4.21	3.63	3.20	2.85
K_2	-	-	-	0.08	-	0.00	-	-	0.08	-	1.02	0.25	0.25	0.74	0.02
TOTAL	101.84	99.79	99.45	98.73	99.85	99.512	98.186	97.22	99.80	100.17	97.89	97.42	97.24	97.93	97.27

R = Rim, C = Core, S = Symplectic pyroxene

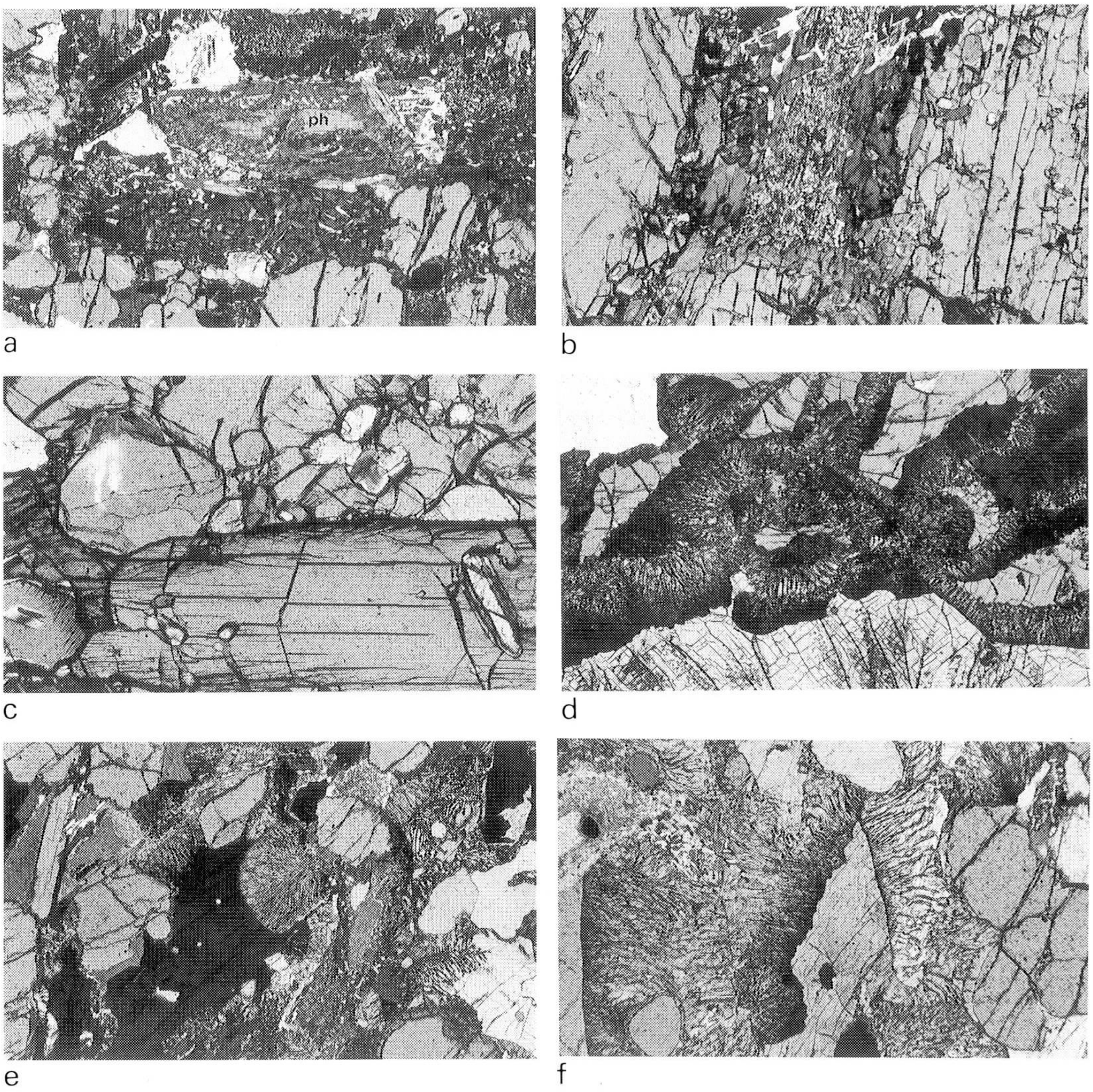


Fig. 5

a. Biotite-albite replacing phengite (ph). Note dark amphibole rims on symplectites, top centre. Length 3 mm.
b. Biotite intergrown with amphibole-feldspar on rim of garnet which also overgrows central symplectite. Length 3 mm.
c. Large kyanite appears to overgrow eclogite assemblage. Length of plate 3 mm.
d. Interlocking lobate symplectites replacing omphacites. Darker areas are finer grained margins of symplectites. Length 3 mm.
e. Mica rich eclogite with dendritic albite in omphacite, bottom left. Phengites being replaced by bi + ab and garnets are rimmed by amphibole. Length 3 mm.
f. Coarse-grained symplectic pyroxene in optical continuity with parent omphacite. Length 3 mm.

logite association are analysed here; micas which may be belong to pegmatoid alteration are not included. In the Kupplerbrunn eclogites the phengites are typically found in the same rocks as those with kyanite. Except where they are pinned between two pyroxene grains most of these micas are surrounded by biotite-albite intergrowths which tend to be coarse grained on the rim and decrease in grain size towards the core of the phengite (Fig. 5a). These reaction rims are commonly found where the mica is in close proximity to amphireaction relations are clear, the breakdown of micas, the pyroxene-feldspar symplectites and the amphibole-quartz overgrowths appear to have occurred at the same time. Mica analyses (Tab. 2) were calculated on the basis of 11 oxygens.

4.5. BIOTITE

Biotite is invariably found in association with plagioclase in reaction rims around phengites or as intergrowths with amphibole-quartz surrounding garnets (Fig. 5b).

4.6. FELDSPARS

In all eclogites the feldspars are varieties of plagioclase found associated with diopsidic pyroxenes, pargasitic to magnesio-hornblende amphiboles and biotite in reaction zones between omphacites and garnets. The composition of the plagioclase varies (Tab. 2) with its association so that where it is intergrown with pyroxene (Jd38) in the coarse grained symplectites or with biotite around the phengites it is usually albitic (An 16 max.). In the finer grained symplectites the An contents of the feldspars are around 24–25 (the pyroxenes are ca. Jd19). When it occurs with the poikiloblastic amphibole compositions of An 74–An 82 are not unusual. These compositional changes are used below to estimate the retrograde PT path of the eclogite assemblages.

4.7. EPIDOTES

The epidote group of minerals are common in the eclogites. Where they form part of the prograde eclogite assemblage the epidotes have a high zoisite content (up to 92%). Epidotes enclosed in the poikiloblastic amphiboles or forming part of a retrograde reaction are more iron rich and often zoned (Fig. 2d) usually with higher Ca rim compositions.

4.8. OTHER PHASES

In the Kupplerbrunn and Kirchberg bodies kyanite is found intergrown with the omphacites (Fig. 5c) or else in zoisite-quartz segregations lying in the dominant foliation. Rutiles are found in most eclogites usually as small rounded interstitial grains but very occasionally as lines of inclusions in omphacites or garnets. Where the eclogite has a strong greenschist facies overprint the rutiles are frequently overgrown by titanite (sphene). Apatite and zircon are only sparsely distributed throughout the eclogites.

Tab. 2 Phengite, biotite, feldspar and epidote analyses from the Saualpe eclogites.

Sample no.	PHENGITES			BIOTITES		FELDSPAR			EPIDOTES			
Element	J198	J198	Gk244	Gk244^S	Gk248^S	Gk244	Gk248^{PS}	Gk224^{BS}	Gk125	Gb3	K142	J194
SiO_2	48.53	50.30	50.75	37.89	38.93	62.88	65.70	65.12	39.99	38.97	38.91	38.9
TiO_2	0.095	0.72	1.03	2.09	3.05	0.10	-	0.11	0.10	-	-	0.13
A_2O_3	29.92	31.03	28.48	20.34	18.39	20.51	22.41	22.99	31.97	31.81	31.02	27.80
FeO_T	1.70	1.83	2.48	13.76	16.53	0.73	0.1	0.17	1.46	2.09	1.85	8.56
MnO	-	-	-	0.13	0.03	0.10	-	0.10	-	0.20	0.10	-
MgO	2.48	2.64	3.49	12.51	11.01	1.12	-	-	-	0.01	0.15	0.40
CaO	-	-	0.13	0.05	0.19	5.16	3.51	4.32	24.32	23.8	24.76	20.70
Na_2	0.74	1.14	1.12	0.64	0.35	8.44	9.59	8.68	-	-	-	-
K_2O	9.53	10.10	10.05	10.25	9.78	0.19	0.20	0.19	-	-	-	-
TOTAL	93.85	97.76	97.53	97.66	98.28	99.23	101.51	101.68	97.84	96.88	96.79	99.49

S = Symplectic biotite PS = Pyroxene symplectite BS = Biotite symplectite

4.9. SYMPLECTITES

In common with many other eclogites from gneissic terrains those of the Saualpe often exhibit symplectic intergrowths between adjacent pyroxenes. The symplectites display a wide range of forms and compositions (WEISSENBACH, 1975) but, in the simplest case, these may be restricted to narrow (kelyphitic) rims of very fine pyroxene lamellae. More commonly the symplectites develop as interlocking (Fig. 5d) lobes consisting of plagioclase-pyroxene lamellae which in some cases have a dendritic form (Fig. 5e) suggestive of rapid growth. Usually there is a decrease in grain size of the lamellae from the point of nucleation of the lobes. In the early formed coarser grained segment the pyroxene lamellae are in optical continuity with the parent omphacite and compositionally identical (Fig. 5f). The feldspar lamellae are fewer and appear as exsolved strings of albite. As the grain size of the symplectite decreases feldspar and pyroxene appear in equal proportions and compositions change to ca. Jd_{19} and An_{25}. These are finally rimmed by even finer symplectites with the same mineralogy but resolvable only with the aid of the scanning electron microscope. Outward grain coarsening is not observed in any of the symplectites even where they are overgrown by the later poikiloblastic amphiboles. The pattern of decreasing grain size (and changing compositions) is consistent with simultaneously falling pressures and temperatures (VAN ROERMUND and BOLAND, 1983) during the eclogite alteration. If a second eclogite (Cretaceous) event had overprinted these rocks, as argued by FRANK (1987), grain coarsening and increasing Jd contents of the symplectite margins would be expected. Equally some sign of prograde reaction relicts affecting the Hercynian pegmatoid-related amphiboles would be expected were they enclose pyroxene-plagioclase symplectites or the garnets. These features are nowhere observed and the evidence, taken together, does not support Frank's (opp cit) interpretation.

