Epidotization of the sheeted dike-plutonic contact, Troodos Ophiolite, Cyprus

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INTRODUCTION

Isolated, lenticular plagiogranite bodies are found between the upper level gabbros and the sheeted dike complex of the Troodos ophiolite (Kelley and Robinson, 1990). Hydrothermal epidotization is common throughout the sheeted dikes and the upper gabbros. Extensive studies of epidotization in the sheeted dikes indicate that circulation of seawater derived fluids at approximately 400°C and 400-500 bars in hydrothermal cells along off-axis faults caused the epidote alteration and lead to the formation of epidosites (Gillis and Robinson, 1990; Richardson et al., 1987; Schiffman and Smith, 1988; Bettison-Varga et al., 1992; Bettison-Varga et al., 1995) . Epidotization of the plagiogranite has received little attention in the Troodos ophiolite (Kelley and Robinson, 1990; Kelley et al., 1992), however several studies have been completed on other ophiolites, such as the Semail and Trinity ophiolite complexes (e.g. Nehlig, 1991). Richardson et al. (1987) claim that the sheeted dike-gabbro interface is the base of seawater dominated hydrothermal systems. This leads to the question: what types of fluids caused epidotization of the rocks below this contact?

This study focuses on the epidotization of the plagiogranites in the upper level plutonic rocks just below the plutonic-sheeted dike contact of the Troodos ophiolite complex. I use fluid inclusion and microprobe analysis in conjunction with textural data on a microscopic and macroscopic scale to determine possible sources of fluids which caused epidotization of plagiogranites and related rocks.

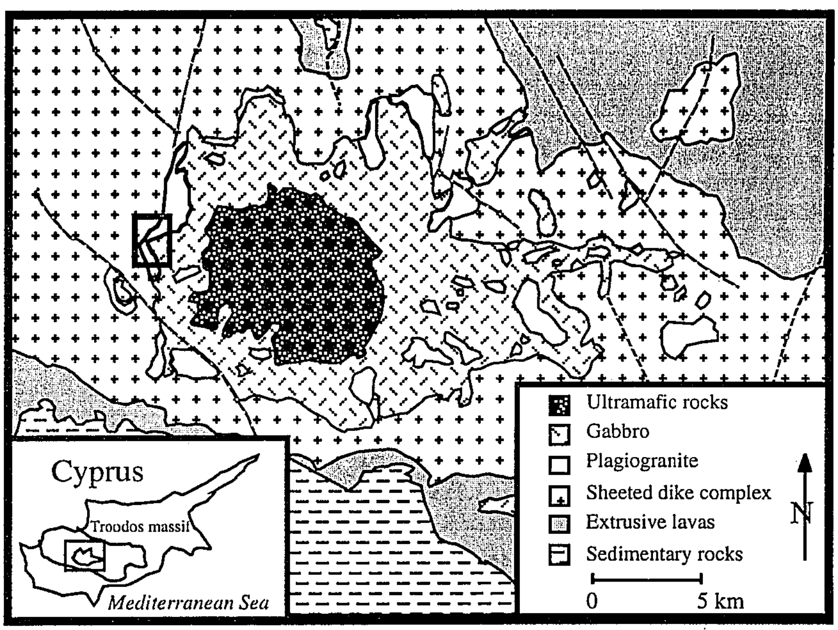


Figure 1. Geology of the Troodos massif and location of field area (in box) (after Kelley et al., 1992)

RESULTS and METHODS

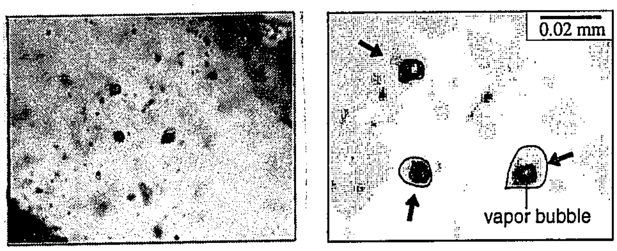
Field relationships. Epidotization of the plagiogranite is highly variable ranging from less than 5% epidote alteration to 100% epidosite (epidote+quartz±chlorite±sphene). Epidosite occurs as pods up to 30 cm in diameter, filling faults and fractures, and alteration of entire outcrops up to 3 meters across. Garnet+epidote patches from 1 cm to 20 cm in diameter were located in one outcrop. Epidotized and non-epidotized dikes, often having well-developed chill margins, cut the plagiogranite. In some cases plagiogranite screens are included in the dikes. Hydrothermally altered xenoliths of gabbro and amphibolite are often seen in the plagiogranite.

