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M.J. Giaramita · S.S. Sorensen

Primary fluids in low-temperature eclogites: evidence from two subduction complexes (Dominican Republic, and California, USA)

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Abstract Eclogites occur as isolated blocks in melanges of both the Samana Peninsula, Dominican Republic, and the Franciscan Complex, California, USA. In some of these eclogites, fluid inclusions were found in omphacite and sodic-calcic amphibole grains. Textures show that non-planar populations of fluid inclusions formed during growth of clinopyroxene and amphibole. In addition, planar arrays of secondary fluid inclusions are found along healed cracks. Homogenization temperatures to liquid were used to calculate isochores for the fluid inclusions. These data were compared with petrologic geothermobarometry. Temperature conditions of 500–700° C were estimated from garnet-clinopyroxene geothermometry. The jadeite contents of omphacite indicate minimum pressures of 8–11 kbar in this temperature range. The P-T estimates agree well with calculated isochores for primary fluid inclusions from the Samana Peninsula, and show some overlap for both primary and secondary fluid inclusions from the Franciscan Complex. Salinities of 1.2–5.3 wt% NaCl equiv. were estimated for both primary and secondary fluid inclusions from Samana and Franciscan eclogites. These data suggest that low-salinity aqueous fluids attended eclogite-facies metamorphism and perhaps retrograde metamorphism in both subduction complexes. The salinities and densities of fluid inclusions in eclogites from the Samana Peninsula and the Franciscan Complex resemble those of counterparts from garnet amphibolites of the Catalina Schist, southern California. An external source for such fluids is suggested by their homogeneous populations coupled with their low salinities. Geologic evidence suggests that the Samana and Franciscan eclogites may have been derived from a Catalina-like source terrane. The Catalina rocks are inferred to have interacted with large volumes of sediment-derived fluid during subduction zone metamorphism at similar P but higher T conditions than those determined for Samana and Franciscan eclogite blocks. These results contrast with data for fluid inclusions from eclogites of the Monviso area, western Alps. The Monviso eclogites yield similar estimates for metamorphic P-T to those obtained in this study, but contain fluid inclusions of brine and of other saline aqueous fluids, all of which are less dense than expected for incorporation at the reported eclogite-facies conditions. The differences between the properties of fluid inclusions from the eclogites and garnet amphibolites of the Samana-Franciscan-Catalina subduction complexes and those of Monviso probably reflect differences between fluid-flow regimes during metamorphism.

M.J. Giaramita[1] ✉ · S.S. Sorensen
Department of Mineral Sciences, NHB-119,
National Museum of Natural History, Smithsonian Institution,
Washington, DC 20560, USA

Present address:
[1] Department of Physics and Geology,
California State University, Stanislaus,
801 West Monte Vista Avenue, Turlock, CA 95380, USA

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Introduction

Fluids play a major role in mass transport in subduction complexes (e.g., Tatsumi 1989; Bebout 1991; Moran et al. 1992; Peacock 1990; Moore and Vrojlik 1992). Furthermore, fluid flow may influence the evolution of thermal regimes of subduction zones (e.g., Anderson et al. 1976, 1978; Delany and Helgeson 1978; Peacock 1990). The compositions of fluids attending moderate depths of subduction (ca. 25–35 km) can be estimated from stable isotope data, inferred from petrologic calculations, or measured if fluid inclusions preserve fluids trapped at these depths.

Petrologic studies of low-temperature (LT) eclogites (classification of Carswell 1989) from high-pressure metamorphic terranes suggest that, in general, these rocks return to the surface from depths that correspond to minimum pressures of 11 kbar; metamorphic temperature estimates range to 550–600° C (e.g., Schliestedt

1989; Oh and Liou 1990). Metamorphism of LT eclogites is probably not "dry." This is attested to by the modal abundance of hydrous minerals such as sodic amphibole, clinozoisite, epidote, or zoisite, and phengite in apparent equilibrium with garnet and omphacite, and occurrences of euhedral omphacite filling cavities in eclogites (Cloos 1986; Schliestedt 1989). Studies of LT eclogite blocks indicate that lower-T exposure to subduction zone fluids forms an interior-to-exterior zonation of retrograde mineral assemblages as well as veins of low-T, high-P hydrous minerals, and mediates reactions between blocks and ultramafic rocks (Coleman 1967, 1980; Moore 1984). Thus, if fluid inclusions are preserved in LT eclogite blocks, they could record a long history of fluid-rock interactions at various temperatures and depths in the subduction zone metamorphic environment.

This paper reports occurrences of fluid inclusions in omphacite and sodic-calcic amphibole grains in eclogite blocks from the Samana Peninsula, Dominican Republic, and from the Franciscan Complex, California, USA. We discuss the geologic settings of the host eclogite blocks, and report the textures, compositions, and densities of the fluid inclusions. We then compare our results with those of previous studies of a low-temperature (LT) eclogite terrane in the Alps and of a related terrane in California, and propose a hypothesis for the controls of the compositions of fluids that attend LT eclogite-facies metamorphism.

Metamorphic geology of the eclogites

The geologic settings of the Franciscan and Samana eclogites have several features in common, but an important contrast. In both regions, eclogite blocks are found in continental-margin subduction complexes in which large amounts of both hydrated ocean crust and subducted sediment were consumed (Hamilton 1969; Nagle 1974; Perfit et al. 1980; Bowin and Nagle 1982; Cloos 1985; Joyce 1991). In both areas, the eclogite blocks are found in matrices of both metasedimentary and meta-ultramafic rocks. Blocks that are not presently in a matrix of serpentinite or talc schist matrix display schistose Mg-rich rinds of Ca-amphibole $\pm$ layer-silicate minerals. Rinds are evidence that at one time in their history, the eclogite blocks were metasomatized in direct contact with ultramafic rocks (Coleman 1980; Moore 1984; Cloos 1986). A significant geologic contrast between the Samana Peninsula and the California Coast Ranges is the predominance of calcareous metasedimentary rocks in the former, and of metagraywacke-metashale sequences in the latter (cf. Bailey et al. 1964; Joyce 1991). The sections below briefly describe the field occurrences of eclogites in the two subduction complexes, and cite articles that review the geology and petrology in more detail.

