Petrogenesis of eclogites and peridotites from the Western and Ligurian Alps

W. G. Ernst

Department of Earth and Space Sciences
Institute of Geophysics and Space Physics
University of California, Los Angeles, California 90024

Abstract

Aluminous peridotites and eclogites of the Western and Ligurian Alps have been investigated in terms of their mineral assemblages, major element phase compositions, and bulk-rock REE and major element chemistries. Except for the garnetiferous ultramafic lens exposed at Alpe Arami, all studied peridotites are spinel lherzolites. The peridotites show light REE depletions due to low-temperature hydrous alteration, to the hypothesized incipient fusion of a now completely obliterated garnet-bearing protolith, or—more probably—to the existence of mantle already fractionated relative to primordial REE abundances. Eclogitic rocks are tholeiitic in their major element affinities, but show apparent metasomatic effects of iron, titanium and REE loss, and alkali enrichment during pervase and ubiquitous late-stage retrogression to greenschist-facies assemblages. Alternatively, these differences may reflect the former existence of two chemically distinct protoliths. Employing various geothermometers and geobarometers, the following P-T conditions for the last reequilibration of ultramafic and mafic units have been computed:

SOUTH ALPINE PLATE			NORTH ALPINE PLATE		
Peridotites			*Peridotites*		
Finero	900°C	~10 kbar	Alpe Arami	950°C	40 kbar
Balmuccia	925°C	~15 kbar	Zermatt	<600°C	(10 kbar)
Baldissero	925°C	~15 kbar	w. Liguria	<600°C	(10 kbar)
Lanzo	1000°C	≤12 kbar	*Eclogites*		
w. Liguria	1100°C	~15 kbar	Alpe Arami	900°C	(40 kbar)
e. Liguria	1000°C	≤12 kbar	Zermatt	525°C	≥10 kbar
Eclogites (none)			w. Liguria	435°C	≥10 kbar

Retrograde assemblages are interpreted in terms of a nearly adiabatic ascent towards present crustal levels for all investigated rock types. In western Liguria and the vicinity of Zermatt—and in general for the North Alpine plate—this P-T trajectory may reflect buoyant return towards the surface of southward and eastward subducted crustal sections plus serpentinized periodotite underpinnings during late Mesozoic closure of Mesozoic Tethys. The crustal emplacement of large masses of relatively dense lherzolite of the South Alpine plate apparently is a consequence of tectonic imbrication accompanying overthrusting and the transportation of deeper portions of the more southerly plate northward and westward during convergence.

Lithotectonic framework

Introduction

The Alpine chain represents the most intensely studied orogenic belt in the world. Over the past century, careful investigations of this magnificently exposed terrain by more than a thousand European earth scientists have provided us with detailed knowledge concerning relationships among the various lithologic units and the manifest structures. More recently, the concepts of global tectonics have been applied to the Alps (Laubscher, 1971a,b; Smith, 1971; Ernst, 1971; Dal Piaz *et al.*, 1972; Dewey *et al.*, 1973; Hunziker, 1974). That petrologic features can be attributed to associated lithospheric plate motions is now becoming clear. The goal of the present paper
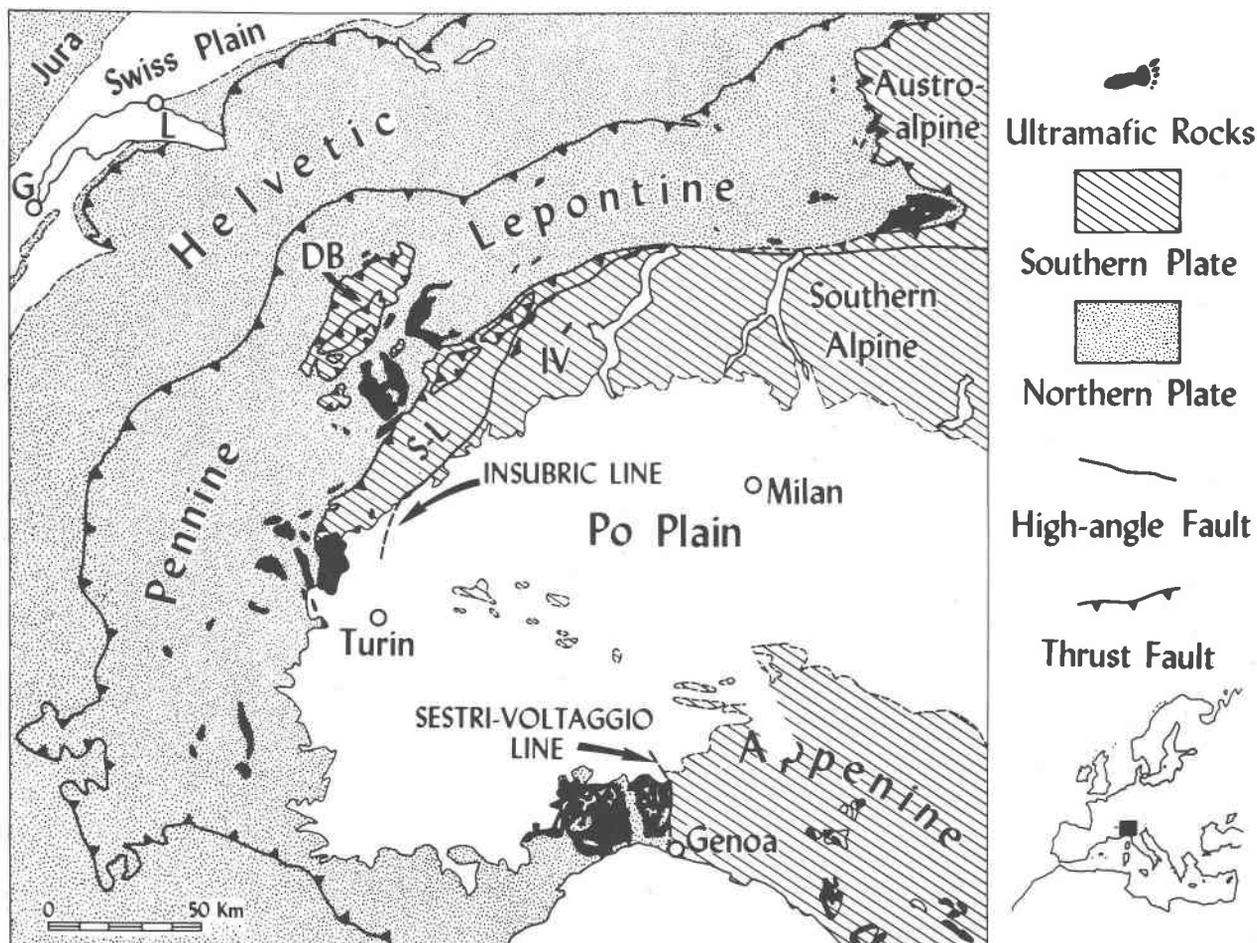
Fig. 1. Western Alpine–Ligurian tectonic setting and geography, largely after Niggli *et al.* (1973). Abbreviations are as follows: G = Geneva; L = Lausanne; DB = Dent Blanche nappe; S–L = Sesia–Lanzo realm; IV = Ivrea zone. Parts of the Dent Blanche and Sesia–Lanzo zones decoupled from the Southern Alpine plate during Early Alpine convergence and began descending with the Tethyan–European (Northern Alpine) plate.

is to summarize the major element and REE chemistries and mineral parageneses of selected lherzolitic and eclogitic rocks of the Western and Ligurian Alps already investigated by the author, and to provide a new analysis of the operating *P-T* conditions; a secondary purpose involves the correlation of these occurrences to inferred Alpine plate tectonic processes.

Regional geology

Major tectonic realms of the Western Alps and Liguria (the northernmost Appenines and the region bordering the Ligurian Sea) are illustrated in Figure 1. This strongly arcuate mountain belt consists of three principal domains (Trümpy, 1960, 1973, 1975): (1) the structurally high Southern Alps—and its basal portion, the Ivrea zone, Austroalpine nappes and Appenines bordering the Po Plain; (2) the structurally low continental margin of Europe, including

the European Foreland, Jura, Swiss Plain and Helvetic nappe system; and (3) an interleaved, composite Pennine terrain. Structural entities of Southern Alpine derivation, such as the Sesia–Lanzo zone, and the Dent Blanche and related thrust slices, as well as more northerly European continental basement (*e.g.,* the Lepontine gneisses and the internal massifs) have been tectonically juxtaposed and are intimately associated with rocks of the Pennine realm. The terrain adjacent to the Po Plain is referrred to as "internal" by Alpine geologists, whereas the outer portions of the arc, lying farther away from the Po Plain, are termed "external."

Both European and Southern Alpine realms consist of Hercynian and pre-Hercynian sialic basement rocks, plus a well-ordered superjacent series of Mesozoic and younger strata. In contrast, the Pennine terrain, although containing Hercynian and pre-Hercy-

nian allochthonous complexes, is characterized by Mesozoic continental margin and deep-sea sediments which were deposited at least in part on oceanic basement, especially in the internal portions of this zone. Serpentinized peridotitic rocks are scattered throughout and adjacent to the Pennine + Sesia–Lanzo realm; high-pressure metamorphic rocks are also best developed in these complexes. The present summary, therefore, focuses on portions of the Pennine and Sesia–Lanzo terrains.

The post-Hercynian tectonic history of the Alps and Appenines involves several principal contrasting stages. (A) In Late Triassic time, a major rifting event initiated the separation of European and Southern Alpine sialic crust-capped plates. Sea-floor spreading produced a narrow intervening sea, Mesozoic Tethys, situated between the fragmented continental margins. Newly generated oceanic crust evidently provided the basement for more southerly and easterly Pennine sediments of Jurassic and Cretaceous age, accounting for the abundance of ophiolitic material in this realm. (B) During mid- and Late Cretaceous time, the narrow seaway began to close as a consequence of consumption of the Tethyan plate southward and eastward beneath the Southern Alps. Continental impaction seems to have ensued during Late Cretaceous time along a complex, imbricate suture zone. Portions of the European basement were subducted during this event, as evidenced by their participation in the Pennine-style deformation and high-pressure metamorphic overprint. Many of the Alpine nappe structures and décollements, which demonstrate that structurally higher units were transported away from the Po Plain relative to underlying units, seem to bear witness to the underflow and loss of basement (as long ago described and pondered by Ampherer, 1906). This latest Cretaceous event is termed Early Alpine in terms of the orogenic history. The collisional zone included not only the Pennine ophiolitic realm, but the Sesia–Lanzo zone and lower parts of the Dent Blanche nappe system as well. Imbricate thrust movement apparently continued into, or was reactivated in, the Early Tertiary. (C) The counterclockwise rotation of the Italian Peninsula commenced at the end of Cretaceous time in response to renewed rifting and localized sea-floor spreading between microplates in the Mediterranean region (Zijderveld et al., 1970). By the Early Tertiary, referred to as Late Alpine in the mountain-building cycle, compressional forces had given way to major strike-slip faulting along breaks such as the Insubric and Sestri–Voltaggio lines (Gansser, 1968; Scholle,

1970; Laubscher, 1975), probably accompanying the formation of the intense arcuate curvature of the Western and Ligurian Alps. It should be noted that the sense of vergence changes across the Sestri–Voltaggio Line; hence rocks of the northern Appenines consitute the stable, nonsubducted plate and do not exhibit the blueschist metamorphic parageneses characteristic of that produced in western Liguria and the Alps. Perhaps the Sestri–Voltaggio Line is a late Mesozoic structural feature which was reactivated under contrasting dynamic conditions during the more recent 70° counterclockwise rotation of Italy (Lowrie and Alvarez, 1975). In summary, post-Hercynian plate tectonics in the western part of the Alpine chain seem to have involved first divergence, then convergence (perhaps several stages), followed by periods of rotation and conservative (transform?) motion.

Petrologic relations

The Alpine metamorphic zonation, general structural features, distribution of peridotites and both peridotite and eclogite localities referred to in the text are presented in Figure 2.

Serpentinized peridotites constitute a common rock type in the Western and Ligurian Alps. Volumetrically, they are most important in the western Appenines, the southerly and easterly, more internal sectors of the Pennine terrane, associated with the Sesia–Lanzo realm, and near the base of the Ivrea zone. Ignoring late hydration effects, at least four different types of ultramafic protolith appear to be represented: (1) pre-Mesozoic basement ultramafic complexes, such as the strongly foliated and prograde metamorphosed Val Malenco body (Trommsdorff and Evans, 1972, 1974); (2) small garnet lherzolite pods with associated eclogite, confined to the southern Lepontine region, such as the enigmatic occurrence at Alpe Arami (O'Hara and Mercy, 1966; Möckel, 1969; Rost et al., 1974); (3) completely serpentinized, post-Hercynian harzburgite and eclogitized gabbro-pillow lava complexes such as present in the vicinity of Zermatt–Saas Fee (Bearth, 1967; Dietrich et al., 1974); and (4) pre-Mesozoic lherzolitic masses associated with the Southern Alps, such as the Ivrea zone bodies of Lanzo, Balmuccia, Baldiserro and Finero (Vogt, 1962; Lensch, 1968; Nicolas, 1968, 1974; Boudier, 1978; Shervais, 1979). Although mafic rocks are associated with all these ultramafics, only type (3), which characterizes more oceanic parts of the Pennine and Appenine realms, can be considered as disrupted ophiolite in the strict sense (Anony-
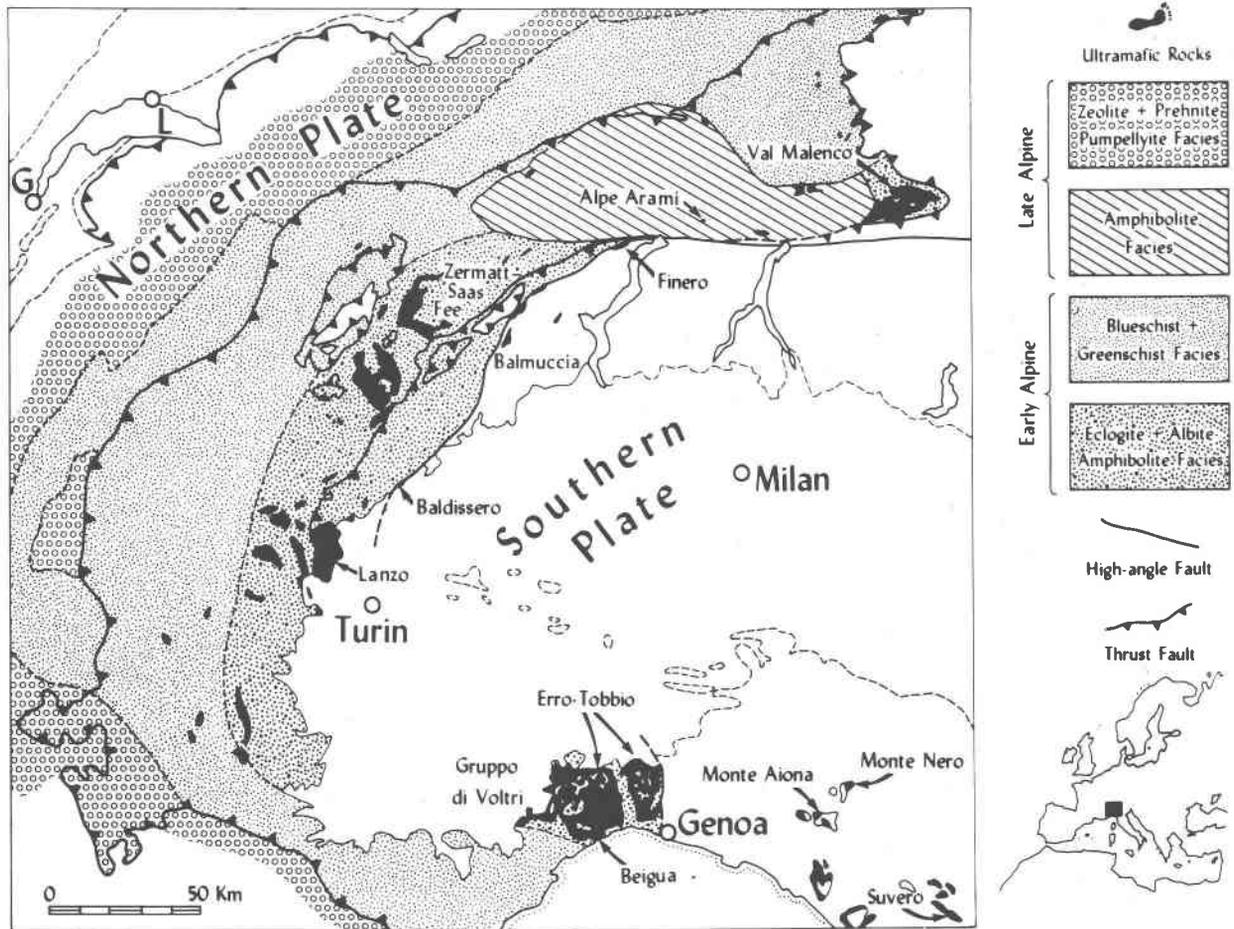
Fig. 2. Alpine age metamorphism of the Western and Ligurian Alps, largely after Niggli *et al.* (1973). Abbreviations are: G = Geneva; L = Lausanne. Although the Dent Blanche and related nappes as well as the Sesia–Lanzo zone were derived from the Southern Alps, they were subjected to the Early Alpine high-pressure metamorphism. Because of the difficulty in distinguishing between similar metamorphic products, some of the greenschists assigned on this map to Early Alpine crystallization—especially in the Lepontine region—are probably of Late Alpine metamorphic age.

