# THE PETROLOGY OF MAFIC SCHISTS OF SOUTHERN SYROS, GREECE

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## INTRODUCTION

The Greek Cyclades are part of the Cycladic Massif between Greece and Turkey that is comprised of several stacked rock units which are interpreted to be a result of the Alpine convergence (Avigad, 1993). The Cyclades experienced high-pressure metamorphism in a subduction zone during the Eocene and later underwent regional, lower-pressure, greenschist facies metamorphism in the Miocene according to Schliestadt et al. (1987). An alternative timing of 83 ± 10 Ma for the high-pressure metamorphic event was recently proposed using $^{206}Pb/^{238}U$ dating of metamorphic zircons (Bröcker and Enders, 1999; Cheney et al., 2000). The lower pressure greenschist is related to widespread extension throughout the Cyclades during the Miocene (Wijbrans et al., 1993). High pressure rocks of the Cyclades of the Aegean Sea are best preserved on the islands of Sifnos and Syros, which makes the study of Syros important to understanding the metamorphic and tectonic evolution of the region. This study centers on two sites on Syros: South Point and Katergaki Point. Both areas have interlayered mafic and felsic schists. The mafic rocks of the two areas are the focus of this paper. I describe and compare their mineralogy, microtextures, and mineral chemistry to determine their metamorphic histories within the blueschist and greenschist facies.

## METHODS

Fieldwork was completed during June, 2000. More than 70 samples were collected from both Katergaki Point and South Point, from which I chose 32 samples for further study. Thin sections from each sample were prepared for petrographic study. Of these thin sections, I chose four to analyze with an EDS/SEM during a short course at Amherst in January, 2001. The purpose of using an EDS probe was to obtain mineral compositions, and to map element concentrations in garnets to determine whether they are compositionally zoned. The mineral compositions from garnet and pyroxene were used for thermometry/barometry to constrain the P-T-t path.

## PETROGRAPHY

**Blueschist.** At Katergaki, blueschist outcrops are dark green on weathered surfaces, but show a nice blue color on a fresh surface (cf. Sable, 2000). The rock is medium to coarse grained and displays a schistocity defined by glaucophane and phengite. The common mineral assemblage is glaucophane + epidote + phengite + garnet ± omphacite ± quartz. Rutile and titanite appear as accessory minerals. Retrograde minerals are present in minor amounts, namely chlorite and albite around the garnets. Secondary calcite is also present in veins and clusters.

The near-blueschist rocks at South Point are interspersed with greenschist and can be difficult to distinguish in the field. The South Point blueschists are fine to medium-fine grained and blue-gray to blue-green in color. Outcrops commonly have visible epidote concentrations on the surface that are more resistant to weathering, creating a slight relief. The glaucophane laths are black in hand specimen. Mineral assemblages are similar to Katergaki: glaucophane + epidote + albite + garnet ± phengite ± quartz. Rutile, titanite, and opaques appear as accessory minerals. Omphacite is only present as minute inclusions in garnet where it was identified using the SEM. Locally, glaucophane has rims of actinolite in rocks that are gradational between blueschist and greenschist. Garnet is finer grained than at Katergaki and has been partially replaced by chlorite.

**Greenschist.** The greenschist at South Point is dull, green-gray, and fine-grained with coarser epidote visible on fresh surfaces. It alternates with better-preserved blueschist on the scale of tens of meters. The rock is locally fractured and jointed, giving outcrops a blocky appearance. The common assemblage is epidote + actinolite + albite + chlorite + white mica + garnet. Titanite, rutile, opaques, and rarely tourmaline occur as accessory minerals. Secondary calcite is also present. Magnetite, which has been mined at South Point, and tourmaline commonly are associated with hydrothermal activity and may not reflective of regional metamorphic conditions. Seven of the greenschist samples did not fit the above description but had assemblages of albite + epidote + plagioclase + chlorite + opaques ± white mica, plus titanite and rutile in trace quantities. In the field these show good foliation and look dark green in color. They are proposed to be metasediments and not metabasalts.

