ENCLAVES OF THE CADILLAC MOUNTAIN GRANITE, MOUNT DESERT ISLAND, MAINE

Marnie Sturm
Trinity University, San Antonio, TX

Introduction

The Cadillac Mountain Granite (CMG) of the southern coastal Maine magmatic province is a coarse grained pink granite composed mostly of alkali-feldspar, quartz, and hornblende. The granite is host to fine to medium grained enclaves of varying texture and composition that are sprinkled throughout the pluton. Enclaves, as defined by Didier and Barbarin (1991), are fragments of rocks of any origin enclosed in a homogeneous igneous host rock. Four origins are generally proposed for enclaves (Blundy and Sparks, 1992): as magmatic enclaves formed by mixing of magmas; as restite blocks from the source region of partial melting; as fragments of cumulate material; or as xenoliths of wall rocks.

The goals of this project are to (1) document the field, textural, and mineralogical characteristics and major and trace element compositions of the enclaves, (2) establish their magmatic origin, and (3) evaluate the nature of host-enclave magma interactions.

Field Relationships

The field area consists of the entire exposed area of the CMG, with sites concentrated on the eastern flank of the batholith. Nine sample locations were selected vertically through the batholith, from the base to the top of the chamber. The enclaves vary in texture and size throughout the CMG with no evident correlation with position within the batholith. For example, the entire spectrum of textural variation can be found at a single sample site.

The enclaves vary in size from about 1 to 4 cm in diameter and in color from gray to salt and pepper. There is a continuum of average grain sizes in the enclaves that varies from aphanitic to medium grained. Most are equigranular, but some are porphyritic with phenocrysts of quartz and alkali feldspar which are similar in shape and size to crystals in the host granite. The enclaves are generally ovoid in shape with distinct crenulate margins, although the medium grained enclaves have slightly more gradational boundaries than the finer grained enclaves.

Petrography

The enclaves are dominated by fine to medium grained, subhedral plagioclase + clinopyroxene and/or amphibole (ferroedenite); accessory phases include opaque minerals, apatite, zircon, and allanite. The host granite is generally medium to coarse grained, equigranular, and dominated by perthitic alkali feldspar, quartz and amphibole. Accessory phases in the host also include opaque minerals, apatite, zircon, and allanite (Wiebe and Chapman, 1993).

Three enclave groups can be distinguished on the basis of mineralogy. Group I has primary mineral assemblages consisting of fine grained clinopyroxene (up to 0.2 mm), discreet amphibole (up to 0.4 mm), and plagioclase (up to 0.2 mm). Group II has primary mineral assemblages consisting of fine to medium grained plagioclase, discreet amphibole, and highly corroded clinopyroxene rimmed by amphibole. Group III has primary mineral assemblages consisting of medium grained amphibole (up to 3 mm) and plagioclase (up to 2.5 mm). One enclave reflects a gradational change in mineralogy from a pyroxene-rich half to an amphibole-rich half; the zonation is not concentric. Interstitial quartz and alkali feldspar occur sparsely in all enclave types, and epidote and chlorite are common alteration products.

As noted above, some enclaves have porphyritic textures with "phenocrysts" of quartz and alkali feldspar. The quartz phenocrysts have embayed margins upon which fine grained amphibole crystals are concentrated.

Apatite occurs as acicular needles (length:width ratios > 30) in all enclave types, whereas apatite in the host granite has a stubby habit. Zircon and allanite are additional accessory phases; most are subhedral to euhedral, but many, particularly the larger crystals, exhibit extremely embayed grain boundaries.

Magmatic origin for CMG enclaves

Field and petrographic evidence indicate that the enclaves crystallized from globules of relatively mafic magma that underwent previous magma mixing (or hybridism) with a silicic host. Crenulate margins between enclave and host granite suggest liquid-liquid (vs. solid-liquid) contacts (Seaman and Ramsey, 1992). The abundant acicular apatite and fine grain size of the enclaves relative to the host granite indicate quenching of enclave melt within cooler granitic magma (Wyllie et al., 1962). Evidence for mixing includes the occurrence of apparent quartz "phenocrysts" with corrosion textures and rims of fine amphibole (Vernon, 1990). Such "phenocrysts" are interpreted to be xenocrysts from the host granite, as are the embayed allanite and zircon crystals. The alkali feldspar "phenocrysts" are also likely to be xenocrystic in that they are similar in size and shape to those in the host granite, although they do not exhibit disequilibrium textures.

Mafic end-member compositions could be represented by the mafic dikes and chilled gabbros associated with the CMG. Felsic end-member compositions are presumed to be represented by the most silicic variants of the CMG and/or the Somesville granite (also of the Maine province).