mous, 1972). All four petrologic types seem to have reached their present structural positions through tectonic processes involving largely solid-state emplacement, although incipient partial melting effects are thought to characterize Liguria, Lanzo and Finero occurrences (Bezzi and Piccardo, 1971; Boudier and Nicolas, 1972; Cawthorn, 1975). Nicolas and Jackson (1972) called attention to the fact that lherzolite tectonites are commonest in the Western Alps, whereas the Dinarides and Turkey are characterized by harzburgitic peridotites; these authors assigned the former group to subcontinental lithosphere of the Southern Alpine plate, and the latter group to the Mesozoic Tethyan suboceanic plate. In the Gruppo di Voltri Complex of western Liguria, Southern Alpine lherzolites of the Erro–Tobbio unit have been thrust over the structurally lower Beigua

serpentinite, of presumed Tethyan affinities (Messiga and Piccardo, 1974; Chiesa *et al.*, 1975; Mottana and Bocchio, 1975).

High-pressure metamorphic assemblages (Bearth, 1959, 1962, 1974; Niggli, 1960, 1970; Bocquet, 1971; Compagnoni, 1977; Compagnoni *et al.*, 1977) were produced in rocks of the more northerly terrain, especially the Pennine and Sesia–Lanzo zones during Early Alpine descent of the Mesozoic sea floor and adjacent European foreland beneath the Southern Alpine plate (Ernst, 1971; Hunziker, 1974). The more internal sections were subjected to the most profound subduction, hence bear relics of the highest pressure assemblages (Ernst, 1973; Dal Piaz, 1974a,b). Subsequent to continental collision—which evidently took place in stages and led to pronounced tectonic imbrication and recrystallization (Dal Piaz *et al.*,

1972)—these sections rose buoyantly towards the surface, probably producing the pervasive greenschist facies (prasinitic) metamorphic overprint and back-folding characteristic of the more internal portions of the Western Alps. Regions such as the Lepontine gneiss terrain which evidently experienced a delayed return to the surface, were subjected to substantial heating before buoyant, plastic, diapiric upward motion was initiated; this more complicated thermal history may account for the obliteration of the hypothesized Early Alpine high-pressure phase compatibilities, the production of high-rank amphibolites and the incipient melting of quartzofeldspathic units during the Late Alpine metamorphic culmination in the Lepontine zone (Wenk, 1962, 1970; Wenk and Keller, 1969; Jäger et al., 1967).

Upper mantle fragments in the Western Alps and Liguria

Peridotite petrography

Mineralogic and bulk-rock chemical data have been obtained by the author and his coworkers (Ernst, 1978; Ernst and Piccardo, 1979; Ottonello et al., 1979) for five Western Alpine peridotites—Alpe Arami, Finero, Balmuccia, Baldissero and Lanzo—for the structurally high Erro–Tobbio mass of western Liguria, and for single samples of ultramafics from eastern Liguria (northern Appenines)—Monte Aiona, Monte Nero and Suvero. With the exception of Alpe Arami, which is a garnet peridotite, all investigated masses are spinel lherzolites, evidently derived from the South Alpine lithospheric plate. Incipient fusion phenomena and/or partial recrystallization to plagioclase peridotites on decompression are widespread at Lanzo, less so at Finero and in the Ligurian specimens. Average modes are summarized in Table 1. The investigated peridotite suites contain essential

clinopyroxene and are appropriately classified as lherzolites (Streckeisen, 1974, 1976). All have penetrative (tectonite) fabrics and show evidence of plastic deformation (e.g., sectoral strain in olivines, bent lamellae in pyroxenes, minor granulation and gradational extinction among primary phases). Some of the crystallographic orientation may reflect differential flow within the upper mantle, whereas late, superimposed strain effects probably were produced during tectonic emplacement in the present continental setting (e.g., see Nicolas et al., 1971).

The Erro–Tobbio and eastern Ligurian rocks contain greater proportions of late hydration products, but otherwise appear to be mineralogically similar to the other spinel lherzolites examined. The garnet-bearing peridotite of Alpe Arami is distinctly lower in orthopyroxene proportions, and carries substantially more late-stage calcic amphibole, but is otherwise quite comparable to the other studied samples.

Peridotite bulk-rock chemistry

Major elements. Bulk-rock XRF analyses for 35 lherzolites have been published previously by the author. Averages for each occurrence are presented in Table 2. Analyses appear to be remarkably similar from one sample to another, and the bulk-rock chemistries of these rocks are sensibly indistinguishable. Individual analyses as well as means are quite comparable to data presented by other workers (O'Hara and Mercy, 1966; Nicolas, 1966; Lensch, 1971; Rost et al., 1974; Boudier, 1976, 1978) for these same localities. The lherzolites studied correspond well to estimates of relatively primitive mantle composition proposed by Wyllie (1970) and Maaløe and Aoki (1977) based on natural occurrences, but are slightly depleted in CaO and Al_2O_3

Table 1. Average estimated modes and one standard deviation for petrographically investigated lherzolites from Liguria and the Western Alps (original data from: Ernst, 1978; Ernst and Piccardo, 1979).

Locality – No. of Samples	Olivine	Ortho-pyroxene	Clino-pyroxene	Garnet	Spinel (Incl. opaques)	Plagio-clase	Ca-amphibole	Phlogo-pite	Alteration Products*
Alpe Arami – 14	47.0±14.4	13.0±5.9	16.1±11.0	5.6±5.8	2.3±2.7	0.5±1.9	6.9±8.3	–	8.6± 7.0
Finero – 7	55.0± 9.1	23.6±6.3	9.9± 7.8	–	4.4±0.8	–	1.0±1.9	2.7±5.6	3.4± 4.5
Balmuccia – 18	52.9±14.1	22.8±8.1	16.5±10.8	–	5.1±0.9	–	0.2±0.4	–	2.4± 5.9
Baldissero – 20	48.3±14.4	24.9±8.8	16.9±11.4	–	4.4±1.6	0.1±0.4	1.0±2.8	–	4.4± 7.2
Lanzo – 21	38.8±14.2	26.1±6.7	16.9± 9.9	–	2.4±0.4	2.6±5.5	1.1±2.5	–	12.1±12.2
Erro-Tobbio – 8	35.9±12.1	23.4±8.1	13.3± 5.0	–	3.5±1.1	–	–	–	23.9±10.0
Eastern Liguria – 3	44.0± 6.6	28.0±6.1	8.3± 2.9	–	5.0±1.0	–	–	–	14.7± 7.2

*chlorite, serpentine minerals, talc

Table 2. Average whole-rock XRF compositions and one standard deviation for chemically analyzed lherzolites from Liguria and the Western Alps (original data from: Ernst, 1978; Ernst and Piccardo, 1979).

Locality - No. of Samples	SiO_2	Al_2O_3	TiO_2	Cr_2O_3	Fe_2O_3*	NiO	MgO	MnO	CaO	Na_2O	K_2O	Ignition Loss
Alpe Arami - 6	44.45±1.39	1.50±0.27	0.15±0.07	0.38±0.05	8.23±0.10	0.25±0.02	39.84±1.23	0.12±0.00	2.18±0.57	0.49±0.17	0.05±0.05	2.61±0.84
Finero - 2	42.16±1.20	0.65±0.56	0.05±0.05	0.24±0.21	8.84±0.60	0.33±0.04	46.54±2.45	0.13±0.01	0.51±0.54	0.38±0.00	0.24±0.33	0.07±0.08
Balmuccia - 7	47.14±1.58	1.49±0.16	0.14±0.04	0.36±0.04	8.01±0.48	0.23±0.01	39.23±1.83	0.12±0.01	2.92±0.84	nd	0.00±0.00	0.44±0.70
Baldissero - 6	47.66±1.94	1.62±0.44	0.16±0.07	0.40±0.09	7.82±1.03	0.23±0.02	38.58±2.87	0.12±0.01	2.98±1.28	nd	0.00±0.00	0.61±0.46
Lanzo - 3	47.17±2.59	2.73±1.53	0.29±0.12	0.41±0.10	7.37±1.20	0.21±0.01	36.09±4.43	0.12±0.01	3.87±2.11	0.15±0.00	0.00±0.00	1.74±0.99
Erro-Tobbio - 8	41.43±0.71	2.65±0.41	0.13±0.03	0.34±0.03	8.06±0.32	0.23±0.02	37.69±0.90	0.12±0.00	2.06±0.42	0.08±0.09	0.01±0.01	6.97±1.25
Eastern Liguria - 3	42.38±0.34	2.90±1.10	0.22±0.02	0.30±0.08	7.88±0.25	0.20±0.02	37.99±0.86	0.12±0.00	2.45±0.28	0.18±0.05	0.05±0.08	5.61±1.02

* total iron as Fe_2O_3; nd = not determined

compared to the model pyrolite of Ringwood (1975, Table 5–2).

The high ignition loss for the Ligurian samples (Erro–Tobbio, Monte Aiona, Monte Nero and Suvero) reflects extensive late-stage serpentinization; in contrast, most of the Western Alpine samples contain only small amounts of amphibole, phlogopite and/or serpentine. The Finero peridotite appears to be especially low in CaO, Al_2O_3 and TiO_2, and rich in MgO, NiO and K_2O. The rest are chemically rather homogeneous.

Rare earth elements. Bulk-rock radiochemical neutron activation analyses of rare earth elements (REE) for some Ligurian periodotites—eight Erro–Tobbio lherzolites and a single sample from Monte Aiona—were published by Ottonello *et al.* (1979). Preliminary REE contents of 7 specimens from Balmuccia and 6 from Baldissero have been obtained more recently (Ottonello and Ernst, unpublished). The chondrite-normalized rare earth element patterns are presented in Figure 3 for all 22 rocks. These peridotites exhibit light rare earth element (LREE) depletion relative to chondrites.

Assuming an initial chondrite-like pattern for the Ligurian specimens, Ottonello *et al.* (1979) ascribed the LREE depletion to the combined effects of less than five percent partial fusion of the original mantle material, (spinel lherzolite) and of hydrous alteration under oxiding conditions. Inasmuch as the Erro–Tobbio peridotites contain an average of nearly 25 volume percent alteration products as indicated in Table 1, such conclusions seem reasonable. However, analyzed Balmuccia and Baldissero peridotites contain only very minor serpentine and other secondary phases, yet display light REE depletions analogous to patterns for the Ligurian rocks (compare Figs. 3A, B and C). Accordingly, if the low LREE concentrations at Balmuccia and Baldissero reflect leaching which attended an hypothesized near-surface hydration, the alteration minerals so produced must have been subsequently obliterated later during high-temperature

recrystallization and annealing, because volatile-bearing phases are rare in these "fresh" samples.

The Western Alpine lherzolites in general contain slightly greater abundances of each REE, so their distribution patterns are shifted up compared to the investigated Ligurian samples. Higher concentrations of REE in many of the Balmuccia and (especially) the Baldissero peridotite samples may reflect either lower degrees of incipient fusion, or the existence of an initial protolith enriched in rare earth elements relative to the Erro–Tobbio protolith. In general, higher CaO samples tend to possess higher modal proportions of clinopyroxene, and greater concentrations of REE as well; such peridotites may be regarded as more nearly primitive.

An alternative hypothesis to explain the LREE depletion and the slight heavy rare earth element (HREE) enrichment relative to chondrites displayed by all the analyzed spinel peridotite samples involves the incipient melting of an hypothesized garnet lherzolite precursor. Distribution coefficients (the fractionation of elements between crystal and melt phases) are appropriate to realize this effect (*e.g.*, see Hanson, 1980, Table 2), but no mineralogic or textural relics are present which would support the prior existence of a garnet-bearing protolith. Bulk-rock REE analyses of garnet peridotites from Alpe Armai now underway may shed light on this problem, but as discussed below, this body appears to be very different from all other lherzolites investigated in this study.