Petrography. Petrographic analysis of 30 thin sections displayed the wide variation in plagiogranite composition as well as degree of alteration. The plagiogranite consists of fine to medium-grained plagioclase, quartz, and epidote, with lesser amounts of sphene, chlorite, actinolite, garnet, and opaques. Relict igneous textures are well preserved in all but the most altered epidosite specimens. Granophyric intergrowths of plagioclase and quartz are present in about half of the plagiogranites. All epidote found in plagiogranite is secondary. Epidote replaces plagioclase and sometimes garnet. It can be found in isolated patches and along microfractures. Epidote is associated with chlorite and quartz and often with sphene and opaques.

Fluid-inclusion results. Microthermometric analysis of fluid inclusions was completed using a Fluid Incorporated adapted U. S. Geological Survey gas-flow heating and freezing stage attached to a Nikon Optiphot 2-POL polarizing microscope. Homogenization and halite dissolution temperatures were recorded when the vapor bubble or halite crystal disappeared. Temperatures have not been corrected for pressure, pressure correction would increase homogenization temperatures 40-100°C, for inclusions trapped between 470-1000 bars (Potter, 1977).

At least 2 types of fluid inclusions exist in the plagiogranite: 2-phase liquid dominated inclusions, and 3-phase liquid dominated inclusions containing halite daughter crystals (fig. 2). Homogenization temperatures of 2-phase inclusions in quartz grains range from 224-490°C, and 284-312°C in epidote-hosted inclusions (table 1). 3-phase inclusions yield vapor homogenization temperatures of 220-325° C (mean=287°C), and halite dissolution temperatures of 335-450° C (mean 399°C) (fig. 3). All 3-phase inclusions homogenized by halite dissolution indicating entrapment in the absence of a vapor phase (Roedder, 1984).

Figure 2. Photomicrographs of quartz-hosted 2-phase inclusions (left) and 3-phase inclusions (right). Inclusions marked by arrows.



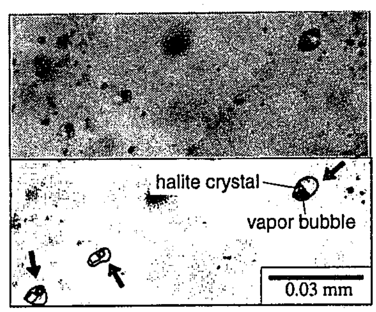


Table 1. Homogenization temperatures of 2-phase inclusions

Specimen number (chip)	**Host** lithology	**Homogenization temp. °C** min.	range	mean
SH 95-2 (1)	plagiogranite	qtz.	265-480	408
SH 95-2 (2)		qtz.	273-473	335
SH 95-33 (1)	plagiogranite/	qtz.	230-307	283
SH 95-33 (2)	diabase contact	qtz.	224-320	288
SH 95-44	epidosite	ep.	284-312	297

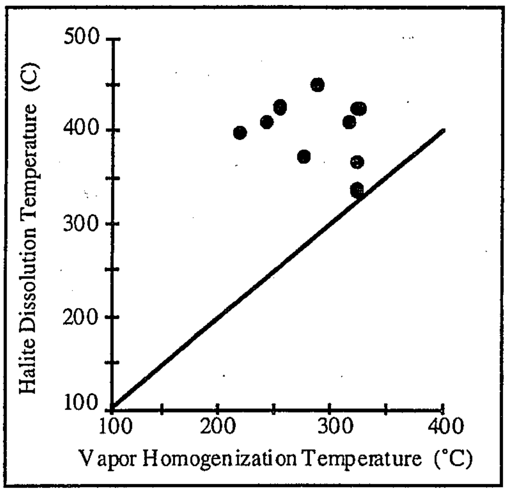


Figure. 3. Vapor homgenization vs. halite dissolution temperatures in 3-phase presumably secondary quartz-hosted inclusions. Line indicates temperatures where bubble disappearance coincides with salt crystal disappearance.

