ORIGIN OF BLUESCHIST BRECCIA, SYROS, GREECE

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INTRODUCTION

The Cycladic islands have undergone two periods of Alpine-Himalayan-type metamorphism. The first episode, late Cretaceous or Eocene high-pressure blueschist facies metamorphism, is associated with subduction zone metamorphism. A second Miocene greenschist overprint is associated with extensional exhumation of these rocks. The greenschist overprint completely effaced the blueschist metamorphic events on all but two of the Cycladic islands, Syros and Sifnos (Dixon 1987).

On Syros, there is a continuous alternating sequence of N to NE dipping pelitic schists, marbles and metamorphosed mafic igneous rocks. Protolith textures and assemblages have been obscured during the deformation and metamorphic events (Dixon1987). We focus on a breccia that is found along the NNE coast of the island. Various workers have understood the protolith of this breccia as sedimentary, tectonic, or igneous. In a combined petrographic, structural, and geochemical study, we are comparing the clasts and matrix of the breccia to other meta-igneous rocks in the region to understand the protolith of the breccia.

PETROGRAPHY

The rocks in this study can be divided into five groups.

Glaucophane Schist. Glaucophane schist occurs in the field as breccia matrix and within the breccia as coarser grained clasts. Oriented glaucophane and paragonite and clast shapes define the NE striking, shallowly W dipping foliation. In some samples, top to the NW sense of shear indicators are associated with a moderately NW dipping lineation. Concentrations of mica, fuchsite, quartz or coarse glaucophane from 5mm to 3cm long are common. Glaucophane + epidote + garnet + paragonite + albite ± chlorite are the main minerals in the glaucophane schist. Titanite, calcite, rutile, and zircon are present as accessories. Often garnets touch each other, pinching the foliation between them. Garnets contain inclusions of quartz, muscovite and biotite. Some glaucophane crystals have epidote inclusions. Chlorite is concentrated around anhedral garnets, suggesting that it is a secondary alteration product. Inclusion relationships suggest that quartz, muscovite, and biotite formed before garnet, and epidote formed before glaucophane. Foliation drapes around garnet suggesting that flattening along this foliation occurred after garnet growth. This indicates that the rock could have experienced late flattening perpendicular to the foliation.

Mica Schist. Mica schist occurs as clasts in metabreccia and to a lesser extent in chlorite schist and metagabbro. Alternating layers of mica and quartz + albite define the NE striking shallowly dipping foliation. In samples where glaucophane is present, it defines a lineation parallel to the foliation. Mica + quartz + albite + epidote ± garnet ± chlorite make up the largest percent of each sample while rutile, titanite, glaucophane, and tourmaline can be found as accessories.

Quartz has straight to serrate grain boundaries and undulose extinction. Euhedral garnets edged with chlorite contain inclusions of quartz and mica. Quartz textures suggest metamorphic recrystallization. Inclusions in garnet suggest that quartz and mica formed before garnet. The foliation drapes garnet, which often touch each other, suggesting late flattening perpendicular to foliation. Isoclinal fold hinges in mica, quartz and chlorite parallel to the foliation may preserve an earlier deformational event.

Metagabbro. The metagabbro is characterized by a weak foliation, large omphacite crystals, up to 2 cm long, and rusty weathering. It contains the assemblage pyroxene + epidote / clinozoisite + albite with minor chlorite, actinolite, pumpellyite, and white mica. There are large bodies of metagabbro to the south, west and north of the metabreccia outcrop. Within the metabreccia body, there are metagabbro clasts and smaller units of metagabbro in fault contact above and below the metabreccia. To the west and south, the contact between metabreccia and metagabbro is gradational. Towards the breccia, the metagabbro starts to become richer in glaucophane and contains some clasts of mica schist and glaucophane schist. Closer to the breccia, glaucophane becomes more abundant than omphacite, and mica schist clasts and metagabbro clasts become more common.