Enclave Chemistry

Silica varies in the enclaves from ~58 to 65 wt. % vs. ~73 - 74.5 wt. % in the host granite (Figure 1). Similar to other enclave occurrences world-wide (e.g. Adamello Massif, French Massif central; Blundy and Sparks, 1992; Didier, 1973), the CMG enclaves have higher Mg/(Mg+Fe), Al_2O_3, total Fe_2O_3, MgO, CaO, and TiO_2, Na_2O, but lower K_2O, than the host granite.

Figure 1 illustrates enclave compositions and also presumed mafic and felsic end-member compositions. Although some of the elements exhibit near-linear trends among presumed mafic and felsic end-members and the enclaves (Figures 1a, c), most major and trace elements exhibit non-linear trends, ruling out simple binary mixing. The compatible elements Mg, Co, and V exhibit somewhat lower abundances in the enclaves than those expected for binary mixing between mafic and felsic end-members. Many elements (Ba, Rb, Be, Ce, Na, Mn, P, Zr, Yb, Y) exhibit anomalously high values in the enclaves compared to simple binary mixtures (Figures 1d, e, g, h). Similar enrichments have been noted in other enclave suites (Blundy and Sparks, 1992).

There is little distinction among the three enclave groups with respect to most major and trace elements. However, the amphibole-rich enclaves generally have higher CaO, Be, Y, and Yb concentrations and lower Na_2O concentrations than the clinopyroxene-bearing enclaves (cf. Figure 1). There is no correlation between enclave chemistry (or mineralogy) with vertical position within the CMG batholith.

Discussion

Since simple binary mixing cannot account for the chemical characteristics of the CMG enclaves, some other process(es) must account for their features. Other possible modes of enclave-host magma interactions include (a) selective diffusion of elements during equilibration between host and enclave residual melts and (b) incorporation of early-formed crystals from the partially crystalline granitic magma into enclave melts.

Elements with higher diffusivities would be expected to be more abundant in the enclaves than those with lower diffusivities, especially if equilibration between host and enclave residual liquids was incomplete. The enclaves are enriched in Na_2O relative to K_2O (Figures 1b, d), consistent with estimates for Na_2O diffusion coefficients which are twice as large as that for K_2O (6×10^{-7} and $= 3 \times 10^{-7}$ for Na_2O and K_2O, respectively; van der Laan and Wyllie, 1993). The wide ranges in these and other elements in the enclave suite are interpreted as the result of varying degrees of equilibration among separate enclave globules with the host.

Volatiles probably played an important role in modifying enclave compositions since water has been shown to enhance diffusivities by one to two orders of magnitude above values for dry conditions (Baker, 1991). Seaman and Ramsey (1992) suggested that a residual, water-rich liquid associated with enclave crystallization migrated *out* of the enclave into the partially crystalline granitic liquid and that crystals precipitated from this liquid formed medium grained amphibole-plagioclase enclaves which they called "pegmatite pods". However, it seems more likely that the granitic magma, which was probably more water-rich than mafic magma, provided water to the enclave in a process of equilibration between the two magmas (Wiebe, pers. comm.). Infusion of volatiles would enhance diffusion of elements into the relatively drier enclave residual liquid, especially those with geochemical affinities for aqueous solutions, e.g., K, Ba, Rb (Pearce et al., 1984). These elements would be expected to have relatively high concentrations in enclaves modified by a fluid phase. It is also possible that incorporation of alkali feldspar xenocrysts (from the host granite) could account for these enrichments. Petrographic evidence indicates that a fluid phase altered clinopyroxene assemblages to amphibole-bearing ones, especially in the case of the zoned enclave.

Diffusion involving volatiles occurred, in at least one case, before disaggregation and final dispersion of the enclaves throughout the CMG chamber. The previously described mineralogical zonation in one sample indicates that reaction with a fluid phase, altering pyroxene to amphibole from the enclave margin inward, did not occur *in situ*. Rather, it appears that the enclave was disaggregated from a larger globule because of the non-concentric nature of the zonation.

The elements Zr, Y, Ce, and Yb are generally considered to be immobile and would not be expected to be enriched in the enclaves via a fluid phase. However, these elements also occur in anomalously high concentrations in the enclaves (Figure 1g, h). Incorporation of xenocrysts from the host granite, specifically zircon and allanite, can explain these anomalous abundances. Zircon and allanite have high contents of these elements, and inclusion of even a small proportion of these crystals within a relatively small enclave melt volume could greatly enrich the enclaves in these elements.