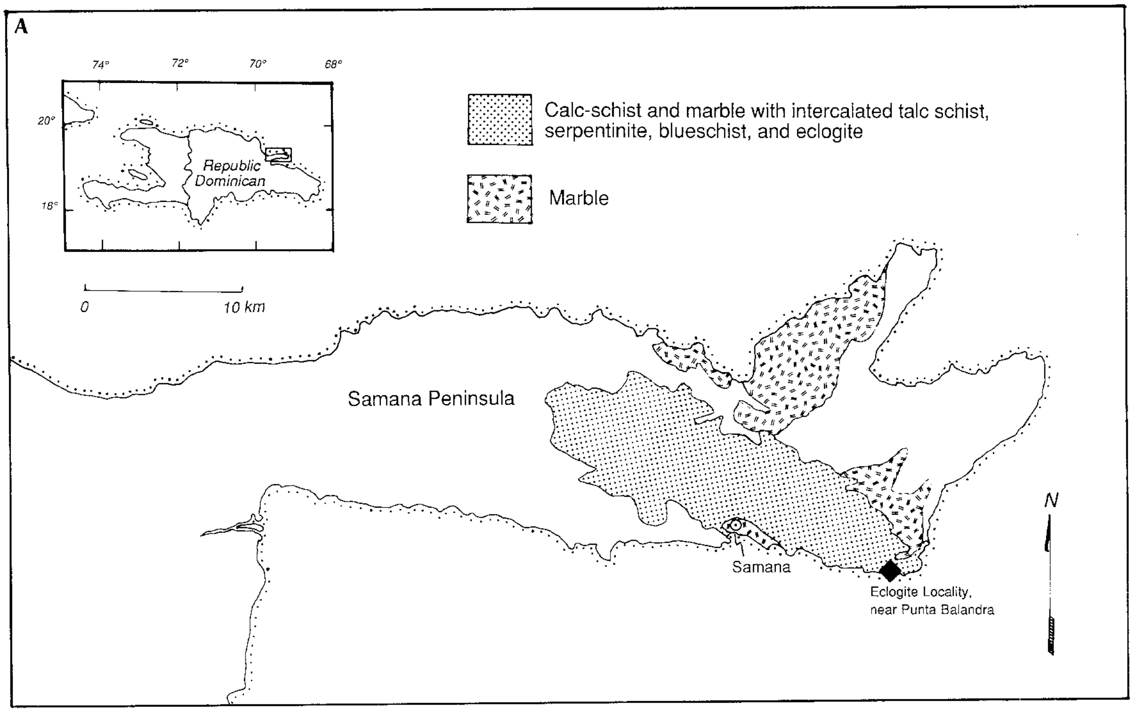
Samana Peninsula, Dominican Republic

On the Samana Peninsula of the Dominican Republic, high-grade blocks occur in a zone (the Punta Balandra zone) within the Santa Barbara Schist of the Samana Metamorphic Complex (of Joyce 1991). The eclogite blocks sampled for this study are located east of the town of Samana, near Punta Balandra on the south coast of the Samana Peninsula (Fig. 1A). In this area, eclogites occur: (1) as boudins 0.5 m or less in their longest dimension in a single outcrop of coarse-grained calcite marble along the coast road near Punta Balandra, (2) as inclusions 0.5 to 3 m in diameter, with or without rinds, in lenses of talc and chlorite schist within metasedimentary rocks, and (3) as meter-scale loose blocks in canyons or on beaches between the "marble locality" and the town of Samana (cf. Joyce 1991). The loose blocks, many of which display rinds, are presumably derived from outcrops similar to setting (2). The small eclogite lenses and boudins in the marble outcrop show extensive cataclasis and alteration of clinopyroxene, replacement of pyroxene and garnet by carbonate, and development of retrograde epidote-blueschist facies assemblages; the remnants of clinopyroxene in these boudins lack fluid inclusions and were not studied.

The eclogite-bearing talc and chlorite schist lenses range to tens of meters wide and have foliations parallel with their borders, which locally crosscut the foliation of surrounding calcareous schists, micaceous marbles, and semipelitic schists. The mineral assemblage of the semi-pelitic schists indicates greenschist facies: it consists of actinolite, albite, quartz, clinozoisite, chlorite, white mica, calcite, and sphene. Inclusions of lawsonite are present only in albite and clinozoisite porphyroblasts of the semi-pelitic schists. This texture suggests that an earlier, relatively high-P/low-T metamorphism in the host rocks of the eclogite-bearing lenses of ultramafic rock was overprinted by greenschist-facies conditions. Although the eclogites contain epidote and sodic amphibole, the textures of these minerals do not demonstrate that these phases are retrograde, and no indications of retrograde greenschist-facies metamorphism are present (cf. Joyce 1991). The lack of a common metamorphic history and the local discordance between foliation in the eclogite-bearing lenses and that of their metasedimentary host rocks together suggest that metamorphism of the high-grade blocks did not occur in situ in the regional P/T trajectory (cf. Joyce 1991). Nagle (1974) first pointed out the significance of occurrences of eclogite and blueschist in Hispaniola for the tectonic evolution of the region. The metamorphic geology of the Samana Peninsula was studied by Joyce (1980 1985 1991); the metamorphic geology of high P/T rocks in Hispaniola was reviewed by Draper and Lewis (1991). Perfit et al. (1980, 1982) and Perfit and McCulloch (1982) reported trace element and radiogenic isotope data for eclogites and blueschists from the Samana Peninsula, and for similar metamorphic rocks from the Puerto Rico Trench.

Franciscan Complex, California, USA

The eclogites of the Franciscan Complex of the California Coast Ranges have a long history of petrologic study (Holway 1904; Switzer 1945; Borg 1956; Coleman et al. 1965; Coleman and Lanphere 1971; Ghent and Coleman 1973; Brown and Bradshaw 1979; Oh and Liou 1990). Eclogite blocks from three well-known localities were sampled for this investigation (Fig. 1B). These are: (1) at Jenner, just north of where the Russian River enters the Pacific Ocean (Crawford 1965; Oh 1990), (2) on Ring Mountain of the Tiburon Peninsula (Ransome, 1895; Taliferro 1943; Dudley 1972; Rice et al. 1976; Ingersoll et al. 1984; Oh 1990), and (3) on the road to Mt. Hamilton (Cloos 1986, Moore and Blake 1989; Nelson 1991). Locality (3) was bulldozed in the summer of 1990 during road work, and existed then only as partly buried, tumbled slabs. In all three of these localities, eclogite occurs as one or more blocks within melange, or as float. One block at Jenner, several blocks at Tiburon, and the Mt. Hamilton block bear rinds of actinolite $\pm$ chlorite, white mica, and talc. The nature of the melange matrix is uncertain at the three localities studied. At



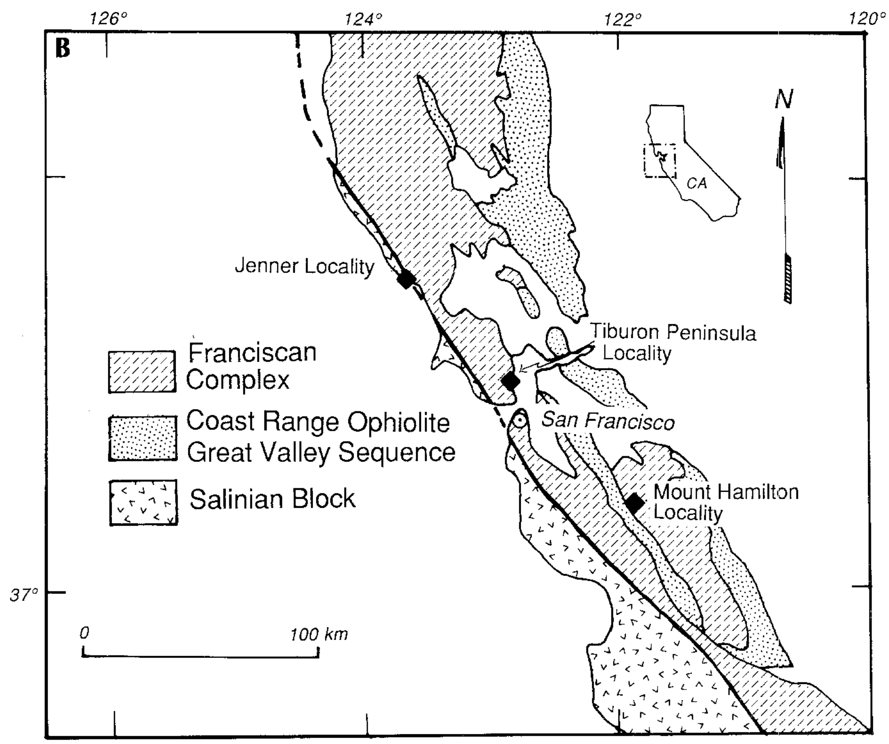


Fig. 1A,B Index maps of eclogite localities in the Dominican Republic and California. **A** (after Joyce 1980, 1991), shows the eclogite locality near Punta Balandra and the town of Samana on the south coast of the Samana Peninsula; **B** (after Moore and Blake 1989), shows eclogite localities at Jenner, the Tiburon Peninsula, and Mount Hamilton, all in the Coast Ranges of northwestern California

Tiburon, serpentinite is present, but nowhere are high-grade blocks observed cropping out in serpentinite matrix. A detailed map at ~1:17,000 and structure sections by Rice et al. (1976) place the blocks in melange horizons of sheared shale ± sandstone matrix, which are intercalated with serpentinite. At Jenner and Mt. Hamilton, outcrops in the immediate area contain a substantial component of metasedimentary rock and shale-matrix melange (Crawford 1965; Moore and Blake 1989; Cloos, personal communication 1993). Cloos (1986) reported that many high-grade blocks of the Central Melange Belt of the Franciscan Complex are found in a matrix of fine-grained argillaceous metasedimentary rock, but noted that many bear Mg-rich rinds. Most of the Central Melange Belt consists of metagraywacke and metashale, and the latter rock type probably makes up much of the melange matrix of this unit (e.g., Bailey et al. 1964; Cloos 1983; 1986). The matrix rocks of the Central Melange Belt were metamorphosed at relatively high pressures and low temperatures, although the argillaceous bulk compositions of these rocks may not form blueschist-facies index minerals (Cloos 1983). Coherent sequences of metagraywacke rocks in the Diablo Range contain the blueschist-facies assemblage glaucophane + lawsonite + jadeite (Ernst 1971, 1993).