Felsic dike. Dikes are in an outcrop of metagabbro along the coast, north of the metabreccia. It averages about 60 cm wide. The contact between dikes and the metagabbro is sharp. Dikes crosscut each other. White mica defines a weak foliation. Medium grained and equigranular, the rock contains quartz + mica + zoisite + feldspar + chlorite ± garnet + clinozoisite + epidote + opaques. Quartz has straight to serrate boundaries suggesting metamorphic recrystallization.

Chlorite Schist. Chlorite and mica define the foliation. Glaucophane defines a lineation in some samples. The schist is medium grained and green to dark green in color, often with orange weathering dolomite. The minerals associated with chlorite schist are chlorite + mica + epidote + dolomite; quartz, garnet, glaucophane, titanite, and rutile are common accessories. The foliation drapes dolomite and epidote. Isoclinal fold hinges, defined by mica, have axial planes parallel to foliation. Anhedral chlorite is often at a high angle to the foliation. This suggests it formed after the foliation. The mica folds may preserve evidence of a previous deformational event. Foliation draping dolomite and epidote records late flattening.

STRUCTURE

Figure 1 shows foliation and lineation in the glaucophane schist breccia. Foliation in the glaucophane schist that forms the matrix for the breccia strikes NE and dips approximately 30° to the W. This is consistent with the general N to NE strike all of the rocks units on Syros have.

Clasts in the breccia define a stretching lineation that plunges moderately NW. The clasts are elongate parallel to the lineation and are flattened parallel to the contacts between breccia, metagabbro, and chlorite schist. Clasts have a prolate shape and aspect ratios of approximately 30:1.

The only crosscutting relationship between the five rock types in this area is the felsic dike cutting the metagabbro, otherwise all contacts are approximately parallel to the breccia foliation. The breccia contains metagabbro and mica schist clasts and there are glaucophane schist and mica schist clasts in the metagabbro.

Figure 2 shows the contacts between the five rock types. In outcrops where the contact between metagabbro and breccia is visible, it is parallel to this foliation. The same is true of the contacts between breccia and chlorite schist. The chlorite schist has a well- defined foliation and it is also parallel to the contact. A gradational contact between breccia and metagabbro exists. The matrix becomes richer in pyroxene, there are fewer clasts, it becomes less schistose. Over 8-15 m metagabbro will have taken over, with the occasional mica or glaucophane schist clast. Most of the other contacts between breccia and metagabbro are sharp.

GEOCHEMISTRY

Figure 3 shows metagabbro (open circles) and breccia matrix (filled circles) plotted on an alkalis vs. silica graph. Figure 4 shows the same samples plotted on a MgO vs. SiO_2 graph. Metagabbro samples display how crystal fractionalization of more primitive magma will drive the composition towards higher silica and alkalis and lower MgO. The arrows in figures 3 and 4 illustrate the trend towards more evolved rocks as the magma continues to crystallize minerals rich in calcium and magnesium. The composition of the breccia matrix samples do not lie along this trend, they are more alkalic and lower in silica. Magmatic processes cannot derive the metagabbro from the breccia composition either, since the breccia is lower in MgO and higher in silica. Assuming that both the metagabbro and the breccia matrix were closed systems during metamorphism, it is unlikely that they are co-magmatic.

SUMMARY

Geochemical analysis shows that the composition of the breccia matrix is that of an alkalic basalt similar to an ocean island alkali basalt. Despite this similarity the geochemical data does not rule out the possibility that the breccia matrix protolith was sedimentary. Field observations did not yield any signs of sedimentary structures, but in light of the metamorphic and deformation history of the Cyclades, this is to be expected.

Assuming that the protolith of the breccia was igneous, it is unlikely that it is co-magmatic with the metagabbro. Compositionally, the protolith for the metagabbro is closer to MORB. This difference could help to constrain the tectonic environments in which each of these rocks formed. This information in the context of the geologic history of Syros, will further our understanding of where the clasts came from and how they became part of the breccia.