## MICROTEXTURES

**Fabric.** Samples from Katergaki show alignment of minerals, meaning that the growth of the blueschist minerals was pre- or syntectonic. The foliation wraps around garnets, signifying that they were also formed before the termination of metamorphic deformation. A few epidote grains truncate the foliation indicating a later growth that spans from syn- to post-deformation. Glaucophane, while one of the main foliation-defining minerals in most samples from Katergaki, also occurs as coarser grains that truncate the foliation. Rarely, both habits occur in the same rock. Omphacite, where present, has two habits as well. One is small and aligned with foliation, and the other is porphyroblastic with deformation twins. The latter form augen, with the groundmass grains wrapping around the deformed coarser omphacite. The variety of habits of the minerals show a complex metamorphic and strain history.

At South Point the blueschists of igneous parentage are not foliated. Greenschists of the same origin are foliated rarely in the field. In these, needles of actinolite and chlorite form the foliation.

**Evidence of Greenschist Facies Overprinting.** South Point lithologies grade from well preserved blueschist facies rocks to ones that have been overprinted by greenschist facies assemblages. Garnet shows varying degrees of replacement by chlorite. In places chlorite has grown in fractures in garnet. As chlorite aggregates replace more of the garnet, the textures of the remnant garnet resembles an atoll. Chlorite is associated with other retrograde minerals such as albite in places. Some spherical masses of chlorite are interpreted to be completely retrograded pseudomorphs after garnet (Rast, 1969 in Bard, 1986). Glaucophane is rimmed by actinolite that formed under lower pressures, also indicative of retrogression. Actinolite is the main amphibole in more retrograded samples, with glaucophane only preserved as relict inclusions in the centers of epidote or garnet. Another retrograde indication is titanite rims on rutile (Barker et al., 1990).

## MINERAL CHEMISTRY

To compare the mineral chemistry of Katergaki Point and South Point, four representative samples were analyzed on the Zeiss SEM at Amherst College with an Oxford EXL microanalysis EDS system. The two from South Point represent end members of a gradation from relatively un-retrograded blueschist to mostly greenschist mineral assemblages. The two from Katergaki Point are typical of the site.

**Amphibole.** The amphibole formulas were corrected for ferric/ferrous iron using an Excell spread-sheet created by Brady (1999). The least upper bounds and greatest lower bounds of the Fe 3+ were averaged to obtain their final presented formulas. Sodic amphiboles characterize the blueschist facies, lending their color to the name of the facies. Most amphiboles analyzed in the blueschists plot on a sodic amphibole diagram (Deer et al., 1997) as glaucophane, although some extend into the ferro-glaucophane field. Calcic amphiboles are present in the greenschist facies rocks of South Point and as rims on some of the glaucophane. The samples plot in the actinolite field of the calcic amphiboles diagram (Figs. 1,2) (Leake et al., 1997).

**Garnet.** Garnet from Southern Syros has four components: almandine (Fe), grossular (Ca), pyrope (Mg), and spessartine (Mn). The garnets from the four samples I analyzed are 65-70% almandine (+ minor spessartine), 20-25% grossular, and 5-10% pyrope (Fig. 3) (Deer et al, 1997). Garnets from both locations are zoned. Maps of the elements in the garnet show their zonation from rim to core, with the inverse relation between Mn and Fe being the most dramatic. Mn is concentrated in the cores and decreases towards the rims, whereas Fe increases from core to rim. Garnet incorporates MnO into its structure during early crystalization, leaving less available in the nearby environment to be incoporated into the outer portions of the grains (Spear, 1993).

**Pyroxene.** Pyroxenes from Katergaki plotted in the omphacite field on a pyroxene Di+Hd-Jd-Acm diagram. Typically omphacite is defined as 50% Jadeite- 50% diopside, but because the omphacites of southern Syros have a significant acmite component, a ternary diagram was necessary to represent them (Fig. 4).