Analytical methods

Electron probe microanalysis

Garnet, clinopyroxene and amphibole grains were analyzed with the ARL-SEMQ microprobe in the Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC. The accelerating voltage was ~15 kV, and the sample current ~0.025 μA. Counting time for each point was 20 s, and a focussed beam was used. Standards for garnet were United States National Museum catalog numbers (USNM) 87375, 110752, and 143968. Clinopyroxene standards were USNM 110607 and 143965. Amphibole standards were USNM 143965 and manganite. Wet chemical analyses of these minerals are reported in Jarosewich et al. (1980). Precision is estimated at ±2–3% for the elements used in the thermobarometric calculations.

P-T calculations

Mineral compositions were converted to mineral formulae and chemical components for use in thermobarometric equations (Table 1). Pyroxene formulae were calculated by adjusting the ratio of FeO to Fe_2O_3 to satisfy the constraint of four cations per six oxygens per formula unit. The jadeite component of these omphacitic clinopyroxenes ($NaAlSi_2O_6$) was calculated as Na p.f.u minus Fe^{3+} p.f.u. to account for Na in the acmite component ($NaFe^{3+}Si_2O_6$). Garnet formulae were calculated on a 12 oxygen basis, assuming all iron is Fe^{2+}.

In each specimen, one to three garnet grains, each in contact with as many as three clinopyroxene grains, were chosen for microprobe analysis. Three pairs of spots across garnet-clinopyroxene contacts were analyzed. Each analytical pair consists of one spot on each side of the grain boundary approximately 5 to 10 μm from the boundary. Temperatures and minimum pressures of metamorphism were calculated for each garnet-clinopyroxene pair using the geothermometer of Ellis and Green (1979) and the geobarometer reported by Ghent (1988) (Table 1). The two equations were iterated to obtain a single temperature at a minimum pressure for each pair of analyses. The mean temperatures and pressures reported in Table 1 are the values obtained for each sample, which are averages of all garnet-clinopyroxene pairs. The one-sigma uncertainties in Table 1 are the standard deviations of the calculated pressures and temperatures for each sample.

Freezing and homogenizing of fluid inclusions

Measurements of the final melting of ice (T_m, nomenclature of Roedder 1984) and of homogenization of vapor to liquid (T_h) were made on a United States Geological Survey design heating and freezing stage as modified and assembled by T. James Reynolds (Fluid Inc.). Replicate determinations of calibration points suggest the precision of these measurements is ±0.1° C between −56.6 and 0.0° C; homogenization of vapor to liquid in the artificial pure water fluid inclusions up to T~300° C suggests that precision at high temperatures is ±1° C. Ideally, replicate measurements of both T_m and T_h were made for each fluid inclusion. In many cases, however, both types of data were not obtained for a single fluid inclusion due to our inability to observe the phase change or other experimental problems.

Results

Mineral assemblages and P-T conditions of eclogite metamorphism

Eclogites from the two field areas show no significant differences in their mineral assemblages. In addition to garnet and omphacite, the eclogite samples contain calcic, sodic-calcic, or sodic amphibole, white mica, rutile, sphene, and chlorite; most samples also contain pyrite and epidote (Table 2). Sample (SS85-27E) contains quartz in the matrix, and samples SS84-24B, T90-1B1, and MH90-1A contain quartz as inclusions in garnet. The common occurrences of fine-grained white mica + chlorite either as veins that cut garnet or as partial pseudomorphs of garnet suggest that these minerals are retrograde (Table 2). However, elsewhere in the same thin sections, coarse-grained, foliation-parallel muscovite is common, and in samples SS84-24B and MH90-1A, chlorite also appears to be part of the eclogite-facies assemblage. In half of the samples, amphiboles are complexly zoned. Brown, green and blue-green amphiboles appear as cores of blue amphiboles in samples SS85-

Table 1 P-T and fluid inclusion data. Fluid inclusion data were collected from texturally primary, clinopyroxene-hosted, liquid+vapor (L+V) fluid inclusions except as noted otherwise. Temperatures are calculated from partitioning of Fe^{2+} and Mg between garnet and clinopyroxene (Ellis and Green 1979); minimum pressures were estimated from the jadeite content of clinopyroxene (Ghent 1988) (*dau* possible daughter crystals were observed; *2nd* some texturally secondary fluid inclusions were measured) Samana Peninsula, Dominican Republic

Specimen	Garnet			Clinopyroxene				P(kbar)	T_h (°C)			T_m (ice) (°C)			Comment
	Fe	Mg	X(Ca)	Fe	Mg	X(Jd)	T(°C)		n	min	max	n	min	max	
SS84-24B	1.636	0.424	0.296	0.116	0.447	0.411	597±59	9.6±1.1	24	129	173	19	−3.7	−1.6	2nd, dau
SS85-27E	1.689	0.441	0.269	0.118	0.424	0.440	601±55	9.9±1.0	24	138	297	25	−5.8	+4.1[a]	dau
SS85-22	1.815	0.238	0.298	0.133	0.449	0.412	507±42	8.2±0.8	8	103	134	7	−4.5	−2.6	
Franciscan Complex, California															
Tiburon (T), Mount Hamilton (MH), and Jenner (J)															
T90-1B1[b]	1.619	0.426	0.270	0.181	0.440	0.343	691±84	10.4±2.1	14	182	333	17	−4.9	−1.0	
T90-5A	1.697	0.407	0.289	0.124	0.452	0.341	593±63	9.0±1.3	5	255	285	7	−2.7	−1.5	2nd
MH90-1A	1.644	0.433	0.280	0.155	0.419	0.366	671±77	10.5±1.5	5	220	372	5	−2.8	−1.1	
J90-3A	1.784	0.247	0.313	0.156	0.431	0.372	561±55	8.8±1.1	4	273	310	2	−1.8	−1.6	
J90-4A1A	1.766	0.419	0.281	0.145	0.450	0.373	618±27	9.7±0.6	13	166	302	3	−1.3	−1.1	2nd

[a] Final melting temperature of metastable aqueous phase
[b] Fluid inclusions in sodic-calcic amphibole

Table 2 Mineralogy of eclogites – minerals present in addition to garnet and clinopyroxene. (*G* present only as inclusions in garnet; *P* pyrite – ? where inferred but not observed; *R* present only as a relict phase; *X* present in apparent textural equilibrium. Sub- and supescripts: *abl* some syn- to post-Na-amphibole; *ag* some replacing garnet; *blgc* some with blue green cores; *br-blg-bl* core to rim zoning from brown to blue-green to blue; *brg-blg-bl* core to rim zoning from brown-green to blue-green to blue; *g* some present as inclusions in garnet; *g-blg-bl* core to rim zoning from green to blue-green to blue; *gc* some with green cores; *ht* retrograde hematite present; *r* some retrograde; *v* some present in vein; *vm* some present in vein margin)