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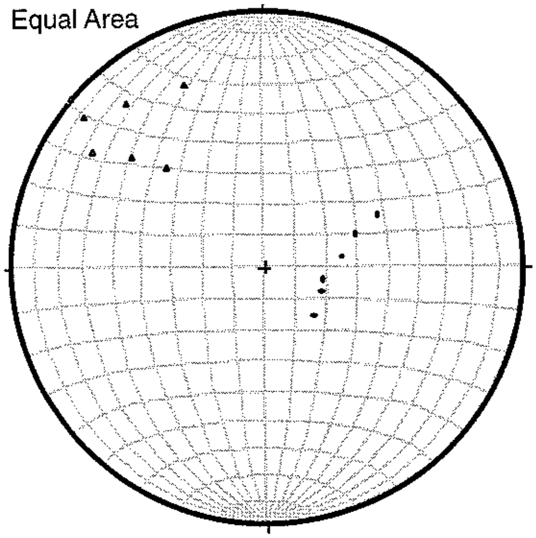

Figure 1. Equal area stereonet showing poles to foliation (circles) and lineation defined by long axes of clasts (triangles).

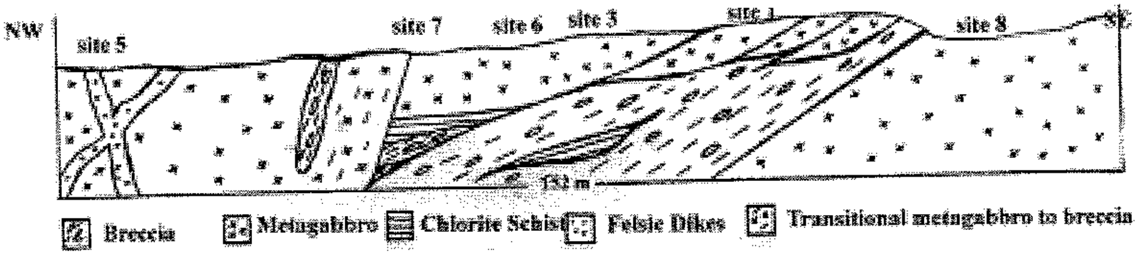

Figure 2. Schematic cross section of NNE coast of Syros.

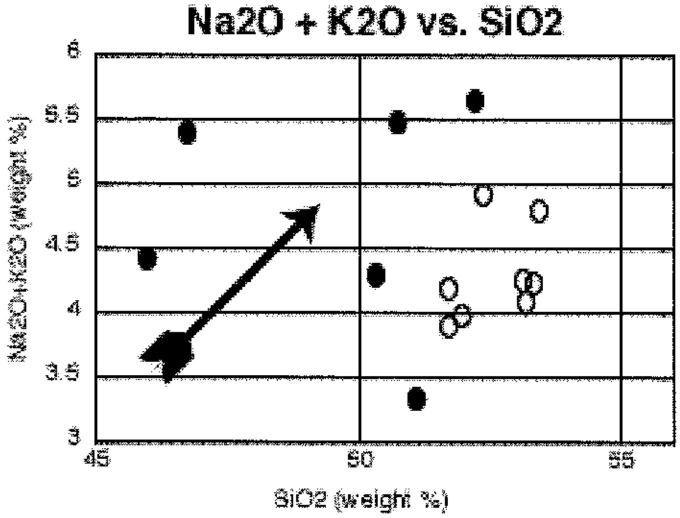

Figure 3. Breccia matrix represented by filled circles, metagabbro represented by open circles, arrow shows fractional crystallization trend.