5. Mineral-fabric relations

In the unaltered eclogites, regardless of mineral abundances, granoblastic and lineated textures are frequently found in alternating layers. The junctions between the two textural types are usually sharp. The lineated fabric implies synkinematic crystallization whilst the granoblastic fabric suggests static growth. The two contrasting modes of crystallization can be reconciled in a shearing deformation where movement is confined to specific horizons rather than affecting the whole rock package. In the lineated bands imposed, synkinematic strain effects in the component grains would be rapidly removed because of the high ambient temperatures. In the bands not being subjected to shear strain phases would effectively continue to adjust their grain boundaries toward lower energy polygonal (granoblastic) configurations.

Because these rocks are so poorly exposed and dismembered the relationship of these fabrics to any large scale structures is indeterminate. All that can be said is that they indicate heterogenously distributed shearing during the formation of the eclogite assemblages.

The extensive preservation, even in the most strongly lineated eclogites, of the symplectites and the phengite decomposition textures demonstrates clearly that their development postdates the above shearing deformation and that these rocks have not suffered any subsequent homogeneous bulk rock deformation.

6. Rock chemistry

Rock analyses of the Saualpe eclogites have been reported by several previous authors (MOTTANA et al., 1968; LODEMANN, 1970; RICHTER, 1973 and MILLER et al., 1988). The tholeiitic affinities of the eclogite protoliths has been firmly established but until MILLER et al.'s (1988) recent work no attempt had been made to assign the protoliths to a plate tectonic setting.

MILLER et al. (1988) present analyses from a wide range of eclogite bodies in the Saualpe and the adjacent Koralpe. In common with many other high pressure metamorphic sequences the Saualpe eclogites group broadly into those with and those without kyanite. These mineralogical differences correspond generally to low Ti, high Al_2O_3, MgO and CaO in the former case and high Ti and FeO in the latter. MILLER et al. (1988) have concluded that the two types originated from different protoliths. The high Ti eclogites representing original mid-ocean ridge basaltic liquid composi-

Tab. 3 Selected major and trace element analyses from the Saualpe eclogites.

Sample element	GRÜNBURGER					KUPPLERBRUNN				JURKIKOGEL				GERTRUSK			
wt %	Gb1	Gb2	Gb3	Gb5	Gb6	K19	K20	K26	K146	J190	J191	J192	J193	GK250	GK251	GK253	GK254
SiO_2	49.74	53.01	51.29	49.38	49.62	51.02	49.51	52.79	50.26	53.03	49.52	48.60	49.97	47.89	47.14	46.89	47.8
TiO_2	0.54	0.80	1.67	0.42	1.59	0.34	0.43	0.49	0.64	1.02	1.48	1.39	1.45	2.07	2.14	3.18	2.06
Al_2O_3	18.64	15.53	15.63	19.28	14.74	14.04	16.97	15.98	16.87	15.66	14.69	15.30	15.33	15.08	14.44	15.30	14.02
Fe_2O_3	6.77	8.26	10.90	5.78	13.25	9.30	7.10	7.03	5.95	10.90	11.50	11.26	11.14	14.32	13.64	17.6	13.3
MnO	0.11	0.13	0.17	0.10	0.28	0.12	0.10	0.12	0.10	0.15	0.18	0.16	0.17	0.24	0.23	0.29	0.27
MgO	8.18	8.25	7.69	8.09	8.66	12.68	9.83	8.96	10.14	8.65	8.29	8.60	8.28	6.90	6.21	6.10	6.36
CaO	14.25	13.09	12.21	14.04	10.74	9.66	13.65	13.26	13.03	10.78	12.64	12.88	12.42	12.90	13.28	10.98	13.29
Na_2O	2.0	2.26	1.94	2.82	2.43	2.06	2.71	2.05	3.08	1.43	2.74	3.0	2.59	2.72	3.16	1.88	3.41
K_2O	0.05	-	0.01	0.20	0.01	0.23	0.02	0.05	0.08	-	0,02	0.08	0.01	0.03	0.11	0.01	0.14
P_2O_5	0.03	0.06	0.13	0.02	0.10	-	-	0.03	0.01	0.04	0.10	0.04	0.10	0.13	0.18	0.20	0.14
PPM																	
Rb	4	1	2	8	1	5	1	2	3	1	3	2	1	0	3	0	4
Sr	146	146	145	190	29	18	82	96	54	57	157	163	120	136	178	23	166
Y	13	24	38	13	40	7	11	13	10	31	34	38	38	52	50	75	48
Zr	27	51	91	33	100	21	14	29	41	57	80	99	90	131	124	209	126
Pb	6	6	11	17	2	4	1	5	5	1	3	3	5	4	10	1	9
Th	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0
Nb	2	3	5	2	4	2	2	2	4	3	4	4	4	4	4	6	4
Zn	27	45	52	49	122	100	65	44	68	35	65	66	66	138	146	156	141
Ni	112	126	62	124	73	214	130	130	166	82	97	100	96	77	71	55	79
Cr	384	349	230	1433	201	566	785	374	856	278	288	249	262	202	341	72	283
V	175	252	316	170	365	189	222	183	168	239	356	341	336	378	401	411	403
Ba	25	12	24	41	25	4	1	3	19	17	34	14	26	18	23	43	36
LoI	0.85	1.29	1.33	0.60	0.49	2.59	-	0.97	0.47	1.33	-	0.86	0.44	0.56	-	0.36	0.27

tions whilst the low Ti, kyanite bearing eclogites were more likely to have been mafic cumulates.

Here we concentrate on the systematic analysis of the larger eclogite bodies in the upper part of the Crystalline Complex nappe. A total of 74 samples have been analysed (see Tab. 3 for representatives) from the Gertrusk, Jurkikogel/Beilstein complex, Grünburger Bach, Kupplerbrunn and Kirchberg bodies (Fig. 1).

6.1. MAJOR ELEMENTS

The absolute major element abundances of virtually all rocks analysed fall within the basalt-gabbro compositional ranges. In terms of their Ti v Fe/Mg contents all eclogite bodies except that of Kupplerbrunn (kyanite bearing) exhibit a tholeiitic FeO-TiO_2 enrichment trend (Fig. 6a). On the AFM diagram (Fig. 6b) the Gertrusk eclogite appears to have originated from the most highly evolved protolith, the Jurkikogel/Beilstein examples are less evolved but more so than Kirchberg body. The Grünburger Bach eclogite exhibits the widest FM range and probably reflects the originally fractionated character of the protolith. The Kupplerbrunn eclogites have the least evolved character with low FeO, TiO_2, P_2O_5 and Zr concentrations. One of the Grünburger samples consistently plots with the Kupplerbrunn examples.

Decreasing Mg-numbers from 66–79 for Kupplerbrunn/Kirchberg, 53–71 for Grünburger, 48–53 for Jurkikogel/Beilstein and 34–50 for Gertrusk may well reflect derivation of the protoliths by increasing fractional crystallization from a common magma source.

6.2. TRACE ELEMENTS

From the trace element chemistry of the Saualpe eclogites Miller et al. (1988) have shown that most of the high-Ti eclogites resemble normal mid-ocean ridge basalts (N-MORB). However, as might be expected from consideration of the major elements, trace element abundances in some samples deviate markedly from the average N-MORB composition.