Yet a third explanation is that upper mantle material in general—and in the western Mediterranean area in particular—was slightly fractionated relative to chondrites at an earlier stage in its history. Hence, prior to the crystallization event recorded in the investigated peridotites, the mantle protolith would have possessed a LREE depletion and a slight HREE enrichment relative to the primordial earth. Such conclusions are suggested by examination of rare earth element patterns from similar lherzolitic masses
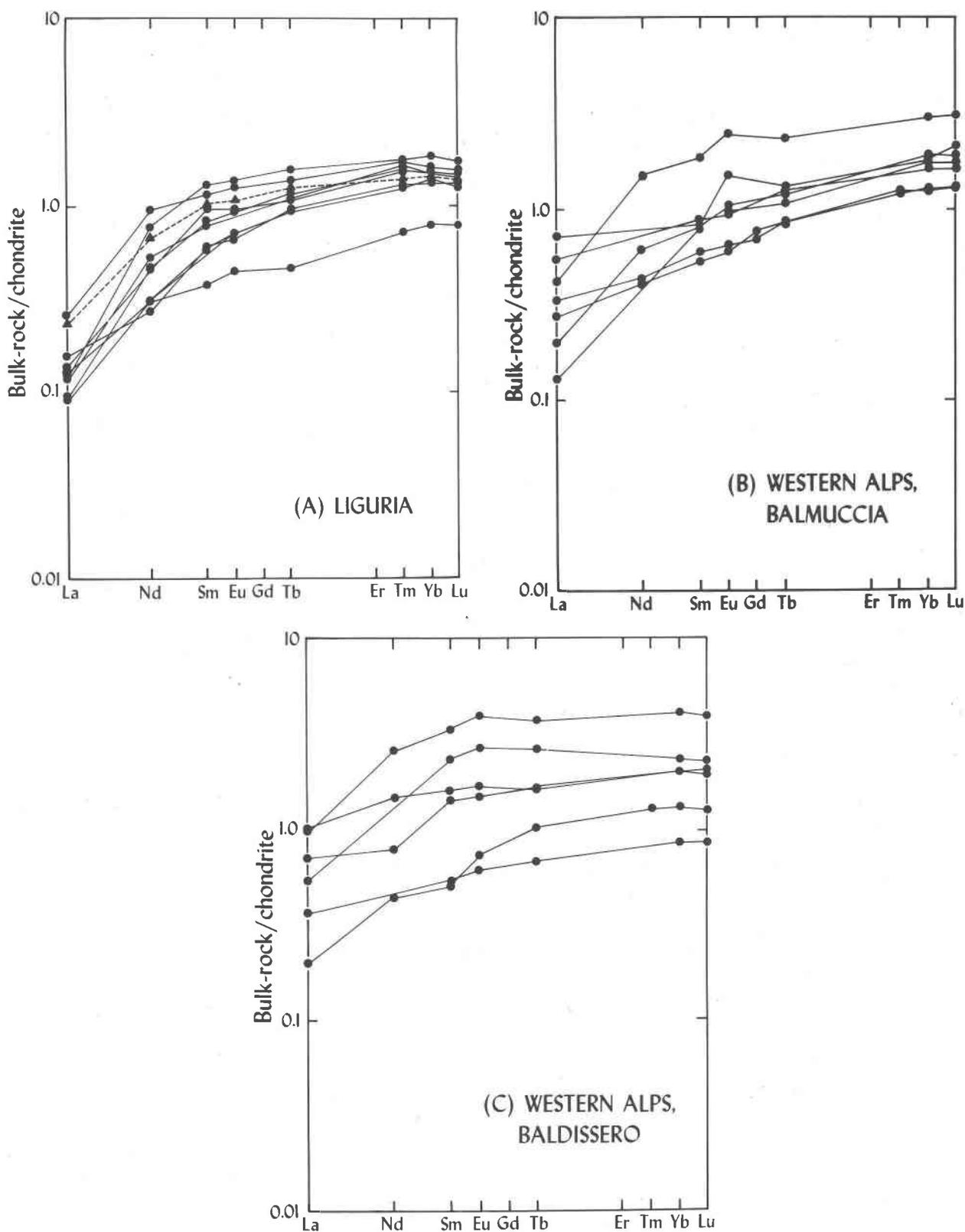
Fig. 3. Chondrite-normalized rare earth element concentrations in lherzolitic samples from Liguria and the Western Alps. Data are from: (A) Ottonello *et al.*, 1979, modified; (B) and (C) Ottonello and Ernst, unpublished and preliminary. Analyzed Ligurian specimens are from the Erro–Tobbio unit except for one sample from Monte Aiona (triangles and dashed lines).
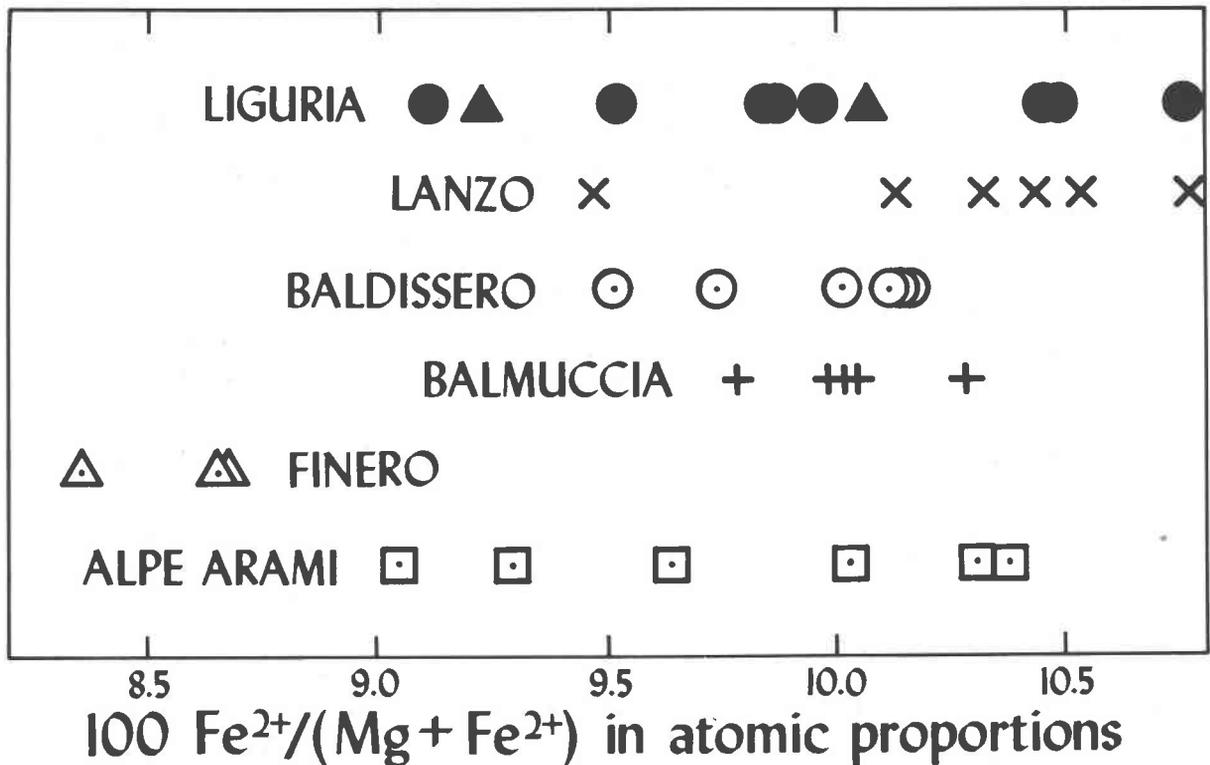
OLIVINES

Fig. 4. Mole proportions of Fa in analyzed olivines from Western Alpine and Ligurian peridotites. Filled triangles indicate analyses from eastern Liguria, filled circles are ol from the Erro–Tobbio unit. Data from: Ernst (1978); Ernst and Piccardo (1979).

(*e.g.*, see: Frey, 1969, 1970; Menzies, 1976; Menzies *et al.*, 1977).

Peridotite mineral chemistry

Electron microprobe analyses of coexisting phases from 37 peridotites have been published previously by the author. Analyzed minerals include olivine, orthopyroxene, clinopyroxene, garnet, spinel, plagioclase and calcic amphibole. The data are comparable to analyses presented by O'Hara and Mercy (1963), Nicolas (1966), Lensch (1971, 1975), Lensch and Rost (1972), Boudier (1972), Boudier and Nicolas (1972), Rost *et al.* (1974, Cawthorn (1975), Boudier (1979) and Shervais (1979).

Similar to bulk rock compositions, the mineral chemistries vary little among the analyzed samples. Olivines range from Fa_{08-11}, with the following averages: Finero, 8.6; Alpe Arami, 9.8; Baldissero and Liguria, 9.9; Balamuccia, 10.0; and Lanzo, 10.3. Olivine compositions are illustrated in Figure 4. Manganese and calcium contents are small but measurable. As

evident from Figure 5, orthopyroxenes are slightly more magnesian than the coexisting olivines (except for a few pairs from eastern Liguria), and show similar Fe/(Fe+Mg) trends. Alumina contents of orthopyroxenes (Fig. 5) are also relatively consistent, with significant contrasts in measured average weight percents of Al_2O_3: Alpe Arami, 0.87; Finero, 1.08; Lanzo, 3.10; Balmuccia, 3.80; Liguria, 4.11; and Baldissero, 4.57. Calcic pyroxenes, although chemically more complex than orthopyroxene, nevertheless exhibit analogous systematic compositional trends, being a trifle more magnesian than the associated orthopyroxenes, and, of course, are considerably enriched in cations such as Na and especially Ca. Average ternary compositions are: Alpe Arami, $Wo_{47.2} En_{49.5} Fs_{3.3}$; Finero, $Wo_{48.2}En_{49.2}Fs_{2.6}$; Balmuccia, $Wo_{49.1}En_{46.8}Fs_{4.1}$; Baldissero, $Wo_{49.3}En_{46.8}Fs_{3.9}$; Lanzo, $Wo_{47.6}En_{47.4}Fs_{5.0}$; and Liguria, $Wo_{42.0}En_{53.1}Fs_{4.9}$. Calcic pyroxene compositions are shown in Figure 6. Probably one of the most remarkable aspects of these mineral data is their internal consistency. Although
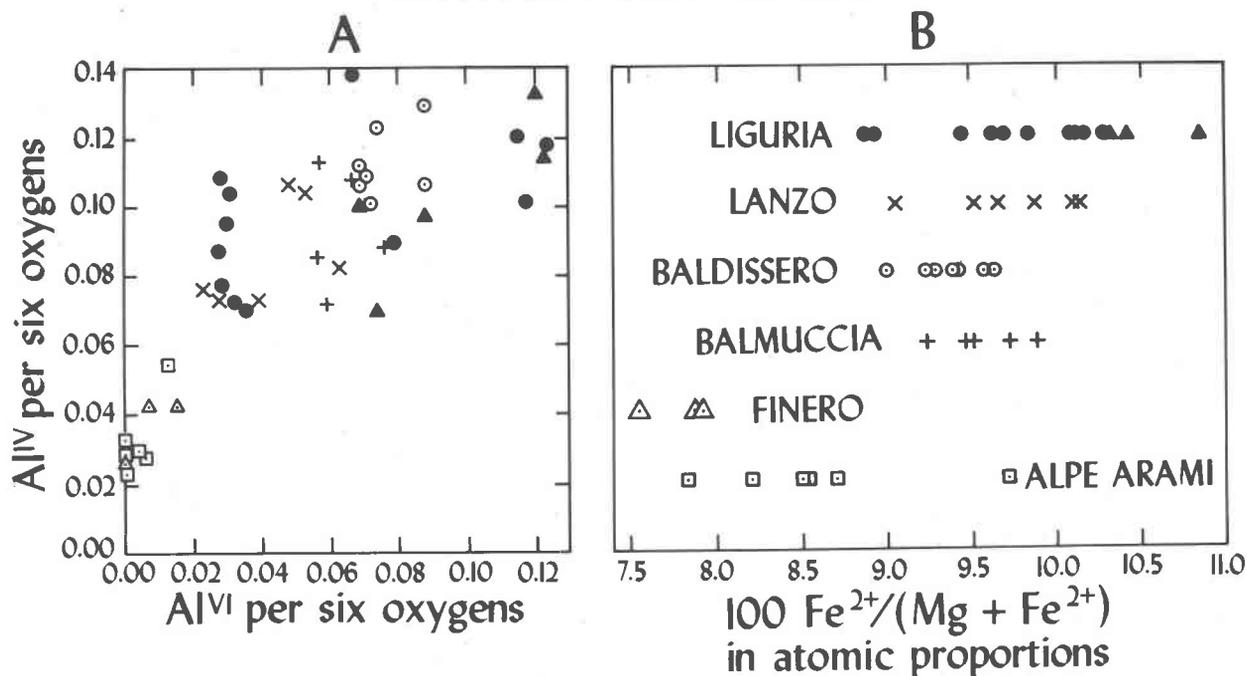
ORTHOPYROXENES

Fig. 5. Computed octahedrally and tetrahedrally coordinated aluminum (A), and mole proportions of Fs (B) for orthopyroxenes from Western Alpine and Ligurian peridotites. Filled triangles indicate analyses from eastern Liguria, filled circles are orthopyroxene from the Erro–Tobbio unit. Data from: Ernst (1978); Ernst and Piccardo (1979).

well within the analytical uncertainties, small but systematic chemical differences exist among the major phases from the different occurrences.

For the investigated samples, garnet is restricted to the Alpe Arami body. The composition of this phase is quite uniform, averaging 71 percent pyrope end member. Among the analyzed spinels, at least two different types are present—a primary translucent brown Mg + Al-rich variety which averages about 70 percent $MgAl_2O_4$ end member, and a secondary opaque phase rich in chromium and iron which probably was produced during alteration and recrystallization. A few plagioclase grains have been analyzed from Liguria (An_{59}) and Lanzo (An_{77-88}). Several different types of primary(?) calcic amphibole occur in various Western Alpine peridotites (but not in either Lanzo or Liguria). Titaniferous hornblendes from Balmuccia are very low in silicon and correspondingly rich in aluminum and sodium; they appear to be primary upper mantle phases. Finero hornblendes probably formed during reequilibration of the peridotite under basal crustal P-T conditions in the presence of an aqueous fluid. Alpe Arami amphiboles include an analogous aluminous hornblende, overgrown and partly replaced by actinolite

which crytallized subsequent to the emplacement of the ultramafic body in the present sialic environment.

P-T conditions of peridotite crystallization

The generalized phase relations for aluminous lherzolites under physical conditions extant in the upper mantle and crust are well known. A diagrammatic petrogenetic grid for such lithologies, largely after Wyllie (1970) is presented as Figure 7. Due to solid solution among the various minerals, "univariant" curves illustrated in this diagram which separate the fields for plagioclase-, spinel- and garnet-peridotite are actually zones of finite P-T width. A recent study by Jenkins and Newton (1979) suggests that the transition between garnet- and spinel-bearing lherzolitic assemblages may lie at lower pressures than illustrated here, but the topology is unchanged.