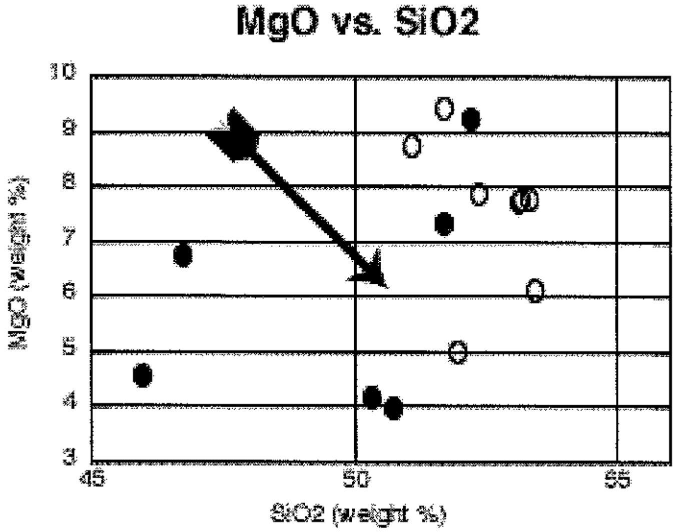

Figure 4. Breccia matrix represented by filled circles, metagabbro represented by open circles, arrow shows fractional crystallization trend.

ORIGIN AND EVOLUTION OF THE HIGH-PRESSURE META-IGNEOUS ASSEMBLAGE NEAR ST. MICHALIS, SYROS, GREECE

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INTRODUCTION

Metamorphic rocks of the island of Syros in the Cyclades, a group of Greek islands located in the southern Aegean, are the product of the Alpine Orogeny. This orogeny was initiated by convergence among Africa, Eurasia, and several microplates between them (Smith and Woodcock, 1982). Northward-directed under-thrusting of one such fragment, the Apulian microplate, beneath Eurasia was most likely responsible for eclogite/blueschist facies metamorphism of rocks now exposed on Syros and other Cycladic islands (Avigad and Garfunkel, 1991). This subduction may have begun as early as the Cretaceous (Bröcker and Enders, 1999). Although Syros is mostly composed of a thick pelitic schist-marble succession, several meta-igneous bodies with the mineralogy associated with high-pressure low-temperature metamorphism are embedded in the northern, central, and western parts of the island (Okrusch and Bröcker, 1990).

OBJECTIVES

This study concentrates on the geochemistry and history of the diverse high-pressure, low-temperature, meta-igneous rocks in the complex located near the village of St. Michalis in the northeastern corner of Syros. This meta-igneous assemblage includes (from most to least abundant) coarse-grained metagabbros, blueschists, fine-grained clinopyroxene-garnet rocks, meta-igneous rocks with a gneissic fabric, meta-breccias, serpentinite, and a small felsic body thought to be a jadeitite. The majority of the diverse rocks composing the St. Michalis assemblage appear to form large coherent meta-igneous bodies, but some also occur as tectonic blocks in serpentinite melange zones. The two wide (at least 50 m) coastal zones of meta-breccia bound on two sides the smaller of the metagabbro bodies and contain dominantly meta-igneous blueschist and clinopyroxene-garnet rock clasts. The entire assemblage appears to be tectonically separate from the marble-schist succesion (Okrusch and Bröcker, 1990). The diversity of rock types in the assemblage suggests that there might also be fault surfaces within it, separating blocks that may have been juxtaposed either during subduction or exhumation.

METHODS

Chemical analyses of major, minor, trace, and rare earth elements have been obtained for eighteen of the samples in an attempt to constrain the origin and petrogenetic history of the St. Michalis assemblage. Are these meta-igneous rocks genetically related or were they assembled from completely separate protoliths prior to or during the subduction? The results of these analyses suggest that these meta-igneous rocks had at least three chemically different, separate source magmas, and that the major variations in mineralogy are most likely the result of these chemical differences. These data may also provide an answer to the question of whether the two areas of meta-breccia are tectonic in origin or if they in fact were created through the emplacement of the metagabbro pluton. In addition, mineral composition data are being gathered on the SEM/EDS (Scanning Electron Microscope/Energy Dispersive Spectrometer). These data will be used to characterize differences in mineral compositions among various rock types and to constrain the metamorphic evolution of these meta-igneous rocks, especially the conditions of the high-pressure, low-temperature metamorphism.