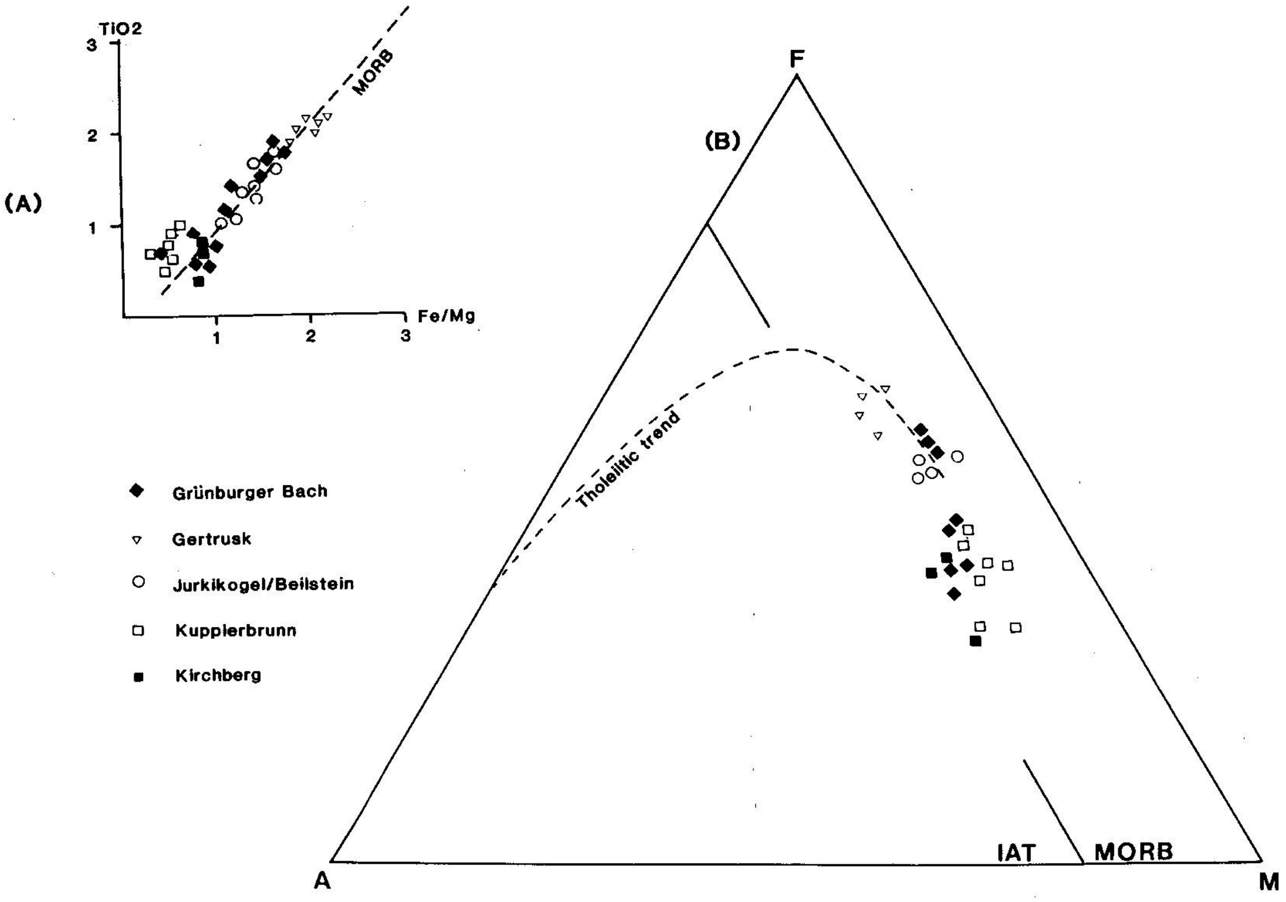


Fig. 6 (A) Fe/Mg v TiO_2 and (B) AFM diagrams showing tholeiitic affinities of the Saualpe eclogites.

Transition element abundances such as Sc, Cr, Ni and V are the lowest in the Gertrusk body, greater in the Jurkikogel and most diverse in the Grünburger eclogites. The lower than N-MORB values if significant suggest a slightly more fractionated character for the Saualpe protoliths which appear to have been pyroxene dominated. The survival of the V indicates that this fractionation involved little or no Fe-Ti oxide phases. The higher than N-MORB Ni-Cr values for the Kupplerbrunn eclogites (low-Ti) is consistent with olivine crystallization in the protolith, a feature also suggested by the high Mg-numbers for these rocks (cf. MILLER et al., 1988).

The use, often uncritically, of immobile element discrimination diagrams to assign igneous precursors to tectonic settings has become common practice. In recent studies a more cautious application of immobile element tectonic discrimination diagrams is being advocated, (PIBOULE and BRIAND, 1985; WEAVER and JOHNSON 1987). To illustrate the point, all the Saualpe high-Ti eclogites, when plotted in the Nb-Zr-Y discrimination diagram (Fig. 7a) after MESCHEDE (1986), cluster very distinctly in the N-MORB field suggesting that these incompatible element ratios have remained unchanged through the metamorphism and deformation. The low-Ti eclogites on the other hand plot partially outside of the basalt liquid field. However if the various eclogites are plotted on discrimination diagrams relying partially or wholly on absolute element abundances the grouping becomes less distinct and may indicate some degree of mobility of the so-called immobile elements during hydrothermal/metamorphic alteration of the protoliths. For example on the Zr/Y v Zr diagram (Fig. 7b, after PEARCE and NORRY, 1979) only

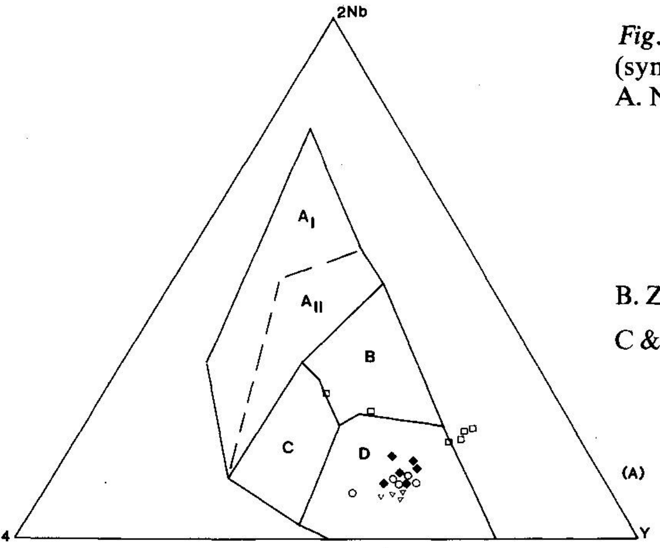


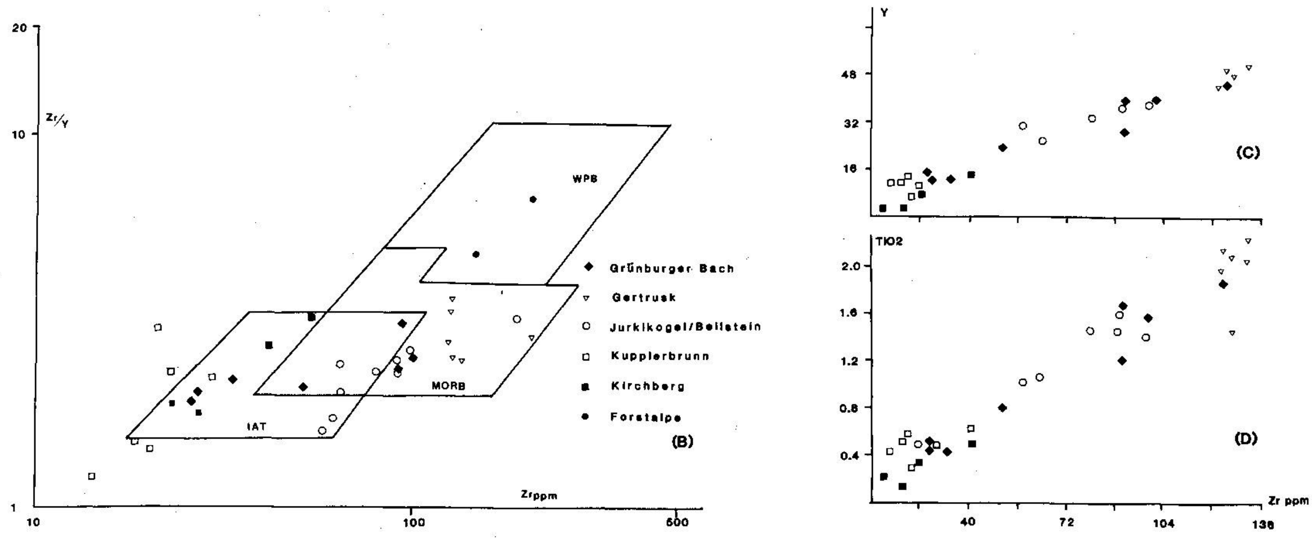
Fig. 7 Trace element discrimination diagrams, (symbols as in Fig. 6).

A. Nb-Zr-Y after Meschede, 1986.

AI & AII = within plate alkali basalts.
C & AII = within plate tholeiites.
B = P-type MORB
C & D = volcanic arc basalts
D = N-MORB

B. Zr/Y v Zr diagram after PIERCE and NORRY, 1979

C & D. Y and TiO_2 v Zr diagrams.



the high-Ti eclogites of Gertrusk lie exclusively in the MORB field, Jurkikogel / Beilstein samples span the MORB-IAT fields and the Grünburger samples again show the greatest variation. Analyses of samples from the thinner highly sheared eclogite sheets below the Forstalpe plot in the WPB field. In contrast the kyanite eclogites of Kupplerbrunn and Kirchberg fall predominantly outside the field of basalt liquid compositions. Nevertheless, the very strong positive correlation of Zr v Y and Ti v Zr (Figs. 7c and 7d) within the Saualpe eclogites suggest that both the low and high-Ti varieties were derived from the same geochemical source. The slope of the line in each case approximates the cpx-plag-ol crystallization vectors suggesting that these were the dominant phases and the source area was therefore subject to low pressure fractionation.