Judging from Figure 7, garnet lherzolites form at depths exceeding about 60–80 km, with plagioclase-bearing equivalents confined to depths shallower than approximately 25–35 km. Most of the peridotites studied in the present investigation contain spinel as the chief Al-rich phase, hence must have been derived from mantle depths on the order of 50±20 km. Those which contain plagioclase replac-
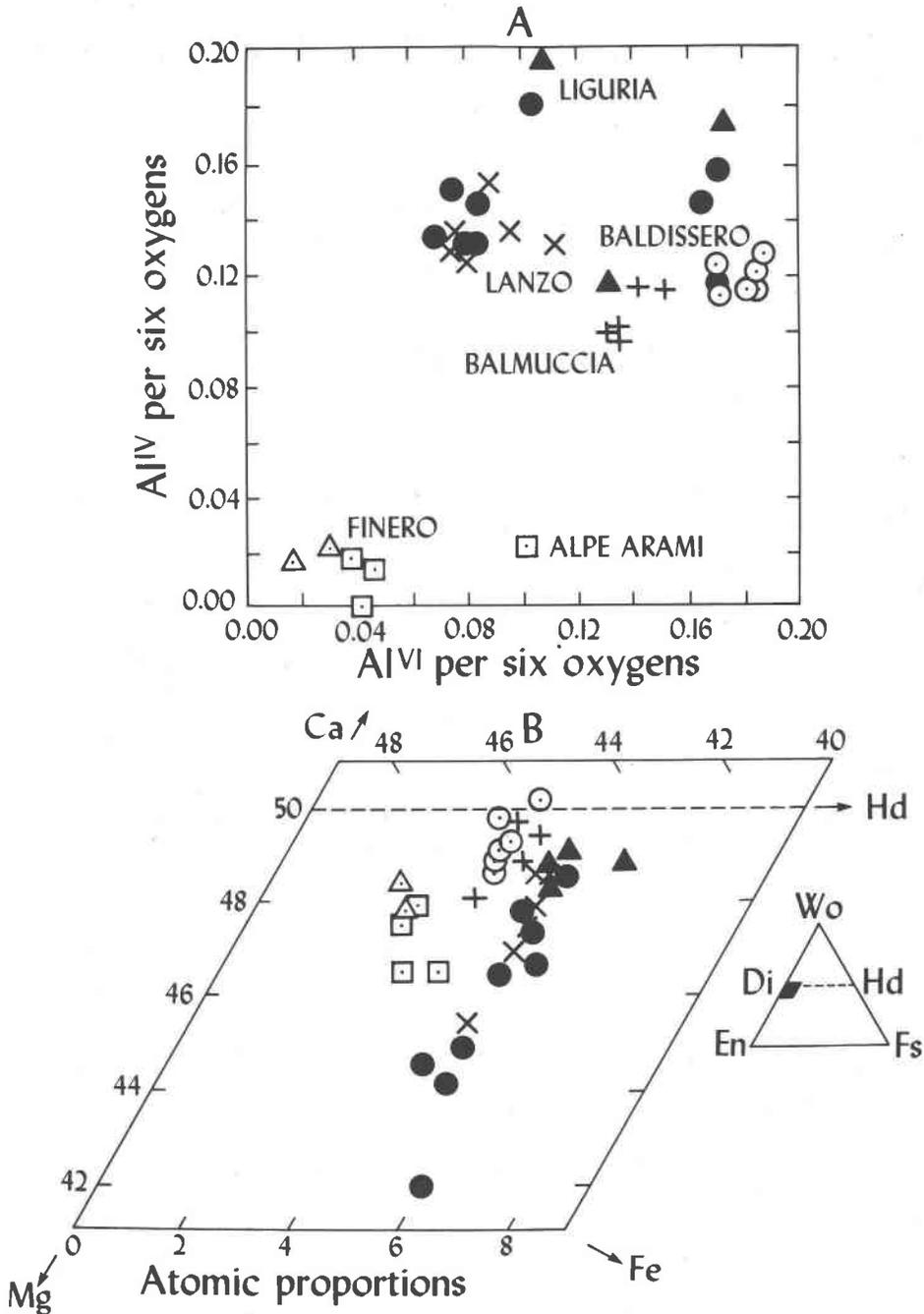
CLINOPYROXENES

Fig. 6. Computed octahedrally and tetrahedrally coordinated aluminum (A), and Ca/Mg/Fe proportions (B) for clinopyroxenes from Western Alpine and Ligurian peridotites. Filled triangles indicate analyses from eastern Liguria, filled circles are clinopyroxene from the Erro–Tobbio unit. Data from: Ernst (1978); Ernst and Piccardo (1979).

ing and surrounding spinel, such as Lanzo and Ligurian units, have recrystallized during decompression. These bodies contain locally-derived gabbroic dikes and stringers, and appear to have undergone in-

cipient partial fusion during their ascent towards the surface. The Finero mass contains large tracts of coarsely crystallized hornblende gabbro, and seems to have undergone extensive reequilibration in the
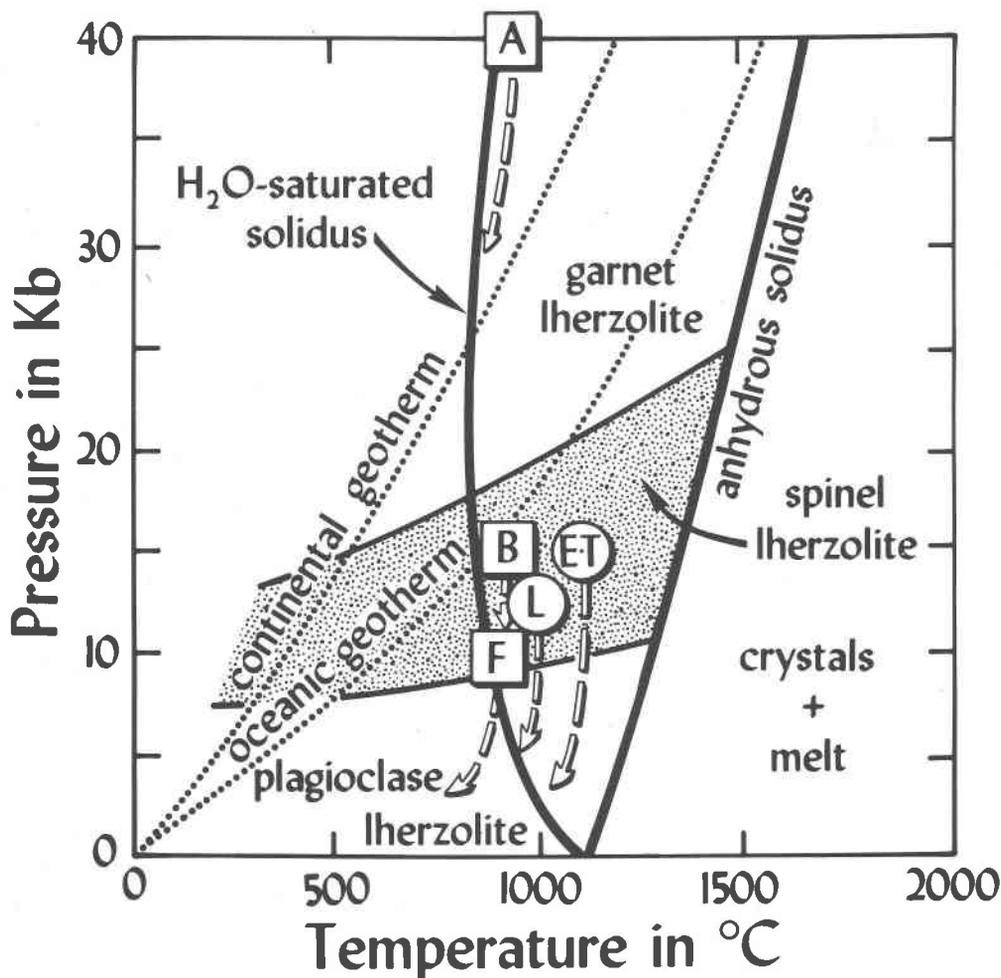
Fig. 7. Phase equilibria for pyrolite compositions (Wyllie, 1970). The dry solidus is after Kushiro *et al.* (1968), the wet solidus from Mysen and Boettcher (1975a). Subsolidus assemblages are generalized after Green and Ringwood (1967a,b), Ito and Kennedy (1967), O'Hara (1967, 1968) and MacGregor (1968). For general reference, steady-state intraplate geothermal gradients (Clark and Ringwood, 1964) are also illustrated. Estimated *P-T* conditions of equilibration for the analyzed lherzolites are shown as follows: A = Alpe Arami; B = Balmuccia and Baldissero; ET = Erro–Tobio (western Liguria); F = Finero; L = Lanzo and eastern Liguria. Arrows show inferred *P-T* trajectories as the studied peridotites partly reequilibrated during transit towards their present crustal environments.

presence of an aqueous fluid under deep crustal conditions. The Alpe Arami body, on the other hand, contains pyropic garnet and evidently was derived from a more profound level in the mantle (it also carries plagioclase, but as a subsolidus symplectic reaction product formed during later metamorphism accompanying emplacement in the sialic Lepontine terrain). Thus all the masses reported on here may be assigned provisional *P-T* sites of origin, and their decompression recrystallization paths roughly delineated from consideration of the framework of Figure 7.

More quantitative evaluations of the operating physical conditions attending formation of the peridotites depend on accurate experimental or ther-

mochemical determinations of chemical variations for the constituent phases as a function of *T, P* and composition. Usually, the partitioning of components, such as Ca and Mg between coexisting orthopyroxene and clinopyroxene, Fe and Mg between clinopyroxene or olivine and garnet, or between spinel + olivine pairs, and the solubility of Al_2O_3 in orthopyroxene are used. The theory of element fractionation has been treated by numerous authors and will not be repeated here (for a recent review, see Saxena, 1973).

Implicit in all such studies, in which geothermometers and geobarometers are applied to natural rocks, is the assumption that chemical equilibrium has been attained for the analyzed phases under a

specific set of conditions, and that subsequent transportation of the material to the present site of exposure has not disturbed the partitioning. If in fact partial reequilibration has been imposed on the analyzed assemblage, a smearing out of apparent P and T values will be obtained at best, whereas in the more general case, the derived set of physical conditions may be practically meaningless due to nonequilbrium chemical readjustment of the minerals. With these provisos in mind, let us consider the analytical data for coexisting phases in the investigated peridotites, and the nominal physical conditions so indicated. A program devised by A. A. Finnerty of the Jet Propulsion Laboratory allowed machine treatment of the microprobe data (Ernst, 1978; Ernst and Piccardo, 1979) to provide applicable geothermometers and geobarometers. For the purpose of calculation, all iron was treated as ferrous in olivine, garnet and orthopyroxene, as half ferric in clinopyroxene, and the Fe^{2+}/Fe^{3+} ratio in spinels was obtained by recasting cations to 3.00 assuming no anion omissions. These assumptions result in sensible cation proportions for the analyzed mineralogic samples, as discussed previously by Ernst and Piccardo. The presence of minor amounts of additional components in natural phases required that corrections be applied to allow use of the synthetic experimental data (Wood, 1974; Wells, 1977).

Alpe Arami is the most confidently addressed of the lherzolite localities, for many studies have dealt with element partitioning in garnet peridotites, numerous relevant mineralogic geothermometers are available and the pressure effect on alumina concentration in orthopyroxene is known accurately, hence estimates of operating P and T are readily obtained. Moreover, as will be described later, conditions of origin for the associated eclogitic lenses at Alpe Arami have also been quantified.

Apparent conditions of equilibration for six Alpe Arami garnet peridotites are listed in Table 3. The new computer-generated values presented are based on $Al_2O_3^{opx}$ isopleths as determined by MacGregor (1974). P-T values were obtained utilizing the following geothermometers: orthopyroxene, Mercier (1976); orthopyroxene + clinopyroxene pairs, Wood and Banno (1973) and Wells (1977); garnet + olivine pairs, O'Neill and Wood (1979) and Kawasaki (1979). As evident from the table, the Mercier and Wells methods yield slightly lower temperatures and pressures (~900°C, 37 kbar) than the formulations of Wood and Banno, O'Neill and Wood, and Kawasaki (~1000°C, 44 kbar). Summation of all the P-T estimates of Table 3 provides a grand average of 949±75°C, 40.9±5.7 kbar, considered by the present writer to be the "best" assignment. These values are nearly identical to a previous grand average (Ernst, 1978) of 966±78°C obtained using the Wood and Banno technique plus several different geothermometers (Mysen and Boettcher, 1975a,b; Mysen, 1976; and Lindsley and Dixon, 1976), and an attending pressure of about 43–44 kbar employing both the data of MacGregor (1974) and Akella (1976). They are slightly higher than P-T estimates determined for Alpe Arami lherzolites by Carswell and Gibb (1980), but lower than thermal equilibration values presented by Mori and Green (1978). As will be discussed below, these values for physical conditions are compatible with temperatures obtained by assuming a lithostatic pressure of 40 kbar for garnet ± clinopyroxene pairs in both lherzolite and associated eclogitic lenses employing yet another method (Ellis and Green, 1979). However, Evans and Trommsdorff (1978) and O'Neill and Wood (1979) obtained less extreme conditions of crystallization, on the order of 25 kbar and 800°C, for two samples of garnet peridotite associated with eclogite nearby (as well as an Alpe Arami sample).

Disparites in apparent physical conditions of equilibration probably reflect differential chemical readjustment of the coexisting minerals during depressurization and cooling. Possibly Fe–Mg exchange between olivine and garnet diminished sharply or actually ceased at a higher temperature than characteristic of the Ca–Mg fractionation between coexisting pyroxenes. Shervais (1979) has demonstrated that at Balmuccia, clinopyroxene + orthopyroxene pairs continued to reequilibrate at lower temperatures than did spinel + olivine + pyroxene assemblages.

Alumina isopleths for orthopyroxenes are nearly independent of pressure in the spinel lherzolite field, and are as yet poorly constrained in the plagioclase lherzolite field (Presnall, 1976; Obata, 1976, 1980; Danckwerth and Newton, 1978), thus only the temperatures of equilibration may be obtained with reasonable accuracy for the other Western Alpine and Ligurian peridotites studied in this report. For this reason, only geothermometers whose formulation is independent of pressure can be used. Average values are presented in Table 4, where they are compared with earlier estimates for the same samples by Ernst (1978) and Ernst and Piccardo (1979).

As in the case of the Alpe Arami complex, there seems to be no obvious indication as to which of the

Table 3. Apparent temperatures and pressures of equilibration for analyzed Alpe Arami garnet lherzolite samples employing Al_2O_3 solubilities in orthopyroxene after MacGregor (1974).

