PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2013
Pomona College, Claremont, CA

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KECK GEOLOGY CONSORTIUM
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PETROLOGY AND GEOTHERMOMETRY OF GARNET AMPHIBOLITE BLOCKS, SANTA CATALINA ISLAND, CA

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Research Advisor: Christine Siddoway

INTRODUCTION

Despite its importance to our understanding of fluid flow in subduction zones, (e.g. Sorensen and Grossman, 1989, Sorensen and Barton, 1987, and Sorensen, 1988) the thermobarometry of the tectonic melange, consisting of garnetiferous mafic gneiss blocks within a matrix of metasedimentary and metaultramafic rock, of the Santa Catalina Island subduction complex has been little studied in the last 25 years. Study of the microstructural relationships and geothermometry of the garnet-rich gneisses will yield information about processes and conditions for high temperature metamorphism within subduction systems that are poorly understood.

The Catalina Complex differs from typical subduction complexes in that there are amphibolite grade gneisses, produced by high temperature metamorphism, in the subduction melange. Questions exist about the origin of the high temperature rocks in a subduction zone, when such zones are normally characterized by high pressure-low temperature assemblages. Furthermore, the juxtaposition of higher temperature, older gneisses upon colder, younger metamorphic assemblages counters expectations. The amphibolite unit experienced T = 580-620 °C and P = 8.5-12.5 kbar for metamorphism (Sorensen and Barton, 1987) at 120-115 Ma, based on detrital zircon U-Pb thermochronology (Grove et al., 2008).

The three types of garnet amphibolite blocks are 1) non-migmatitic, clinopyroxene-bearing gneiss that resemble mid-ocean ridge basalt; 2) gneiss with alteration rinds, or blackwall, suggesting local chemical alteration; and 3) gneiss containing leucocratic segregations, described as migmatitic, enriched in trace elements (Sorensen and Grossman, 1989). This enrichment is a result of infiltration by aqueous fluid that could have introduced Na-Al silicate and/or induced partial melting (Sorensen, 1988, and Sorensen & Grossman, 1989). The protoliths for the matrix of hornblende-zoisite schist and serpentinite is harzburgite and dunite (Platt, 1975), whereas the garnet gneiss blocks are derived from a tholeiitic protolith (Sorensen and Barton, 1987); thus, the mineral makeup, petrogenesis, and geochemistry of the garnet gneiss blocks differ between blocks and contrast starkly with the surrounding serpentinite matrix.

My research examines the petrography, garnet characteristics, mineral compositions, and accessory phases of two mafic gneiss blocks affected by high temperature metamorphism. Each contains information about physical and chemical conditions that existed during subduction. Objectives are to gain insight into 1) the nature of HT metamorphism in the subduction setting, and 2) the metamorphic history of disparate blocks within the Catalina serpentinite melange. Physical conditions are determined using Zr-in-rutile geothermometry.

METHODS

Fieldwork consisted of sampling plagioclase-bearing garnet hornblende blocks produced by partial melting (Sorensen, 1988). At Oberlin College, select samples were made into polished thin sections, then used for petrographic and SEM analysis at Colorado College. Identification of mineral phases, observations of mineral relationships and microstructures, yielded information about equilibrium/disequilibrium relationships and evidence of the order of events. At the University of Wyoming, a JEOL electron microprobe (EMP) was used to make compositional maps of major element distribution, to evaluate garnet zoning. Guided by the compositional maps, quantitative mineral analysis was performed upon the major phases of garnet, amphibole, and feldspar, and upon mineral inclusions. At Rensselaer Polytechnic Institute, Zr concentration (ppm) of rutile, in polished sections, was analysed using a Cameca SX 100 EMP. The Zr-in-rutile geothermometer (Watson et al., 2006; Eq. 1) was used to calculate peak metamorphic temperatures for the two samples.

