Phase Relations of Pyroxene and Amphibole in Greenstone, Blueschist and Eclogite of the Franciscan Complex, California

E.H. Brown and J.Y. Bradshaw*
Department of Geology, Western Washington University, Bellingham, Washington 98225, USA

Abstract. The phase relations of pyroxenes, amphiboles and associated minerals in metamorphic rocks of the Franciscan Complex can be graphically depicted on a ternary diagram which has at its apices the metamorphic clinopyroxene end members, viz NaAl- NaFe²⁺-Ca(Fe²⁺, Mg). Phases are plotted by projection from a constant subassemblage of minerals. This analysis allows interpretation of the effects of pressure, temperature, bulk rock composition and fluid composition on stability of minerals within the Franciscan.

Pyroxenes in meta-igneous rocks and metagraywackes have a limited compositional range and fall into two groups: the omphacites, with 50 ± 5% diopside + hedenbergite component; and the jadeitic pyroxenes with 10 ± 5% diopside + hedenbergite. Pyroxenes intermediate between these two groups are unstable relative to assemblages containing Na-amphibole + other minerals.

Coexisting pyroxenes and amphiboles in eclogites and associated coarse blueschists comprise equilibrium assemblages, and the proportion of pyroxene to amphibole is a function of rock composition. Eclogites are stable at higher temperature than regionally developed fine-grained greenstones and blueschists in the Franciscan, and at higher pressure than amphibolites. $X_{H_2O}$ is not an important factor in the stability of Franciscan eclogite relative to amphibolite.

Introduction

Current knowledge of the influence of pressure, temperature, bulk rock composition and fluid composition on the occurrence of Na-pyroxene and Na-amphibole in high pressure metamorphic terranes is limited and uncertain. The research reported here is an attempt to partially solve this problem by analysis of mineral compositions and mineral assemblages in the Franciscan Complex of California. Of special interest in this work are the metamorphic conditions under which eclogite forms in association with rocks of the blueschist facies. For general background concerning the Franciscan Complex the reader is referred to papers by Bailey et al. (1964) and Ernst et al. (1970).

This report is based on our own field and petrographic observation of approximately 200 samples collected in the Skaggs, Cazadero, Jenner, Healdsburg, Laytonville, Tiburon, Valley Ford, New Almaden, and Pacheco Pass areas (Fig. 1). It is also heavily dependent on publications of other workers. Our chief contribution to the long-standing Franciscan problems are new mineral analyses and a new projection-type ternary graph for analyzing phase relations. A preliminary account of this work was given by Brown (1977).

Mineral Abbreviations

 Qtz = quartz, Ab = albite, Chl = chlorite, Lw = lawsonite, Ph = phengite, Ep = epidote, Pp = pumpellyite, Ga = garnet, NaA = Na-amphibole, NaP = Na-pyroxene, CaA = Ca-amphibole, Ba = barroisite, Di = diopside, He = hedenbergite, Ac = aegirine, Om = omphacite, Jd = jadeite, Ajd = aegirine jadeite, Cm = chloromelanite, Ar = aragonite, Aug = augite, Cc = calcite, FeOx = iron oxide, Hem = hematite, Sph = sphene.

Field and Petrographic Relations

Ideally, a study of phase relations should be based on a suite of specimens collected across a continuous metamorphic gradient and containing coarse-grained equilibrium assemblages. Field and petrographic relations of the Franciscan metamorphic rocks depart...
morphic minerals are very fine-grained (<0.1 mm) and igneous transitions between rocks of different metamorphic grade are almost completely unknown. In much of the low-grade rocks metamorphic minerals are very fine-grained (<0.1 mm) and igneous minerals and textures have not been completely obliterated. In some of the higher-grade rocks, which have relatively coarse grain-size and complete metamorphic recrystallization, there is clear textural evidence of polymetamorphic assemblages, generally a relict higher-grade assemblage and an incipiently developed lower-grade assemblage.

The equilibrium associations in the incompletely recrystallized low-grade rocks and the polymetamorphic high-grade rocks are not easily discerned. In this work metamorphic minerals have been interpreted to comprise an equilibrium assemblage only if the minerals are in contact along sharp, smooth grain boundaries, and, for pyroxenes and amphiboles, if the grains are approximately equal in size. Photomicrographs representative of rocks used for this study are shown in Fig. 2.