In the N-MORB normalised multi-element plots (Fig. 8a–8d) it is apparent that the eclogites do not show the fit expected from some of the above diagrams. The large ion lithophile (LIL) elements for example have been subjected to significant mobility whilst the high field strength (HFS) elements show more uniform but depleted distributions.

Allowing for detection errors, Rb, in all but a few of the Gertrusk eclogites, is enriched relative to N-MORB. Ba is similarly enriched but not sufficiently so to suggest any affinity with island arc tholeiites (IAT); IAT's should also show strong Nb depletion, a feature not evident in any of the eclogites.

Whilst Th abundances are low and close to detection limits in most samples there does appear to be a correlation between Th, Ta and Ti abundances in most rocks. The observed variations in Ta and Ti contents can to a degree be accounted for by their partitioning into minerals such as rutile, sphene (titanite) or ilmenite during magmatic and metamorphic crystallization. If Ta is presumed to have been immobile throughout then it would apear that even within one eclogite body different liquid compositions are represented.

K and Sr in all the eclogites differ significantly from N-MORB. The micas and amphiboles account for most of the K although some is found in the feldspars intergrown with the

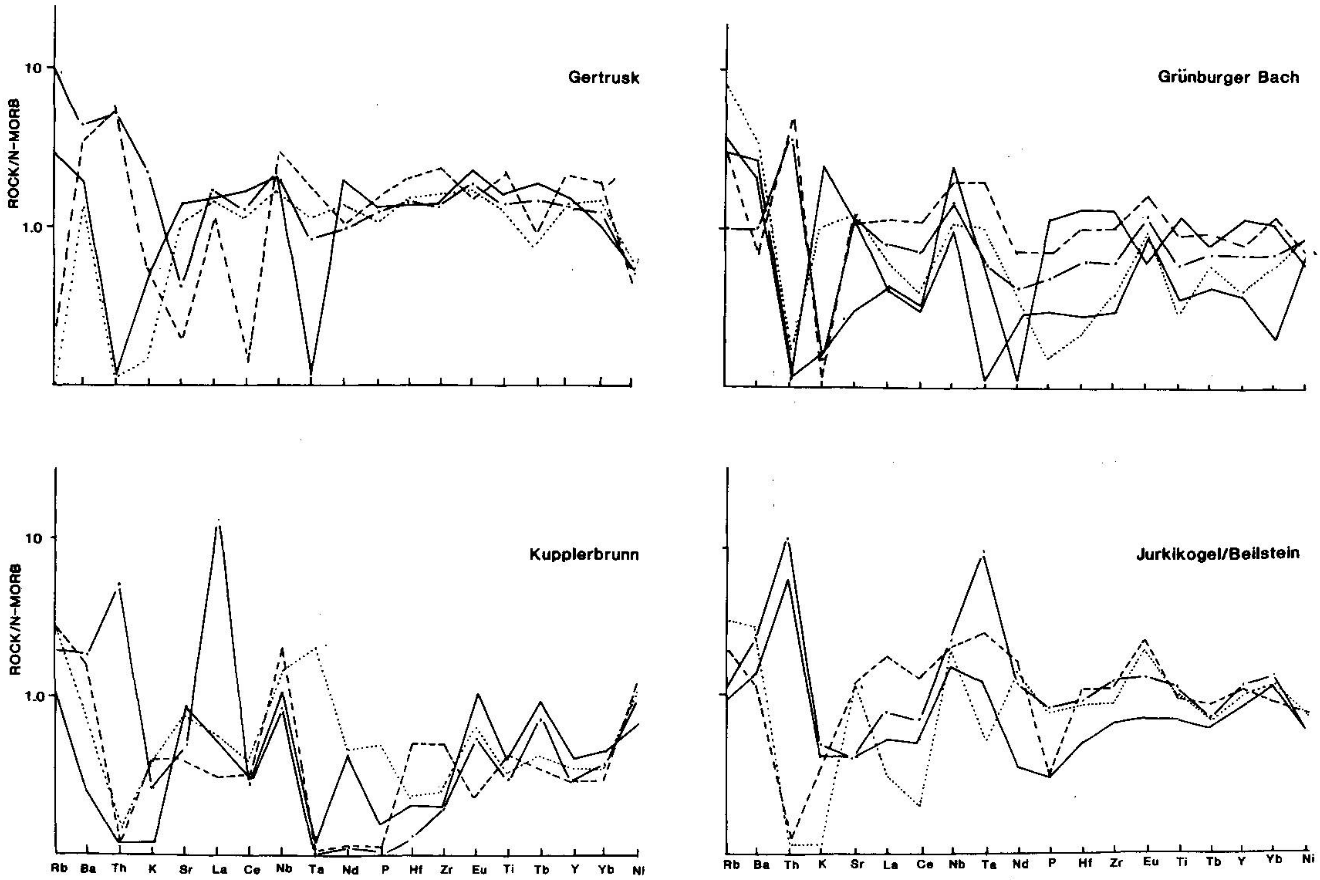


Fig. 8 N-MORB normalised multielement plots of the Saualpe eclogites. (after SAUNDERS and TARNEY, 1985).

amphiboles. Sr and Eu follow each other probably reflecting variations in the relative role of feldspar crystallization in the protoliths.

Except in the immediate vicinity of the contacts variations in eclogite LIL abundances are not connected with the injection of the pegmatoids when, with increased fluid phase activity, these elements might be expected to have been mobile.

The HFS elements in all but the Kupplerbrunn eclogites exhibit more uniform evolved protoliths. The Gertrusk eclogites, which represent the most evolved protoliths, have HFS abundances almost identical to N-MORB. The Jurkikogel / Beilstein complex has only slightly lower abundances whereas the Grünburger eclogites range from near N-MORB to more depleted (0.3–0.5 N-MORB) compositions. The Kupplerbrunn HFS element abundances are significantly more depleted but the overall pattern has a positive slope.

The transitional character, between MORB and IAT on the Zr / Y v Zr diagram, of many of the eclogites is also apparent in the multielement plots. The HFS element abundance patterns compare favourably with those of some back arc basin basalts reported by SAUNDERS and TARNEY (1985).

6.3. REE CHARACTERISTICS

The chondrite-normalised REE values of the Saualpe eclogites plotted in Fig. 9 are remarkably uniform in their overall profiles. Most profiles show slight LREE depletion relative to the HREE. As might be expected the more evolved Gertrusk and Jurkikogel / Beilstein samples show greatest REE abundances relative to Chondrite whilst those of Kupplerbrunn are significantly lower. The Grünburger eclogites fall into two distinct groups but have generally flatter profiles than those of the other bodies. Samples from the upper and lower exposed parts of the Grünburger body are more depleted whilst those from the internal part are relatively enriched. One sample from the highly sheared rim of the eclogites shows marked LREE depletion (x6 chondrite) and HREE enrichment (x25 chondrite). These differences are not immediately apparent in the multielement plots described above. When all the profiles are plotted together they define a continous and parallel sequence of enrichment which could suggest derivation from the same but fractionating source of N-MORB character.

6.4. Sm/Nd ISOTOPE SYSTEMATICS

In this section the garnet-whole rock Sm / Nd isotopic age determinations reported by MANBY et al. (1987) are re-examined and we emphasise the preliminary nature of the analyses. The main reason for the uncertainty of the age data obtained is the low Sm / Nd levels in the rocks analysed. The low levels, close to detection limits, are primarily a function of the parent liquid composition from which the eclogites were derived.

The fact that only Jurkikogel sample gave sufficient separation of the garnet-whole rock Sm / Nd ratios to define the 693 ± 39 Ma (Fig. 10a) isochron may be due to a combination of other factors. Differences in the Sm / Nd diffusion rates and blocking temperatures of the primary igneous phases combined with the textural and mineralogical transformation of the protoliths during synkinematic eclogitization may, in some cases, have resulted in some degree of isotopic disequilibrium. The later isothermal decompression, evidenced by the symplectite textures, may also have selectively disturbed the pyroxene isotopic ratios.

Those eclogites which have been amphibolitised during the Hercynian event often contain garnets which have chemistries and textures indicative of more than one stage of growth (see below). The new garnet would preferentially partition the Sm / Nd released by the pyroxene breakdown and consequently give a mixed age. It would also explain why in most cases the garnets appear to contain virtually all the Sm / Nd and hence the proximity of the garnet and whole rock ratios. Although the garnet and whole rock ratios from the other samples show little separation all plot close to the Jurkikogel whole rock value and allow an errorchron of 716 ± 30 Ma to be drawn (Fig. 10a). Any subsequent (post-Hercynian pegmatoid injection) eclogite event, such as that proposed by FRANK (1987), would have completely reset the Sm / Nd ratios and should have manifested itself in our analyses.