Reference Sample No.	(1) T(°C)	(1) P(kb)	(2) T(°C)	(2) P(kb)	(3) T(°C)	(3) P(kb)	(4) T(°C)	(4) P(kb)	(5) T(°C)	(5) P(kb)
A-2a	907	41.0	–	–	–	–	–	–	–	–
F-16a	970	38.0	854	34.2	980	42.4	959	41.0	916	38.2
F-16b	867	36.8	850	34.4	973	42.4	1130	52.6	1064	48.3
F-16c	869	29.0	–	–	–	–	–	–	–	–
F-52c	911	38.9	957	43.2	1064	50.4	–	–	–	–
F-56	924	38.6	871	36.8	989	44.6	985	44.4	944	41.7
Average 3-6	908±38	37.1±4.2	883±50	37.2±4.2	1001±42	45.0±3.8	1025±92	46.0±6.0	975±79	42.7±5.1

(1) *opx: Mercier (1976)*
(2) *opx + cpx: Wells (1977)*
(3) *opx + cpx: Wood and Banno (1973)*
(4) *gar + ol: O'Neill and Wood (1979)*
(5) *gar + ol: Kawasaki (1979)*

methods employed provides more accurate results. Apparent temperatures of Ca-Mg equilibration between orthopyroxene and clinopyroxene are approximately as follows: Finero, 900°C; Balmuccia and Baldissero, 925°C; Lanzo and eastern Liguria, 1000°C; and western Liguria, 1100°C. Attending pressure must have been on the order of 7–20 kbar, with the hotter Ligurian and Lanzo masses undergoing partial melting to produce the observed mafic dikes and plagioclase-bearing lherzolites during ascent towards the surface. Hypothesized *P-T* paths are illustrated in Figure 7. Similar histories have been documented recently for the Ronda peridotite by Obata (1980). Study of Figure 7 yields several important tentative conclusions.

(1) The Alpe Arami garnet lherzolite contains a primary assemblage indicative of very high pressures and relatively modest temperatures. Such values are appropriate to deep portions of a thick subcontinental lithosphere, where geothermal gradients typically are lower than those capped by continental margins and island arcs. Estimated physical conditions are similar to those obtained for kimberlites (*e.g.*, see Boyd, 1973). Another, perhaps more reasonable, site of origin for the Alpe Arami peridotite and associated eclogite involves formation within the descending lithospheric slab of a subduction zone where relatively elevated *P/T* ratios would have prevailed (Toksöz *et al.*, 1971; Turcotte and Oxburgh, 1972). Both the very high pressures and temperatures estimated in the present work, and the more moderate values proposed by Evans and Trommsdorff (1978) are several hundred degrees and several tens of kbar in excess of the *P-T* conditions attending metamorphic culmination in the surrounding Lepon-

tine quartzo-feldspathic gneisses. The latter have been estimated (Ernst, 1977) as approximately 600–650°C and 6–7 kbar, at a moderately high activity of H_2O; in corroboration, Hoernes and Friedrichsen (1980) obtained a maximum temperature in the Lepontine gneiss region of 650°C employing oxygen isotopes. The presence of plagioclase rather than jadeitic pyroxene in these country rocks limits the attending pressures to a maximum of 10–11 kbar (Newton and Smith, 1967; Green and Ringwood, 1967b).

(2) Provided the temperatures of equilibration are accurate, the hornblende-bearing Finero complex must have recrystallized at pressures on the order of 10 kbar near the base of the crust under high activities of H_2O (Lensch, 1971; Nicolas *et al.*, 1971; Cawthorn, 1975). As evident from Table 4, estimated temperatures of crystallization employing the Wells (1977) method would seem to be subsolidus no matter how high the a_{H_2O}, unless a total fluid pressure considerably exceeding 10 kbar is assumed.

Table 4. Average apparent temperatures of equilibration for analyzed spinel lherzolite samples of the Western and Ligurian Alps employing pressure-independent geothermometers.

Reference Locality – No. of Samples	(1)	(2)	(3)	(4)
Finero – 2	858±58°C	983±52°C	893±94°C	–
Balmuccia – 5	832±44°C	948±40°C	973±50°C	–
Baldissero – 5-7	828±37°C	946±33°C	1002±37°C	–
Lanzo – 6	918±51°C	1022±44°C	1069±85°C	–
Erro-Tobbio – 8	1012±61°C	1100±52°C	–	1150±50°C
Eastern Liguria – 3	891±50°C	997±37°C	–	1000±50°C

(1) *Wells (1977)*
(2) *Wood and Banno (1973)*
(3) *Ernst (1978)*
(4) *Ernst and Piccardo (1979)*

ALPE ARAMI

PHASE \ STAGE	ECLOGITIC	AMPHIBOLITIC	GREENSCHISTIC
Garnet	————————————————	– – –	
Clinopyroxene	———————————————	– –	
Ca—amphibole	– – –	Pargasitic ————	Actinolitic
Biotite			± Chlorite
Epidote		– Al-rich	
Kyanite	– – – – –		
Plagioclase		Oligoclase	Albite
Quartz	– – – – – – – – – –		
Symplectite	– – – – – – – – –		
Rutile	————————————————	– –	
Opaques	– – – – – – – – – –		

Fig. 8. Schematic paragenetic sequence developed in mafic lenses associated with garnet lherzolite at Alpe Arami (Ernst, 1977). Early stages are shown on the left. Solid line indicates essential presence of a phase, dashed line symbolizes minor or sporadic presence.

(3) Baldissero and Balmuccia lherzolitic masses contain traces of a Ti-rich hornblende, indicating at least a low to moderate a_{H_2O}, but show little or no transformation to plagioclase-bearing rocks. Apparently their transportation towards the surface did not result in back-reaction, nor did wholesale partial fusion ensue. Pressures on the order of 15 kbar, well within the spinel peridotite field, seem to be indicated.

(4) The occurrences of Lanzo and Liguira, indicated as circles in Figure 7, exhibit incomplete conversion to plagioclase-bearing assemblages and more extensive fractional melting phenomena, hence their P-T trajectories must have intersected the solidus during decompression. Therefore, although the higher temperature western Ligurian lherzolites probably equilibrated at lithostatic pressures approaching 15 kbar, the lower temperature eastern Ligurian and Lanzo masses must have intersected the solidus at pressures equal to or less than 12 kbar. None of these peridotites contain primary hornblende, although late-stage, colorless amphibole occurs at Lanzo; therefore, these rocks probably recrystallized under conditions involving a_{H_2O} insufficient

to allow the formation of hornblende in the mantle, but high enough to permit incipient fusion. Of the two geothermometers employed in Table 4, apparent temperatures by the Wood and Banno (1973) computation are more compatible with the inferred conditions of origin.

(5) With the possible exception of the Finero complex, all the peridotites studied in this report recrystallized at relatively shallow upper mantle depths characterized by high temperatures, subsequently were transported to their present locale and were tectonically juxtaposed against crustal rocks under conditions of much lower P and T.

(6) Employing Al_2O_3 isopleths for orthopyroxene as presented by Obata (1976), Danckwerth and Newton (1978) and Lane and Ganguly (1980) and the assignments of pressures in the range 10–15 kbar as discussed above in points 2–4, approximate temperatures of equilibration for the investigated peridotites containing $MgAl_2O_4$-rich spinel may be obtained which are independent of the Ca/Mg partition method. Although values for Balmuccia and Baldissero bodies are roughly compatible with geothermometric data based on Ca/Mg partitioning

listed in Table 4, nominal crystallization temperatures averaging 100 to more than 200°C lower than Table 4 values are indicated for Finero, Lanzo and Liguria. In part, this reflects small amounts of iron and chromium in the $MgAl_2O_4$-rich spinels, but chiefly it may be a consequence of the fact that the described partial melting in these latter masses during decompression has promoted reequilibration of the pyroxenes at shallower depths. Although Ca/Mg fractionation would be virtually unaffected by the nearly isothermal pressure drop, alumina content of orthopyroxene would be expected to decrease substantially due to the steep negative dP/dT slope for $Al_2O_3^{opx}$ calculated for the plagioclase lherzolite field by Obata (1976). The alumina contents of these orthopyroxenes are therefore probably more appropriate for the plagioclase lherzolite field than the spinel lherzolite field.

High-pressure metamorphic rocks in the Western Alps and Liguria

Eclogite petrography

Mineralogic and bulk-rock chemical data have been published by the author and his coworkers (Ernst, 1976, 1977; Cortesogno *et al*, 1977; Ernst and Dal Piaz, 1978; Dal Piaz and Ernst, 1978) for eclogites from the Alpe Arami and the Zermatt–Saas Fee areas of the Western Alps and from the structurally low Beigua serpentinite of western Liguria.

At Alpe Arami, ecologitic lenses occur as mafic selvages along the margins of the garnet lherzolite described in previous sections; although discontinuous, the eclogitic layers tend to separate the peridotite from the surrounding Lepontine gneiss (Möckel, 1969). The contact between eclogite + peridotite and encompassing quartzofeldspathic gneiss is mylonitic according to Buiskool Toxopeus (1976). Similar to the associated ultramafic body which shows the effects of chloritization of original garnet and growth of Ca-amphiboles at the expense of clinopyroxene (see Table 1), the primary eclogitic assemblage exhibits extensive conversion to later stage symplectic amphibolite and lower-grade assemblages. Early-formed garnet and omphacitic pyroxene ± rutile have been partly replaced by hornblende, kyanite, clinozisite and plagioclase ± biotite ± chlorite. A schematic paragenetic diagram is presented as Figure 8.

Eclogitic metabasaltic and metagabbroic rocks in the Zermatt–Saas Fee (Breuil–St. Jacques) area near the Matterhorn have developed in a typical ophiolitic suite representing the inner, more oceanic portion of the Pennine realm (Bearth, 1959, 1974; Dal Piaz and Ernst, 1978). Similar assemblages have been produced in mafic layers within the Beigua serpentinite of the Gruppo di Voltri, western Liguria (Cortesogno *et al.*, 1975; Mottana and Bocchio, 1975). In both regions, the early-formed garnet + omphacite + rutile association and less abundant metarodingitic rock types have been progressively replaced by glaucophane-, barroisitic hornblende-, and actinolite-bearing assemblages. Although a continuum of phase proportions is present, average modes of the somewhat arbitrarily distinguished stages are presented for the Gruppo di Voltri parageneses in Table 5 to provide the reader with a feeling for the sequence. Margins of the bodies tend to be greenschistic, successively more interior portions barroisitic and glaucophanic, with eclogitic cores; however, abundant relict phases in all lithologies demonstrate that the rocks share a common recrystallization history. The paragenetic diagram for the Gruppo di Voltri illustrated as Figure 9 is almost identical to the sequence of phase compatibilities observed at Zermatt, and is remarkably similar to reported parageneses from the Sesia–Lanzo eclogites (Compagnoni, 1977), as well as those developed in Pennine ophiolites of the Tauern Fenster, Eastern Alps (Richter, 1973; Miller, 1977). In contrast to the production of pargasitic hornblende at Alpe Arami, the ophiolitic eclogites of the inner Pennine realm show important stages characterized by blue amphibole and by blue-green subcalcic hornblende (=barroisite).

Eclogite bulk-rock chemistry

Major elements. Bulk-rock XRF analyses for 101 eclogitic rocks from the Western and Ligurian Alps have been previously published by the author and his colleagues, 5 from Alpe Arami, 13 from the Zermatt–Saas Fee area, and 83 from the Gruppo di Voltri. Averages for Alpe Arami and Zermatt analyses are presented in Table 6. Although the Alpe Arami eclogites appear to be more magnesian than those of the Zermatt ophiolitic terrain, both groups have tholeiitic affinities, being very low in K_2O, relatively low in TiO_2, and reasonably rich in SiO_2.

Metagabbros of the Gruppo di Voltri in western Liguria are enriched in iron, titania and soda, and are relatively siliceous and K-poor (Table 6), hence are regarded as the products of somewhat differentiated tholeiitic magmas. An early metasomatic event which preceded the high-pressure metamorphism is

Table 5. Average modes for the paragenetic sequence developed in mafic layers within the Beigua serpentinite; Gruppi di Voltri, western Liguria (original data from Cortesogno *et al.*, 1977).

Mineral	Stage				
	Metarodingitic (pre-eclogitic)	Eclogitic	Glaucophanic	Barroisitic	Greenschistic
plagioclase	tr	0.6	3.6	9.9	23.1**
garnet	5	34.9	13.0	9.7	2.4
Na-clinopyroxene	25	37.8	26.5	11.7	8.8
rutile	0	5.8	2.4	2.1	0.6
sphene	5	1.0	3.1	3.3	3.8
ores	3	3.0	3.1	5.1	2.5
Ca-amphibole	17	7.2	5.0	42.2	23.5
Na-amphibole	0	6.6	24.8	1.6	1.2
epidote-clinozoisite	38	1.0	13.5*	9.3	20.0
chlorite	7	1.0	2.9	3.4	8.8
white micas	0	0.2	0.9	0.4	1.9
biotite	0	0.0	0.0	0.4	1.8
quartz	0	0.4	0.4	0.0	0.8
apatite	0	0.5	0.7	0.6	0.1
carbonate	0	0.0	0.1	0.3	0.7

Including lawsonite in one sample; **Including oligoclase in one sample.*

attested to by the Gruppo di Voltri (meta)rodingites. Such rocks, thought to reflect original mafic units associated with peridotites, have been converted to high Ca + Al, low Si + alkali compositions during serpentinization of the enclosing ultramafic body (Coleman, 1966, 1967; Dal Piaz, 1969). The rodingites of western Liguria were subsequently converted to garnet + clinopyroxene assemblages during eclogitization of less altered—hence more gabbroic—layers within the Beigua serpentinite (Piccardo *et al.*, 1980). A somewhat similar metarodingitic sequence near Alpe Arami has been reported by Evans *et al.* (1979). Still later recrystallization gave rise to the glaucophanic, barroisitic and actinolitic (*i.e.*, greenschistic) temporal gradation referred to in the previous section. That metasomatic effects evidently accompanied this latter process may be seen from study of Table 6. In particular, greenschists seem to be depleted in TiO_2 and iron and enriched in K_2O relative to the higher pressure lithologies. However, if some of the greenschistic lithologies reflect a magnesian leucogabbro precursor, as mentioned by Cortesogno *et al.* (1977) and Messiga and Piccardo (1980), some of the metasomatism may be more apparent than real.

Rare earth elements. Preliminary bulk-rock instrumental neutron activation analyses of rare earth elements for 29 samples of Gruppo di Voltri eclogitic parageneses have been obtained by Ernst and Rambaldi (supported by NSF EAR78-03336). Specimens include 2 metarodingites, 8 eclogites, 5 glaucophane schists, 7 barroisitic amphibolites and 7 greenschists.

Chondrite-normalized REE patterns are presented in Figure 10 for all 29 rocks.

In aggregate, the analyses show broad dispersal of the REE trends, reflecting the metasomatism which operated to a variable extent during one or more stages in the metamorphism. Many of the chondrite-normalized patterns are nearly horizontal from Tb to Lu, with a systematic light rare earth depletion; such patterns are characteristic of most oceanic tholeiites (Frey *et al.*, 1968; Kay *et al.*, 1970; Schilling, 1975). However, the impoverishment in LREE accompanying the hypothesized late metasomatic event probably is a consequence of the abundance of garnet (and clinopyroxene) in the precursor eclogitic assemblage; these phases preferentially concentrate HREE over LREE during crystal-aqueous (and/or CO_2-rich) fluid reequilibration (Hellman *et al.*, 1979; Mysen, 1979; Wendlandt and Harrison, 1979). Some—but by no means all—analyses of a particular rock type (especially the greenschists) include a positive Eu anomaly, but this does not seem to be correlated with the presence and modal amount, or absence of sodic plagioclase. During the late-stage metasomatism, rocks rich in feldspar—such as the greenschists—would be expected to preferentially concentrate Eu (see also Sun and Nesbitt, 1978).