$$T\ (^\circ C) = \frac{4470}{7.36 - \log(Zr)} - 273 \qquad \text{Equation 1}$$

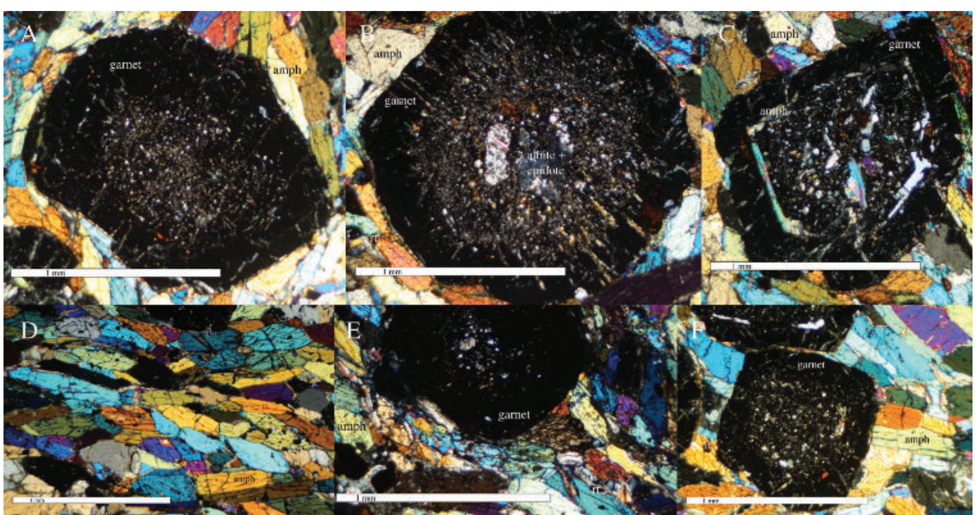
SAMPLE DESCRIPTIONS

SAMPLE 712C-1

Sample 712C-1 is foliated garnet amphibole gneiss. It contains garnet, amphibole, and rutile. Garnet (30%) forms euhedral, inclusion rich porphyroblasts with diameters of 0.35-2.5 mm. The groundmass is euhedral amphibole (67%) that has a shape preferred orientation and uniform length of 0.75 mm (Fig. 1D). Rutile (3%) is throughout the groundmass as anhedral and euhedral grains (0.05-0.2 mm). Apatite and monazite appear as small, rounded accessory grains.

Garnets have two to four zones denoted by the distribution and abundance of inclusions (Fig. 1 A-C). All garnet interiors are inclusion rich with numerous, small (~0.03 mm), sub-rounded inclusions. The outermost ~0.23 mm is inclusion free. There is no evident alignment of inclusions. Some garnets contain large ~0.2-0.25 mm round included grains in their centers. In some grains, a “ring” of elongated minerals that crystallized along a relict garnet border demarcates the inclusion-rich core and inclusion free rim.

Compositional maps created using the EMP show that garnet is compositionally zoned (Fig. 2A-D), with rims exhibiting increased Mg and decreased Ca compared to the interior garnet. Fe and Mn show no change throughout garnet.



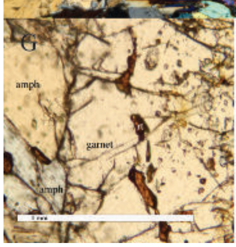


Figure 1. Sample 712C-1 A) An example of the garnets that contain the two zones. The innermost zone contains small, isolated, sub-rounded inclusions. The outer zone is inclusion free. B) A garnet that presents three zones, with the innermost having three large inclusions; succeeded by an inclusion rich zone, then a zone that is inclusion free. C) A garnet with four zones discerned by the differences in inclusion distribution. This garnet shows a large inclusion in the core surrounded by a zone of small, sub-rounded inclusions. There is a thin zone of elongated minerals before the inclusion free border. D) Aligned amphibole that defines a dynamic fabric. E) Cracked amphiboles next to garnet show differential stress on the amphibole. F) Amphiboles truncated against garnet, with absence of wrapping foliation indicate that growth of garnet porphyroblasts occurred after amphibole formation and deformation. G) Rutile inclusions parallel to the garnet margin, suggesting that the precipitation of the plagioclase and amphibole was influenced by a relict garnet margin (A-F are Cross-polarized light and 5x magnification, G is Plain polarized light and 10x mag.)