If the calculated initial ^{143}Nd / ^{144}Nd ratios are plotted against time (Fig. 10b) the slopes of the lines are close to the Depleted Mantle Uni-

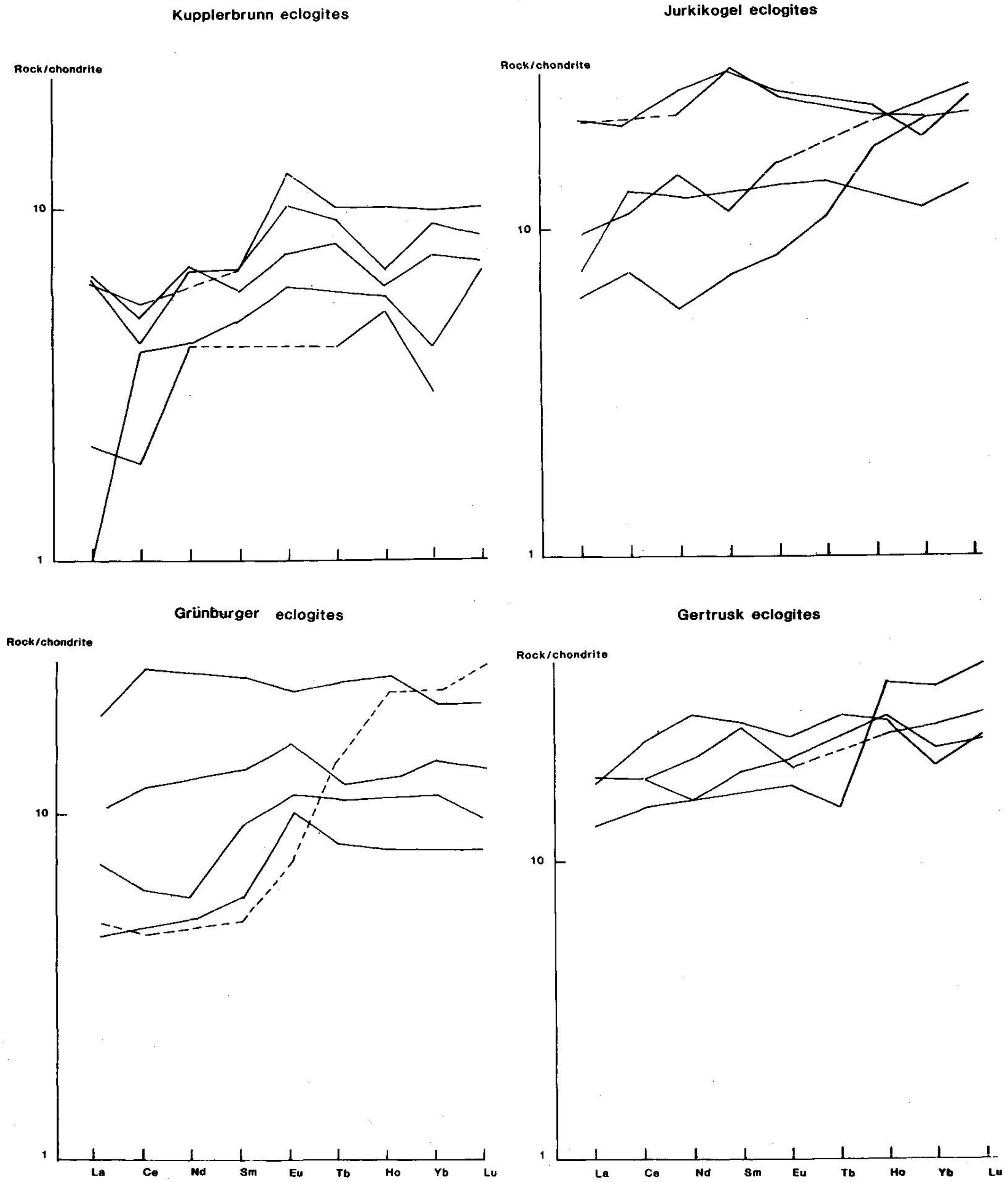


Fig. 9 REE element plots of the Saualpe eclogites.

form Reservoir (DMUR) evolutionary line and intersect it at time equivalents in excess of 800 Ma; when the eclogite protoliths were derived from the DMUR. The calculated εNd(t) values of +5, +5.6 and +6.1 (cf MILLER et al., 1988, who quote +7) are within the range of those for modern ocean island to island arc mantle sources (MCCULLOCH et al., 1981) rather than MORB. This may be, in part, consistent with the trace element data which indicates a similar transitional origin for some of the eclogite protoliths. It may indicate however, that rather evolving through a two stage process with DMUR differentiating from CHUR (CHondrite Uniform Reservoir) at ca. 2000 Ma, the mantle has evolved through a more contin-

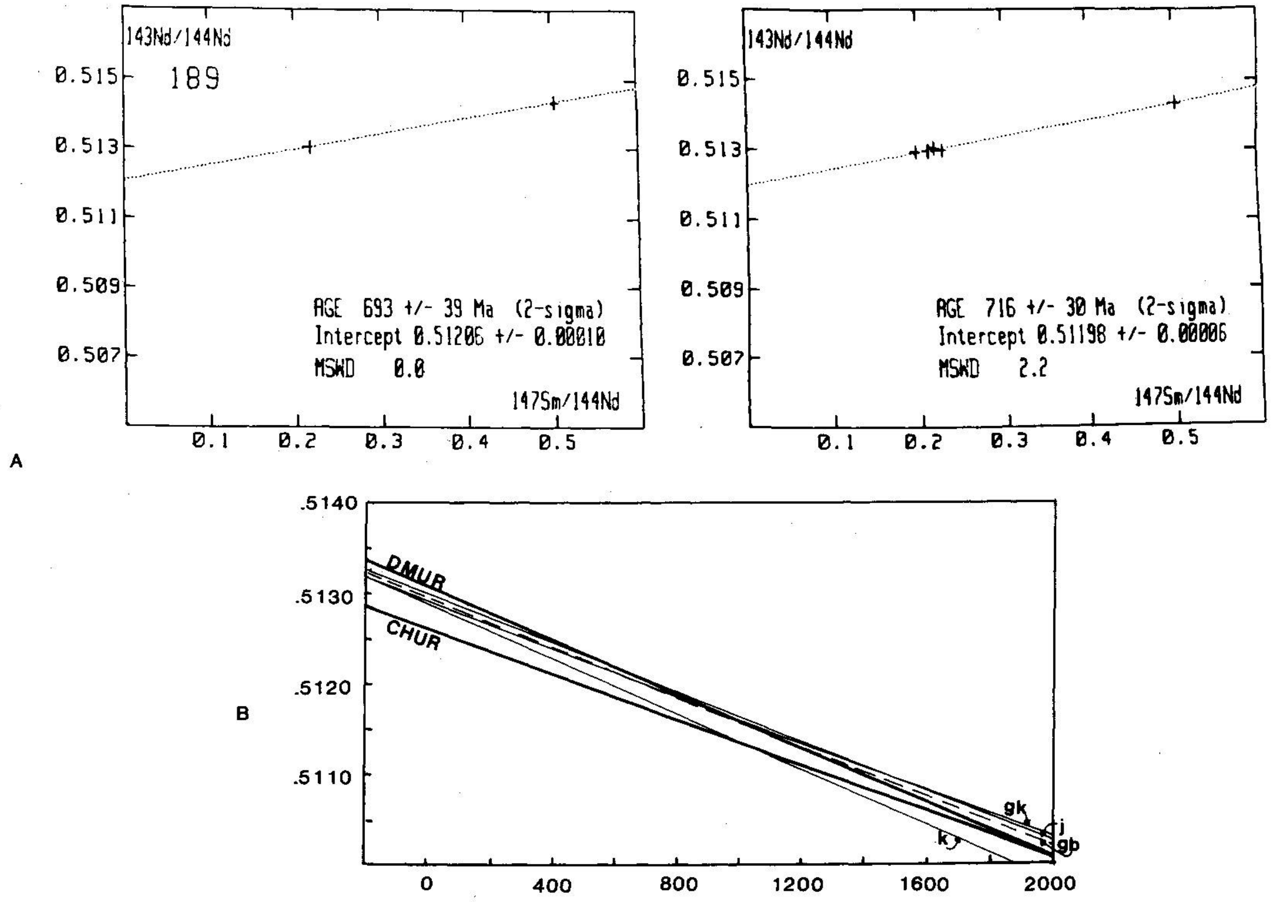


Fig. 10

A. Sm/Nd isochron for Jurkikogel (189) gt-wr sample and the errorchron for added data from Gertrusk, Grünburger and Kupplerbrunn.

B. Initial $^{143}Nd/^{144}Nd$ v Time: gb = Grünburger, Gk = Gertrusk, j = Jurkikogel, k = Kupplerbrunn, DMUR = Depleted Mantle Uniform Reservoir, CHUR = Chondrite Uniform Reservoir.

uous path or alternatively, it may indicate a heterogeneous mantle source for the protoliths.

The positive εNd(t) values and LREE depleted profiles of the eclogites would also support the contention that the protoliths were emplaced with little or no contamination by older crustal components which might give a falsely high Sm/Nd age. It is not possible to decide from these data whether the eclogite protoliths were emplaced in an oceanic or a back arc, marginal basin setting.

Despite the statistical uncertainty of the Sm/Nd data the Jurkikogel isochron at least gives the first indication that the eclogites and consequently the Crystalline Complex could be considerably older than hitherto suspected. The combined information, from the calculated $^{143}Nd/^{144}Nd$ initial ratios, the positive εNd(t) values and the REE patterns, we suggest, is not inconsistent with the ca. 700 Ma obtained. Further analyses (garnet-whole rock Sm/Nd and zircon) of the least altered and compositionally more evolved (higher REE contents) eclogites is currently in progress to test this preliminary age determination. If the ca. 700 Ma is substantiated then presently held evolutionary models for at least this segment of the Austro-Alpine System will need some revision. Here an evolutionary path for the eclogites is tentatively proposed which assumes the 700 Ma age to be valid.

