TECTONOMETAMORPHIC EVOLUTION OF CYCLADIC SUBDUCTION ZONE ROCKS: THE SYROS BLUESCHIST-ECLOGITE TERRANE III

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REGIONAL INTRODUCTION

The Cycladic islands, located in the Aegean Sea (Figure 1), contain high-pressure metamorphic rocks that are believed to be the dismembered roots of the mountain belt formed during Eurasia-Africa subduction (Lister and Raouzaios, 1996), which began in the Eocene (Tomaschek et al., 2003) or late Mesozoic (Bröcker and Enders, 1999). The Cyclades are part of the Attic-Cycladic complex, an island belt of crystalline culminations linking continental Greece with Turkey. The complex consists of two main tectonic units. The upper unit contains various intercalated fragments of ophiolites, Permian sedimentary rocks and high temperature metamorphic rocks. In contrast, the lower unit is polymetamorphic and consists of a series of thrust sheets containing pre-Alpine basement, Mesozoic marble, metavolcanics and metapelites. The polymetamorphic nature of this lower unit is manifest by: 1) high-pressure, blueschist facies metamorphism, 2) normal regional metamorphism, and 3) contact metamorphism associated with the intrusion of granitic rocks (Schliestedt et al., 1987).

The high-pressure rocks are best preserved on the islands of Sifnos and Syros. Mineral assemblages vary with protolith and include metabasalts with clinopyroxene (omphacite) + garnet + glaucophane + epidote, felsic metavolcanics with jadeite + quartz, metapelites with muscovite + glaucophane + garnet + epidote, marbles containing dolomite + calcite ± quartz ± epidote ± phlogopite, ultramafic rocks, and quartzites (Schliestedt, 1986; Ridley, 1984b: Dixon and Ridley, 1987). Maximum metamorphic condition for the high-P event of 460°C and 14 kilobars at Sifnos (Schliestedt, 1986) are similar to the 480°C and 16 kilobars proposed for Syros by Trotet et al. (2001a).

A younger metamorphic event has been related to widespread late Oligocene/early Miocene extension throughout the Attic-Cycladic belt (Wijbrans et al., 1993). This second event overprints the earlier blueschists and eclogites, culminating at Naxos in a migmatite dome. On most islands and in particular on Syros and Sifnos, this second event is recorded in the rocks as a pervasive–yet localized– greenschist facies overprinting (Trotet et al., 2001b). Delamination of supracrustal rocks proximal to active subduction provided the cooling mechanism to preserve the blueschists and eclogites (Wijbrans et al., 1993) and may have been responsible for exhuming deeply buried (>50 km) rocks.