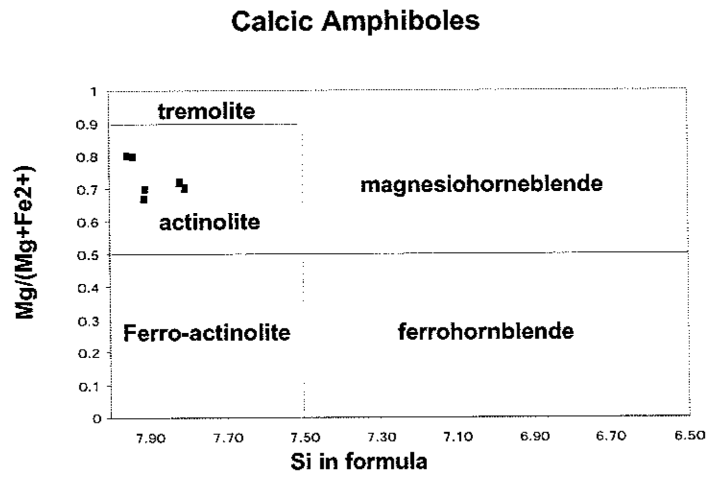

**Fig. 1.** Amphiboles from a South Point greenschist, EPV 26, plotted in the actinolite field of the Calcic Amphiboles diagram (Leake et al., 1997).

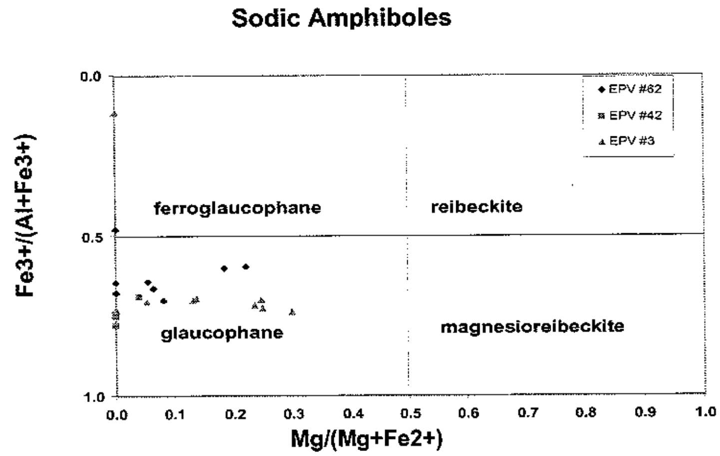

**Fig. 2.** Amphiboles that were blue in thin section from both Katergaki and South Point primarily plotted as glaucophane with two in the ferro-glaucophane field (Deer et al.,1997).

## THERMOBAROMETRY

One of the goals of the SEM work was to analyze minerals to use their compositions to confine the P-T path followed by the mafic rocks of Katergaki. Finding a point on a P-T diagram would help define the tectonometomorphic history of Syros. The garnet-pyroxene thermometer was chosen based on the mineralogy of the rocks; it uses the exchange of Fe and Mg between omphacite and garnet to estimate the highest temperature attained by the rock. The barometer of garnet, albite, pyroxene, quartz was chosen also based on the mineralogy to estimate the greatest pressure the rocks underwent. The program created by Kohn and Spear (1996) was used to create the P-T plots. Chemical analyses from garnet rims were chosen because they represent a composition more likely to be in equilibrium with adjacent minerals. One result was chosen that represented the average of results using several different garnet-clinopyroxene pairs. Original results were also corrected for iron according to the method of Brady (1999) and both results were plotted (Fig. 5).. The Brady- corrected data shifts the result from Kohn and Spear (1986) from 430°C, 18 kbar P to 470°C, 19 kbar P. The results from the calibrations used by the Kohn and Spear program produce a range of pressures and temperatures, which have a number of possible sources (Spear, 1993). Despite this, the results do help constrain the peak temperatures and pressures.

## DISCUSSION

Katergaki Point is characterized by well preserved blueschist facies rocks with a penetrative foliation and coarser grains whereas South Point is characterized by finer grained rocks that are displaying variable amounts of overprinting of blueschist by retrograde greenschist assemblages. Both areas have complex metamorphic histories. At Katergaki Point there are several episodes of mineral growth: one is represented by the porphyroblastic omphacite, succeeded by the minerals that formed during the main foliation event, and another by later minerals that cut the fabric of the rock. South Point shows a history of greenschist facies overprint with rims of actinolite around glaucophane, and chlorite and albite replacing garnet. The mineralogy and mineral chemistry are concordant with Katergaki and South Point undergoing similar metamorphic histories, for both show some degree of retrogression; but that the retrogression is more complete at South Point. One possible cause of the retrograde metamorphism may be the hydrothermal event indicated by the presence of tourmaline and magnetite.