The presence in some of the enclosing gneisses of kyanite after andalusite (MEIXNER, 1975) might suggest that they were already, or in the process of being, metamorphosed under LP/HT conditions at the time of intrusion of the eclogite protoliths. The replacement of the andalusite by the kyanite would not be at variance with the eclogite forming event. It seems likely therefore that the enclosing gneisses are significantly older than the eclogite protoliths and may be Late Proterozoic in age.

7. Early eclogite PTt history

Except for the gabbro-eclogite transformation described by HERITSCH (1973) from the Koralpe other eclogites from this region, particularly those from the Saualpe record only retrograde assemblages.

Despite the inclusion and colour zoning in some garnets most are found to be chemically homogeneous and indicate volume diffusion which may have influenced their compositions. Assuming volume diffusion is only effective above 650 °C (TRACY, 1982) temperature estimates based on Fe-Mg exchange between coexisting gn-cpx pairs might be expected to give values with this as a minimum. This approximation is confirmed by the application of the ELLIS and GREEN (1979) geothermometer to gt + cpx pairs presumed to be in equilibrium by their lack of reaction relations. Temperature gradients calculated for a range of pressures are plotted in Fig. 11. Estimates of pressure from overburden are, because of the complex tectonics, out of the question but an approximation can be arrived at from the jd content of the pyroxenes (Fig. 11). The average jd content of the main pyroxene porphyroblasts is X_{jd} = 0.4 suggesting that they have normal C2/c structures and indicating pressures at the time of crystallization were in the 12–17 kb range. From the intersection of the P and T fields thus defined and the textural features described above it would appear that the protoliths were transformed to eclogites under conditions in the 14 kb/650 °C to 18 kb/840 °C range.

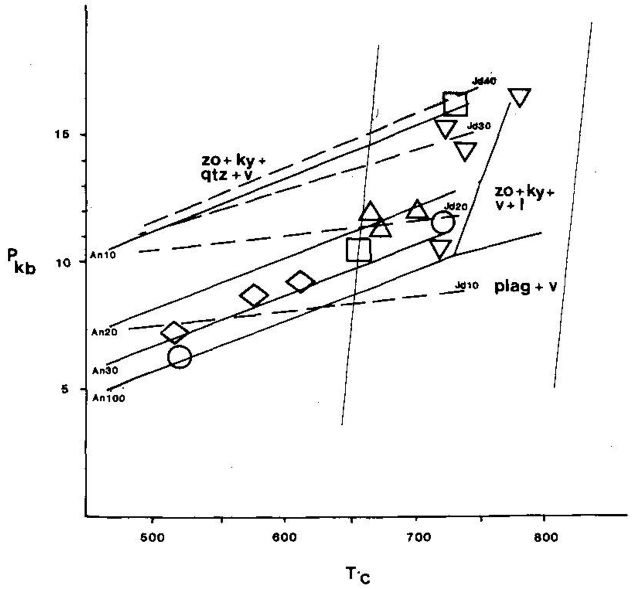


Fig. 11 Plot of symplectite pyroxene and feldspar compositions. Jd isopleths after HOLLAND (1983). Feldspar stabilites after GOLDSMITHS (1982). PT gradients calculated from ELLIS and GREEN geothermometer (1979).
Different symplectites from the same sample have the same symbol except the upside-down triangles which are approximations of PT positions for amphibole/feldspar intergrowths.

Temperature estimates using the garnet-early amphibole pairs have not been attempted because many amphiboles are associated with exsolved quartz or plagioclase which may invalidate the calculated values.

The abundant kelyphitic and symplectic textures in the eclogites are thought to signal decompression of the eclogites. As noted above there is a systematic relationship between the grain size of the pyroxene/plagioclase lamellae and their respective compositions. By combining the jd + qtz + ab equilibrium of HOLLAND (1983) with the stability of plagioclase determined by GOLDSMITH (1982) it is possible to place the various symplectite associations in fairly well constrained PT regions (Fig. 11). If the path so defined is at all realistic then the symplectites suggest the eclogites were subjected to an initial isothermal decompression (down to 10 kb?) giving way to more gradually declining pressures and temperatures across the eclogite-amphibolite facies transition.

GOLDSMITH'S (1982) plagioclase stability curves can also be applied to the breakdown of phengite to albite (An_{16}) + biotite and they give PT estimates in the same range as those from the early pyroxene-plagioclase symplectites, a feature also suggested by their textural relations.

We would conclude therefore that the cpx-plag symplectites, bi-plag breakdown of phengite, amph-plag overgrowths on garnets and exsolution of quartz from the early amphiboles are products of the eclogite decompression under elevated temperatures (>500 °C).

For the most part homogenisation of garnets and the decompression reactions took place above the blocking temperature (650 °C) for the Sm/Nd system and the preliminary age determination of ca. 700 Ma reported here dates only the later stages of these retrograde reactions. The preservation of the often intricate symplectite textures throughout large parts of the eclogite bodies indicates that they have remained unaffected by any post-decompression penetrative deformation.

Given the above retrograde PT path of the eclogites it could be suggested that volatile release during mica and amphibole breakdown reactions gave rise to some anatexis. If this was so then the pargasite-zoisite-quartz-muscovite (rarely kyanite) network pegmatoids might also be expressions of the decompression. However the K/Ar and Rb/Sr age determinations described below point decidedly to a Hercynian age for the origin of the pegmatoids in the country rocks and it is most likely that the eclogite pegmatoids are of the same age. It follows that the stockwerk amphibolitisation and other large pegmatoid related amphiboles engulfing the relict eclogite assemblages (including the symplectites) are also Hercynian in age. In some cases garnets enclosed by the later amphiboles have clearly enlarged although temperature estimates using the GRAHAM and POWELL (1984) gt + hb geothermometer range from 798 to 922 °C are high and suggestive of incomplete equilibration.

The surrounding schists and gneisses frequently contain syntectonic gt + bi assemblages to which various published geothermometers (THOMPSON, 1976; FERRY and SPEAR, 1978; HODGES and SPEAR, 1982; GANGULY and SAXENA, 1984) have been applied. The temperatures calculated in all cases lie within the granulite facies field and are unacceptably high. The excessive temperatures derived for the Saualpe rocks arise from the non-ideality of the Fe-Mg exchange in the biotites which is invariably greater than 0.15 regarded as the limit for thermometry. However temperatures at this time must have been in the 600–700 °C range depending on the P_{H_2O} and confining pressures, to account for the formation on the ab + qtz + mv + zo pegmatites. The disturbance of the Sm/Nd system, as already noted, found for some of the analysed samples must have occured at this time. Pressures are uncertain but metamorphism at the time was a low $\Delta P/\Delta T$ (Abukuma) type.

8. Eclogite/Pegmatoids relations

Cross-cutting the eclogites and the country rocks are a series of variably deformed pegmatoid bodies. Mineralogically the pegmatoids are complex (MEIXNER and CLAR, 1953; MEIXNER, 1975) but quartz, feldspar (albite), muscovite, amphibole and iron poor epidotes are the most common phases. In some cases these pegmatoids are no more than a few centimetres wide, consist largely of quartz, muscovite and feldspar and cut the host rocks at high angles to the dominant foliation. Whilst they appear to be late fissure-fills they nevertheless show internal deformation with strongly kinked mica books. Other pegmatoids have a distinct network character (Fig. 12a) and dilate the eclogite host (Fig. 12b). Amphibole, quartz and epidote occupy the main part of these networks but towards the tips of the individual veins quartz and muscovite tend to dominate. The coarser grained internal parts of the networks show little deformation whereas the tip regions are frequently rotated and the micas are kinked or broken. In some cases trails of garnet and epidote can be traced from the eclogite into the networks with little or no disruption.

Howevermuch the pegmatoids are deformed it is apparent in the field that their emplacement was accompanied by alteration of the host eclogites. Where the pegmatoids cut the eclogites at a high angle and are least deformed alteration, which takes the form of amphibole-quartz/feldspar replacing the garnet-omphacite, develops as a stockwerk effect extending along the foliation for a few centimetres. Similar alteration of the eclogites is seen in association with the network pegmatoids. In some cases alteration is concentrated at vein tips and large poikiloblastic amphiboles, studded with garnet, epidote and quartz, develop. Variably sized amphiboles, often as single crystals (upto 5 cm, Fig. 12c), overgrow the eclogite assemblage and these crystals are commonly seen as thin plates with their long axes parallel to the dominant foliation. This would suggest that fluid infiltration, permitting the growth of the amphiboles, was controlled to a large degree by the pre-existing foliation in the eclogites.