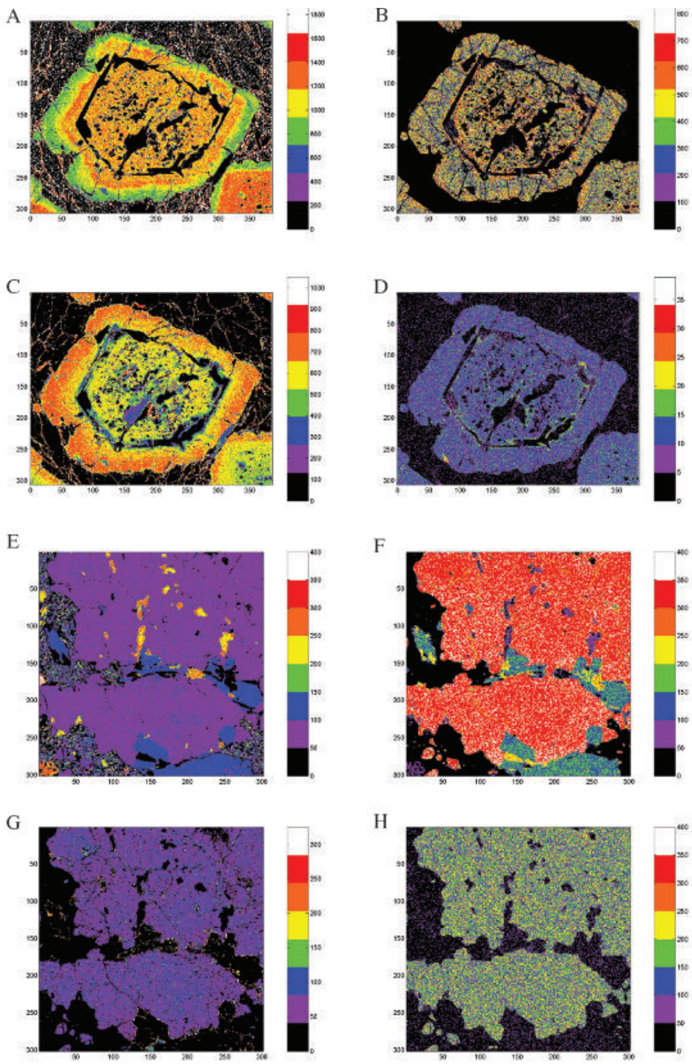


Figure 2. Compositional Maps A-D for garnet, sample 712C-1. E-H for garnet, sample H2718D. A) Ca map, showing depletion in the rim. B) Fe map, spotty and does not show zoning. C) Mg, enriched near the rim. D) Mn, which is patchy and does not indicate zoning. E) Ca. F) Fe. G) Mg. H) Mn. All of the elements for sample H2718D are patchy and do not indicate zoning.

Truncation of aligned amphiboles against garnet indicates that garnet growth post-dated solid-state deformation that formed foliation (Fig. 1F). Bordering garnet, amphibole exhibits undulose extinction and cracking (Fig. 1E). From microstructure observation, the interpreted order of events is amphibole growth during tectonism with development of foliation under differential stress conditions. Subsequently, euhedral garnet formed. This is indicated by the lack of wrapping foliation around the garnets, which would form by an intensification of strain around the garnets.

Inclusions in garnet, which were too small to identify optically, were identified by SEM/EDS as albite and epidote, with some rutile. Rarely there is a titanite, quartz, and amphibole. The albite and epidote form symplectite. Inclusions in the intermediate zone are 70% quartz, 17% amphibole, and 13% rutile. The inclusion phases, or elongated rutile alone, mimic the shape of an old grain boundary (Fig. 1G). Albite is only found as inclusions, and then only as feldspar-epidote symplectite, and is not present in the groundmass.

A brittle structure, evident as a network of cracks with distinct evidence of alteration, possibly oxidation, cuts through the sample. The cracks represent a possible fluid migration pathway.

