Petrogenesis of silica-undersaturated migmatite xenoliths via contact metamorphism, Vinalhaven Island, Maine

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INTRODUCTION

Vinalhaven Island is comprised of a Devonian bimodal pluton intruding older country rock. The pluton is dominated by medium- to coarse-grained granite and preserves evidence of a series of basaltic injections. The Vinalhaven intrusion is the southernmost member of a string of contemporaneous bimodal plutons stretching from Penobscot Bay, Maine, to New Brunswick, Canada. Within the Penobscot Bay region, the Vinalhaven intrusion is similar in several respects to the Cadillac Mountain Intrusive Complex studied by Wiebe (1994). Along the southern and eastern coasts of Vinalhaven Island, mafic and felsic rocks are both mechanically mingled and chemically mixed; Mitchell and Rhodes (1989) interpreted these complex relationships as evidence for the contemporaneous existence of liquids from both units.

The Vinalhaven pluton intrudes Siluro-Devonian rhyolite, basalt, and volcanogenic sediments in the west and pre-Silurian well stratified greenschist facies rock, known as the Calderwood Formation (CWF), in the east. The CWF has been correlated to the Ellsworth terrane of coastal Maine (Robinson et al. 1998), which was thrust over Taconian-modified Laurentia during the late stages of the Acadian orogeny (Figure 1). Geochemical analyses, gravity studies, and field relations of similar bimodal plutons in the Maine coastal region suggest that the Vinalhaven granite-gabbro complex was emplaced at shallow depths following the accretion of Avalon. The coexistence of mafic and felsic melts in this geological setting suggests a heat source supplemental to the one provided by simple subduction of the Laurentian plate. Lithosphere delamination has been proposed as one possible source (Nelson 1992), although other models have been invoked to explain these Devonian intrusions (Hogan and Sinha 1989; Chapman 1962).

Several roof pendants of variable composition and size also occur within the bimodal pluton and document conditions of low P - high T metamorphism. These xenolithic blocks are located in regions where basaltic and granitic melts pooled together, and as a result, local temperatures were likely highly elevated. Contact metamorphism of pendants enveloped by granite on the eastern coast produced migmatites via partial melting. Melanosomes within these migmatites contain two dominant mineral assemblages: a quartz-plagioclase dominated unit bearing minor garnet, and a silica-undersaturated unit bearing corundum, andalusite, spinel, and cordierite. Petrological study of these xenoliths can be used to document their metamorphic history and to constrain the temperatures and pressures of their formation, thereby providing data for the modelling of the Vinalhaven intrusion.

METHODS

Three pendants located on Coomb's Neck, each about 25 m by 45 m, were chosen for field and laboratory analysis (Figure 2). Several samples were extracted from each block and examined with a standard petrological microscope. Selected samples were then chosen for quantitative mineral chemistry analysis on a Zeiss Digital Scanning Electron Microscope (SEM) with a LINK Energy Dispersive Spectrometer (EDS). These electron microprobe analyses are considered accurate to within ±2%. Photomicrographs were obtained using an Olympus optical camera and the Zeiss SEM was used to produce images of mineral textures too fine to be observed with an optical microscope.

LITHOLOGICAL DESCRIPTION

Field Relations. Each of the three pendants studied is enveloped by granite on all sides, although mafic injections contemporaneous with the granite were found adjacent to one block. Additionally, an older mafic dike cuts this particular pendant. Although large-scale features such as closed folds, local brecciation, compositional melting, and flow patterns are readily observable in outcrop, all pendants are extremely fine-grained. Other than sucrosic textures indicating the quartz-rich nature of some of the units, mineralogy generally cannot be determined in hand sample.