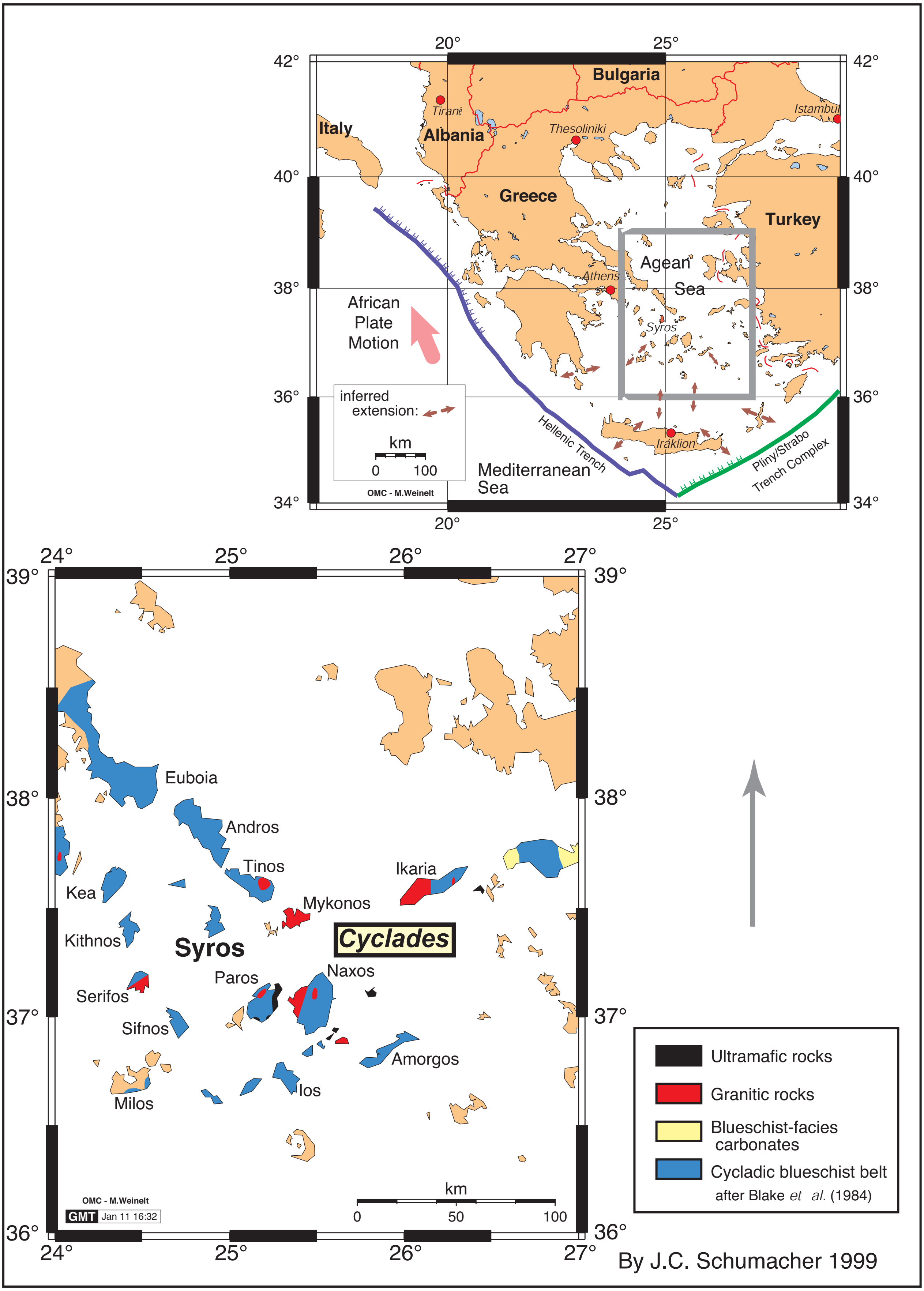

Figure 1: Tectonic map of the Agean Sea with the location of Syros and the Cycladic Islands (top) and the important rock types in the Attic-Cycladic complex (bottom).

