Characterization and tectonometamorphic evolution of ophiolitic blocks and ultramafic matrix in a Cycladic melange unit, Syros, Greece

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INTRODUCTION

This study targets two outcrops of a small unit of ophiolitic melange, henceforth referred to collectively as the Syros melanges or individually as the Kampos and Kastri melanges. These outcrops are located on the island of Syros in the Greek Cyclades. The objective of this research is twofold. First, to petrologically classify the rocks as a basis from which to draw comparisons with studies of other melanges. Secondly, to confine the P-T-t path followed by this unit, so as to both understand the tectonometamorphic history of the unit, and to contribute to a greater understanding of the geological development of the island.

During an Eocene (~40-45 M.a.) compressional event, an orogenic belt formed the Attic-Cycladic complex (Dixon and Ridley, 1987). Subsequent periods of extension, combined with erosive processes, have left the Cycladic islands where the substantial mountain range once existed. Evidence suggests that the Syros melange formed as part of this process.

Jackson and Bates (1987, p.410) define a melange as any: "...body of rock characterized by a lack of internal continuity of contacts or strata and by the inclusion of fragments and blocks of all sizes, both exotic and native, embedded in a fragmental (sic) matrix of fine-grained material." The blocks in the Syros melange are ophiolitic, bound together by an interstitial matrix of ultramafic material (Fig. 1). There is neither internal structure nor discernible strata to the Syros melange.

Two theories on the uplift of ophiolitic melange. A handful of different theories have been proposed in explanation of ophiolitic melange. Despite general agreement regarding the suture-zone origins of ophiolites and ophiolitic melange (Gansser, 1974), the mechanism for the uplift of these units is the subject of long-standing debate. Platt (1986, 1987) proposes a widely accepted model in explanation of the Franciscan melange in the California Coast Range: Melange rocks are formed in the accretionary wedge and brought to the surface before they have been given time to absorb heat. As an oceanic plate enters the subduction zone, massive blocks are torn from the top through contact with the accretionary wedge and the overriding plate. As more terrigenous sediment and sea water are drawn down into the subduction one, under-packing of the ophiolitic block drives it upward in the accretionary wedge. Over time this process is repeated until there are several of these ophiolitic blocks separated by layers of sediment. Eventually the accretionary wedge becomes gravitationally unstable, either through excessive buildup of sediment or through the subduction of a larger geologic body, for example, an island arc (Ernst, 1988). This causes an outward collapse through extensional normal faulting. Via these processes, sections from the middle of the extension zone are drawn to the surface.

A contrasting model proposed by Cloos, (1982, 1985) and Shreve and Cloos (1987), has also been used to explain the Franciscan melange. This particular model requires a small angle between the overriding and subducted plates. As material from both plates is collected in the accretionary wedge, friction with the overriding plate causes a cycling of material to occur (Spear, 1993). This convective process quickly draws the material in and then out of the wedge

The field area. The Kampos melange, the larger of the two, outcrops on a long, sloping hillside that plunges from the village of Kampos to the beach at Mega Lakkos. The outcropping itself is roughly one kilometer in length—the width varies from tens to hundreds of meters. The Kastri melange outcrops by the sea off the north shore of the island, at the foot of the hill that protected a Bronze Age village of the same name. The whole outcrop is only 50 meters long, but was particularly valuable to my research because it is completely devoid of vegetation, allowing one to see the melange in three dimensions.

PETROLOGY

One of the difficulties of studying the metamorphic history of an ophiolitic melange is attempting to reduce the diversity of protoliths and possible metamorphic grades to comprehensible levels. Among the blocks surveyed, virtually all constituent sections of an ophiolitic column appear, as well as evidence of three different metamorphic facies. To simplify investigation of the Kampos and Kastri melanges, a series of categories derived from the mineralogical composition of the rocks are designated, thus relating the categories to both the protolith and the metamorphic grade.

Blueschist. The most common assemblage for the blueschist category of samples is glaucophane+clinozoisite+phengite±garnet. These appear in a variety of proportions, although glaucophane and clinozoisite tend to appear in greater quantities than phengite or garnet. Titanite, rutile, and chromite also appear in the blueschists as accessory minerals. The samples in this category are foliated. Most exhibit compositional banding, with alternating bands of amphibole and clinozoisite, or amphibole and phengite. The compositional bands formed by the white-micas and the clinozoisite are rarely planar—rather they tend to undulate and form bands that look more gneissic than schistose.