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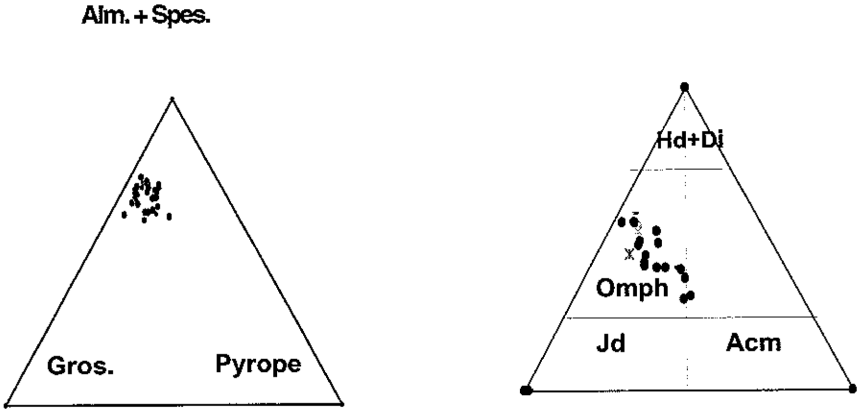

**Fig. 3,4.** Ternary diagrams showing the compositions of garnet (L) and pyroxene (R). Garnets are ~65% alm., ~25%gros., and ~10% pyrope. Spessartine is a minor component, thus was added to the almandine. Pyroxenes plot in the omphacite field. Note the significant acmite component in the pyroxenes.

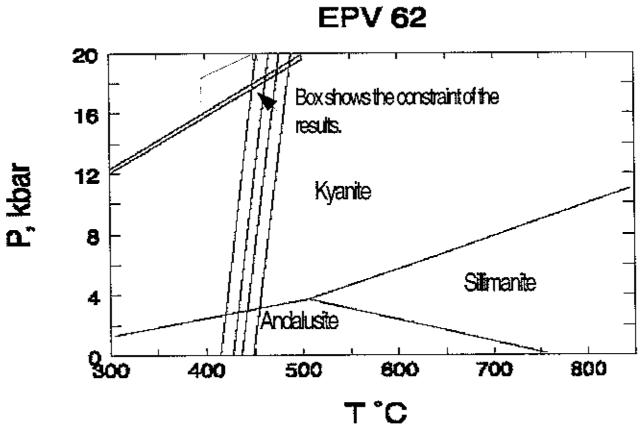

**Fig. 5.** Plot of thermobarometry results for EPV 62. Peak temperature and pressure was 430-470°C and 18-19 kbar. Results are based on garnet-pyroxene thermometer and garnet-albite-pyroxene-quartz barometer. The lower calibration shows the result using Kohn and Spear's (1996) ferric/ferrous corrections, and the upper calibration were based on iron corrections of Brady (1990). Note the minimal difference between the two.

# PETROLOGY OF THE “AIRPORT OPHIOLITE”, SYROS, GREECE

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## INTRODUCTION

Syros, one of the Cycladic Islands of Greece, is part of a high-pressure metamorphic belt in the Attico-Cycladic crystalline massif (Cheney et al., this volume). Beginning in the Cretaceous this region experienced eclogite and blueschist facies metamorphism. Metasediments including marble and meta-igneous rocks cover most of the island. Fragments of remnant ophiolitic rocks are well exposed on the island including a proposed ophiolitic sequence just south of Ermoupolis (Dixon and Ridley, 1987) These rocks, referred to as the Airport Ophiolite, contain blueschist and eclogite facies rocks with areas retrograded to greenschist. The purpose of this project includes mapping, determining the conditions of metamorphism, and constraining the origin of the protolith of the Airport Ophiolite.