SAMPLE H2718D

Sample H2718D is garnet rutile gneiss lacking foliation. It contains garnet, amphibole, and rutile. Garnet (47%) porphyroblasts have a diameter of 0.5-3 mm and are sub- to anhedral. They form masses of coalesced grains (Fig. 3A). The groundmass is composed of amphibole (14%) and rutile (18%). The amphiboles are sub-euhedral to anhedral, with lengths of 0.1-0.5 mm. Rutile forms large, anhedral grains (~0.05-1 mm wide) distributed around the perimeter of garnet (Fig. 3B) and as small grains in the groundmass. The large rutiles are rimmed by titanite (Fig. 3D), but the smaller rutiles ordinarily lack titanite rims. There is a significant amount of bluish grey alteration material (21%), which forms a web-like net throughout the groundmass, fingers along fractures, into some of the garnets, and corresponds to altered garnet cores. Accessory phases are zircon, apatite, and monazite. Sparse chlorite appears as a retrograde mineral in association with rutile (Fig. 3C).

Garnets are coalesced garnets that show microstructures of impingement and moulding around each other. The garnets of sample H2718D are un-zoned. No changes of distribution or size of the sparse inclusions are discernable; they are all isolated and tiny. The distribution of inclusions does not indicate a relict garnet border. Spot SEM analyses do not suggest compositional differences between garnet cores and rims.

Symplectic textures are found in several locations in the sample (Fig. 3E). Two are encircled by garnet and one is in the middle of groundmass amphiboles. This texture indicates disequilibrium.

Compositional maps of garnet were obtained using the EMP (Fig. 2E-H). The garnets show a lack of compositional zoning in Ca, Fe, Mg, and Mn, in addition to the lack of zoning indicated by the distribution of inclusions. This suggests that garnet in this sample is homogeneous.

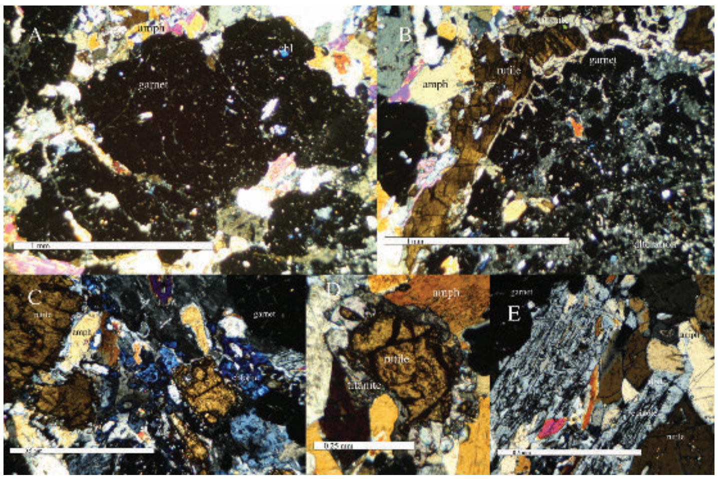


Figure 3. Photomicrographs of sample H2718D. A) Clump of coalesced garnets, with minor amphibole or alteration material in between the garnet perimeters. B) Rutile is located around the perimeter of garnet. C) Chlorite (retrograde) and symplectite. D) High relief, transparent rim of titanite surrounding rutile is common on the large rutile grains. E) Albite and epidote symplectite, a disequilibrium microstructure. (All images are Cross-polarized light, A + B are 5x magnification and C-E are 10x magnification.)

Mineral phases that were too small to distinguish optically were identified by SEM/EDS. The symplectite is composed of albite and epidote, indicating that they are in disequilibrium. The alteration material is made up of albite and epidote symplectite, also suggesting disequilibrium of these phases. No quartz exists in the sample and feldspar is only present in disequilibrium textures.

A brittle structure goes through this sample, indicated by a microgranular texture. It appears to crosscut the rutile and alteration material seems to run along it. This fracture system could have allowed fluid to flow through, altering the composition of the surrounding minerals.