PETROGRAPHY

Although the St. Michalis assemblage is composed of many different rock types, three are by far the most abundant: metagabbros, clinopyroxene-garnet rocks, and blueschists. Metagabbros contain mostly coarse-grained (5-20 mm) green clinopyroxene (40%), fine-grained epidote (40%), coarse-grained (5-20 mm) amphibole (15%), and rutile (5%), although an iron-rich variety with more glaucophane than omphacite can also be found in few locations. Fine-grained (up to 2 mm) clinopyroxene-garnet rocks are characterized by clinopyroxene (40-60%), quartz (typically 25-30%; sample 21A is the one exception that has less silica and as the result contains far less quartz), and garnet (10-15%). These rocks also usually contain a white mica (paragonite or phengite), rutile/titanite, and apatite. The significant amount of quartz found in clinopyroxene-garnet rocks suggests that their protolith was probably not basaltic, but a different, more felsic igneous rock type. Blueschists are composed of mostly fine-grained glaucophane (50-70%) and coarse-grained (1-5 mm) garnet porphyroblasts (20-30%), with smaller amounts of epidote, rutile, and white mica. All three of these rock types are foliated where they contain elongate or platy minerals. Meta-breccia and a distinctive gneiss also form a significant proportion of the St. Michalis assemblage. Meta-breccia contains two major rock types that are very similar to clinopyroxene-garnet rocks and blueschists, which are likely to have been the major source materials. Meta-igneous gneiss is the least common of the rock types described here. Its mineralogy is intermediate between those of blueschists and eclogites, with glaucophane, clinopyroxene, and garnet concentrated in darker bands, and epidote and albite being the two most abundant minerals in lighter bands.

MINERAL COMPOSITIONS

Scanning Electron Microscope analyses (Figure 4) show that clinopyroxenes in fine-grained cpx-garnet rocks have a large jadeitic component, with 0.7 to 0.9 formula units of sodium and 0.4 to 0.8 formula units of aluminum. The smaller amounts of aluminum (compared to sodium) indicate that these clinopyroxenes also have a small amount of acmite, in which ferric iron substitutes for aluminum. Two of these rocks (10A and 15C) also contain garnet + paragonite + quartz + albite, which makes them excellent candidates for geothermobarometry. A garnet-clinopyroxene geothermometer can be applied to constrain the temperature at which these rocks underwent metamorphism, and albite = jadeite + quartz and paragonite = jadeite + quartz + kyanite geobarometers can be used to constrain a range of possible pressures. Preliminary results suggest that these rocks and probably the whole assemblage experienced high-pressure low-temperature metamorphic conditions similar to the accepted peak values of 15-18 kilobars and 500 degrees Celsius (Avigad and Garfunkel, 1991).

Another interesting result of SEM analysis is that the alleged jadeite knocker (sample 7C) in fact has neither jadeite nor any other pyroxene. The most common mineral in this small meta-igneous body is albite, with small amounts of phengite, chlorite, epidote, and glaucophane.

CHEMICAL ANALYSIS

Whole-rock chemical data (Tables 1 and 2) show conclusively that the three major rock types in the St. Michalis assemblage, epidote-omphacite metagabbro, fine-grained garnet-clinopyroxene rocks, and garnet-glaucophane blueschist, are indeed chemically different and are likely to have had different protoliths. These three meta-igneous rock groups have major oxide compositions that are consistent within each group, but that vary among these rock types. For example, garnet-clinopyroxene rocks are much richer in silica (56-70%) than blueschists (45-48%), but have much less iron than the latter. Metagabbro samples have an intermediate silica composition (53%), but, with one exception, these rocks have the most aluminum. Other major oxides also show significant differences. Rare earth element plots (Figures 2 and 3) for these three rock groups also suggest major differences in origin. Garnet-glaucophane blueschists show a pattern consistent with undifferentiated ocean floor basalts. The REE plots for garnet-clinopyroxene rocks, on the other hand, is slightly downward-sloping for the most incompatible section of the graph, and has a Europium spike that suggests that there had been plagioclase in the source of this rock type. The pattern for metagabbros is the reverse of that for garnet-clinopyroxene rocks; it shows REE concentrations ten times lower, indicating that the source magma was highly differentiated and probably accumulated plagioclase. Although these plots suggest that clinopyroxene-garnet rocks and metagabbros may be related, the time of their emplacement is probably separated by the formation of meta-breccia (see below), which contains many clinopyroxene-garnet clasts but no metagabbro clasts. Field relationships indicate that although chemical data may suggest a single protolith, these two rock types formed at different periods of time and therefore probably from separate magmas. Their only relationship may be the similarity of environments at which they formed.