	Amphibole Blue	Amphibole Blue-Green & Green	Epidote	Albite	White Mica	Rutile	Sphene	Quartz	Apatite	Opaque	Chlorite
SS84-24B	X	..	X	..	X	X	X^{r}	G	..	PY	X
SS85-27E	$X^{g\text{-}blg\text{-}bl}$	R	X	..	X^{ag}	X	X^{r}	X^{g}	..	PY	X^{ag}
SS85-22	X	..	X	X^{ag}	X^{ag}	X	X^{r}	G	..	PY^{ht}	X^{ag}
J90-3A	X	..	..	G	X	X	X^{r}	..	X	PY	X^{ag}
J90-4A1A	X^{blgc}	X	..	..	X^{ag}	X	X^{r}	G	X	PY^{ht}	X^{ag}
T90-1B1	$X^{blg\&gc}$	$X^{g\text{-}blg\text{-}bl}$	X	..	X^{abl}	..	X^{r}	G	..	$PY?^{ht}$	X^{vm}
T90-5A	X	..	..	..	X^{ag}	X	X^{r}	G	..	PY	$X^{ag,\,v}$
MH90-1A	X	$X^{br\text{-}blg\text{-}bl}_{brg\text{-}blg\text{-}bl}$	..	..	X	X	X^{r}	X	..	PY^{ht}	X

27E, J90-4A1A, T90-1B1 and MH90-1A. In sample T90-1B1, optical zoning is from green to blue-green to blue, and in sample MH90-1A, from brown to blue-green to blue. Sample MH90-1A is from the same eclogite block described by Moore and Blake (1989) as block GL16. Microprobe data obtained by these authors indicate that the brown amphibole is edenitic hornblende, the blue-green is barroisite, and the blue amphibole is glaucophane-crossite. Moore and Blake (1989) interpreted the edenitic hornblende as a relict of a high-P amphibolite-facies mineral assemblage that predates eclogite-facies metamorphism.

Despite large overlap, the results reported in Table 1 indicate that the eclogites from the Franciscan Complex were metamorphosed to slightly higher temperatures at similar calculated minimum pressures than those from the Samana Peninsula. Mean temperatures for the Franciscan rocks range from 561–691° C at 8.8 to 10.5 kbar; mean temperatures for the Samana eclogites range from 507–590° C at 8.2 to 9.9 kbar.

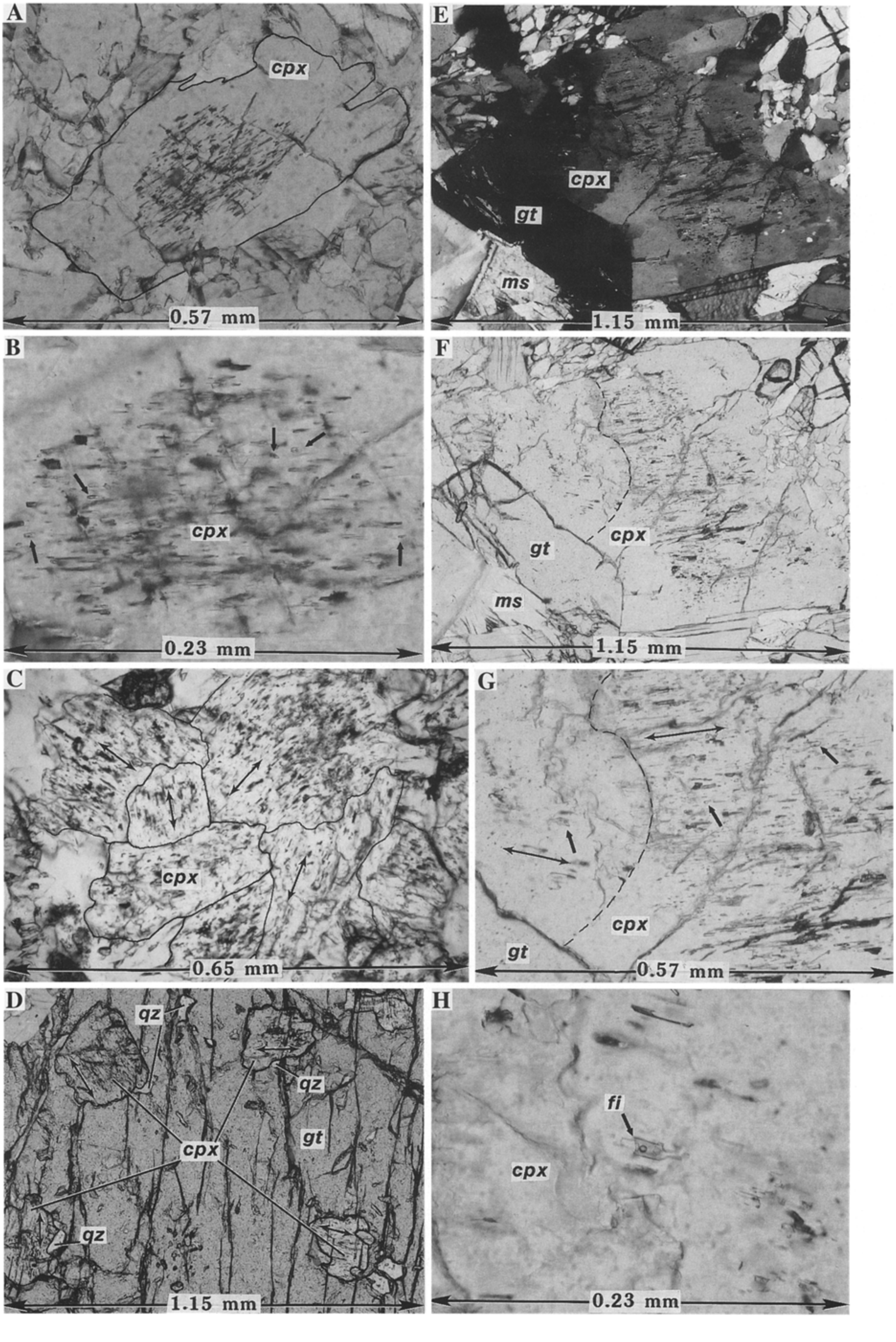
Some discrepancies exist between our P-T estimates for Franciscan eclogites (Table 1) and other data for the same blocks. Moore and Blake (1989) estimated P-T conditions for the interlayered eclogite and amphibolite in their block GL-16 (block MH-90 of this study) using the geothermometers of Ellis and Green (1979) and Graham and Powell (1984). They obtained $P_{min}=10$–11 kbar for amphibolite and eclogite layers, respectively, at T=596–702° C for amphibolite and T=566–591° C for eclogite. The "eclogite" temperatures obtained here are quite comparable to the high-range "amphibolite" temperatures of Moore and Blake (1989), but somewhat higher than their "eclogite" temperatures. When corrected for different formulations of the geothermometer, these data are systematically higher-T than the "upper limit" of 540° C defined by Oh and Liou (1990) for eclogite blocks in the Franciscan.This suggests that the Franciscan eclogite blocks either display disequilibrium or compositional heterogeneities on the scale of sampling for the P-T studies, or that systematic differences exist between the Oh and Liou (1990) data and those of other workers.

Petrography of fluid inclusions

In both Samana and Franciscan samples, some fluid inclusions in omphacite and amphibole appear to have been trapped during grain growth and are thus of primary origin. The fluid inclusions in omphacite occur as tubes that are oriented parallel with the *c*-axes of host grains. The tubes average about 9 μm in length and 2.7 μm in width. Four textural criteria suggest that some fluid inclusions were trapped during the growth of omphacite, and therefore during eclogite-facies metamorphism. These are: (1) the fluid inclusions occur as non-planar clusters of parallel tubes that are found predominantly in the cores of omphacite grains (Figs. 2A,B), (2) in both aggregates of matrix grains and in groups of omphacite inclusions in garnet, "core clusters" of fluid inclusions in different grains of omphacite have different orientations, and do not cross grain boundaries (Figs. 2C,D), (3) in large, strained omphacite grains, fluid inclusion orientations change from one domain of a single crystal to another (Figs. 2E–H), and (4) the abundance of fluid inclusions appears to decrease across some subgrain boundaries in strained omphacite grains (Figs. 2E–H). Taken together, criteria (3) and (4) suggest that "core cluster" inclusions were trapped prior to the strain event recorded by the large omphacite grains.