RESULTS

MINERAL CHEMISTRY

Garnet

Garnet, amphibole, and plagioclase were analysed on the EMP. The garnet in samples 712C-1 and H2718D is dominantly almandine.

Sample 712C-1 shows elemental zoning of major elements between the garnets core, intermediate, and rim. Between the core and intermediate zone, Fe and Al decrease, although between the intermediate zone and the rim the Al increases very slightly but Fe remains the same. Mg increases near the rim, with a decrease in Ca and Mn.

Sample H2718D does not show variation in composition from core to rim, or between garnets located outside and within the brittle fracture. The core has lower Ca and the rim has lower Mn and Fe. However, other than those slight differences the garnet is chemically homogeneous.

Amphibole

The amphibole in sample 712C-1 changes from pargasite inclusions in the intermediate zone to gedrite in the relict border to tschermakite in the groundmass. The major elements of amphibole inclusions do not smoothly increase or decrease from the interior of garnet to the outside; but rather vary sporadically. From the intermediate inclusions to the relict border inclusions Ti, Ca, and Na decrease and Mg, Fe, Mn, and Cl increase. But between the inclusions and the groundmass, Al decreases but Ti, Na, and K increase.

According to its major element composition, the groundmass amphibole in sample H2718D is tschermakite. In close proximity to garnet, the groundmass amphibole increases in Na, but amphibole inclusions were not analysed so comparison is impossible.

Plagioclase

All of the plagioclase in samples 712C-1 and H2718D is albite. Along fractures in sample H2718D, the albite

Garnet

	712C-1			H2718D			
	Core	Intermediate	Rim	Core	Intermediate	Rim	Brittle Fx
SiO_2	39.294	39.075	39.201	38.351	38.336	37.917	38.659
MgO	5.399	4.687	6.578	4.071	4.029	4.072	3.831
Na_2O				*Not Measured*			
Al_2O_3	21.113	21.258	21.629	21.003	20.987	20.908	21.082
FeO	30.347	29.028	28.186	27.321	26.948	25.443	27.289
MnO	0.933	1.155	0.83	0.722	0.756	0.649	0.71
Cr_2O_3				*Not Measured*			
K_2O				*Not Measured*			
CaO	4.771	6.024	4.766	6.731	7.006	7.671	7.04
TiO_2				*Not Measured*			
Total	101.857	101.227	101.19	98.199	98.062	96.66	98.611
				Formula based on 12 oxygens and 8 cations			
Si	3.0372	3.0363	3.0187	3.0563	3.0573	3.0554	3.0668
Mg	0.622	0.5429	0.7551	0.4836	0.479	0.4891	0.453
Na							
Al	1.9236	1.947	1.9632	1.9729	1.9728	1.9858	1.9713
Fe	1.9618	1.8864	1.8152	1.8209	1.7974	1.7146	1.8105
Mn	0.0611	0.076	0.0542	0.0487	0.0511	0.0443	0.0477
Cr							
K							
Ca	0.3952	0.5016	0.3933	0.5748	0.5987	0.6624	0.5984
Ti							
Total	8.0009	7.9903	7.9998	7.9572	7.9563	7.9517	7.9478

Amphibole

	712C-1			H2718D	
	Intermediate	Relict Border	Groundmass	Groundmass	Gm edge
SiO_2	36.267	25.776	43.992	42.143	41.505
MgO	0.053	16.779	12.589	10.776	11.117
Na_2O	0	0	2.153	1.755	1.856
Al_2O_3	28.874	21.628	15.489	15.143	14.827
FeO	5.364	22.891	10.429	12.461	12.682
Fe_2O_3			*Not Measured*		
MnO	0.1	0.231	0.08	0.068	0.029
Cr_2O_3			*Not Measured*		
K_2O	0	0.006	0.289	0.316	0.313
CaO	24.011	0.063	10.964	11.221	11.248
TiO_2	0.253	0.019	0.7	0.91	0.919
Total	94.938	87.434	96.708	94.833	94.496
			Formula based on 23 oxygens		
Si	5.4014	4.4112	6.3996	6.3319	6.2861
Mg	0.0118	4.2806	2.7299	2.4135	2.5099
Na	0	0	0.6074	0.5113	0.5449
Al	5.0687	4.3628	2.6558	2.6817	2.6469
Fe	0.6681	3.2763	1.2688	1.5658	1.6064
Fe^{3+}					
Mn	0.0127	0.0335	0.0098	0.0086	0.0037
Cr					
Ca	3.8317	0.0116	1.709	1.8065	1.8254
Ti	0.0283	0.0024	0.0766	0.1028	0.1047
Total	15.0362	16.4057	15.5266	15.5104	15.5885