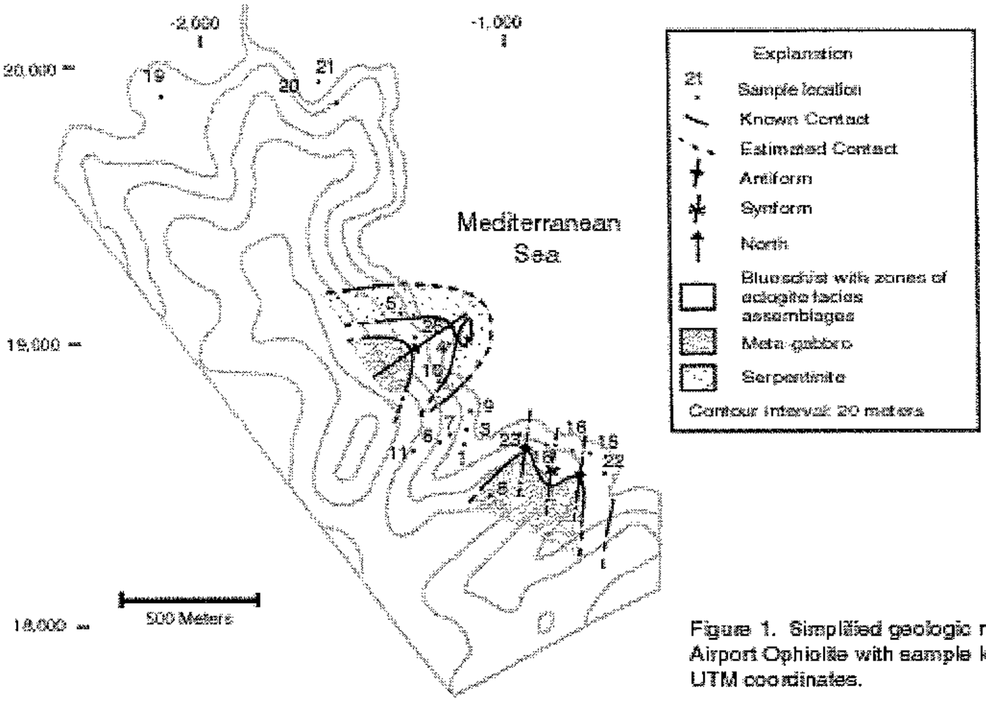

Figure 1. Simplified geologic map of the Airport Ophiolite with sample locations and UTM coordinates.

## AIRPORT OPHIOLITE

The Airport Ophiolite was mapped at a 1:10,000 scale (Fig. 1). Blueschist, meta-gabbro, serpentinite, greenschist, and eclogite were identified in the field. The eclogite facies rocks have little to no internal deformation and occur as dikes and boudins in penetratively deformed blueschists. Similar to the blueschist, the greenschist and serpentinite facies rocks have well-developed foliation, with defined glaucophane lineations in some areas. The meta-gabbros are moderately foliated in areas closest to the blueschist rocks but have remained mostly unfoliated. Structural data show that the foliation is folded with near vertical NE to NNE striking axial planes. Serpentinite is folded within the blueschist (Fig. 1)

## MINERAL ASSEMBLAGES

**Eclogite**: Medium to coarse grained (up to 1 cm), massive rock only found as a dike and as a few boudins within the blueschist at locality 4. It contains almost entirely omphacite and garnet.

**Blueschist**: Very fine to medium grained, well-foliated schist. All of these rocks contain glaucophane, epidote group mineral (mainly clinozoisite), phengite, titanite, rutile, and quartz. Other minerals appear in varying amounts such as garnet, clinopyroxene, and paragonite. Some of the samples contain retrograde greenschist minerals such as chlorite, albite, and actinolite.

**Meta-Gabbro**: Coarse grained, moderately foliated to massive rock. It contains the same mineral assemblages as the glaucophane schist, and includes omphacite porphroblasts, epidote, and phengite. It contains varying amounts of glaucophane, garnet, chlorite, and albite. Rutile, titanite, and quartz are accessory minerals. This lithology is classified as a meta-gabbro primarily due to its relatively coarse grain size (up to 3 cm) compared to the blueschists and greenschists, which presumably reflects the igneous protolith (Dixon and Ridley, 1987).

**Greenschist**: Very fine to fine grained, well-foliated rock. The most common assemblage is chlorite + albite + epidote ± actinolite. In some samples, corroded glaucophane is present.