In the eclogite samples, many epidote grains commonly contain abundant fluid inclusions, but these were not analyzed because of potential problems with H-diffusion in epidote. In addition, some garnet grains contain isolated, ~1 μm, negative crystal fluid inclusions associated with abundant solid inclusions. These are too rare and small for us to analyze.

Many of the fluid inclusions in the Samana eclogite samples exhibit the textures listed above, but others display textures that indicate a secondary origin. Such fluid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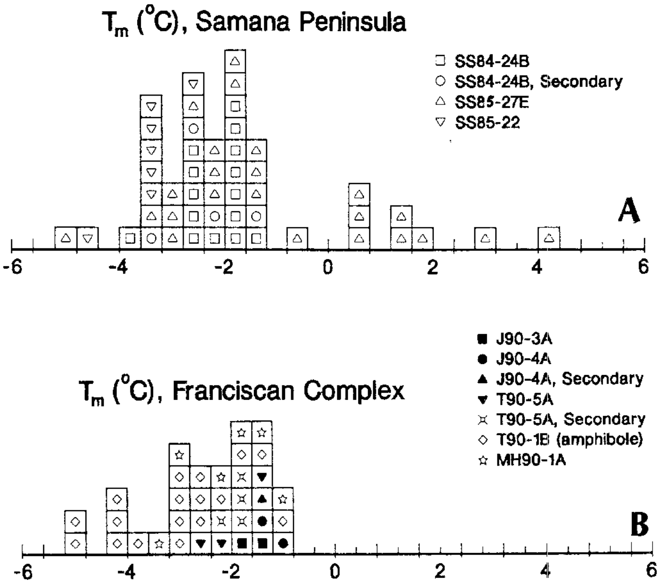


Fig. 3A,B Histograms of T_m data for fluid inclusions from Samana (**A**) and Franciscan (**B**) eclogites

inclusions (which, like those in "core clusters," are tubes oriented parallel to the *c*-axis of grains) nucleate from planes in a texture that suggests an origin by crack healing. Some of the "plane-rooted" fluid inclusions occur along continuations of visible cracks. One sample of Samana eclogite displays a population of fluid inclusions that contain what appears to be a single type of daughter mineral. Some of the "core-cluster" fluid inclusions in specimen SS85-27E contain miniscule crystals of an anisotropic mineral with apparently low interference colors. However, the same mineral appears also to occur as larger solid inclusions in the same grains. Study with the scanning electron microscope reveals that many 1–10 μm quartz inclusions are present in clinopyroxene grains, and that some of these inclusions appear to occur in the "daughter mineral" locations in the host grains. We are thus unable to demonstrate unequivocally that these grains are daughter minerals.

Unlike the Samana samples, the textures of fluid inclusions in Franciscan eclogites are typically equivocal. In Franciscan eclogites, clusters of fluid inclusions that do not cross grain boundaries are generally found in interior regions (if not cores) of the largest omphacite grains in individual thin sections. The fluid inclusions are similar in size and aspect ratios to fluid inclusions in Samana eclogites. However, many of the clusters of fluid inclusions are aligned along planes that in general are oblique to the focal plane of the microscope. This suggests that they were trapped during the healing of cracks in Franciscan eclogites. Clusters of *c*-axis-aligned fluid inclusions decorate growth zones of sodic-calcic amphibole in specimen T90-1B1, but it is not clear that this mineral is a stable part of the eclogite-facies phase assemblage (cf. Oh and Liou 1990). Such observations suggest that many of the fluid inclusions in the Franciscan eclogites are secondary or pseudosecondary in origin. However, texturally primary fluid inclusions do occur in Franciscan eclogites, and the section below will report homogenization data that support a primary or pseudosecondary origin for some of the texturally secondary inclusions.

T_m and T_h data for fluid inclusions

Values of T_m for texturally primary fluid inclusions from both Samana and Franciscan samples show a significant range of overlap (Table 1, Fig. 3). Most of the data range from −0.4 to −5.2° C. Although the values appear to cluster between −3.6 and −0.8° C (Fig. 3), no single strong maximum is seen in either population. Fluid inclusions from Samana eclogite specimen SS85-27E yielded eight T_m values greater than 0.0° C in addition to 13 low negative values (Fig. 3A). We interpret the positive T_m values to represent the final melting of a metastable aqueous solid phase (see Roedder 1967). However, because SS85-27E is the only sample with possible daughter crystals, the high T_m values may reflect a small population of fluid inclusions which differ in their fluid chemistry from other samples.

There appears to be no strong correlation between texturally primary versus secondary fluid inclusions and T_m values in either Samana or Franciscan eclogites. For example, in Samana sample SS84-24B the range of T_m values for secondary fluid inclusions lies within that of primary ones (Fig. 3A). This feature is also seen in Franciscan samples J90-4A and J90-5A (Fig. 3B). Values of T_m for texturally primary fluid inclusions in sodic-calcic amphibole in Franciscan sample T90-1B span the range for all inclusions from omphacites. However, even though 11 texturally primary fluid inclusions in sodic-

Fig. 2A–H Photomicrographs of fluid inclusions in eclogite samples (*cpx* clinopyroxene, *qz* quartz, *gt* garnet, *ms* muscovite, *fi* fluid inclusion). **A,B** are plane light views of a cluster of fluid inclusions in the core of a large omphacite grain from sample SS84-24B (Samana). **A** shows the entire grain, which is outlined in black ink for clarity. The area of *dark streaks* in the core of the grain consists of a cluster of fluid inclusions. In **B**, *black arrows* point to 5 coplanar (i.e., in focus) (l + v) fluid inclusions. **C** is a plane light view that shows the orientations (highlighted with *double-headed arrows*) of the long dimensions of fluid inclusions that occur as core clusters in matrix clinopyroxenes in sample SS85-22. **D** is a plane-light view that illustrates the orientations (highlighted with *double-headed arrows*) of fluid inclusions that occur as core clusters in four clinopyroxene inclusions within a single garnet grain in sample SS84-24B. The grain contacts between clinopyroxene and garnet are highlighted with black ink for clarity. Also note the occurrence of clinopyroxene + quartz in contact within the garnet grain. **E–H** show the different textures of fluid inclusions within a large, strained matrix grain of clinopyroxene in sample SS85-27E. **E and F** are crossed-polars and plane light views of the same field. A subgrain boundary of the strained grain is shown with a *dashed line* in **F and G**. In **G**, note the difference in orientation (*double-headed arrows*) and in the number of fluid inclusions in the two domains of the strained grain. Coplanar fluid inclusions in **G** are indicated by thick, *single-headed arrows*. **H** is a close-up view of the large (l + v) fluid inclusion on the left of **G**

Table 3 Salinities from melting temperatures

Locality	Type	Melting Temp. ° C (T_m)			Salinity (wt % NaCl equiv.)		
		Max	Min	Average	Min	Max	Average
Samana	Primary	−0.7	−5.8	−2.5	1.2	8.9	4.1
	Secondary	−1.6	−3.3	−2.4	2.6	5.3	3.9
Franciscan	Primary	−1.1	−3.2	−1.9	1.8	5.2	3.1
	Secondary	−1.3	−2.2	−1.8	2.1	3.6	3.0
	Amphibole	−1.0	−4.9	−3.1	1.7	7.7	5.0