Chemical data also suggest that the differences in mineralogy among the several major rock groups in the St. Michalis assemblage result from the differences in bulk composition and not metamorphic grade. There are large variations in mineralogy of rocks with different chemical compositions, but chemically similar rocks have similar proportions of the same minerals. For example, silica-poor and iron-rich blueschists contain mostly glaucophane and garnet whereas silica-rich garnet-clinopyroxene rocks have almost no glaucophane but large amounts of clinopyroxene. Because these rocks have silica compositions consistent with dacites, eclogite is probably not the appropriate name for them. The unique mineralogy of metagabbros is probably also the result of their specific chemical composition.

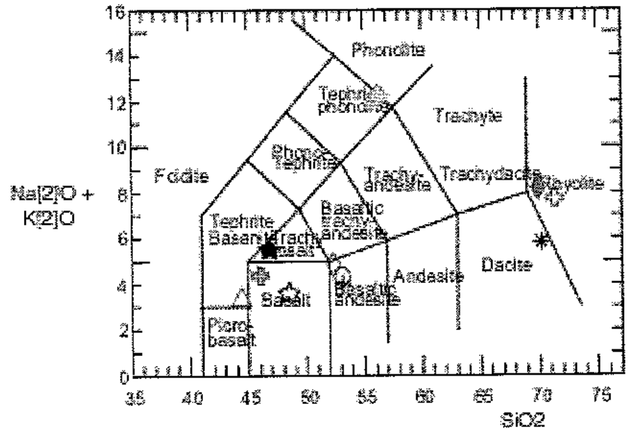

Figure 1: Total Alkalies Vs. Silica

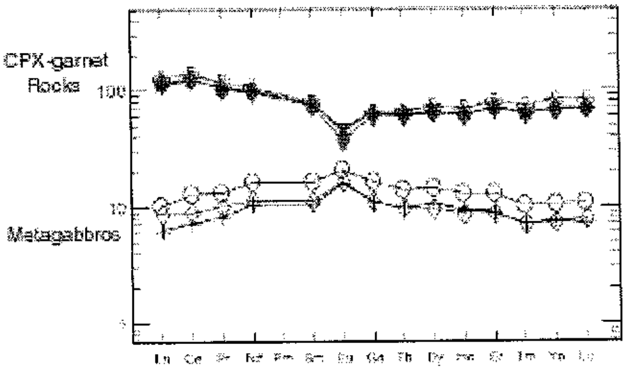

Figure 2: Rare Earth Elements (after Sun & McD. 1989) - Clinopyroxene-Garnet Rocks and Metagabbros