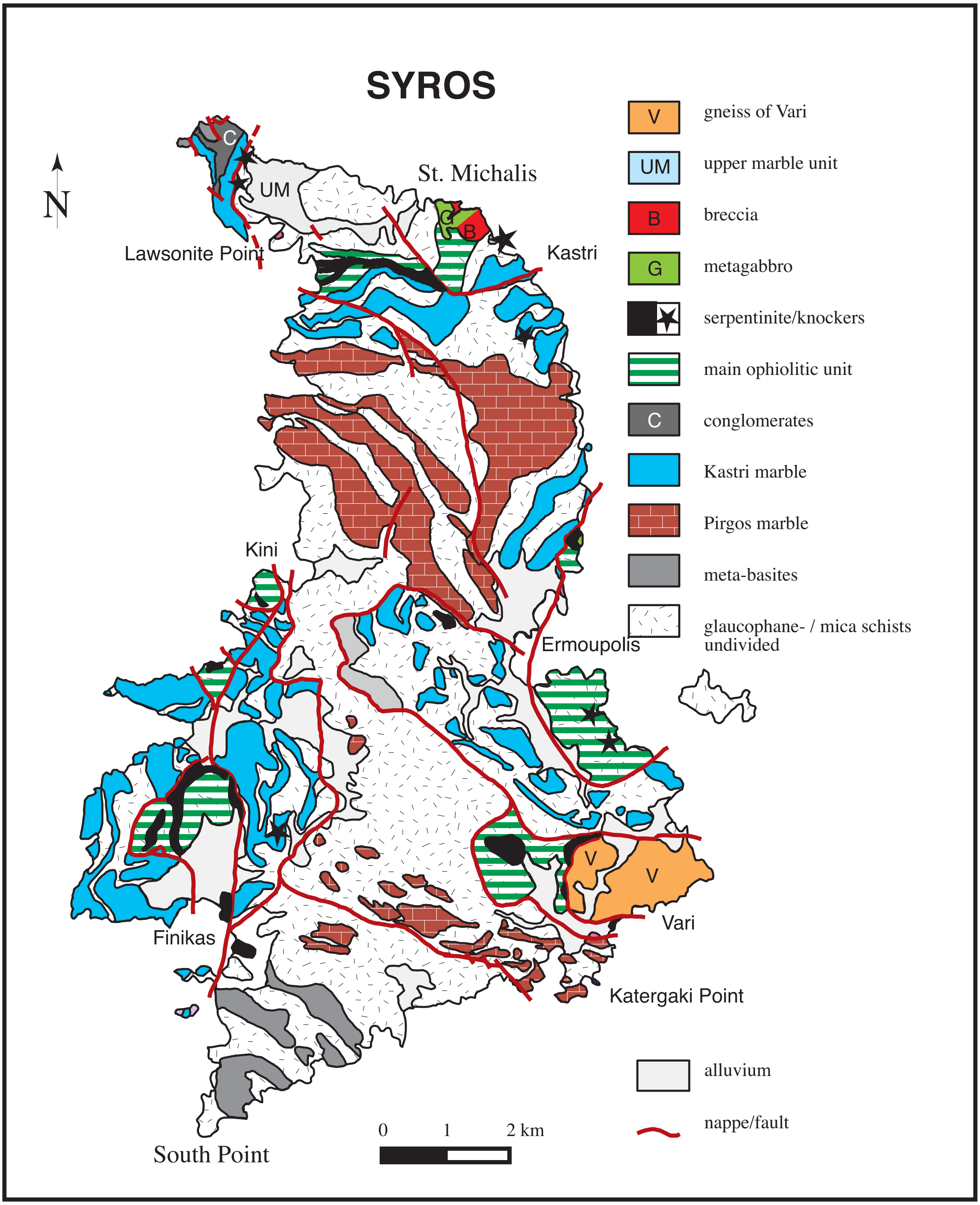

Figure 2: Generalized Geology of Syros modified from Höpfer and Schumacher (1997)

The rocks on these islands are isoclinaly folded and extensively sheared and flattened. Four generations of deformation have been recognized in terms of fabric and porphyroblast relations in rocks from Sifnos by Lister and Raouzaios (1996). Thus, rocks from Syros and Sifnos have been intensely deformed and significantly recrystallized so that most of the original igneous and sedimentary textures have been obliterated (Lister and Raouzaios, 1996; Dixon and Ridley, 1987).

GEOLOGY OF SYROS

The rocks of Syros can be broadly divided into two tectono-stratigraphic units as shown on Figure 2 (Schumacher et al., 2000): (I) metasedimentary and metavolcanic rocks and (II) remnants of oceanic crust. The lowermost rocks of Unit I are metamorphosed felsic tuffs, mafic schists, marbles, and finely-laminated manganese cherts. These rocks give way upwards to a section dominated by marbles. The two main lower marble horizons are typically dolomitic, in part, and are separated from each other by glaucophane-schists, greenschists (retrograde), and minor quartzites and manganese cherts.

Unit II consists of several discrete, fault-bounded packages of blueschist/eclogite-facies mafic rocks that contain minor serpentinite. The mafic rocks occur with a variety of textures and modes but most are either fine grained, glaucophane-rich blueschists or coarse-grained (>1cm), massive omphacite- or glaucophane-rich rocks. These rock types have been interpreted as metabasalt and metagabbro, respectively (e.g. Dixon and Ridley, 1987). This hypothesis has been verified by 38 whole-rock XRF and INAA analyses for 18 fine-grained and 20 coarse-grained samples reported by Brady et al. (2000) and Schumacher et al. (2001, 2004). These results show that the protoliths of the coarse-grained mafic rocks are indeed gabbros that have been chemically differentiated by fractional crystallization, whereas the protoliths of the fine-grained mafic rocks are largely undifferentiated ocean floor basalts. This interpretation is consistent with the conclusions of previous workers based on field (Dixon, 1969), geochemical (Seck et al., 1996), and isotopic (Putlitz et al., 2000) data. This result raises the interesting question of why a coarse-grained igneous protolith should lead to a coarse-grained metamorphic rock containing all new minerals. The massive character of the original gabbros appears to have had a strong influence on their metamorphism (coarse texture, little hydration) and deformation (little fabric, coherent blocks) during subduction and exhumation.

The occurrence of multiple generations of high-P minerals, hornblende as inclusions in glaucophane, intricate chemical zoning of high-P minerals, and partial to complete "euhedral" pseudomorphs after lawsonite that contain inclusions of garnet all attest to the complexity of the PTt path that was followed by these rocks during subduction and exhumation. One constraint on this path is provided by the occurrence of calcite pseudomorphs after aragonite that are widespread in the marbles of Syros. These striking features consist of polycrystalline bundles of calcite rods that are elongate and oriented at a high angle to the matrix foliation. Brady et al. (2004) have used the chemical composition, shape, and occurrence to postulate that the aragonite grew in a preferred orientation during high-P metamorphism and that it was subsequently topotacticaly replaced by calcite during exhumation.