The two metarodingites (Fig. 10A) exhibit relatively flat patterns, but differ in rare earth proportions. This suggests that REE concentrations have been affected by the early metasomatism accompanying serpentinization which preceded the high-pressure metamorphism. Differing abundances of
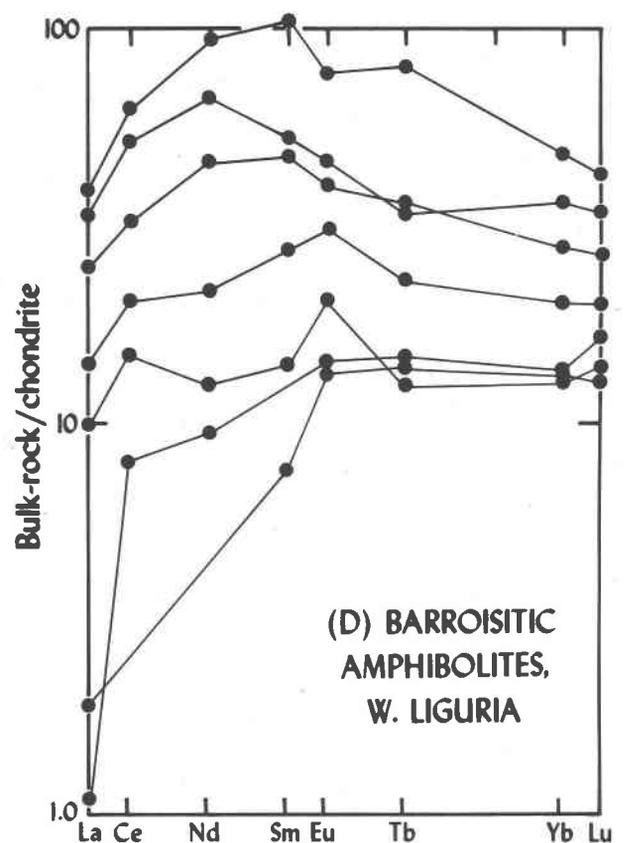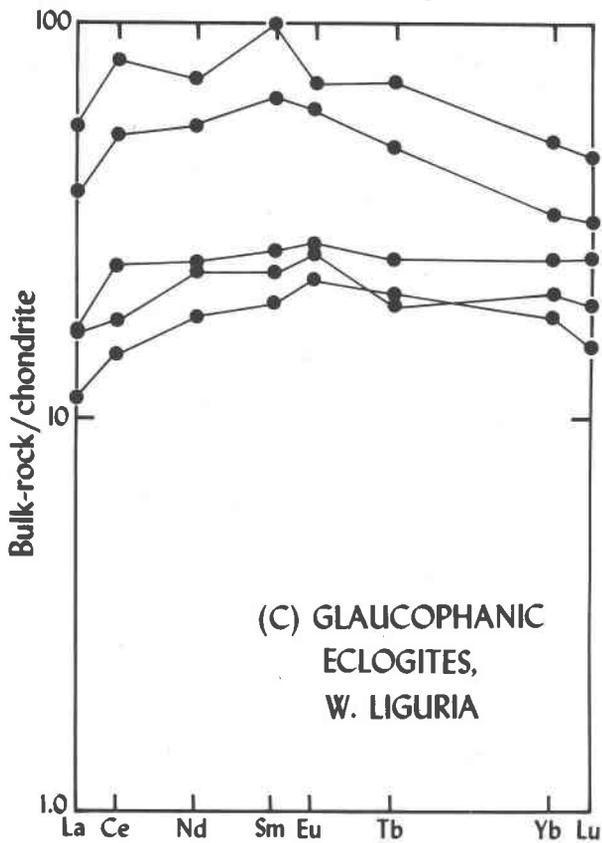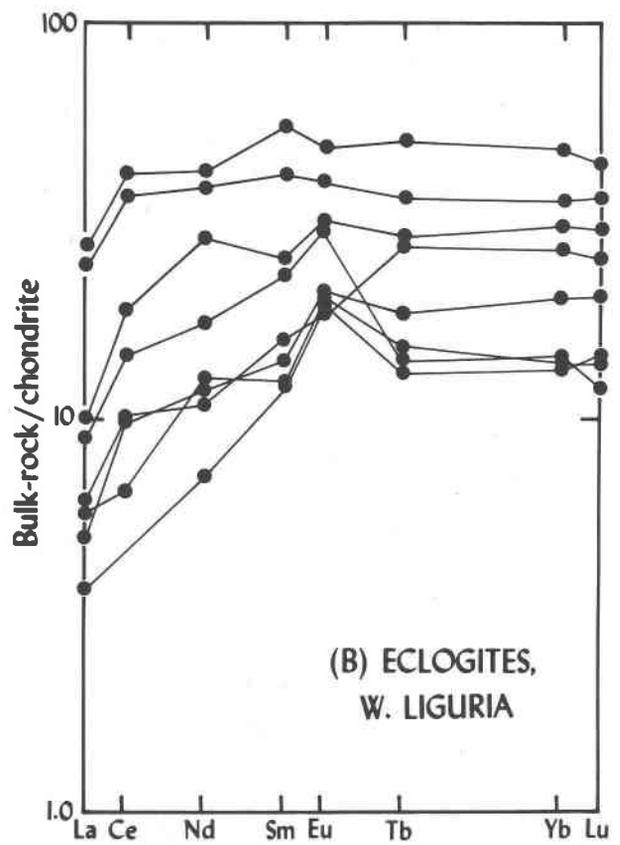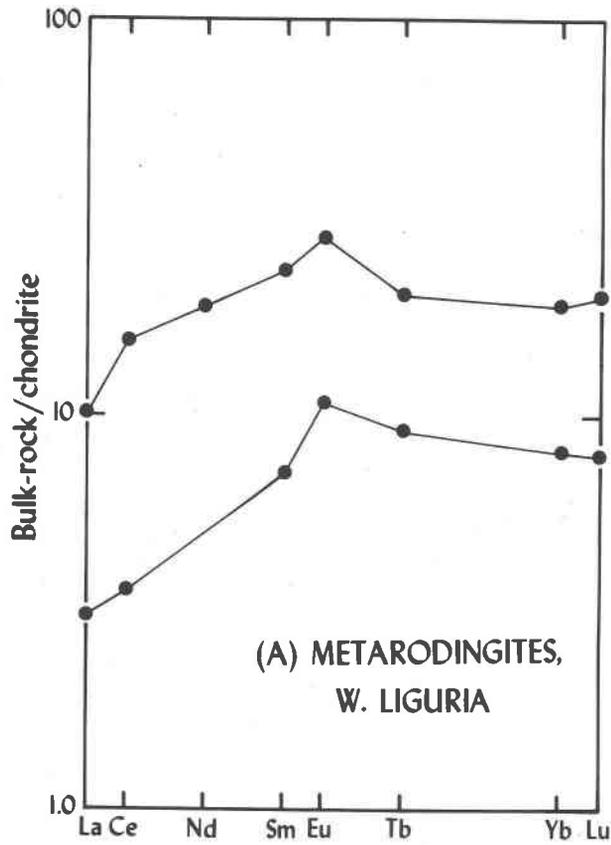
WESTERN LIGURIA

Fig. 9. Schematic paragenetic sequence developed in mafic lenses of the Beigua serpentinite, Gruppo di Voltri (Cortesogno *et al.*, 1977). Early stages are shown on the left. Very similar parageneses occur in dismembered ophiolites exposed in the vicinity of Zermatt–Saas Fee (Dal Piaz and Ernst, 1978). Solid line indicates essential presence of a phase, dashed line symbolizes minor or sporadic presence.

Table 6. Average whole-rock XRF compositions and one standard deviation for chemically analyzed eclogitic rocks from Liguria and the Western Alps (original data from: Cortesogno *et al.*, 1977; Ernst, 1977; Dal Piaz and Ernst, 1978).

Locality / Oxide	Western Alps		Gruppo di Voltri, western Liguria				
	Alpe Arami	Zermatt	Metarodingitic	Eclogitic	Glaucophanic	Barroisitic	Greenschistic
SiO_2	47.32±2.96	48.39±2.87	43.25±0.57	46.02±2.02	47.99±0.49	45.05±3.85	48.64±6.46
Al_2O_3	13.77±1.20	14.45±1.58	11.87±2.09	9.81±1.05	12.36±2.04	11.23±1.30	13.80±2.12
TiO_2	1.33±0.22	1.92±0.89	1.20±0.70	4.61±1.27	3.18±1.47	4.15±1.80	1.73±1.72
Fe_2O_3*	10.95±0.77	4.00±1.17	9.06±2.04	18.21±1.69	14.90±4.70	17.22±3.78	10.17±4.72
FeO	-	6.51±2.31	-	-	-		-
MnO	0.18±0.02	0.20±0.09	0.18±0.02	0.25±0.06	0.18±0.08	0.28±0.06	0.16±0.09
MgO	11.14±2.62	6.43±1.39	11.46±1.00	6.81±1.41	6.48±1.54	7.03±2.57	8.63±4.27
CaO	11.32±1.21	10.20±2.39	19.04±0.49	9.32±1.67	7.58±2.60	9.20±2.67	9.16±3.45
Na_2O	2.73±0.42	4.46±0.99	0.92±0.18	3.85±0.85	4.60±1.10	3.77±1.28	4.13±1.44
K_2O	0.26±0.30	0.18±0.12	0.02±0.03	0.05±0.05	0.16±0.17	0.14±0.10	0.52±1.03
P_2O_5	0.18±0.04	0.19±0.13	0.66±0.10	0.43±0.33	0.61±0.53	0.38±0.21	0.37±0.19
H_2O+ or ignition loss	0.58±0.59	2.65±1.84	2.22±0.64	0.78±0.88	2.04±1.75	1.05±1.77	2.36±1.41
Number of samples	5	13	2	37	6	15	23

* *Total iron as Fe_2O_3 except for analyses of Zermatt eclogites and associated rocks.*

(A) METARODINGITES, W. LIGURIA

(B) ECLOGITES, W. LIGURIA

(C) GLAUCOPHANIC ECLOGITES, W. LIGURIA
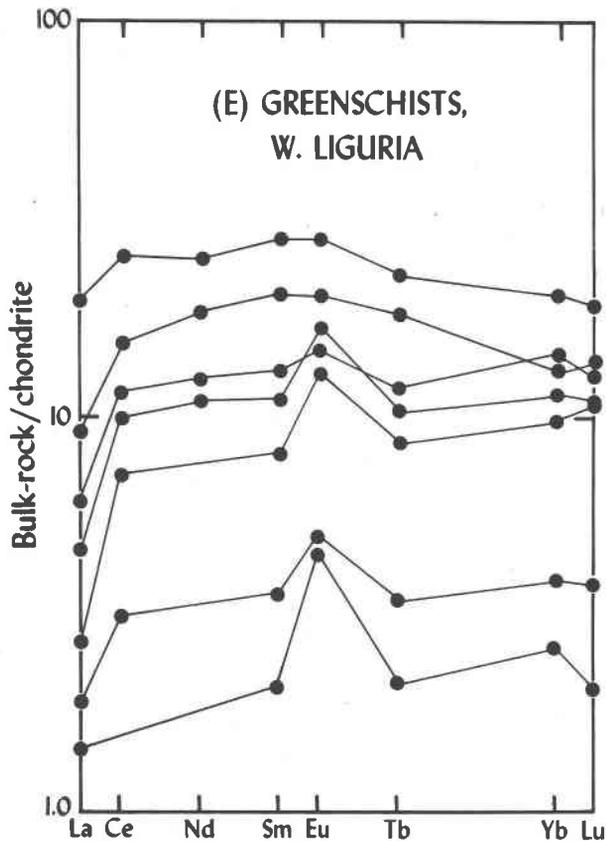
(D) BARROISITIC AMPHIBOLITES, W. LIGURIA

Fig. 10. Chondrite-normalized rare earth element concentrations in eclogites and related rocks from the Beigua serpentinite, Gruppo di Voltri, western Liguria. Data are from Ernst and Rambaldi, unpublished and preliminary. Although a continuum of transitional assemblages was produced by the recrystallization of earlier metarodingites (A), and eclogites (B), three principal stages in this later metamorphism have been delineated, glaucophane-rich (C), barroisite-rich (D), and actinolite-rich (E).

layer silicates, presumably impoverished in REE, may account for the disparity in REE concentrations in the two samples.

Eclogite analyses display uniformly flat, sub-parallel HREE trends, and consistent LREE depletions (Fig. 10B). Samples with high concentrations of rare earth elements generally contain less modal epidote and more garnet ± apatite than samples with low REE proportions. All analyzed rocks carry 41±6 volume percent omphacite, so although clinopyroxene is expected to be a major host of lanthanide series elements, the observed dispersal of the data cannot be ascribed to variable proportions of this mineral.

Glaucophane schists possess flat patterns, although La contents tend to be relatively low in all analyzed rocks (Fig. 10C). Abundances of rare earth elements range to higher values than those of parental eclo-

gites. Similar to the eclogitic protolith, higher concentrations of REE more or less reflect the abundance of apatite, and perhaps also are inversely proportional to the modal layer silicates formed during the late-stage greenschistic metasomatism.

Fairly flat HREE patterns and marked LREE depletions, especially of La, characterize the barroisitic amphibolites (Fig. 10D). An indistinct tendency for apatite-bearing amphibolites to be enriched in rare earths, and chloritic amphibolites to be impoverished in rare earths may be recognized.

Greenschists have lower REE contents relative to sodic and calcic amphibole-bearing precursors (Fig. 10E). From this we may infer that interaction between metasomatic fluid and chlorite does not concentrate REE in the layer silicate as strongly as between the aqueous phase and chain silicates. Because most silicates experimentally investigated thus far concentrate REE relative to an associated aqueous phase (Hanson, 1980), it appears that large amounts of such a metasomatic fluid must have coursed through the pre-existing high-pressure Gruppo di Voltri mineral assemblages to account for the systematically lower rare earth concentrations in the greenschists. An alternative explanation is that most greenschists studied had an Mg-rich leucogabbro parent, as advocated by Cortesogno et al. (1977) and Messiga and Piccardo (1980), and hence reflect the REE abundances of a source rock different from the eclogitized ferrogabbros.

Eclogite mineral chemistry

Electron microprobe analyses for coexisting minerals from Western Alpine and western Ligurian eclogitic parageneses have been previously published by the author. Phases from 6 rocks from Alpe Arami, 13 from the Zermatt area and 25 from the Gruppo di Voltri were investigated in these studies. Chemical data were provided for garnet, omphacite, sodic amphibole, calcic amphibole, epidote, plagioclase, layer silicate minerals (chlorite, biotite, paragonite, phengite), kyanite and sphene. For the purpose of calculating cation proportions, iron was considered as half ferric in sodic amphiboles and omphacites, as exclusively ferrous in calcic amphiboles. Similar mineral analyses have been obtained for the general area by Bearth (1967, 1973), Chinner and Dixon (1973), Kienast (1976), Compagnoni (1977), Compagnoni et al. (1977), and Desmons and Ghent (1977).