Plagioclase

	712C-1		H2718D		
	Core 1	Core 2	Inside grt	Groundmass	Brittle Fx
SiO_2	67.807	66.534	66.744	67.636	62.965
MgO			*Not Measured*		
Na_2O	11.479	11.349	11.303	11.902	10.001
Al_2O_3	20.097	20.359	19.649	19.331	21.171
Fe_2O_3	0.061	0.045	0.082	0	0.529
MnO			*Not Measured*		
Cr_2O_3			*Not Measured*		
K_2O	0.014	0.032	0.038	0.012	0.023
CaO	0.91	1.115	0.697	0.392	3.981
TiO_2			*Not Measured*		
Total	100.368	99.434	98.513	99.273	98.67
			Formula based on 8 oxygens		
Si	2.9589	2.9353	2.9656	2.9825	2.8309
Mg					
Na	0.9713	0.9709	0.9738	1.0177	0.8719
Al	1.0337	1.0587	1.0291	1.0048	1.1219
Fe^{+3}	0.002	0.0015	0.0027	0	0.0179
Mn					
Cr					
K	0.0008	0.0018	0.0021	0.0007	0.0013
Ca	0.0426	0.0527	0.0332	0.0185	0.1918
Ti					
Total	5.0094	5.0209	5.0066	5.0242	5.0357

Table 1. Representative mineral make-ups of garnet, amphibole, and feldspar.

has higher Al and Ca, but lower Na compared to the standard groundmass albite.

ZR-IN-RUTILE GEOTHERMOMETRY

Because there is evidence of disequilibrium in the thin sections and indication of voluminous fluid movement in H2718D, conventional geothermometry cannot be applied to these Catalina garnet-gneiss block samples. Consequently, we used the new Zr-in-rutile thermometer for determination of the temperature of metamorphism during garnet growth and comparison between different settings.

Using the relation given in the methods, the zirconium content of rutile samples equates to metamorphic T's in vicinity of 500 °C. In sample 712C-1, rutile was analysed as inclusions in different garnet zones and euhedral and anhedral grains in the groundmass. Rutile grains within garnet have Zr concentrations and temperatures ranging from 27 to 32 ppm and 481 ± 5 °C to 489 ± 4 °C. Grains do not show a significant temperature difference between the garnet zones. Rutile grains within the groundmass have average Zr concentrations and temperature of 40 ppm and 502 ± 3 °C. Euhedral and anhedral rutile grains in the groundmass were analysed and compared, but no difference is discernable.

In sample H2718D rutile inclusions, around the perimeter of garnet, within the brittle fracture, and in the groundmass were analysed. Many of the large rutile grains have titanite rims, and were found to have temperatures ~30 °C lower than compared to rutile lacking titanite rims in the same setting. Because titanite is thought to affect the Zr concentration in rutile (Kapp et al., 2009), rutile grains with titanite rims were excluded from data analysis. Rutile grains within garnet have an average Zr concentration of 33 ppm and temperature of 490 ± 8 °C. Grains that are around the perimeter of garnet have an average Zr concentration of 46 ppm and temperature of 512 ± 2 °C. Grains within the groundmass have an average Zr concentration of 50 ppm and temperature of 516 ± 1 °C. Grains within the brittle fracture system have an average Zr concentration of 33 ppm and temperature of 488 ± 8 °C. For all analyses, calculated temperature uncertainties are better than ± 10 °C (Table 2). Therefore, the garnet interior temperatures are lower