**Serpentinite:** Very fine grained and very well foliated rock composed of serpentine. It also contains magnetite.

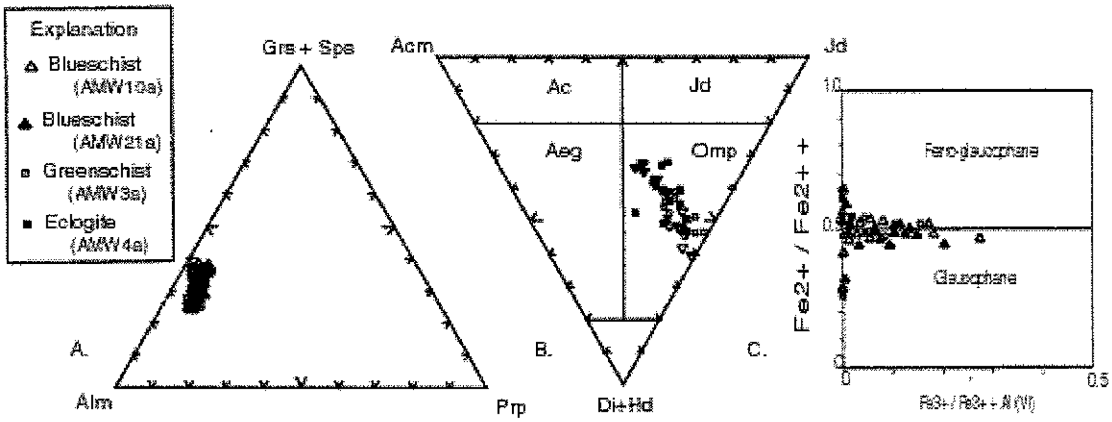

Figure 2. Mineral compositions from the airport ophiolite. A) Ternary diagram for garnet showing grossular, spessartine, pyrope, and almandine compositions. B) Ternary diagram for omphacite (Omp) showing jadeite (Jd), diopside (Di), hedenburgite (Hd), and acmite (Ac). C) Sodic amphibole compositions showing variations of Fe.

## MINERAL CHEMISTRY

Four representative samples were analyzed on the Zeiss scanning electron microscope at Amherst College with an Oxford EXL microanalysis EDS system. Samples AMW10a and AMW21a are blueschist, AMW3a is an intermediate greenschist/blueschist, and AMW4c is an eclogite.

**Garnet:** Garnet is almandine rich with grossular contents ranging from 0.454 – 0.222 % (Fig. 2a). With the SEM/EDS, garnet traverses and maps were made on several garnets from all samples. The garnets are relatively unzoned with near-rim depletions of Mn and enrichments in Mg and Fe. Inclusions in garnet are mostly quartz, albite, and titanite. Chlorite has commonly replaced some garnets.

**Sodic Amphibole:** Ferric/ferrous ratios, assuming 13 cations and only Ca and Na in the M (4) site, were calculated to determine the variety of amphibole using an algorithm written by Prof. John Brady (1999). All compositions plotted in the glaucophane-ferroglaucophane range (Fig. 2b).

**Omphacite:** The diopside + hedenburgite content of the pyroxene ranges from 0.323 to 0.61%, jadeite from 0.364 – 0.463%, and acmite from 0 – 0.293%, which places all the samples in the omphacite range (Fig. 2c).

## GEOTHERMOBAROMETRY

The garnet-clinopyroxene Fe-Mg exchange thermometer and albite-jadeite-quartz barometer were used to calculate the pressure and temperature of equilibration of an eclogite and blueschist sample (Fig. 3). Garnet, clinopyroxene, and albite compositions were used from AMW10a (blueschist) and AMW4c (eclogite) using thermometers from Ellis and Green (1979) and Powell (1980), and barometers from Holland (1980) and Gasparik and Lindsley (1980). Thermobarometry was calculated using GTB 2.0 (Kohn and Spear, 1999). Figure 3 shows that both the blueschist and eclogite give almost identical pressures and temperatures ranging from 500-520 ° C and pressures from 12,000-12,500 bars.