Proportions of iron, magnesium and Ca + Mn for analyzed garnets from Alpe Arami, Zermatt and western Liguria are illustrated in Figure 11. Distinct compositional clustering is evident. Gruppo di Voltri

protoliths are more ferruginous than the ophiolitic parents from the Zermatt region, hence western Ligurian garnets are more almandine-rich than those from the Western Alps. Both groups, however, are far less pyropic and somewhat more manganiferous than eclogitic layers associated with the garnet lherzolite at Alpe Arami. Average compositions are: Alpe Arami, $Alm_{39}Py_{37}Gross_{23}Spess_{01}$; Zermatt, $Alm_{66}Py_{08}Gross_{23}Spess_{03}$; and Gruppo di Voltri, $Alm_{74}Py_{06}Gross_{16}Spess_{04}$.

Cations inferred to be occupying the larger M(2) site in analyzed clinopyroxenes are shown in Figure 12. Departure of the analytical data points from the dashed line, along which $\sum (Na + Ca) = 1.00$, reflects analytical error and/or the minor presence of additional cations such as Mn, Fe^{2+} and Mg (below line), or the very unlikely actual presence in M(1) of minor Ca + Na (above line). At Alpe Arami, the early stage retrograde metamorphism of the eclogite produced symplectite, consisting of intergrown clinoamphibole, clinopyroxene and intermediate plagioclase; the symplectic clinopyroxene is very diopsidic, as can be seen from Figure 12. In the Gruppo di Voltri, the clinopyroxene of a metarodingite reflects the sodium-poor nature of the host rock, hence also is very diopsidic. All other 31 analyses are of intermediate Na–Ca solid solutions properly termed omphacites (+ chloromelanites). Although extensive compositional overlap is evident, the western Ligurian specimens tend to be slightly more sodic than analogues from the Zermatt area, with the Alpe Arami primary eclogitic clinopyroxenes more calcic. Based on inferred M(1) cation proportions, average compositions for the omphacites are: Alpe Arami, $Jd_{43}Ac_{00}Di_{49}Hd_{08}$[1]; Zermatt, $Jd_{42}Ac_{12}Di_{34}Hd_{12}$; and Gruppo di Voltri, $Jd_{33}Ac_{16}Di_{35}Hd_{16}$. Comparison of these proportions with M(2) proportions illustrated in Figure 12 suggests that the actual Fe^{3+}/Fe^{2+} ratios in Ligurian omphacites may exceed the unit value assigned; higher ratios would increase the computed Ac content at the expense of Hd and would be more reasonable in the light of the observed highly sodic compositions obtained by direct analysis.

Na-amphiboles are not present in the Alpe Arami paragenesis. Analyses of blue amphiboles from the Zermatt and Gruppo di Voltri areas are plotted in Figure 13. The inferred Al^{VI} and Fe^{3+} occupancies of the M(2) site are shown along the abscissa, that of

$Mg + Fe^{2+}$ in M(1) and M(3) along the ordinate. Zermatt phases tend to be more magnesian than sodic amphiboles from western Liguria, undoubtedly reflecting the iron-rich nature of the latter rocks. Average compositions are approximately: Zermatt, $Gl_{77}Rieb_{23}$; Gruppo di Voltri, $Gl_{69}Rieb_{21}$.

Inferred cation occupancies of the large M(4) and A sites in analyzed calcic amphiboles from Alpe Arami, Zermatt and western Liguria are shown in Figure 14. At all three localities, early hornblendes are armored and partly replaced by more actinolitic clinoamphiboles. At Alpe Arami the precursor hornblendes are magnesian, Ti-rich pargasites which contain substantially more tetrahedrally than octahedrally coordinated aluminum, averaging 1.64 Al^{IV} and 0.74 Al^{VI} per formula units. The early-stage calcic amphiboles in both Zermatt and Gruppo di Voltri parageneses are barroisitic; they are intermediate iron–magnesium solid solutions, carry only minor amounts of Ti, and have subequal amounts of Al^{IV} and Al^{VI}. The calcic amphiboles in these metaophiolites also exhibit a gradational and continuous transition from barroisitic compositions to late-stage actinolites.

The eclogites and related rocks studied in this report contain epidote group minerals, plagioclase, layer silicates and sphene as major retrograde phases, and in addition, some of the Alpe Arami assemblages contain very minor amounts of kyanite (see Figs. 8 and 9). Averages of $Fe^{3+}/(Al^{VI} + Fe^{3+})$ for epidote from Alpe Arami, Zermatt–Saas Fee and the Gruppo di Voltri are 0.03, 0.15 and 0.17, respectively. In both latter areas, indistinct zoning occurs in the epidotes, and the late-stage greenschistic compatibilities include a more aluminous clinozoisite compared to the more pistacitic composition which accompanies barroisitic hornblende. Analyzed plagioclase grains are homogeneous in all three areas. It is chiefly oligoclase at Alpe Arami, where three analyses range from An_{15} to An_{37}. In contrast, in the ophiolitic eclogites, greenschistic stages are characterized by pure albite, An_{01} at Zermatt, An_{00} to An_{02} in the Gruppo di Voltri. A single analysis of plagioclase from a metarodingite at the latter locality is An_{22}, reflecting the high calcium and low sodium contents of the host rock. Only a few layer silicates have been analyzed, so conclusions regarding compositional ranges for the eclogitic parageneses remain provisional. A single analyzed Alpe Arami chlorite is compositionally intermediate between sheridanite and iron-poor ripidolite; more extensive chemical data for Zermatt and Gruppo di Voltri chlorites indicate that they range

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[1] Assumption of all ferrous iron in the Alpe Arami clinopyroxene provides Di + Hd proportions equivalent to the analyzed Ca/(Na + Ca).
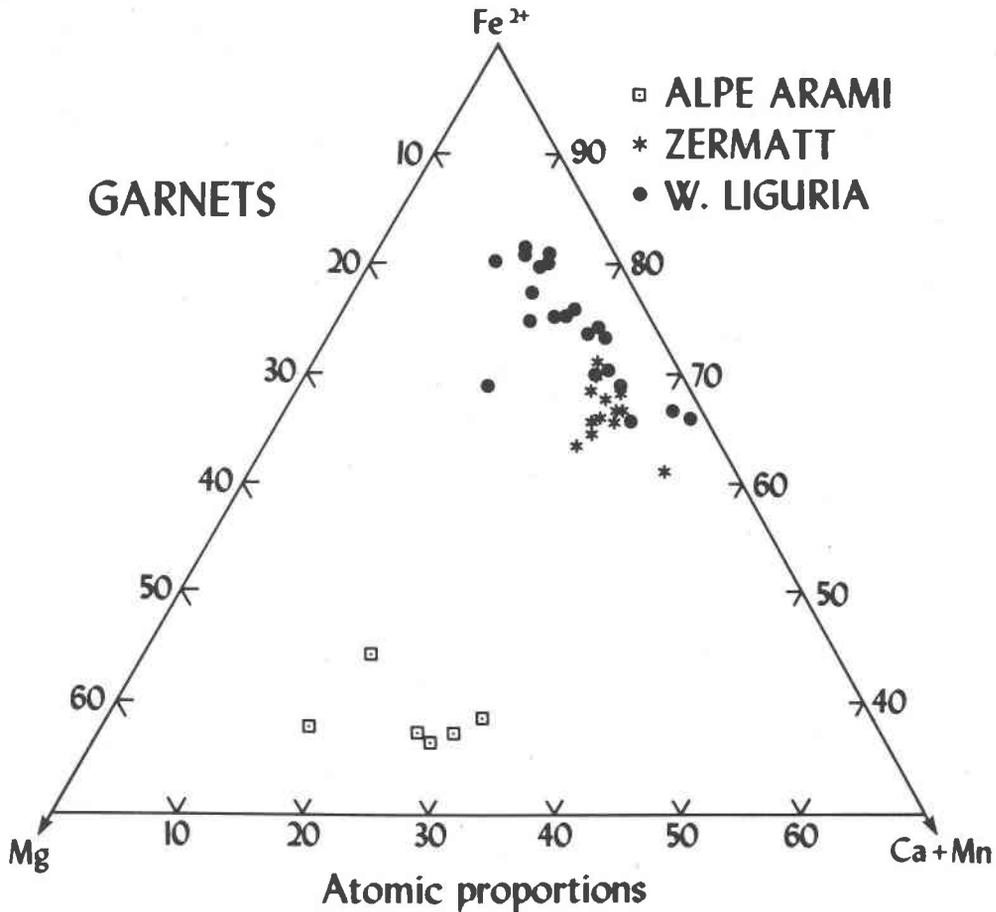
Fig. 11. Atomic proportions of Fe^{2+}, Mg and Ca + Mn in analyzed garnets from Western Alpine and Ligurian eclogites. Data from: Ernst (1976, 1977), Ernst and Dal Piaz (1978). All iron has been considered as ferrous for the computation of cation proportions. Note that only the almandine-rich portion of the ternary diagram is shown.

from ripidolite towards iron-rich clinochlore. White micas in the latter two areas include both paragonite and phengite. Late-stage biotite and sphene occur in all three parageneses, but were not studied in detail.

P-T conditions of eclogite crystallization

In contrast to aluminous peridotite petrogeneses, where numerous theoretically derived and experimentally tested geothermometers and several independent geobarometers may be utilized, only a very few suitable methods are available for the assignment of physical conditions of origin to eclogites. This is a consequence of the fact that lherzolites represent well-constrained mineralogical associations (typically 4 or 5 phases in a 5-component system), whereas eclogitic assemblages possess high variance (2 or 3 phases in a 9-or 10-component system). Moreover, due to the chemical complexities, petrogenetic grids for basaltic compositions are as yet impossible to calculate from fragmentary thermochemical data

on end member minerals, and have proven difficult to experimentally determine at subsolidus temperatures (Yoder and Tilley, 1962; Green and Ringwood, 1967b; Cohen *et al.*, 1967; Essene *et al.*, 1970). Other than $^{18}O/^{16}O$ fractionation studies (*e.g.*, Taylor and Coleman, 1968; Desmons and O'Neil, 1978), which provide an indication of the temperature of oxygen isotopic equilibrium, the most useful estimates of *P-T* conditions appear to be based on the partitioning of iron and magnesium between coexisting garnet and clinopyroxene. K_D values, $(Fe^{2+}/Mg)_{garn}/(Fe^{2+}/Mg)_{cpx}$ are a function of the physical variables (Råheim and Green, 1974, 1975), and to some extent reflect compositional variables as well, especially Ca content (Ellis and Green, 1979).

Employing the eclogitic garnet + clinopyroxene microprobe data previously summarized, and the experimentally calibrated iron–magnesium fractionations elucidated by Ellis and Green, the computer program devised by A. A. Finnerty (see section on
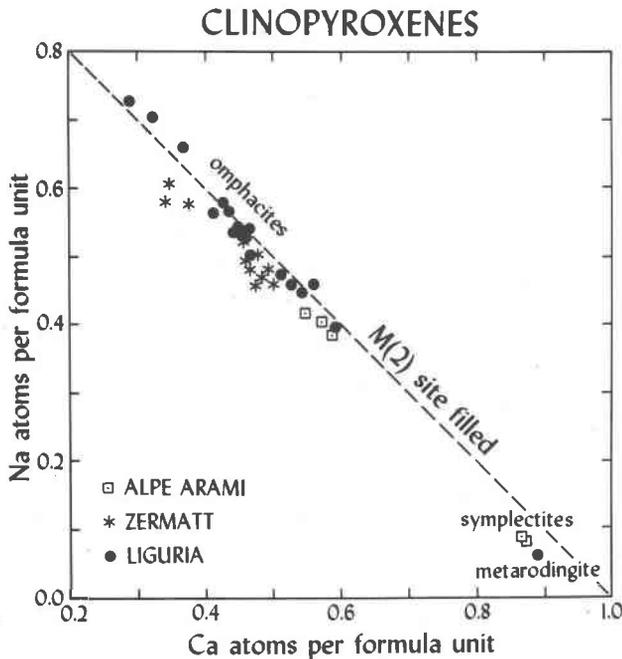
CLINOPYROXENES

Fig. 12. Sodium and calcium atoms per six oxygens in analyzed clinopyroxenes from Western Alpine and Ligurian eclogites. Data from: Ernst (1976, 1977); Ernst and Dal Piaz (1978). Equal proportions of Fe^{3+} and Fe^{2+} have been assumed for the purpose of calculating cation proportions, except for Alpe Arami, where more reasonable cation totals were obtained by assuming that all iron is divalent. Note that the low Ca, high Na portion of the diagram is not shown.

peridotite conditions of crystallization) provided nominal temperatures of eclogite equilibration as a univariant function of pressure. For Alpe Arami, an operating pressure of 40 kbar was chosen to conform with the value obtained for the associated garnet lherzolite. For Zermatt–Saas Fee and the Gruppo di Voltri, a pressure of 10 kbar was arbitrarily selected. Ten kbar appears to represent a reasonable minimal value because of the sporadic occurrence of nearly pure jadeitic pyroxene in associated quartzose rocks (Lorenzoni, 1963; Bocquet, 1971; Compagnoni and Maffeo, 1973); moreover, at lower pressures, more hydrous, lower grade assemblages would have been generated. If the actual pressures did in fact exceed 10 kbar, as appears likely, the calculated temperatures of eclogite formation would also be slightly higher. Results of the computations are presented in Table 7.

Quite clearly the Alpe Arami eclogites, characterized by a K_D of about 6, crystallized at much higher temperatures than the ophiolitic eclogites of Zermatt–Saas Fee and western Liguria, where K_D values average approximately 21 and 29, respectively. As-

signing a pressure of 40 kbar at Alpe Arami yields an average temperature for eclogite equilibration of 898±43°C, in surprisingly good agreement with the grand average value of 949±75°C arrived at previously for the associated garnet lherzolite (compare Tables 3 and 7).