Petrography. In thin section, each of the three pendants studied on Coomb's Neck displays one of two general lithologies. The first assemblage is a relatively homogenous, massive, fine-grained unit composed predominantly of equant, euhedral plagioclase and quartz. Plagioclase is commonly twinned and quartz grains depict undulose extinction, indicating deformation which likely preceded metamorphism. These minerals together comprise approximately 85 percent of the modal volume of the unit. In addition to the quartz-plagioclase groundmass, coarse-grained garnet in association with biotite and cummingtonite was observed in one thin section, and minor garnet was observed in another. Where garnet and biotite are associated, both form compositional layers that define a weak schistosity in the sample. The remainder of the unit is composed of very minor K-feldspar, ragged altered biotite, 5-10% by volume secondary chlorite, and rare late muscovite alteration. Locally, coarse-grained strings of euhedral quartz +plagioclase +minor interstitial K-feldspar cut the massive fine-grained assemblage. In one location, very fine grained spinel +biotite occurs in the region between the groundmass and the coarse-grained pod; elsewhere, the contact was unassuming.

The second unit found on Coomb's Neck is a migmatite assemblage containing well layered white-gray leucosomes, 5-10 cm thick, alternating with slightly thicker dark gray-brown melanosomes. The leucosomes are composed of coarse-grained euhedral quartz +euhedral biotite +perthitic K-feldspar +minor plagioclase. Rare equant garnet porphyroblasts 1-2 mm in diameter occur in some leucosome handsamples, but were not seen in thin section. The migmatite melansome contains a silica-undersaturated assemblage of corundum +cordierite +plagioclase ±spinel ±andalusite +rare interstitial K-feldspar. Accessory minerals include ilmenite, magnetite, pyrite, apatite, and rutile. Plagioclase and cordierite comprise the groundmass of the melanosome, and together account for more than 50% by volume of the subunit. Corundum occurs both as porphyroblastic equant grains and as fine grains dispersed in the groundmass. Spinel occurs in several habits, most commonly porphyroblastic, but also rimming corundum and as tight massed fine grains within pods of cordierite. Andalusite is occasionally porphyroblastic but more commonly occurs as dispersed fine (<0.1 mm) grains in the center of the melanosome, well away from leucosome boundaries. It appears with spinel only rarely. Very fine grained equant late biotite commonly appears dispersed throughout the melanosome groundmass. The melanosome typically displays good schistosity via elongation of cordierite grains in the groundmass and alignment of ilmenite parallel to lamination. Coarse-grained biotite is often concentrated where leucosome and melanosome meet. The migmatite has been subjected to late secondary alteration which overprints many samples.

Mineral Chemistry. Mineral compositions of the primary components of both the quartzofeldspathic and migmatite xenoliths were determined on the SEM/EDS. The quartzofeldspathic unit contains plagioclase with variable An content, from 2 to 20 percent. Biotite has an XFe (Fe/(Fe+Mg)) over 63%, with 1-2% TiO_2 by weight. Garnet has an XFe of 83-86%, with a composition of $Alm_{67-71}Py_{11-13}Sp_{16-18}Gr_{1-2}$. Only minor compositional zoning is apparent. Spinel, where present, is almost pure hercynite, with an XFe value of approximately 90%. ZnO content ranges from one to two percent by weight.

Migmatite leucosomes contain almost pure K-feldspar and albite, with biotite XFe 59-63%. Rare cordierite grains have XFe values of 45-50%. Melanosomes contain plagioclase An_{15-20}, and cordierite XFe 55-58%, substantially higher than in the leucosome. Spinel is nearly pure hercynite, with XFe 89-93%. K-feldspar in the melanosome tends to contain over 10% sodium. Late biotites have variable XFe from 61-69%.

PETROGENESIS

Migmatites containing silica-undersaturated melanosomes and quartzitic leucosomes likely reflect at least one episode of partial melting of a pelitic protolith, at temperatures above the solidus of the chemical system. Lack of primary muscovite and biotite in the melanosomes suggests that these samples underwent dehydration melting during prograde metamorphism. The system may be silica undersaturated because silica was completely drawn off during the partial melting process. Leucosomes represent either partial melt products which remained in place, or injections of Vinalhaven granite into the pendant. Other methods, including fluid flux from the pluton, could account for the mineral assemblages seen in the Coomb's Neck pendants (Kriegsman and Hensen, 1998); these are currently being evaluated.