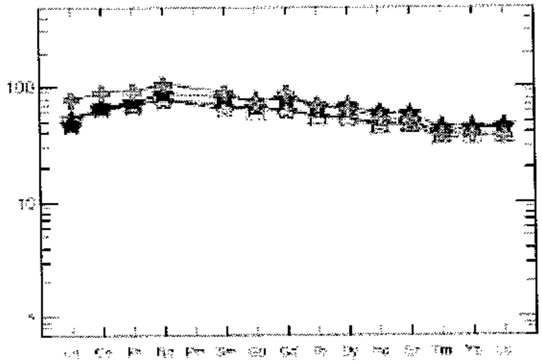

Figure 3: Rare Earth Elements (after Sun & McD. 1989) - Blueschists

Figure 4: Average Mineral Compositions in Formula Units

Sample AGS-15E

	Glaucophane	Garnet	Epidote
	O=23	O=12	O=12.5
Si	7.979	3.0115	3.1022
Al	1.5853	1.9329	2.3397
Ti	0.0109	0.0082	0.0102
Mg	1.5705	0.2141	0.0084
Fe	1.9	2.0831	0.7701
Mn	0.0047	0.0391	0.0149
Ca	0.11	0.6646	1.9628
Na	2.1065	0.0119	0.0254
K	0.0056	0.0031	0.0019
Ba	0.0008	0.0013	0.0013
Cl	0.0024	0.0085	0.0026
Zn	0.0077	0.0051	0.0028
Cr	0.0026	0.0013	0.0017

Sample AGS-10A

	O=6	O=12
	CPX	Garnet
Si	2.0183	3.0096
Al	0.7847	1.9448
Ti	0.0021	0.0075
Mg	0.0494	0.096
Fe	0.1679	1.8848
Mn	0.0016	0.2484
Ca	0.0869	0.8041
Na	0.9492	0.0616
K	0.0002	0.0042
Ba	0.0004	0.0008
Cl	0.0047	0.0131
Zn	0.0001	0.0021
Cr	0.0011	0.0008

Legend:

AGS-4A (blueschist): triangle
AGS-8A (metagabbro): open diamond
AGS-10A (CPX-gt rock): filled diamond
AGS-10C (metagabbro): open circle
AGS-12 (metagabbro): black cross
AGS-13A (CPX-gt rock): black star
AGS-13D (blueschist): open star
AGS-15B (blueschist): filled star
AGS-15C (CPX-gt rock): open cross
AGS-15E (blueschist): filled cross
AGS-21A (CPX-gt rock): filled wide diamond

Last of all, chemical data for meta-breccia samples indicate that these rocks are more likely to be tectonic in origin rather than intrusive. As can be seen from major oxide concentrations and REE plots, breccia samples are very similar to either garnet-clinopyroxene or garnet-glaucophane rocks. None of the samples, however, have compositions like those of metagabbros, as would be expected if the breccia is intrusive in origin. In the field metagabbro is found only at the edges of the meta-breccia bodies. This suggests that metagabbro was emplaced subsequent to tectonic formation of the meta-breccia bodies.

CONCLUSIONS

The St. Michalis assemblage contains at least three major chemically different rock groups, garnet-glaucophane blueschists, garnet-clinopyroxene rocks, and epidote-omphacite metagabbros, and the differences in mineralogy observed among these three rock types are probably the result of their compositions and not metamorphic grade. REE plots suggest that these three rock groups had different and perhaps geographically separate protoliths. Mineralogy of garnet-clinopyroxene rocks makes them good candidates for studying geothermobarometry of the assemblage, and preliminary results are consistent with the accepted values of peak high-pressure low-temperature metamorphic conditions of 15 kilobars and 500 degrees Celsius (Avigad and Garfunkel, 1991).