According to Dixon and Ridley (1987), there is but one penetrative fabric that affects nearly all in the rocks of Syros. More recently, Rosenbaum et al. (2002) have identified at least three phases of deformation associated with the high-pressure metamorphism. The earliest fabric is preserved as inclusion trails in garnet grains and it is commonly at an angle to the matrix schistosity. High-pressure minerals define the matrix schistosity, which is parallel to lithologic contacts. Some glaucophane, the lawsonite, and the pseudomorphs after lawsonite appear to postdate the main fabric. There is some strain partitioning reflected by the massive cores of the metagabbros and some of the breccias. This dominant schistosity is the one identified by Dixon and

Ridley (1987) and glaucophane shear bands locally cut it. Superimposed on these high-P deformation fabrics is a late locally-developed fabric associated with greenschist overprinting.

Cheney et al. (2000) have reported 206Pb - 238U ages from zircon in two blueschists. Ion microprobe spot ages were obtained from three zircon grains in sample SYR99-19A and one zircon grain in sample SYR-7A. The zircon grains selected for dating are large, euhedral and their textual occurrence is consistent with syn- to post-kinematic growth. Some of the euhedral zircon grains are partially included in blue amphibole whereas others crosscut the fabric. There are no grains that are wrapped by the fabric. Thus, these zircons grains appear to have grown during metamorphism in accord with the interpretation of Bröcker and Enders (1999) for a zircon in an omphacitite, also from the north end of Syros. The result of 83+/-10 Ma from sample SYR99-19A is remarkably consistent with the 78+/-1 Ma TIMMS age reported by Bröcker and Enders (1999) and they probably represent the true metamorphic age for all the rocks. Sample SYR-7A is a glaucophanite from the Kampos melange zone and the zircon ages from one euhedral grain range from 81+/-2 to 54+/-4. These dates may indicate activation of the melange zone and continued metamorphism. Of interest is that Bröcker and Enders (1999) also reported similar young ages of 60 Ma and 63 Ma zircon ages in a jadeite rock on Tinos, which they also attributed to a younger "event". These results lend credibility to the occurrence of pre-Eocene high-pressure metamorphism in the Aegean. This 80 Ma Cretaceous event may record heating following the slowing of the subducted slab. The younger Eocene dates reflect later lower pressure retrograding of these rocks and the continuing evolution of the accretionary wedge. These ages are similar to zircon ages reported by Tomaschek et al. (2003). However, they interpret the 80 Ma. ages as magmatic ages of the zircon and thus the ~80 Ma age is that of the ocean crust. Support for this hypothesis comes from the Lu-Hf study of similar mafic rocks by Lagos et al. (2003). Tomaschek et al. (2003) argue that the agreement between the 55 Ma U-Pb ages and the ~ 55 Ma Ar-Ar ages of white micas from the same samples supports the conclusion that the metamorphism is Eocene. They do not, however, explain how zircon crystallized from basaltic MORB-like magma. One likely source of Zr in a basalt is that it resides in augite. When augite breaks down during hydration, either on the sea floor or in the subduction zone, the Zr can be concentrated to form zircon. Thus, the 80Ma ages of the zircons may well be recording augite breakdown and not magmatic precipitation of zircon.

STUDENT PROJECTS

The 2004 student projects were conducted solely on the island of Syros. The student projects were designed to build upon our previous results and to extend our coverage of the island in terms of both area coverage as well as scope. These studies focused upon the structural, mineralogical and textural consequences of the processes involved in the evolution of the Syros Blueschist-Eclogite terrane.

Njoki Gitahi (Amherst) and Elizabeth Holly (Pomona) are studying one of the most distinctive and widespread rocks on Syros in order to assess variation in metamorphic pressures and temperatures over the whole island. They are both focused upon the fabric, mineralogy and phase relationships of the eclogites that occur in the fault bounded mafic enclaves. They are using the newly calibrated thermobaromter of Ravna and Terry (2004) for garnet + omphacite + phengite ± rutile ± quartz bearing rocks. Elizabeth is focused upon eclogitic rocks from the east side of Syros whereas Njoki is studying similar rocks from the west side of the island. Eric Purcell (Beloit) is looking at blackwall reaction zones that have formed on these same eclogites where they occur as exotic blocks in sepentinite mélange. Eric is attempting to determine the nature of metasomatism both spatially and chemically. Laura Frye-Levine (Smith) is examining the graphitic schists that are common on the north end of the island. These rocks typically contain a variety of lumps structures reminiscent of pseudomorph after lawsonite and or garnet and thus provide an interesting continuation of the lawsonite pseudomorph story initiated in our first project (e.g. Sperry 2000) and continued in phase II (e.g. Able, 2001).