SPINEL-CORDIERITE THERMOMETRY

Mineral textures in the melanosomes of the Coomb's Neck migmatites suggest the reaction: corundum + cordierite = andalusite + spinel. This reaction is discontinuous in three component systems, but continuous in the FMASH system, and can thus be used as a thermometer for determining conditions on metamorphism (Figures 3-5). Because of the complexities of spinel, in particular, it is difficult to calibrate this thermometer; Nichols et al. (1992)

have made the most accurate model to date. The temperatures obtained from the Nichols model are depicted in figure 6; these do not correlate well with the predictions made by the petrogenetic grid of Spear et al (1999). The reconciliation of these models is an ongoing objective of this project.

SUMMARY

Xenolith pendants exposed at Coomb's Neck, Vinalhaven Island, Maine, preserve evidence of contact metamorphism caused by injections of both felsic and mafic melt. These pendants contain one of two major units: a massive quartzofeldspathic assemblage, or a layered migmatite; variation in mineralogy is likely due to variation in protolith. The migmatites contain textural and mineralogic evidence for at least one episode of partial melting of an aluminous pelitic protolith. Elevated local temperatures were likely the primary cause for anatexis, but other factors, including fluid flux, could have played a role. The presence of andalusite in the xenoliths, combined with evidence for high T metamorphism, constrains pressures to no more than 2-3 kilobars; this is in line with the current model which suggests the Vinalhaven pluton was emplaced shallowly. The thermometry of Nichols et al. (1992) predicts equilibrium temperatures of 600 °C at 1.5 kilobars on the basis of spinel-cordierite chemical partitioning, but this temperature is not high enough to account for the partial melt textures displayed in the xenoliths. An ongoing objective of this project is to develop a model for spinel-cordierite equilibrium which assimilates the Nichols model with the petrogenetic prediction. This will likely involve further consideration of the role of fluids as well as possible back reactions caused by high temperature liquids.

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Figure 1: Geologic Map of Vinalhaven Island, Maine

Modified from Mitchell and Rhodes (1989)

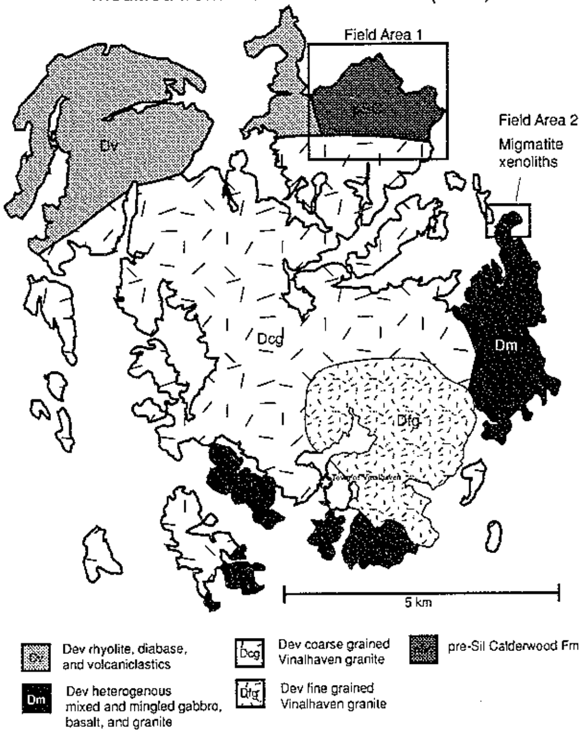
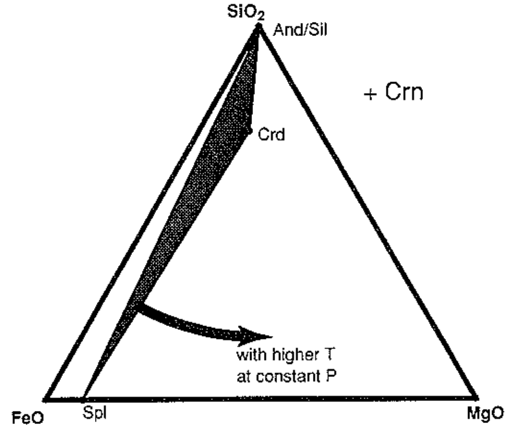