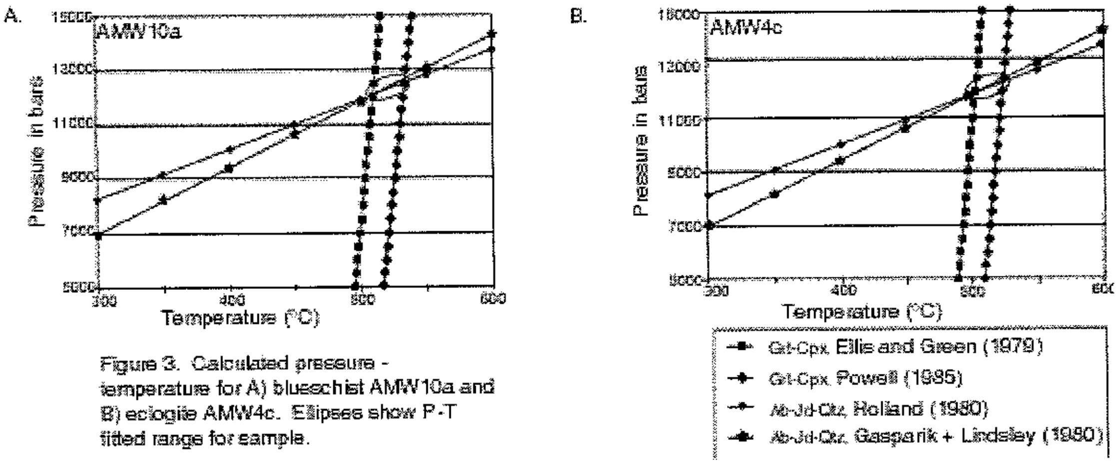

Figure 3. Calculated pressure - temperature for A) blueschist AMW10a and B) eclogite AMW4c. Ellipses show P-T fitted range for sample.

## WHOLE ROCK GEOCHEMISTRY

Whole rock geochemical data were obtained from 14 samples from the Airport Ophiolite in order to help determine protoliths. On a total alkali vs $SiO_2$ plot (Fig. 4a) most samples plot in the basalt range. Two samples have a larger amount of silica, plotting in the andesite range. Figure 4b shows that most samples follow a Tholeiitic trend. Figure 4c shows the rare earth elements (REEs) compared to chondrites. All of the samples are enriched in the REEs and most have a larger enrichment of Eu.

## DISCUSSION AND CONCLUSIONS

Eclogite, blueschist, meta-gabbro, greenschist, and serpentinite units were mapped within the Airport Ophiolite based on field appearance and mineral assemblages. P-T ellipses, from in Figure 3, are shown on a facies diagram in Figure 5. Both samples plot in the transition zone between blueschist and eclogite facies. Geochemistry shows that the airport Ophiolite rocks are basaltic compositions and plot in the Tholeiitic region (Fig. 4b). In addition, the rare earth elements (REEs) do not show a depletion in the heavy REEs (Fig. 4c) suggesting that the basaltic protoliths of these rocks formed from shallow melting of the mantle, perhaps in a mid-ocean ridge environment (McBirney, 1984).

The blueschist and eclogite both equilibrated in the blueschist/eclogite transition zone giving the same P-T ranges (Fig. 5). However, they have different textures and modal mineralogy; the eclogite rock is coarse and massive with mostly omphacite and garnet with minor glaucophane, while the blueschist rocks are medium grained and well-foliated with high modal glaucophane. This suggests that the textures are a function of deformation and not metamorphic grade. That is, deformation was probably concentrated in the rocks mapped as blueschists, thus allowing fluids easier access to allow glaucophane growth. The greenschist facies rocks probably formed in areas where deformation and access to fluids continued during the exhumation of these rocks.