Microprobe. Chemical composition of 76 points (Table 2) and 2 x-ray maps were completed on the Cameca SX-50 microprobe at University of Wisconsin- Madison. Backscatter images show variation in epidote composition, while point analyses indicate epidote varies from 20.57-28.64 wt% Al and 8.36-19.10 wt% Fe or Pistacite-content 16.1-38.4 (Ps=100*Fe/Fe+Al[VI]). Al-rich euhedral epidote grains $Ca_2Fe_{0.803}Ti_{0.020}Al_{2.222}(Si_{2.945}Al_{0.055})O_{12}(OH)$ can be detected within large Al-poor epidote patches, indicating that Al-rich epidote formed earlier than the Fe-rich epidote. Sub-euhedral epidote grains within a 3 meter wide quartz/epidote vein display the least amount of variation (Ps=25.9-29.0). Backscatter images and x-ray maps show spectacular oscillatory growth zonation in the hydrothermal garnet (Fig.4). The growth bands are near end-member andradite (And_{95}, Table 2) alternating with more Al-rich bands (And_{70}, Table 2). Epidote appears to be filling microfractures within the garnet and replacing the Al-rich zones.

DISCUSSION

High temperature, high salinity inclusions in plagiogranites and other upper level plutonic rocks have been reported from the Mathematician Ridge, Mid-Atlantic Ridge (Stakes and Vanko, 1986), Troodos ophiolite (Kelley

Table 2. Representative mineral compositions

	Epidote 1	Epidote 2	Plagioclase	Sphene	Chlorite	Andradite	And. (Al-rich)
				wt. % oxides			
SiO_2	38.23	37.48	66.88	30.53	26.26	35.47	36.77
Al_2O_3	28.64	22.51	25.54	0.18	21.20	0.85	5.82
TiO_2	0.20	0.38	0.00	40.43	0.02	0.02	0.29
Fe_2O_3	8.36	15.81	0.00	0.70	0.00	30.99	24.88
FeO	0.00	0.00	0.29	0.00	23.53	0.00	0.00
MgO	0.00	0.00	0.00	0.00	17.46	0.00	0.00
MnO	0.03	0.06	0.01	0.00	0.12	0.04	0.03
CaO	24.51	23.71	4.90	28.90	0.03	32.94	33.76
Na_2O	0.01	0.00	0.07	0.01	0.03	0.00	0.00
K_2O	0.04	0.02	3.99	0.03	0.00	0.00	0.00
total %	100.01	99.97	101.68	100.71	88.66	100.32	101.55
				*cations**			
Si	2.93	2.95	2.85	1.00	2.71	2.97	2.95
Al (IV)	0.00	0.00	1.28	0.01	1.29	0.08	0.55
Al (VI)	2.59	2.09	0.00	0.00	1.28	0.00	0.00
Ti	0.01	0.02	0.00	1.00	0.00	0.00	0.04
Fe^{3+}	0.48	0.94	0.00	0.02	0.00	1.91	1.41
Fe^{2+}	0.00	0.00	0.00	0.00	2.03	0.04	0.09
Mg	0.00	0.00	0.00	0.00	2.68	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Ca	2.01	2.00	0.33	1.01	0.00	2.96	2.91
Na	0.01	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.22	0.00	0.00	0.00	0.00
OH	0.00	0.00	0.00	0.00	0.00	0.11	0.18
# cations	8.03	8.01	4.68	3.04	10.01	7.97	7.95

* Number of cations based on: epidote (12.5 oxygens); plagioclase (8 oxygens); sphene (1 Si); chlorite (14 oxygens); garnet (Σ cations-Si=5)