A useful petrographic classification of Franciscan metamorphic rocks in the Cazadero area was given by Coleman and Lee (1963): Type I = unmetamorphosed, Type II = fine-grained (<0.1 mm) metamorphic minerals, no foliation, relict igneous textures and minerals, typical metamorphic minerals are lawsonite, chlorite, Na-amphibole, Na-pyroxene, pumpellyite, muscovite, sphene; Type III = medium-grained (0.1-1.0 mm) foliated, completely recrystallized, minerals are epidote, lawsonite, chlorite, Na-amphibole, Na-pyroxene, pumpellyite, muscovite, rutile, sphene, rare garnet; Type IV = coarsely crystalline (>0.5 mm) foliated, commonly gneissic, minerals are epidote, chlorite, Na-amphibole, Ca-amphibole, omphacite, muscovite, rutile, sphene, and garnet.

Type II and III rocks occur on a regional scale (kilometers in extent). In outcrop they may appear blue or green, depending on the proportion of Na-amphibole to omphacite and/or pumpellyite. Relict pillows are typically green in the core and blue on the rim. At Ward Creek, Coleman and Lee (1963) recognized an apparent continuous transition from II to III occurring over a distance of a few tens of meters. However, our field study in the Skaggs Quadrangle, where Types II, III, and IV occur, and the work of numerous other geologists studying the Franciscan (e.g. Bailey et al., 1964; Ernst, 1965; Ernst et al., 1970; Platt, 1976) has generally failed to prove continuous metamorphic transitions; units are fault-bounded.

Most Type IV rocks range from blue (Na-amphibole rich) to green (omphacite-rich). Typically, blue and green lithologies, termed 'high-grade blueschist' and 'eclogite' respectively, are finely interlayered and are associated with nearly monomineralic layers of garnet or epidote. Black, hornblende-rich type IV rock occurs sparsely; and at a few localities (e.g. New Almaden, Catalina Island) true amphibolites (hornblende + plagioclase) are developed. Type IV rocks occur as tectonic blocks mostly only a few meters in extent, and in places can be seen to be in fault contact with Type II or III rocks. Type IV rocks are commonly associated with ultramafic rocks, in close proximity or actual contact, as emphasized by Essene et al. (1965). Most contacts are faults, but an un-faulted contact between ultramafic rock and amphibolite has been observed on Catalina Island (Essene, 1967; and Platt, 1976).

Mineral Compositions

Mineral analyses were obtained using an ARL EMX electron microprobe at the University of Calgary. Standard operating conditions were: accelerating potential 15 kV, emission current 100 μA, beam diameter ~1 μm. Count rates were always less than 4,000 cps and counting was terminated at 20 s live time. The data were corrected according to procedures outlined by Bence and Albee (1968) and Albee and Ray (1970) after correction for background and drift. Computer programs by Nicholls et al. (1977) were used for this data reduction process. The accuracy of the microprobe analyses was estimated by analyzing as unknowns standards of Na-pyroxene, almandine-pyrope garnet, and muscovite and checking these results against other well-known standards. Major elements are considered to be accurate to better than 2% of the amount present, and minor elements to better than 5% of the amount present.

The mineral analyses presented are of individual grains. Analyses of fine-grained minerals represent an average of ~5 spots/grain, and of coarse-grained or zoned minerals an average of ~5 spots/core and ~5 spots/rim. These analyses are representative of a larger number of grains analyzed in each sample. For graphical treatment of the data, all analyses have been utilized.

Mineral compositions are given in Table 1 and relevant data on the rocks containing analyzed minerals are listed in Table 2. Analyses of garnet, epidote and chlorite, not shown in Table 1, are available from E.H.B. Because iron in different oxidation states is not discriminated with the microprobe, some assumptions about Fe2+ - Fe3+ distribution must be made in calculating mineral formulas. Estimation of Fe2+ and Fe3+ in amphiboles and calculated formulas are based on the assumption that Si + Al + Ti + Fe3+ + Fe2+ + Mn + Mg = 13 (cf Stout, 1972). Formulas were also calculated normalizing all cations (including Na and Ca) to 15. Results of the two procedures are generally similar. Normalizing cations exclusive of Na and Ca to 13 assumes no Mg or Fe in M4, but does allow A-site occu-