The large poikiloblastic amphiboles linked to the pegmatoid formation overgrow or replace the symplectites and indicate PT conditions were in the amphibolite facies range and, like the symplectites, rarely show any sign of tectonic disruption. The network forms of the pegmatoid veins also suggests deviatoric stresses were minimal at the time of injection; dilation of the eclogites and formation of the veins can be explained by elevation of the fluid phase pressures and partial melting. A full discussion on the origins of the pegmatoids is out-

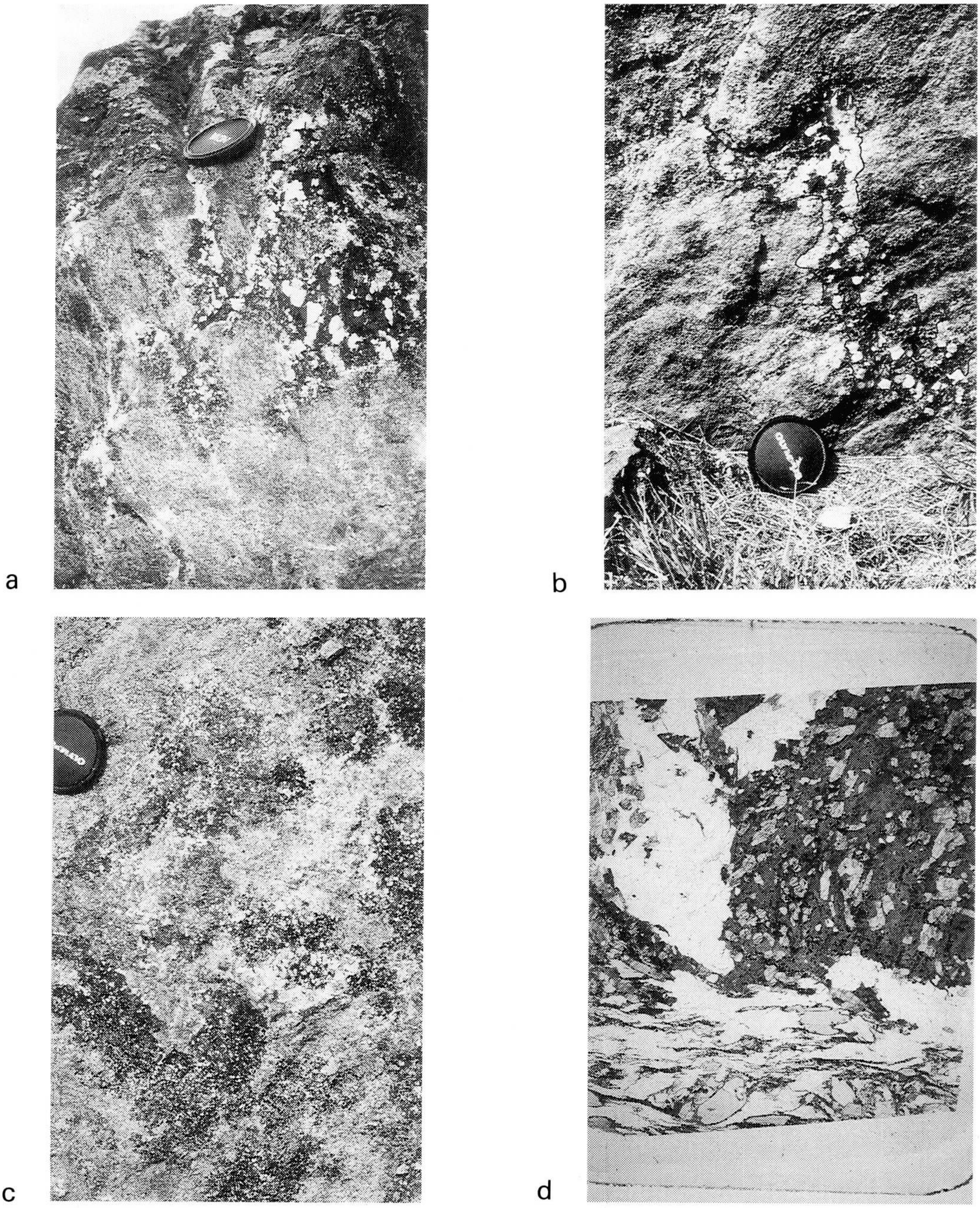


Fig. 12

a. Network veined pegmatoid in Jurkikogel eclogite.

b. Quartz-pargasite pegmatoid in Gertrusk eclogite. This and the previous example are internally undeformed except at tips and marginal zones.

c. Poikiloblastic pargasites related to pegmatoid formation grown along eclogite foliation.

d. Photomicrograph of boudinaged eclogite layer, Gertrusk. Pegmatitic mica quartz / mica is highly deformed and gives Alpine K/Ar age. Plate width is 2 cm.

side the scope of this paper but is being investigated by the authors.

9. Post pegmatoid deformation / metamorphism

Discrete, ductile to brittle deformation zones generating typical greenschist facies assemblages cut both the eclogites and pegmatoids. The retrograde assemblages may pervade the eclogite several cm away from the shear zones without producing any obvious foliation. In these adjacent zones large (1-2 mm) poikiloblastic albites/skeletal biotites, garnets and pargasitic amphiboles (left from the early eclogite decompression event) are replaced by epidote, chlorite, actinolitic amphiboles and rutile is rimmed by titanite (sphene).

Strongly rotated pegmatoids can be observed within the Sandofen eclogite body. The pegmatoids here are lens shaped lying near parallel to the dominant foliation in the eclogites although cross cutting relations can still be discerned. Rotation and deformation of the pegmatoids accompanied the development of ductile-brittle shear surfaces overprinting the mineralogical banding in the eclogite. At this locality large (upto 5-6 cm) muscovites, quartz and epidote comprise the pegmatoids. Despite the degree of rotation the component phases show relatively slight deformation, only the micas are kinked.

Within the Gertrusk body strongly sheared, discontinuous layers of muscovite-quartz wrap around boudinaged pods of the eclogite (Fig. 12d). The coarse grain size of the component muscovites suggests pegmatitic origin but this is by no means certain. In these layers the minerals have been strongly deformed and reduced in grain size.

The pegmatoids within the enclosing schists and gneisses differ in composition to those in the eclogites in that they typically contain abundant tourmaline and no amphibole. Generally the country rock pegmatoids are much larger sheets than those seen in the eclogites but they are very often much more highly sheared and cross-cutting relations are obliterated. The post pegmatoid deformation features described so far were almost certainly produced during the Alpine nappe transport. The recrystallization and neomineralization accompanying this deformation indicates PT conditions were in the greenschist facies range with temperatures probably not in excess of 550 °C, hence the survival of albite + epidote assemblages described above.

Perpendicular to the dominant foliation and cutting the pegmatoids in many of the eclogite bodies is a series of close-spaced, planar, fine (mm scale) parallel vein arrays filled with chlorite / epidote. In thin section the vein arrays appear to have been generated by a crack-seal mechanism. Minerals defining the earlier foliated project into the veins with little displacement. Where these veins are most closely spaced, on a mm scale, pervasive hydration of the eclogite assemblages has occurred. The garnets are heavily fractured and extensively replaced by chlorite, symplectic areas are reduced to optically irresolvable fans, and the earlier amphiboles are rimmed or replaced by actinolite and chlorite. Only the zoisite / clinozoisite aggregates, to large degree, remain unaffected by this hydration. These arrays are the latest recognisable deformation / metamorphism features in the eclogites and represent a loading-triggered dilation response, under conditions of high pore fluid pressures, to the final stages of nappe emplacement. The ambient PT conditions at this stage are not known with any precision but vein mineralogies are consistent with those found in the greenschist facies range.

10. K / Ar, Ar / Ar and Rb / Sr data

Rb / Sr whole rock / mineral and K / Ar dating of the pegmatoids in the country rocks has established beyond doubt that they were injected during a Hercynian amphibolite facies event and that they were subjected to reheating and grain size reduction during Alpine deformation (MORAUF 1981, 1982, 1983; MILLER and FRANK, 1983).

In this study muscovites were separated from the range of the deformed pegmatoids cross-cutting the eclogites and Crystalline Complex rocks (Tab. 4). A pegmatoid, with large (5-6 cm) micas, cutting the 'D1' gneisses of the sequence containing the eclogites (WEISSENBACH, 1978) N of Wolfnitz and showing the least internal deformation yielded a disturbed Hercynian 221 ± 5.4 Ma K / Ar age. The Sandofen pegmatoid gave a 106.12 ± 2.7 Ma age on sections cut from the undeformed cores of the large (5-6 cm) micas whereas the smaller

Tab. 4 K-Ar results for pegmatoid micas, Saualpe.

Sample	%K	Vol Rg 40 Ar (nl/g)	Age +/- 2 sigma (Ma)	Description
WOLFNITZ	8.41	76.96	221.37+/- 5.4	Centre of coarse mica
GRÜNBURGER	8.45	29.37	87.24+/-2.2	Kinked mica
GRÜNBURGER	7.61	27.04	89+/-4.0	Kinked mica
GERTRUSK	8.68	30.84	89.14+/-3.2	Fine mica fraction
GERTRUSK	8.64	30.33	88+/-18	Fine mica fraction
SANDOFEN	6.76	28.72	106.12+/-2.7	Large mica, Kinked
SANDOFEN	7.73	28.74	93+/-4.0	Fine mica fraction
KLIENING MYLONITE	6.23	20.91	84.35+/-2.2	Fine mica fraction

Analyst Chris Rundle

deformed micas gave an age of 93 ± 4.0 Ma. Micas from the highly deformed Gertrusk and the narrow less deformed Grünburger pegmatoid sheets gave ages in the 87 to 89 Ma range. The extent two which the pegmatoid muscovites are reset appears to depend on the size and degree of deformation of the body. Larger bodies are less deformed internally and micas are only partially reset whereas smaller pegmatoids are usually more deformed and consistently yield Alpine ages.

In the pegmatoids quartz invariably exhibits ductile deformation. Micas and feldspars are, in the main, brittly deformed showing kinking and cataclasis although in some instances strain induced recrystallization has occurred. All of these features are consistent with deformation in the greenschist facies PT range which would be sufficient to reset the K/Ar isotopes in the minerals thus affected.