#	Si	Al	Fe	MgO	CaO	Na	K	Ti	P	MnO	Cr
4A	44.3	10.7	17.75	6.49	9.39	3.28	0.06	5.34	0.96	0.18	0.005
6A	53.23	10.07	9	6.24	11.49	6.56	0.19	2.28	0.1	0.1	0.007
6D	49.77	14.51	11.59	7.48	3.95	3.78	2.37	2.65	0.4	0.21	0.006
7C	76.74	12.8	1.11	0.63	0.17	7.35	0.12	0.21	0.01	0.01	0.004
8A	52.31	15.48	6.46	7.88	10	4.67	0.25	0.76	0.06	0.12	0.008
10A	69.88	14.89	3.84	0.54	1.47	8.13	0.07	0.38	0.11	0.06	0.001
10C	53.1	14.97	7.08	7.71	10.4	4.11	0.16	0.84	0.08	0.13	0.007
12	53.14	15.17	6.5	7.76	10.91	3.95	0.13	0.7	0.01	0.1	0.006
13A	70.16	14.66	4.04	0.88	2.53	5.72	0.15	0.42	0.06	0.05	0
13D	48.39	13.64	14.06	5.26	9.14	3.62	0	3.77	0.5	0.28	0.006
15B	46.75	11.06	18.59	6.76	4.6	5.36	0.14	4.02	1.15	0.36	0.006
15C	71.32	14.1	3.83	0.39	0.91	6.9	0.87	0.39	0.07	0.07	0.004
15E	45.98	12.81	18.61	4.54	7.37	4.34	0.07	4.4	1.37	0.33	0.003
15H1	51.94	13.31	13.25	4.98	8.19	3.88	0.11	2.57	0.11	0.3	0.007
17	50.83	12.56	13.47	5.26	7.34	5.19	0.18	3.91	0.13	0.24	0.003
19	53.07	14.48	11.15	4.78	6.12	5.79	1.31	1.61	0.3	0.2	0.001
21A	56.22	17.46	8.33	1.52	2.51	11.55	0.7	0.77	0.15	0.15	0
22A2	54.81	11.43	8.43	7.68	6.92	6.72	0.85	1.59	0.13	0.12	0.022

Table 1: Major Elements (percent; all elements stand for most common oxides; iron is ferrous)

#	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
4A	12	39.9	6.55	36.2	10.6	3.34	13.12	1.99	13.33	2.52	7.52	0.91	6.16	0.94
6A	20.2	66	10.16	52.8	13.9	4.47	15.64	2.3	14.57	2.79	8.59	1.14	8.61	1.42
6D	7.9	26.3	4.38	24.4	7.6	3.62	10.21	1.68	12.31	2.56	8.1	1	7.06	1.03
7C	15	44.4	5.7	23.7	6.5	0.69	8.27	1.77	14.15	3.19	11.5	1.73	13.38	1.99
8A	2.1	5.5	0.96	5.3	1.7	0.95	2.28	0.36	2.43	0.49	1.45	0.18	1.23	0.2
10A	27.3	77.6	9.88	44.6	11.3	2.13	12.55	2.24	16.13	3.44	11.53	1.59	11.43	1.77
10C	2.4	7.9	1.26	7.5	2.5	1.19	3.3	0.52	3.57	0.73	2.14	0.26	1.79	0.27
12	1.5	4.4	0.78	4.9	1.6	0.92	2.24	0.36	2.65	0.53	1.47	0.18	1.29	0.18
13A	25.9	75	10	46.6	11.5	2.71	13.24	2.27	16.49	3.47	11.53	1.59	11.57	1.76
13D	12.6	39.7	6.61	36	10	3.91	12.73	2.04	13.59	2.69	7.98	1	7.51	1.15
15B	11.4	40.8	7.07	41.2	12.4	4.36	16.28	2.54	16.98	3.3	9.42	1.14	7.57	1.12
15C	30.9	84.6	11.18	49.9	12.1	2.56	13.15	2.43	18.05	3.9	13.09	1.87	13.79	2.05
15E	18.4	55.4	8.74	49.2	13.7	4.17	17.76	2.56	16.07	3.04	8.56	0.99	6.57	0.95
15H1	3.3	11.4	2.03	12.2	4.2	2.46	5.63	0.91	6.58	1.32	4.02	0.52	3.66	0.58
17	5.2	14.6	2.48	13.7	4.5	1.67	5.74	0.98	6.9	1.41	4.32	0.58	4.07	0.63
19	9.9	24.1	3.19	16.9	4.3	1.83	5.38	0.84	5.88	1.15	3.63	0.49	3.38	0.53
21A	35.3	101.6	14.53	68.3	16.9	3.93	17.94	3.17	23.02	5.06	17.62	2.61	19.98	3.19
22A2	10.8	33.1	4.97	25	6.6	2.03	8.41	1.47	10.3	2.08	6.68	0.88	6.3	0.91

Table 2: Rare Earth Elements (ppm)

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