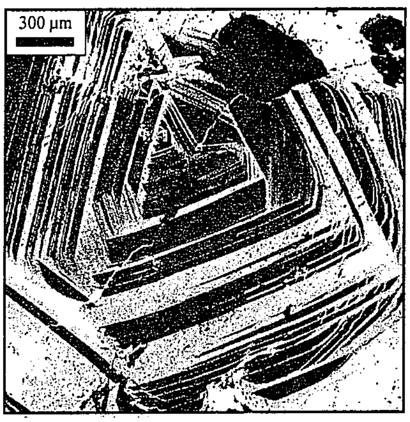


Figure. 4. Aluminum x-ray map of zoned grandite garnet. In this image white=epidote, light grey=high Al, dark grey=low Al garnet

and Robinson, 1990; Kelley et al., 1992), southwest Indian Ridge (Vanko and Stakes, 1991), the Semail and Trinity ophiolites (Nehlig, 1991), and Oceanographer Transform along the Mid-Atlantic Ridge (Vanko et al., 1992). Three models exist to explain the presence of high temperature, high salinity inclusions in the upper level plutonic sequence. Two of the models suggest that the high salinity brines, preserved as 3-phase inclusions, were formed by phase separation and later segregation of seawater or magmatic fluids (Cowan and Cann, 1988; Kelley and Robinson, 1990; Vanko et al., 1992). In an alternative model, Kelley et al. (1992) suggest that the high salinity fluids exsolved directly from late stage highly differentiated melts and that phase separation played a limited role in their formation. Supporting evidence for this model is the absence of vapor-rich inclusions, the presence of high-salinity inclusions within the upper level plutonic sequence but not the sheeted dike complex, and homogenization of 3-phase inclusions by halite dissolution (fig. 3) (Kelley et al., 1992). Vapor-rich inclusions and 3-phase inclusions which homogenize by vapor bubble disappearance are indications of boiling and phase separation (Roedder, 1984); lack of these types of inclusions indicates that phase separation did not occur, or did not play a large role in epidotization of these rocks. This model for brine origin is only applicable in low pressure environments where melts are highly fractionated and have high initial water content, similar to Troodos magmas (Kelley et al., 1992).

The lower temperature inclusions present in the Troodos plagiogranites may have formed later as the result of hydrothermal seawater-derived fluids traveling along brittle fractures in a separate hydrothermal system (Kelley and Robinson, 1990). These low temperature inclusions are often located along healed microfractures or boundaries in a grain which otherwise contains high temp 3-phase inclusions, and are also found in epidote grains within epidosite filled faults. Further insight into fluid source may come from examination of hydrothermal garnet found in the plagiogranite.

Zoned hydrothermal anisotropic andradite-grossular (grandite) garnets are found in skarn deposits (e.g. Manning and Bird, 1990; Jamtveit, 1991) and in hydrothermally altered basalts from lower oceanic crust (Exley, 1982). The small scale oscillatory zoning characterized by sharp transitions between compositional bands often present in grandite garnets is believed to be caused by: (1) rapid fluctuation in fluid composition during garnet growth (Lessing and Standish, 1973; Jamtveit, 1991) and/or (2) phase changes due to immiscibility in the grossular-andradite binary system (Jamtveit, 1991). Jamtveit (1991) shows that a miscibility gap between grossular and andradite at pressures of about 500 bars and temperatures of 300-400°C coupled with a slowly oscilating fluid composition can lead to small scale oscillatory zoning in grandite garnet, similar to the zoning seen in Figure 4.

CONCLUSION

The presence of high temperature/high salinity inclusions with daughter crystals which homogenize by halite dissolution and the lack of vapor rich inclusions suggest that saline fluids exsolved off a late melt and caused a portion of the alteration seen in the upper plutonic sequence. However the presence of large numbers of 2-phase lower temperature inclusions similar to those found in the sheeted dike complex indicate that seawater-derived fluids also played a large role in the alteration of plagiogranites at the dike-plutonic contact. Oscillatory growth zonation of hydrothermal garnet and compositional variation of epidote as seen in x-ray maps, backscatter images, and microprobe point analyses may also be caused by multiple or changing fluids. Epidotization of the plagiogranite, usually in the form of epidote + quartz ± chlorite ± sphene replacing plagioclase, varies in terms of degree of alteration and chemical composition of the epidote and was most likely caused by multiple fluids from different sources percolating throughout the rocks along microfractures.

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