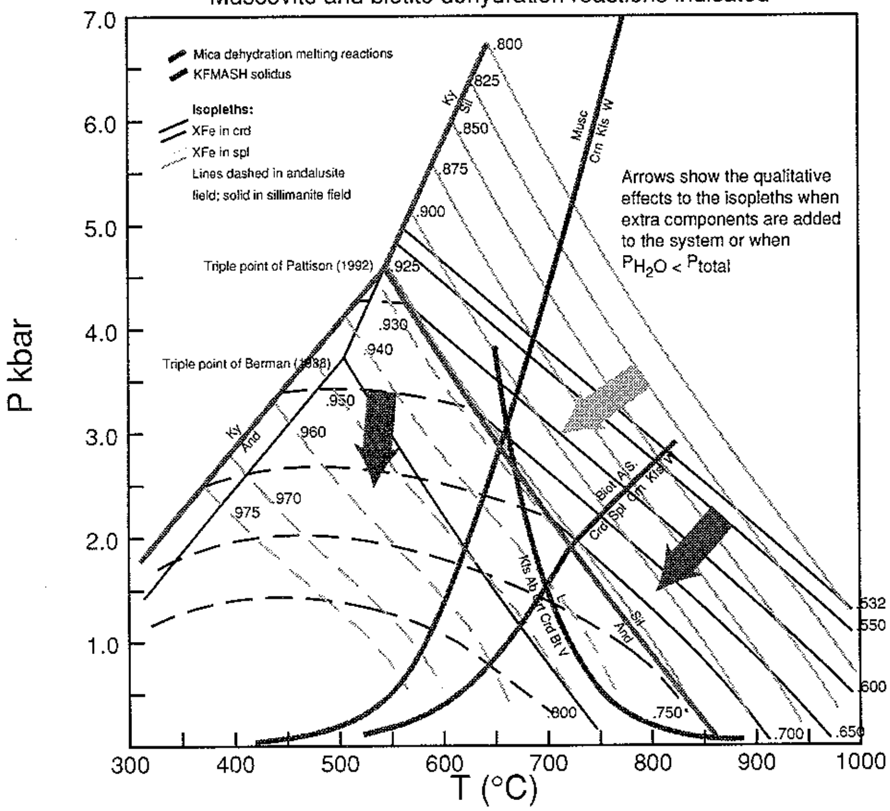
Figure 2: Continuous reaction Crn + Crd = Spl + And in melansomes in the FMASH system



The reaction Crd + Crn = Spl + And becomes continuous with the addition of magnesium to the system

Figure 3: Model for the continuous reaction Crd + A.S. = Crn + Spl in the KFMASH system, $P_{H_2O}=P_{total}$

Muscovite and biotite dehydration reactions indicated



From Program Gibbs_Distribution (Nov 6/98) of Spear using data base of Spear and Cheney (unpublished)

Notes:

- In andalusite field, cordierite composition is not sensitive to temperature change
- Isopleths for cordierite and spinel represent maximum pressure and temperature conditions; addition of extra components to the system or $P_{H_2O} < P_{total}$ will shift curves inward
- The thermometer of Nichols et al. (1992) predicted maximum temperatures of 600 °C at 1.5 kilobars for the compositions of the xenoliths exposed at Coomb's Neck
- Mica dehydration reactions and the KFMASH solidus predict that partial melting will take place between 700 and 750 °C at 1.5 kilobars