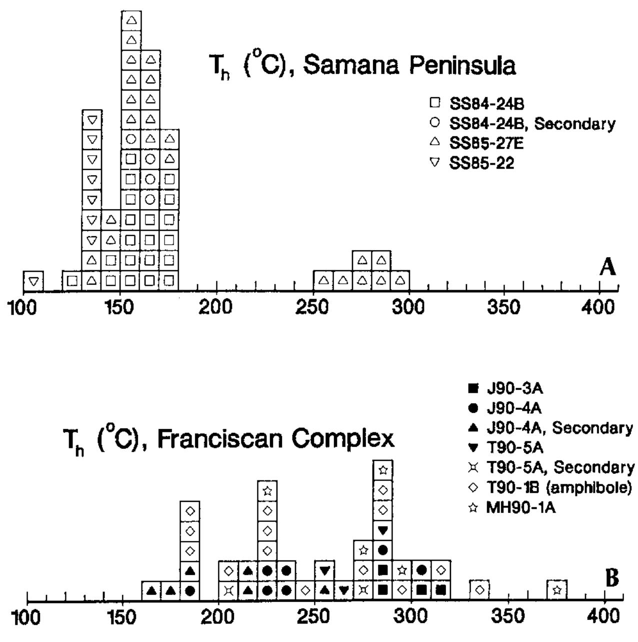


Fig. 4A,B Histograms of T_h data for fluid inclusions from Samana (**A**) and Franciscan (**B**) eclogites

calcic amphibole from sample T90-1B1 have compositions similar to fluid inclusions in omphacite from other Franciscan samples, six others have T_m values that correspond to relatively high salinities (~8 wt% NaCl equivalents; Tables 1,3).

The T_m values for Samana and Franciscan samples are consistent with low-salinity, aqueous compositions for virtually all the fluid inclusions (Tables 1,3). The range of salinities (calculated with FLINCOR software, Brown 1989) is approximately 1.2 to 8.9 wt% NaCl equivalents for texturally primary and 2.1 to 5.3 wt% NaCl equivalents for texturally secondary fluid inclusions. The average salinities resemble those of seawater (about 3.5 wt% NaCl equivalents; Garrels and Mackenzie 1970: as quoted by Fyfe et al. 1978, p. 30).

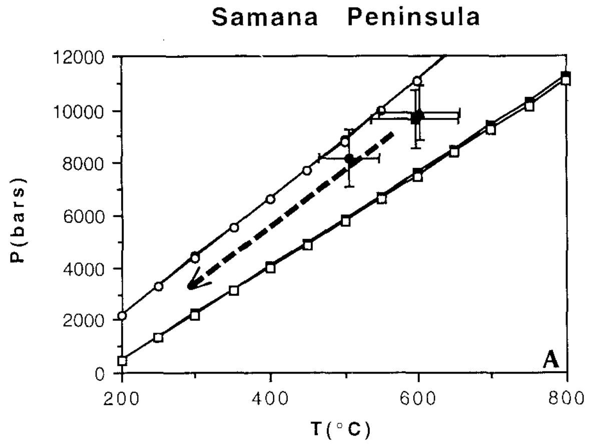
Unlike the T_m data, T_h values for Samana fluid inclusions are quite different from the Franciscan population of data (Table 1, Fig. 4). Values for all but seven of the Samana fluid inclusions range between 100 and 160° C (Fig. 4a); the high-T values are all from sample SS85-27E. The seven fluid inclusions in sample SS85-27E with $T_h > 250$° C are not the same ones that display high T_m values, but several of the high T_h fluid inclusions contain possible daughter crystals. Values for T_h of both texturally primary and secondary fluid inclusions in Franciscan samples range from approximately 160 to 380° C, and show maxima at 180–190° C, 220–230° C, and 280–290° C (Fig. 4b). Ranges of > 100° C are seen in T_h values for texturally primary fluid inclusions in omphacite in samples J90-4A, MH90-1A, and in amphibole in sample T90-1B. T_h values cluster between 280 and 330° C in sample J90-3A.

Discussion

The timing of fluid entrapment

Taken together, both the textural evidence and heating-freezing data suggest several possible explanations for the origin of the fluid inclusions. The overlapping ranges of low-salinity, aqueous compositions for texturally primary and secondary fluid inclusions from both study areas (Tables 1, 3) suggest that if all the fluids were trapped under peak metamorphic conditions, the densities of some were subsequently modified. Alternatively (or in addition), low-salinity, aqueous fluids may have been trapped both during and after peak metamorphism. A third possibility, that all the fluid inclusions are secondary, is inconsistent with the petrographic observations, especially those for the Samana eclogites.

Possible fluid-rock histories can be further examined by combining P-T estimates based on compositions of garnet and omphacite with calculated P-V-T properties of fluid inclusions in omphacite. Isochores for T_h values in the range of 102.5–175.7° C for Samana eclogites (Fig. 4A) and in the range 182.5–310.1° C for Franciscan eclogites (Fig. 4B) were calculated with the equation of Zhang and Franz (1987). These calculated isochores are plotted with P-T estimates for host rocks in Fig. 5. The densities of the population of mildly saline, texturally primary fluid inclusions in the Samana eclogites are consistent with entrapment at peak metamorphic conditions (Fig. 5A). This conclusion would not be affected by assuming a pure-H_2O fluid composition, or by using the proposed corrections of Krogh (1988) to the Ellis and Green (1979) geothermometer. Isochores for the fluid inclusions in sample SS85-27E that have T_h values > 250° C (Fig. 4A) would plot at $P < 5$ kbar at $T = 500$–



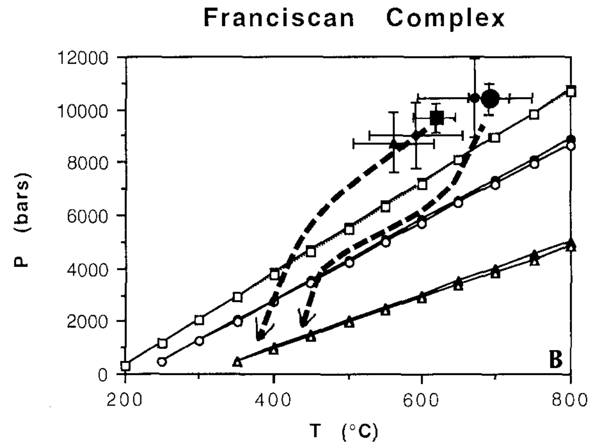


Fig. 5A,B Compilation of P-T estimates based on garnet-clinopyroxene geothermobarometry and isochores for fluid inclusions calculated from calibration of Zhang and Franz (1987). *Curves with solid symbols* were calculated using salinites determined from measured T_m values, and *curves with open symbols* calculated assuming pure-H_2O fluid. *Dashed lines* show possible uplift paths (see text). **A** shows data for the Samana Peninsula. *Circles* SS85-22, *squares* SS84-24, *triangle* SS85-27. High P isochores (*circles*) for T_h 102.5°C, low-P isochores (*squares*) for T_h 175.7°C. **B** illustrates data for the Franciscan Complex. *Triangle* J90-3A, *diamond* T90-5A, *square* J90-4A, *small circle* MH90-1A, *large circle* T90-1B. High-P isochore (*squares*) for T_h 182.5°C, intermediate-P isochore (*circles*) for T_h 220.2°C, low-P isochore (*triangles*) for T_h 310.1°C. In **B**, the salinity of the fluid inclusion for which high-P isochore was calculated was not determined; instead, the salinity for a different fluid inclusion in the same sample was combined with the T_h data

700° C in Fig. 5A. These fluid inclusions either were trapped during mineral growth and subsequently modified, or trapped during uplift of the eclogites. Despite the large volume of carbonate rocks in the outcrop areas of the Samana eclogites, neither T_m data nor petrographic observations indicate that CO_2 is present in major quantities ($> \sim 1$–5%) in the fluid inclusions. This is consistent with the structural and petrographic observations cited above that suggest the eclogites were emplaced into the metasedimentary rocks after the eclogite-facies metamorphism occurred.