Eclogite. Eclogite facies rocks represent the highest grade of metamorphism among all of the rocks on Syros, and all of the blocks in the Kampos and Kastri melanges. Gao et. al. (1999) categorized all rocks with greater than 70%-modal omphacite and garnet to be eclogitic. The same definition is used here. In the field, a uniform light green color is a fairly certain indication of the block's eclogitic make-up. However, a more striking difference between the blueschist and the eclogite blocks is the lack of planar fabric.

Blueschist/Eclogite. Petrologically intermediate between the blueschist and eclogite categories is a suite of blocks that contain minerals belonging to both metamorphic facies. Many of these samples were classified in the field as metagabbros, a determination based exclusively on grain size and composition.

Felsic. Scattered amongst the many mafic blocks in the Kampos melange is a handful of blocks that are light in color, ranging from white to tan to grey. In hand-sample they appear to be sugary in texture, with tiny grains of white mica providing a sparkling sheen to the surface. Large, dark needles of amphibole, between one and three millimeters long, are aligned to form a lineations that runs parallel to the strike of the melange. Thin-sections of these blocks reveal that 75% of the samples, by volume, is quartz. The protolith of these rocks was probably terrigenous sediment that was dragged down into the accretionary wedge.

Matrix. In terms of sheer volume, the ultramafic matrix is much more abundant than the suite of ophiolitic blocks. However the matrix, which is composed primarily of serpentine and talc—two very soft minerals—is heavily weathered and does not appear in many substantial outcrops. The Kastri melange, being completely devoid of vegetation, allows us to see the construction of the matrix in much greater detail than in the Kampos melange. Compositionally the matrices of the two melange outcrops are similar. Much of the serpentine that once made up the majority of the matrix has been reacted away through metasomatic and contact reactions with the more siliceous blocks. These blackwall reactions (Sanford, 1978), have left the matrix a mixture of talc, serpentine, actinolite, and tourmaline. In the matrix of the Kastri outcrop, the Mg-rich carbonate magnesite has been incorporated to a rather impressive extent.

Figure 1: Kastri block in matrix. Fieldbook for scale

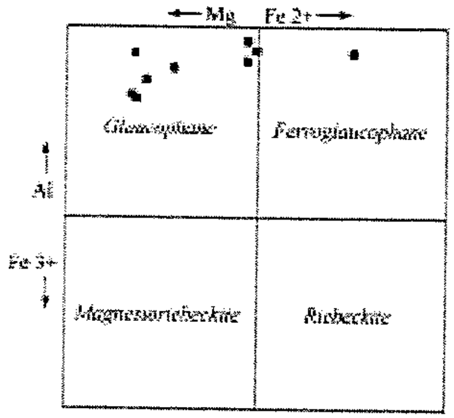

Figure 2: Compositions of sodic-amphiboles from the Syros melanges.

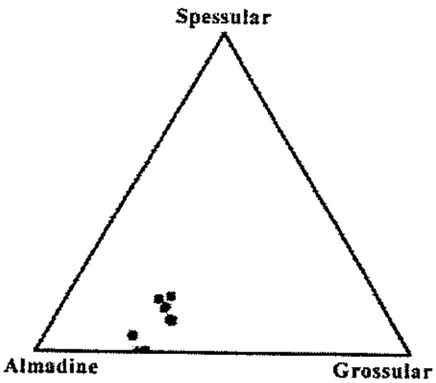

Figure 3: Compositions of garnets from the Syros melanges.

CRYSTAL-CHEMICAL ANALYSIS

Using energy dispersive x-ray spectrometry, several representative samples from the Syros melange were analyzed using the SEM at Smith College, Northampton, MA.

Sodic Amphibole. Sodic-amphiboles are the characteristic mineral of blueschist facies metamorphism, and are found in great abundance throughout the melange. The Kini beach, on the south-western shore of Syros, is the type locality for glaucophane, the most common and best known sodic amphibole. The general formula for sodic amphiboles is $Na_2 (Mg, Fe^{2+})_3 (Al, Fe^{3+})_2Si_8O_{22} (OH)_2$. To determine the actual variety of sodic amphibole, it is necessary to calculate the ferric/ferrous ratio, and compare these values to the molar quantities of magnesium and aluminum. I used a spreadsheet program written by Brady (1999) to determine these ratios.