Sample	Location	No. of spots	Ave Zr ppm	Ave St. Dev.	Ave T (°C)	St. Error
712C-1	Core	10	31.66	6.90	488.83	3.88
	Intermediate	7	30.98	9.68	486.09	7.85
	Relict Border	11	27.69	6.86	480.80	4.68
	Groundmass	15	39.74	6.74	502.23	2.68
H2718D	Inclusions	8	33.34	11.58	489.76	7.85
	Grt Border	2	46.22	1.99	511.85	1.83
	Groundmass	6	49.53	2.24	516.00	1.13
	Brittle Fx	9	33.07	13.04	488.40	8.33

Table 2. Zr-in-rutile concentrations and calibrated temperatures.

then those on the perimeter and in the groundmass, suggesting that garnet grew during increasing metamorphic temperatures.

DISCUSSION

Samples 712C-1 and H2718D, from separate gneiss blocks within melange, show differences in their composition and metamorphic history. Sample 712C-1 exhibits changes in major elements and inclusion phases from core to rim in garnet, indicating compositional changes during garnet growth. Mg increasing towards the rim indicates increasing temperature during garnet growth (Sorensen, 1988). The rutile in the groundmass is small, euhedral, and anhedral.

Sample H2718D has compositionally homogenous garnet and no compositional variation in inclusion phases, suggesting that the source block did not undergo significant composition alteration during garnet growth. Rutile formed small inclusions within garnet and immense grains around the perimeter of garnet.

Sample H2718D has an oddly large presence of rutile for a metabasalt. It indicates that voluminous fluid moved through the rock, transporting titanium from the serpentinite into the blocks, where it formed rutile. The absence of rutile between coalesced garnets indicates that the fluid movement occured after garnet formation.

Zack et al. (2004) analysed Zr-in-rutile for three clinopyroxene bearing garnet amphibolite blocks from Catalina Island. Their temperatures range from 764 to 800 °C, much higher than the 480 to 516 °C range of temperatures from these samples.

Zr-in-rutile temperatures for rutile inclusions provide minimum temperature for growth of the surrounding garnet (Spear et al., 2006). Zr concentrations in rutile inclusions suggest that garnet growth in sample 712C-1 occured at temperatures of 480 °C. The highest rutile temperatures, of around 502 °C, occur in the groundmass, indicating temperature was increasing during garnet growth.

Conditions for sample H2718D were similar, according to rutile temperatures, of ~490 °C within garnet and ~516 °C in the ground mass. The sample records a slight temperature increase during garnet growth.

Assuming rutile formed at P = ~ 1.0-1.5 GPa and correlating with measured temperatures of rutile formation, an instantaneous geothermal gradient can be calculated for a point on the rock's P-T path (Spear et al., 2006). Using minimum rutile formation pressure (1.0 GPa) and temperature (480 °C) the geothermal gradient is calculated as ~14 °C/km. This is a relatively shallow gradient for a subduction complex, suggesting slow or shallow subduction. Assuming metamorphic peak conditions occurred at 515 °C and 1.5 GPa, the P-T path slope would be 10.3 °C/km.

These calculations support Grove et al.'s (2008) suggestion that the amphibolite unit formed from being underthrust beneath the Peninsular Ranges batholith, which provided the heat for high-grade metamorphism. If the batholith had partially cooled, it could explain why these two samples are ~100-200 °C cooler than other temperatures calculated for the unit. They also believe accretion of the Catalina Schist was the beginning of subduction shallowing (Grove et al. 2008), supported by the low geothermal gradient calculated from these samples.

My findings indicate that the two gneiss blocks studied had distinct protoliths and metamorphic histories, suggesting that melange blocks within the upper tectonic unit of Catalina Island derived from different locations within a subduction zone. Furthermore, calculated temperatures for metamorphism would have only been sufficient to cause partial melting in the presence of fluids and are lower than temperatures determined by previous researchers. In the future, the Titanite-Rutile geobarometer could be applied to sample H2718D for more accurate determination of metamorphic pressures (Kapp et al., 2009).

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