In contrast to the results for the Samana eclogites, only a few isochores for texturally primary fluid inclusions from Franciscan eclogites are consistent with entrapment during eclogite-facies metamorphism. Pressures estimated from individual isochores in Franciscan samples are ~2.0–6.5 kbar lower than the geobarometric estimate based on the jadeite contents of clinopyroxene for T ~ 500–700° C (Fig. 5B). Thus, only a small fraction of the population of texturally primary fluid inclusions in Franciscan eclogites have densities that are consistent with entrapment under eclogite-facies P-T conditions. Most of the fluid inclusions in Franciscan eclogites were modified and/or trapped during uplift, which is consistent with textural observations for the samples.

P-T paths and the preservation of fluid inclusions in LT eclogites

The preservation of dense primary fluid inclusions in LT eclogites requires uplift paths that are semi-parallel to isochores in P-T space (Fig. 5A). Such uplift paths require cooling during unroofing, which thermal modelling indicates is possible during low angle extensional uplift attending active subduction (Peacock 1987). Uplift paths in which many lower density isochores are crossed after maximum P conditions are attained by blueschists or eclogites would not favor preservation of primary fluid inclusions (Doyle et al. 1988; Touret 1992). With such uplift paths, fluid inclusions trapped at maximum P conditions should stretch, reequilibrate, or decrepitate, as has been observed in fluid inclusion studies of retrograde-metamorphosed, medium-temperature eclogites from Norway and Germany (Andersen et al. 1989; Klemd 1989; Touret 1992). The agreement between isochores for texturally primary fluid inclusions and geothermobarometric P-T estimates for host mineral phases suggests that the Samana eclogites were uplifted along an "isochore-parallel" path that preserved original fluid densities (Fig. 5A). The general lack of agreement between isochores and geothermobarometry in Franciscan eclogites suggests that most of these rocks were uplifted along paths that crossed isochores, although some evidence favors early isochore-parallel uplift (Fig. 5B). This result contrasts with studies of Franciscan metasedimentary rocks and tectonic blocks that report uplift paths which coincide with or closely parallel burial trajectories in P-T space (Ernst 1977, 1988, 1990).

In summary, data for Franciscan and Samana fluid inclusions indicate that low-salinity aqueous fluids were trapped in omphacite grains both during and after eclogite-facies metamorphism. Densities of some fluid inclusions that were trapped under eclogite-facies conditions were preserved during uplift of the host eclogite, indicating that some uplift paths were in part or entirely isochore-parallel.

Possible sources of trapped fluids

The trapped fluids either originated within the eclogite protolith or infiltrated the rocks during metamorphism. We favor the latter hypothesis because of the compositions of the fluids themselves, the resemblance of fluid compositions among the localities and areas studied, and the similar compositions of both primary and secondary fluid inclusions in individual samples. If the fluid inclusions had been produced by reactions in which "protolith" fluids in hydrated basalt were first stored in layer silicate minerals (e.g., clay, chlorite) and then released during progressive devolatilization reactions in the absence of fluid infiltration (Crawford et al. 1979; also see Bebout 1991), we should observe a diverse or even heterogeneous population of fluid compositions ranging from low salinities to brines (e.g., Nadeau et al. 1993, Touret 1992). We do not. The host eclogite blocks were sampled from widely spaced localities in two different subduction complexes (Fig. 1). They range in size from <1 m to >10 m in diameter. Despite these scale factors, which might be expected to influence compositions of trapped fluids that originated within the protolith, all samples contain fairly homogeneous populations of both primary and secondary low-salinity aqueous fluid inclusions. This observation is consistent with, although not compelling evidence for, a large-scale source of both eclogite-facies and retrograde fluids. In the geologic setting of a paleosubduction zone, the most obvious external source for fluid is the subducting slab and subducted sediment (e.g., Delany and Helgeson 1978; Anderson et al. 1976; Bebout 1991; Philippot 1993).

Fluid inclusions in LT eclogite-bearing (and related) terranes

Data for primary fluid inclusions from LT eclogites and related rocks from other high-grade ($> \sim 450°$ C) subduction zone metamorphic rocks reveal two types of fluid compositions. The first is low-salinity aqueous fluid, which we document in this study and which has also been reported in clinopyroxene-bearing and migmatitic garnet amphibolites from the Catalina Schist, southern California (Sorensen and Barton 1987; Barton, personal communication 1992) and from blueschist-greenschist facies rocks of Ile de Groix, France (Barrientos 1992; Barrientos and Selverstone 1993). A second type of subduction zone fluid, brine, is found in LT eclogites at Monviso, western Alps, Italy (Philippot and Selverstone 1991; Nadeau et al. 1993), in the high-P (minimum 20 kbar) eclogites of the Tauern Window, central Alps, Austria (Selverstone et al. 1992), and in blueschists from Syros, Greece (Barr 1990). In the following paragraphs, we discuss the interpretation of fluid inclusions from these terranes in terms of their bearing on the nature of fluids in subduction zones, comparing our results with two well studied localities of high-T fluid-rock interactions: the Catalina Schist and Monviso.

Textually primary fluid inclusions are abundant in garnet, clinopyroxene and other minerals of garnet amphibolites of the Catalina Schist, which is a Cretaceous subduction complex (Sorensen and Barton 1987). The Catalina garnet amphibolites occur as blocks with metasomatic rinds in a matrix of high-T meta-ultramafic rocks. Although some blocks consist primarily of garnet + clinopyroxene, the clinopyroxenes are diopside with only a small jadeite component. Although the clinopyroxene-bearing rocks are amphibolites, the more omphacitic cores of clinopyroxene grains suggest that the blocks were eclogitic prior to fluid-rock interaction (Sorensen and Barton 1987; Sorensen 1988; Sorensen and Grossman 1989). Pressure-temperature estimates of 640–750° C, 8–11 kbar are based on geothermobarometry and the mineral assemblages of blocks and matrix (Sorensen and Barton 1987). Texturally primary fluid inclusions in garnet, clinopyroxene, and quartz from the Catalina garnet amphibolites yield isochores that coincide with P-T estimates based on geothermobarometry (Sorensen and Barton 1987; M.D. Barton, personal communication 1992). The calculated salinities of the Catalina fluid inclusions are 1.2–3.3 wt% NaCl equiv., which overlap the range of the Franciscan and Samana data (Table 3). Stable isotope data for the Catalina garnet amphibolite blocks and their matrix indicate that large amounts of sediment-equilibrated fluids infiltrated these rocks during high-T subduction zone metamorphism (Bebout and Barton 1989; Bebout 1989; 1991; M.D. Barton, unpublished data). The fluid source is thought to be subducted sediment, with some contribution from the dehydrating slab itself. The fluid evidently infiltrated material (including the ultramafic melange) that had previously been accreted to the base of the mantle wedge (Fig. 6; Bebout and Barton 1989; Bebout 1989).

Catalina differs from the Franciscan sensu stricto in that Catalina high-grade blocks are found in a relatively intact ultramafic-matrix melange, and that Catalina blocks have high-T ($>600°$ C) rinds around them. Platt (1975) proposed that the ultramafic-matrix melanges of Catalina might represent exposures of "source terranes" for rind-bearing blocks in the Franciscan. However, this cannot be strictly correct, because rind-formation can take place at $T = \sim 400°$ C (Moore 1984). We envision Catalina as the "high-T end-member" of what can happen during fluid-rock interaction in ultramafic melanges. Metasomatism in ultramafic melanges at lower-T conditions is evident in the jadeitite-block-bearing New Idria serpentinite body (e.g., Coleman 1961). Harlow (1994) has estimated conditions for a similar metasomatic system in Guatemala at $T = 100–400°$ C, 5–11 kbar. In the presence of infiltrating fluids, we propose that block-matrix-fluid reaction in ultramafic melanges may occur over a substantial range of high-P/T conditions, which would include those of the eclogite-facies.