The compositions for virtually all of the sodic amphiboles lie within the glaucophane range (Fig. 2), along a narrow band of ferric iron quantities. From this we understand that there is more magnesium than ferrous iron, and more aluminum than ferric iron. The most prominent exception to this, which falls in the ferro-glaucophane range, is from an inclusion within a garnet in an eclogitic sample.

Omphacite. Omphacite, by its most common definition, is a 50-50 mixture of the clinopyroxene end-members jadeite ($NaAlSi_2O_6$) and diopside ($CaMg\ Si_2O_6$). For most cases this is a reasonable definition, although it neglects an occasionally substantial acmite ($NaFe^{3+}\ Si_2O_6$) component. The most accurate way to discuss omphacite is as a tertiary system of jadeite, diopside, and acmite. The normal composition for omphacite in eclogites tends towards the jadeitic (Mottana, 1986).

As expected, jadeite is the dominant component in these rocks, ranging from 36 to 73 percent. The prominent actmite component is atypical for eclogites; it is generally larger than the diopside component and accounts for as much as 38 percent of the sample. Consistent with the data on the sodic-amphiboles, magnesium is more abundant than Fe^{2+} and aluminum is more abundant than Fe^{3+}.

Garnet. There are four important garnet compositions, each of which corresponds to a different element in the crystal's cubic site—grossular (Ca,) pyrope (Mg,) almadine (Fe,) and spessertine (Mn). Plotting these four components generally requires a quaternary diagram. However, the garnets in the Syros melange have a very tiny pyrope component. A modest bimodal distribution exists, corresponding to the Mn-enriched and Mn-poor samples (Fig. 3). What is not apparent from Figure 2 is that all of the Mn-poor compositions were collected from the edges of the sample crystals. Using the SEM, I made traverses and maps of several different garnets from three samples. The results were clear and consistent. There is a very pronounced zoning of manganese in all of the garnets studied. According to Meagher (1982), this zoning is the result of a progressive depletion and ultimate exhaustion of manganese from the surrounding crystals.

THERMOBAROMETRY

The original intention of this research was to confine the P-T-t path followed during the evolution of the Kampos and Kastri melanges. From this, I hoped to learn something about the tectonometamorphic history of the island of Syros and contribute to the general body of knowledge surrounding ophiolitic melanges. I planned to apply a series of thermobarometers to the chemical data collected using the SEM, to determine points of pressure and temperature along a P-T-t path.

The most commonly used geothermobarometer applied to the study of metamorphosed mafic rocks is a garnet-pyroxene thermometer, calibrated by Pattison and Newton (1989), which uses the exchange of iron and magnesium between garnets and omphacites to determine the highest temperature a particular sample attained. A problem arises in that the garnet-pyroxene geothermometers are calibrated for a certain quantity of magnesium—optimal results are met when the proportions of almadine and pyrope are roughly equal. Because the garnets in the samples have an extremely small pyrope component, repeated attempts with different versions of the garnet-pyroxene thermometer produced unreasonable temperatures. In spite of this problem, a single point of data was obtained using a garnet-muscovite thermometer (Hynes, Forest, 1988) on a single occurrence of garnet adjacent to phengite, yielding a temperature of 435°C.

CONCLUSIONS

The original intention of this research was to characterize the Kampos and Kastri outcroppings of the Syros ophiolitic melange while collecting sufficient chemical data to confine the P-T-t path followed by the protolith. Several weeks of field work produced a representative suite of samples from both outcrops. Using petrologic analysis of these samples, a series of categories was developed to accommodate each of the samples: blueschist, eclogite, blueschist/eclogite, felsic, and ultramafic matrix.

Several representative samples were studied using an SEM to collect crystal chemistry data. The sodic-amphiboles, rich in magnesium and aluminum, fall in the glaucophane range. The omphacites are of fairly typical composition for a clinopyroxene in an eclogite, with a significant jadeite component. The garnets in both the blueschists and the eclogites are unusual. They have a remarkably small pyrope component (between one and three percent), which is balanced by a large almadine component. The garnets are also zoned, with a manganese deficient rim encircling each crystal. The magnesium-poor nature of the garnets inhibited use of standard geothermobarometers on the samples.

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