The marbles of Syros are the focus of two very different projects. Jessica Driscoll (Amherst) is using electron backscattered diffraction (EBSD) to determine in detail the crystallographic orientation of calcite psuedomorphs after aragonite that have been recently described by Brady et al. (2004). Jessica hopes to learn the extent and distribution of calcite grains with a crystallographically-preferred orientation. Emily Pope (Colorado College) is using Carbon and Oxygen isotopes to characterize the metamorphic history and the nature of metamorphic fluids of the three different marbles on Syros. Emily is also studying the applicability of calcite-dolomite geothermometry in these blueschist facies marbles.

Stacey Kepler is continuing our efforts to characterize the protoliths of the various metamorphic rooks on Syros by studying the major and trace element geochemistry of the glaucophane schist sequences that are associated with the marbles in Unit I. Taken together these schists and marbles comprise the bulk of the island. These rocks are quite variable in appearance ranging from light to dark colored and thus in protolith, possibly from felsic to mafic volcanic rocks, Our earlier work (e.g. Sinitsin, 2001) has identified possible calc-alkaline or arc related volcanic protoliths on Syros. Volcanic protoliths from the nearby island of Sifnos reflect the sequential formation of a subduction zone, an island arc and then a back arc basin (Mocek, 2001).

Three of the students are studying elements of the structural evolution of Syros that encompass the tectonic evolution from subduction to exhumation. Eli Lazurus (Williams) examined in the field three high angle faults associated with distinctive breccia zones that crop out along the west coast of Syros. These post-metamorphic faults are possibly synchronous with or younger than the large-scale normal faults that exhumed the blueschist eclogite terrane of Syros. Fluid inclusion analysis of matrix minerals in the associated fault breccias will help constrain the context in which the faulting occurred. The detailed description and interpretation of microfabrics are at the core of the studies of Scott Dougan (Amherst) and Gabe Nelson (Carleton). Gabe is studying the textural relationship between inclusion fabric within garnet porphyroblasts in glaucophane schists, pressure shadows around the garnet (some of which contain distinctive glaucophane “tails”) and the matrix foliation in schists from around the island. Gabe will assess these relationships in terms pure and simple shear during high-pressure metamorphism. Scott is focused upon the habits and textural variations of white mica elements in micaceous schists. Scott is mining his samples for key occurrences of white mica that will allow stages in fabric development such as crenulation and shearing to be dated by Ar-Ar laser techniques.

JANUARY WORKSHOP

Eight of the ten students and three of the four faculty participants in the 2004 Greece-Syros Keck project assembled for a collaborative workshop at Amherst College over the weekend of 23-25 January, 2004. The workshop provided students and faculty with the opportunity to exchange data and results, and to share experiences and problems encountered in their endeavors. This was particularly useful as several of the student projects are interdependent in that they rely to some extent on the results of each other’s work.

The group assembled Friday evening for a pizza dinner followed by several hours of slides of people, outcrops and views on Syros. On Saturday morning, each of the eight students in attendance gave a 15-minute oral presentation. Varying materials including photomicrographs, projection of critical thin-sections, maps, chemical data, and mineral composition data accompanied these reports. The informal setting provided ample opportunity for questions, discussion, and sharing of results, methods, problems and concerns. During the afternoon, Tekla Harms led a review and discussion of Mediterranean geology. We then spent the rest of the day reviewing and comparing minerals and fabric in our thin sections.

On Sunday, the workshop focused upon a detailed discussion of minerals we had encountered in the rocks from Syros. This involved reviewing the crystal chemistry of several important minerals including omphacite, blue amphibole, phengitic mica and the epidote family. John Brady discussed ferric iron corrections of SEM data for these minerals as well as ways to represent graphically their compositions. Gabe Nelson (Carleton) stayed for several days following the workshop in order to complete the mineral analysis portion of his study using the SEM/EDS system at Smith. Elizabeth Holly (Pomona) traveled to Amherst two weeks before our workshop in order to complete the analytical part of her study using the SEM/EDS systems at Amherst.

RESULTS

The results of the 1999 and 2000 project were summarized in the 2000 and 2001 KECK proceedings volumes. In addition, these groups have produced at least 8 student abstracts that were presented at regional GSA meetings, five abstracts jointly co-authored by project faculty and students were presented at national and international meetings and one paper has been published. A list of these result is appended below.

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