Texturally primary fluid inclusions in eclogites from the Monviso Complex, western Italian Alps were studied by Philippot and Selverstone (1991) and by Nadeau et al. (1993). The compositions of the Monviso fluid inclusions differ markedly from both those reported in this study and from Catalina. Many of the Monviso fluid inclusions contain brines, (i.e., the fluid inclusions display halite and sylvite crystals at room temperature) but others yield salinities of 5.5–14.5 wt% NaCl equivalents (Philippot and Selverstone 1991). These less saline fluids occur with brines in clusters of fluid inclusions in cores of blocky omphacite crystals in annealed domains in mylonites ("omphacite 3" of Nadeau et al. 1993) and decorate growth zones of diopside in large omphacite crystals from undeformed veins in eclogite ("omphacite 4" of Nadeau et al. 1993). The Monviso brine inclusions contain daughter crystals of (in addition to halite and sylvite) calcite, pyrite, hematite, sphene, rutile, baddeleyite, barite, and monazite. Calculated isochores for the Monviso fluid inclusions do not overlap P-T estimates for eclogite-facies metamorphism (Philippot and Selverstone 1991). These authors proposed that the densities but not the compositions of these fluid inclusions were modified during uplift. They also concluded that fluids in eclogite-facies veins may derive from decrepitation of early fluid inclusions and that fluid flow was limited in scale. Compositions of Monviso fluids are heterogeneous on a small scale. Nadeau et al. (1993) reported cm-scale variations of $\delta^{18}O$ in omphacite and δD in fluid inclusions in the Monviso eclogites, but noted that the omphacites preserve a $\delta^{18}O$ signature (+3.0 to +5.3) similar to that of pyroxene and whole-rock values from altered oceanic crust. These authors argued that the Monviso protolith of altered gabbro lost 90% of its postulated "original" fluid (mostly H_2O) content, which they concluded was acquired by seafloor hydrothermal alteration that took place prior to eclogite-facies metamorphism.

Philippot and Selverstone (1991), Selverstone et al. (1992), and Nadeau et al. (1993) all concluded that a fundamental difference exists between high-P (>10 kbar, ~40 km depth, Monviso and Tauern localities) and low-P (Catalina Schist) fluid-rock regimes of subduction zones. However, the P-estimates for Monviso eclogites, like those for their Samana and Franciscan counterparts, are all minimum values of approximately 10 kbar. The Catalina garnet amphibolites and high-grade meta-ultramafic rocks have an upper P-constraint of 12 kbar, which is clearly less than the 18–20 kbar estimates for Tauern eclogites, but which is also within limits of uncertainty for the Samana, Franciscan, and Monviso eclogites.

If estimated P-conditions for the Samana, Franciscan, (Catalina), and Monviso rocks are not significantly different, why do their trapped metamorphic fluids differ in composition? We argue above, the compositions of populations of fluid inclusions in LT eclogites reflects a difference between infiltration (homogeneous population, low-salinity) and generation of fluid in situ (heterogeneous population, low to high salinity). This could result from the location of the zone of eclogite formation within the paleosubduction zone. Material coupled to

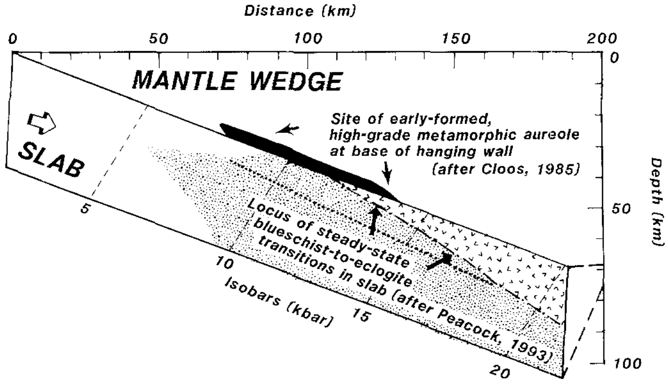


Fig. 6 Cartoon of fluid-rock regimes for LT eclogites, after Cloos (1985) and Peacock (1993). The *stippled field* indicates the physical stability field of blueschist-facies conditions, and the *v-patterned* area that of eclogite-facies conditions on a steady-state slab with a convergence rate of 10 cm/year and shear stress of 670 bar. The *dotted line* represents the boundary between lawsonite- and epidote-blueschist facies conditions, and the *dot-dash line* the locus of steady-state reactions that produce eclogite by devolatilization of blueschist (compare with Fig. 4 of Peacock 1993). The *solid black region* on the hanging wall shows the region in which eclogites and garnet amphibolites can form during early stages of subduction (after Cloos 1985). The slab and the aureole are vertically exaggerated for clarity, as indicated by the *dashed lines* (cf. Peacock 1993). The Samana and Franciscan eclogites and Catalina garnet amphibolites are interpreted as remnants of hanging-wall metamorphic aureoles, whereas the Monviso and Tauern eclogites are envisioned as devolatilized portions of a steady-state slab. See text for discussion

the hanging wall of a subduction zone (at an early stage of underflow and in transient thermal regimes controlled by cooling of the still-hot hanging wall) has the potential to interact with infiltrating fluid being derived from material being subducted and devolatilized beneath it (Fig. 6; see Anderson et al. 1978, Peacock 1992, 1993, and Philippot 1993 for a description of this process). Material that has been devolatilized within the slab (as part of a steady-state process) has a far more limited ability to interact with external fluid sources (Fig. 6; Philippot 1993). The Catalina rocks (and, by analogy, the Samana and Franciscan eclogites) are probably parts of relatively high-T metamorphic aureoles that accreted to the slab-mantle wedge contact *above* a subducting slab during the early stages of subduction (the solid black region in Fig. 6; cf. Platt 1975; Cloos 1985). In contrast, the Monviso rocks are interpreted to have formed via the blueschist-to-eclogite transition *within* a subducting slab itself (the v-patterned area of Fig. 6; Nadeau et al. 1993; Philippot 1993).

The existence of different fluid compositions in LT eclogites and related rocks may also reflect more local controls upon access of infiltrating fluids to the rocks during eclogite-facies metamorphism. The Franciscan and Samana eclogites occur as isolated, exotic blocks in a lower-grade matrix, whereas the Monviso eclogites are boudins in a coherent ophiolite terrane. The Franciscan and Samana eclogites were probably separated from their source terrane (an ultramafic melange?) and emplaced into their present matrix only after retrograde metamorphism and rind formation took place (Moore 1984). If the source terrane for the Franciscan and Samana eclogites was at all like the ultramafic melanges of Catalina and the jadeitite localities, substantial amounts of fluid may have been able to gain access to the blocks. In contrast, the local geology of the fluid-inclusion-bearing Monviso eclogites indicates that external fluids (if present) had little or no access to these rocks during eclogite-facies conditions (Philippot and Selverstone 1991; Burg and Philippot 1991; Philippot and van Roermond 1992; Nadeau et al. 1993).

Conclusions

(1) Fluid inclusions from LT eclogites of the Samana Peninsula, Dominican Republic, and the Franciscan Complex, California, preserve low-salinity aqueous fluids that were apparently trapped during eclogite-facies metamorphic conditions as well as on part of the retrograde P-T path.

(2) The fluid inclusions found in eclogites from the Samana Peninsula and the Franciscan Complex, as well as in garnet amphibolites from the Catalina Schist (Sorensen and Barton 1987), closely resemble each other in composition but are unlike counterparts found in eclogites of the Monviso Complex of the western Alps. The best explanation of the difference is that large scale fluid infiltration occurred during eclogite-facies metamorphism in the first three LT eclogite-bearing terranes, whereas (as noted by Philippot and Selverstone 1991 and Nadeau et al. 1993) only small-scale migration of locally-derived fluids took place during metamorphism of the Monviso rocks. Stable isotope data for the eclogite blocks described herein might help test this hypothesis.

(3) The amount of fluid available for infiltration in the Samana-Franciscan-Catalina terranes versus Monviso could have been controlled by: (I) a hanging-wall versus within-slab origin of the eclogites, or (II) local access of infiltrating fluids to the region of the paleosubduction zone represented by the rocks.

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