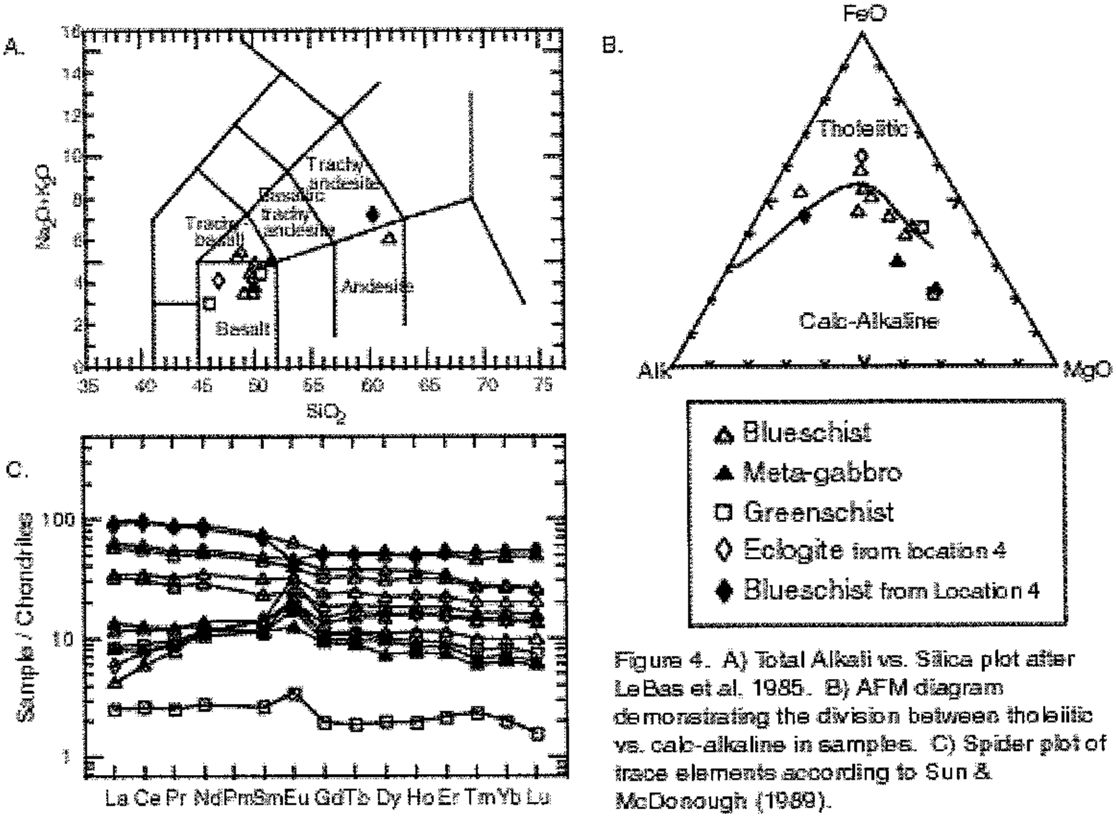

Figure 4. A) Total Alkali vs. Silica plot after LeBas et al. 1985. B) AFM diagram demonstrating the division between tholeiitic vs. calc-alkaline in samples. C) Spider plot of trace elements according to Sun & McDonough (1989).

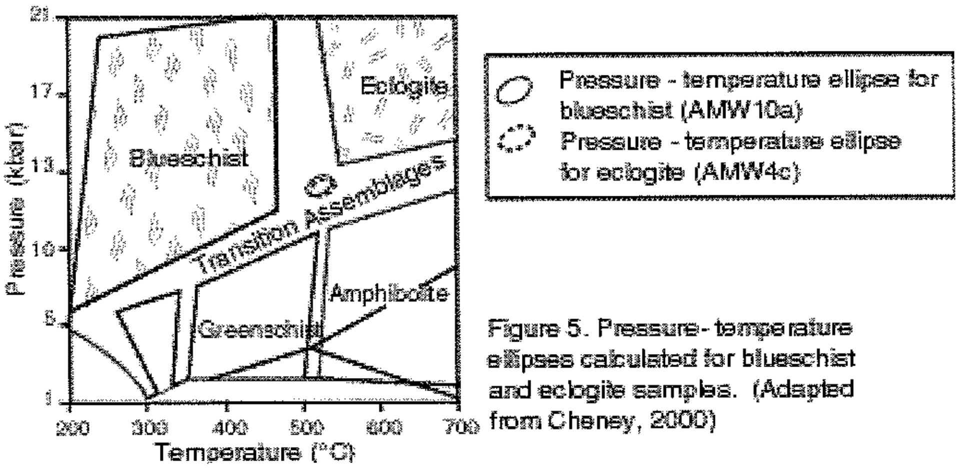

Figure 5. Pressure-temperature ellipses calculated for blueschist and eclogite samples. (Adapted from Cheney, 2000)

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