Assuming a minimal 10 kbar total pressure, the less extreme conditions of origin, 433±62°C for the Gruppo di Voltri and 527±52°C for Zermatt, have been obtained (Table 7). Support for the Zermatt P-T assignments may be found in petrologic investigations by other workers for more internal portions of the Pennine and the Sesia–Lanzo zones (presumably more deeply subducted), where the following physical conditions have been estimated for similar eclogitic assemblages: Kienast (1976), 500–600°C, $P \geq 10$ kbar; Campagnoni (1977), 500–600°C, $P > 15$–17 kbar; Desmons and Ghent (1977), 500–530°C, $P > 12$ kbar; Reinsch (1979) 450–550°C, $P = 12$–16 kbar; and Desmons and O'Neil (1978), 540°C. For the kyanite-bearing eclogites of the Tauern Fenster of the Eastern Alps, Holland (1979) has suggested the attendance of even more extreme physical conditions, approaching 620±30°C and 19.5±2.5 kbar. At Zermatt and in western Liguria, the association of
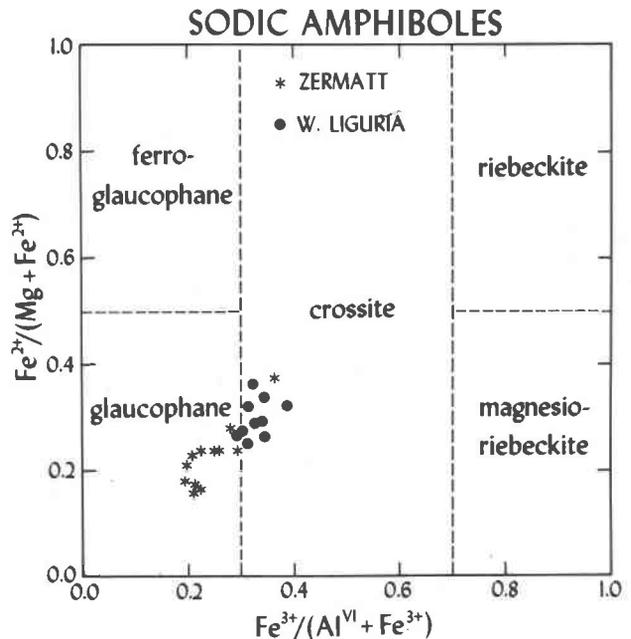
SODIC AMPHIBOLES

Fig. 13. Compositions of analyzed sodic amphiboles from Western Alpine and Ligurian eclogitic rocks. Data from: Ernst (1976, 1977); Ernst and Dal Piaz (1978). Equal proportions of Fe^{3+} and Fe^{2+} have been assumed for the purpose of calculating the cation ratios for M(2) along the abscissa, M(1) + M(3) along the ordinate.
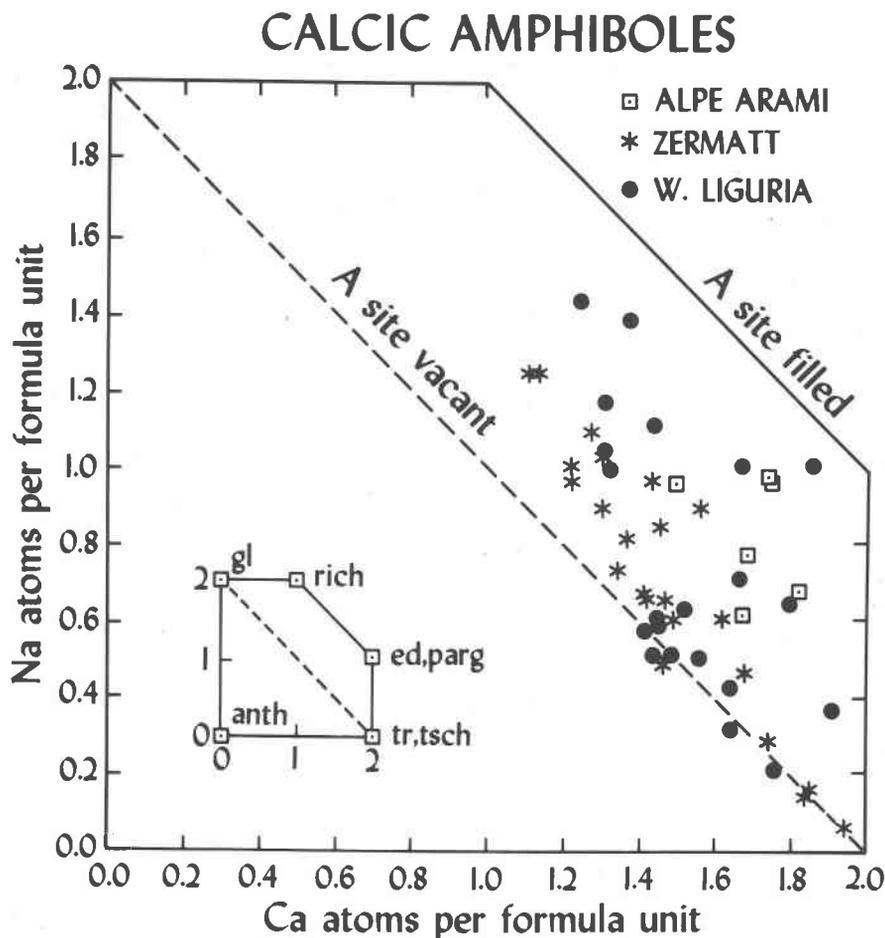
CALCIC AMPHIBOLES

Fig. 14. Sodium and calcium atoms per 23 oxygens (assuming·one H_2O) in analyzed calcic amphiboles from Western Alpine and Ligurian eclogitic rocks. Data from: Ernst (1976, 1977); Ernst and Dal Piaz (1978). All iron has been considered as ferrous for the computation of cation proportions.

eclogitic rocks with antigoritic serpentinite suggest thermal maxima less than about 600°C (Evans, 1977).

Retrograde paths followed by the eclogitic rocks on their transit to the present crustal levels for all three occurrences seemingly involved rapid decompression relative to the rate of temperature decline. As a matter of fact, a small increase in T during the initial stages of decompression is theoretically possible, as discussed by England (1978) and Richardson and England (1979), but such heating is not required by the observed parageneses. The stability relations of glaucophane (Maresch, 1977), barroisite and actinolite (Ernst, 1979), the muscovite–paragonite solvus (Eugster et al., 1972), the greenschist–amphibolite facies transition for rocks of basaltic composition (Liou et al., 1974), and reactions involving amphibolites (Lambert and Wyllie, 1972; Holloway

and Burnham, 1972; Allen and Boettcher, 1978; Spear, 1981), all provide important constraints on the mineral assemblages of interest. A previously discussed petrogenetic grid, consistent with available oxygen isotopic and phase equilibrium data for regional metamorphic rocks of roughly tholeiitic composition is presented as Figure 15. The decompression P-T paths indicated for the retrograde metamorphism in all three cases appear to be nearly adiabatic, reflecting geologically rapid ascent to the present locus. The manner in which this was accomplished is a serious tectonic problem.

Petrology and plate tectonic setting

Mineral assemblages and inferred conditions of crystallization described here for eclogites and peridotites from the Western and Ligurian Alps appear to be consistent with data obtained by other workers.

Table 7. Apparent temperatures of equilibration for analyzed eclogite samples employing the iron–magnesium partitioning data of Ellis and Green (1979).

Sample Number	Temperature (°C)	Assumed Pressure (kb)
Alpe Arami		
F-16d	855	40
F-16f	910	40
F-53	953	40
F-54	874	40
average	898±43	40
Zermatt		
MRO-857	472	10
MRO-1105	499	10
MRO-1109	448	10
MRO-1609	595	10
MRO-1611	576	10
DBL-379	513	10
DBL-409	563	10
DBL-497	551	10
average	527±52	10
Gruppo di Voltri		
EE-3	556	10
EE-31	396	10
EE-43	539	10
EE-63	495	10
EE-64	438	10
EE-66	391	10
EE-72	366	10
EE-77	374	10
EE-79*	413	10
EE-79	395	10
EE-82	432	10
EE-85*	451	10
EE-85	378	10
average	433±62	10

*   core values;   unstarred are homogeneous or rim values.

Of considerable importance is the fact that the contrasting parageneses seem to be related to the plate tectonic settings of the northern and southern Alpine terrains.

Gabbroic rocks of the nonsubducted South Alpine plate are devoid of high-pressure phase assemblages, indicating that they were produced at relatively shallow depths in the upper mantle, or deep within the sialic crust. Those associated with peridotites were probably formed during decompression melting accompanying tectonic ascent of the parental lherzolites. Conditions of last equilibration of the ultramafics appear to be 900–1100°C at 10–15 kbar; for those subjected to incipient partial melting, somewhat lower pressures of pyroxene annealing seem to be indicated. The fact that most of the South Alpine ultramafics are clinopyroxene-bearing rather than being harzburgitic in composition supports the hypothesis that these rocks are samples of subcontinental rather than shallow suboceanic mantle (Nicolas and Jack-

son, 1972). This accounts for their general pre-Mesozoic crustal setting, except for those which have undergone tectonic transport, such as Lanzo and the Erro–Tobbio peridotite of western Liguria.

In contrast, the eclogitized mafic and serpentinized ultramafic associations of the North Alpine plate possess ophiolitic affinities, and were probably generated during the mid-Mesozoic sea-floor spreading event which produced the Tethyan oceanic realm. Although the original peridotites have been totally serpentinized (e.g., see Dietrich et al., 1974), normative anhydrous equivalent assemblages apparently would be harzburgitic. The accompanying mafic rocks include gabbros and pillow basalts (Bearth, 1959, 1967), now variably converted to eclogitic compatibilities. Such assemblages have equilibrated under the high-pressure, low-temperature conditions inferred to characterize subduction zones. Temperatures and pressures of 450–600°C, 10–12 kbar would also explain the association with antigoritic serpentinite (Evans, 1977). The direction of North Alpine lithospheric underflow—to the south and east beneath the South Alpine plate—has been deduced on the basis of fold vergences, décollements, and the externally decreasing grade of high-pressure metamorphism (Ernst, 1971, 1973; Dal Piaz et al., 1972; Frey et al., 1974). Buoyant ascent toward the surface of these subducted ophiolitic sections was probably a tectonic response to the gravitative instability generated by the downward conduction of relatively low-density serpentinized and hydrated oceanic crust and uppermost mantle and sialic massifs with surrounding sediments which characterize the Tethyan realm.

The striking anomaly in an otherwise self-consistent petrologic and plate tectonic scenario is presented by Alpe Arami. Although various authorities have calculated different nominal P-T conditions of origin for this body, all agree that the pressures and temperatures greatly exceed those under which the surrounding Lepontine gneisses recrystallized. For instance, based on methods described in previous sections of this report, Alpe Arami garnet lherzolites and marginal eclogites are computed to have equilibrated at 900–950°C and about 40 kbar, whereas the adjacent gneisses evidently crystallized at approximately 650°C and 6–7 kbar. The sheared, mylonitized contact bounding the Alpe Arami lens (Buiskool Toxopeus, 1976) is evidence that it was tectonically inserted into its present site. Although an overprint of lower grade, hydrous assemblages is evident from the described parageneses (Table 1, Fig. 8), such phenomena occur in the Lepontine gneisses
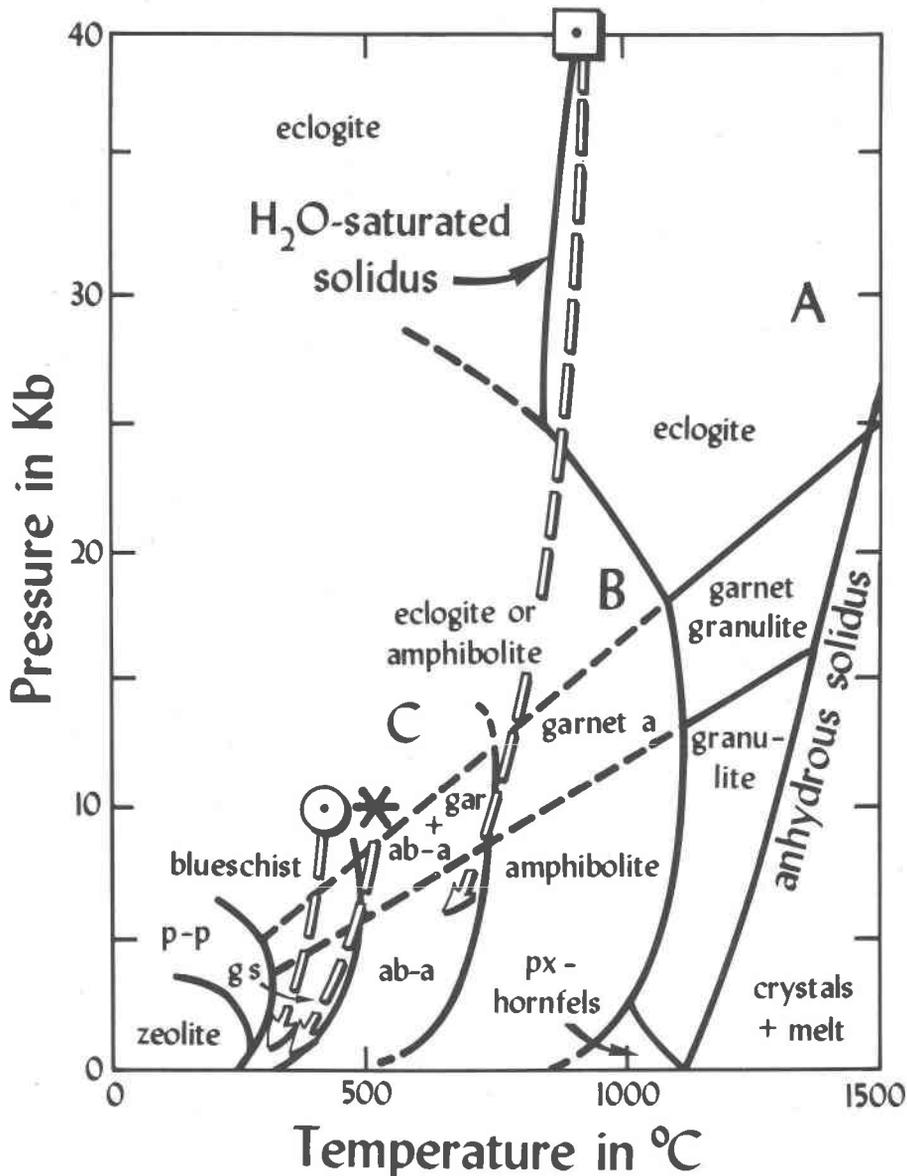
Fig. 15. Petrogenetic grid for rocks of basaltic compositions based on available experimental and oxygen isotopic data (see text and Ernst, 1973). Metamorphic zone boundaries are shown as univariant lines for simplicity, but are actually multivariant *P-T* zones of finite width; their locations and widths are sensitive functions of numerous chemical variables. Facies abbreviations are: a = amphibolite; bs = blueschist; gs = greenschist; pp = prehnite-pumpellyite; z = zeolite. Where aqueous fluid pressure is equal to P_{total}, amphibole-dominant assemblages are stable over most reasonable crustal- and uppermost mantle-type conditions. The approximate fields of formation for type A, B and C eclogites of Coleman *et al.* (1965) are indicated. Symbols denote the initial conditions of eclogite formation as listed in Table 7 for Alpe Arami (= box), Zermatt (= star) and the Gruppo di Voltri (= circle).

as well. It seems unlikely that this small mafic and ul- tramafic body could have been emplaced in such a quartzofeldspathic terrain prior to the penetrative, high-rank amphibolite facies metamorphism without undergoing extensive metasomatic exchange, and re- sulting in the obliteration of the granulated contacts. Evidently the Alpe Arami lens was a late metamor-

phic interloper in the Lepontine gneiss realm. How it got there is unclear and must await investigations for future workers. As an added incentive, it should be noted that *P-T* conditions suggested for crystalliza- tion of this body are not far removed from those esti- mated for diamond-bearing kimberlites (Boyd, 1973).

Acknowledgments

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