The epidote-albite and chlorite retrograde assemblages in the eclogites, some of which are distinctly foliated, may well have formed at the same time as this deformation-controlled resetting was taking place. They are also indicative of greenschist facies PT conditions.

There is, therefore, a strong possibility that the Alpine (87 ± 9 Ma) K/Ar age obtained by MILLER and FRANK (1983) on amphiboles from the Gertrusk eclogite is simply a resetting age and not, as has been suggested, evidence for a Cretaceous amphibole forming event. Other age determinations published by these authors show a wide range of partial resetting and in some cases clear Ar overpressuring.

The Alpine deformation of the Saualpe eclogites was clearly not pervasive but was restricted to spaced ductile to brittle shear zones which frequently locate on pegmatoid bodies as the least competent part of the eclogite/pegmatoid association. This in our view may explain the grouping of the Ar/Ar amphibole ages derived by RITTMANN (1984) from the Kupplerbrunn eclogite and pegmatoid. The amphibole ages from the Kupplerbrunn pegmatoids are reported as being in the 108–189 Ma range whilst those from the eclogite were in the 223–530 Ma range. However the ^{39}Ar degassing profiles are stepped and smooth age plateaus are not apparent in the data presented. The stepping of the degassing profiles may in part be due to incomplete resetting of the Ar isotopes during the Alpine event and/or Ar overpressuring. Nevertheless we suggest that the ages from the fine grained amphiboles in the eclogite, being the least deformed during Alpine time, may well record the Hercynian amphibolite facies overprint. The amphibole ages from the less competent pegmatoid on the other hand may owe their range to the combination of deformation induced recrystallization, partial resetting and overpressuring by Ar released from nearby micas.

The 84.35 ± 2.2 Ma age, obtained from micas separated from mylonitic schists defining the junction between the Crystalline Complex and the Kliening Series rocks, is believed to correspond to latest phase of movement on the intervening thrust zone.

11. Summary of conclusions

In this section the origins, affinities and evolution of the eclogites are summarised.

11.1. THE ECLOGITE PROTOLITHS

The major element data presented here confirms that the Saualpe eclogites have evolved tholeiitic basalt compositions. The Gertrusk eclogite is the most evolved, the Jurkikogel / Beilstein less so and the Kirchberg and Kupplerbrunn bodies are the least evolved. The Grünburger eclogite spans the range occupied by the other bodies. The differences between the high-Ti eclogites within the Grünberger body might be explained by low pressure fractional crystallization of the protoliths involving cpx-plag-ol. The low-Ti Kupplerbrunn eclogites on the other hand appear to have originated from mafic cumulates with olivine and plagioclase as the major phases.

If the trace element abundances and ratios are used to determine the tectonic setting of the protoliths a number of inconsistences become apparent. For example incompatible element ratios (Nb-Y-Zr which are likely to remain unchanged) indicate that the high-Ti eclogites were derived from N-MORB protoliths and that the low-Ti kyanite bearing eclogites fall outside the basalt liquid field. However with the exception of the Gertrusk body the other eclogite HFS element abundances are depleted relative to N-MORB and, whilst LIL elements such as Rb and Ba may be enriched, K and Sr are usually depleted. These variations could indicate hydrothermal or metasomatic alteration of the protoliths as far as the LIL elements are concerned. The lower than N-MORB HFS values may simply reflect slightly more primitive compositions than that chosen for normalising or else the HFS elements were removed as soluble ionic complexes by halide or CO_2 rich fluids. There is no textural or fluid inclusion evidence for large volumes of fluid flow through the eclogites at any time other than in the vicinity of the pegmatoids or along the high strain zones. Absolute element abundances for the bulk of the eclogites are therefore probably close to those of the protoliths.

The distribution of data points in diagrams based on Zr–Y–Ti show a strong positive correlation which spans the MORB-IAT fields and suggests that all eclogite protoliths could be derived from the same geochemical source. REE data confirms the MORB character of the eclogites and that all the protoliths were likely to have been produced from the same slightly depleted LREE magma source. Whilst the data suggests strong affinities with MORB compositions they do not prove conclusively that the protoliths were generated along a major spreading axis.

The associated schists and gneisses are distinctly terrigenous and the larger eclogite protoliths were almost certainly intrusives into these metasediments and do not in our opinion represent a tectonic mélange. The presence of early andalusite (replaced by kyanite) might evidence a pre- or syn-intrusion metamorphism of highT / lowP type. This combined with the low pressure fractionated character of the protoliths would be consistent with high geothermal gradients in an area of extending (thinned) crust. The N-MORB multielement plots of the eclogites have some similarities with back-arc basin basalts and such an environment could account for the association of rocks comprising the Crystalline Complex.

It is of interest to note here that analyses of the amphibolites in the overthrust Mica Schist Group (Plankogel Series) are distinctly bi-modal in character having clear WPB and MORB affinities. Combined with the character of the associated metasediments it is suggested (WILLIAMS and MANBY, in prep.) that these rocks and perhaps the eclogites represent components of an extensional back-arc basin.

11.2. ECLOGITE FORMATION

The Sm / Nd isotope systematics, if valid, would suggest that the parent magmas could have been derived from a depleted mantle source around 800 Ma, metamorphosed within the eclogite PT field and were undergoing decompression at 700 Ma. PT conditions for the eclogite formation were in the 14 kb / 650 °C to 18 kb / 840 °C range from the jd content of the pyroxenes. Garnet compositions are essentially homogeneous and fall within the type-two range typical of eclogites in gneissic terranes. The strongly lineated and granoblastic fabrics are consistent with the operation of high shear strains at this time and the eclogites are in part high temperature mylonites. The retention of distinct magmatic signatures by the eclogites suggests that this deformation was effectively anhydrous. The compositional banding observed in many of the eclogites although emphasised by this deformation/metamorphism must reflect an original igneous layering.

Isothermal decompression down to 10 kb followed by equally declining PT's to 6 kb/-500 °C are indicated by the changing compositions of the symplectites. The widespread preservation of the symplectite textures suggests that this decompression took place under conditions of low directed stress.

11.3. HERCYNIAN EVENTS

Whatever the age of the protolith and eclogite facies metamorphism proves to be these rocks were undoubtedly overprinted by a Hercynian amphibolite facies event. This metamorphism was accompanied by elevated fluid pressures, partial melting and pegmatite formation in the schists/gneisses and the eclogites. Other than the dilation and injection of pegmatites the eclogites appear to have escaped pervasive Hercynian deformation. The enclosing schists and gneisses would have been significantly less competent and appear to have accomodated most of the deformation. If the whole package of rocks is as old as the Sm/Nd ages indicates then it could be suggested that the gt + st^{I} + bi assemblages date from pre-eclogite time whilst the addition of kyanite and breakdown of staurolite ^{I} marks the onset of high $\Delta P/\Delta T$ conditions. The second staurolite (st^{II}) found for example in the matrix of the schists above Sandofen overgrowing the dominant schistosity with helicitic textures could be Hercynian rather than Alpine.

11.4. ALPINE EVENTS

The latest thermal event to affect the Crystalline Complex rocks was Alpine in age, this much is clear from the K/Ar mineral ages (micas and hornblendes) reported by MORAUF (1981); MILLER and FRANK (1983); RITTMANN (1984) and present authors.

Nappe stacking in a northerly direction in Alpine time most probably caused the heating of the pile and resetting of K/Ar and Rb/Sr ratios. In contrast to FRANK's (1987) interpretation the stacking of nappes in order of decreasing metamorphic grade can also be explained by Alpine, N directed backthrusting of a metamorphically inverted nappe pile thrust southwards in Hercynian time.

Alpine tectonics which are characterized by the Plattengneiss fabrics have transformed many of the Crystalline Complex rocks, particularly the pegmatoids, into mylonites and ultramylonites. In the mylonites quartz invariably shows extreme ductile deformation, the feldspars are replaced by fine grained polycrystalline aggregates of albite, muscovite and epidote. Garnets are fragmented and entrained in the foliation and extensively replaced by biotite/chlorite. The eclogites on the other hand have been largely unaffected by the Plattengneiss type of Alpine deformation and most of the deformation at this time would have been accomodated by the distinctly less competent country rocks.

Eclogite body mineral assemblages in zones where Alpine shearing and resetting has occurred are typically in the greenschist facies range. Temperatures in the Crystalline Complex fell below the blocking temperature for Ar release around 90 Ma. The ca. 84 Ma age from mylonites at the base of the Crystalline Complex suggests that displacemet on the thrust continued at least into Santonian time.

MILLER and FRANK (1983) from their age determinations argue for a Cretaceous amphibolite event which FRANK (1987) has revised to an eclogite event but, as discussed above, their data contains some apparently disturbed Hercynian ages reset in a number of cases to Alpine time. It is likely, as we have found with the mica ages reported here that the degree of resetting will depend on the extent of Alpine deformation. Blocking temperatures can be significantly lowered by deformation and much of this resetting could occur within the greenschist facies range. The ab + ep and ep + chl retrograde assemblages in the eclogites are believed to have been generated at the same time as the K/Ar resetting and indicate that PT's were broadly within the greenschist facies range.

The textural (decreasing grain size of symplectites) and the preliminary Sm/Nd evidence presented here argues strongly against an Alpine eclogite (or amphibolite facies) overprinting of the Saualpe segment of the Koriden nappe.

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