Conclusions

Field, petrographic, and geochemical evidence support a complex origin for magmatic enclaves in the CMG and allow development of a working model for their origin. As basaltic magma infused into the CMG chamber, partial quenching of enclave liquids against cooler granitic magma occurred, and mingling between semi-liquid host and enclave liquids resulted in the incorporation of crystals from the granite into the enclave (quartz, alkali feldspar, allanite, zircon). The granitic magma contributed xenocrysts of quartz, zircon, and allanite and possibly alkali feldspar to the enclaves. The xenocrysts underwent disequilibrium reactions which elevated concentrations of generally immobile elements (e.g., Zr, Y, Ce, Yb and perhaps K, Ba, and Rb) in the enclaves. Diffusion processes and water are believed to have been important during host-enclave residual liquid interactions to allow for anomalously high concentrations of several trace elements which readily enter into a fluid phase (e.g., Ba, Rb), and the stabilization of amphibole vs. clinopyroxene. Varying degrees of equilibration among the enclaves with the host account for the variable enrichments in some elements relative to a mixing tie-line between presumed mafic and felsic end members. The non-concentric mineralogical zonation in one enclave and lack of quench margins on all enclaves indicate that disaggregation occurred prior to dispersion of enclaves throughout the batholith, although disaggregation may have continued during dispersion. The lack of correlation between enclave characteristics (texture, mineralogy, chemistry) and vertical or horizontal position within the batholith suggests that turbulent convection efficiently dispersed the enclaves throughout the chamber.

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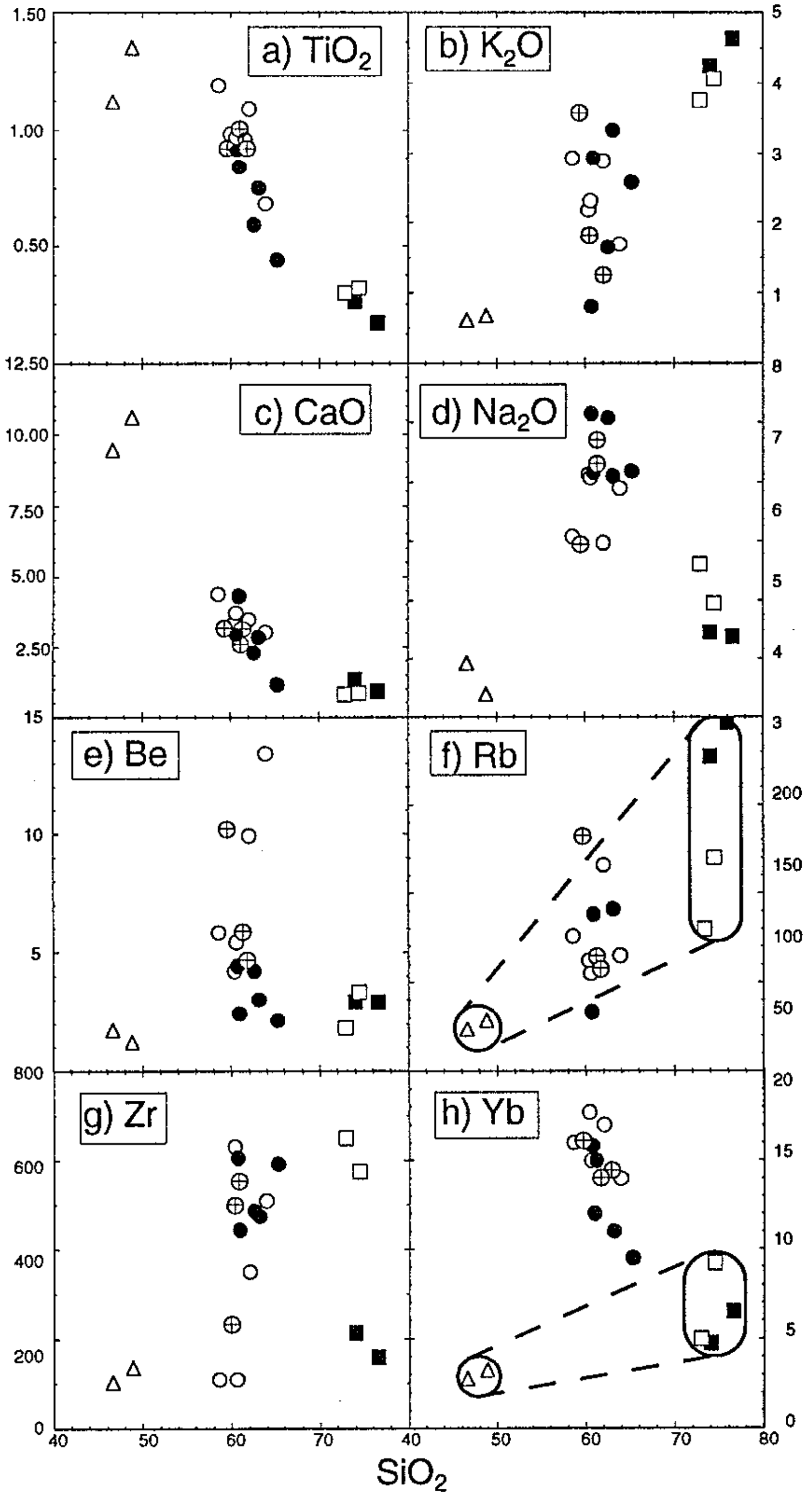

Figure 1a-h. Plots of major and trace elements against SiO_2 for enclaves (Group I: filled circles, Group II: crossed circles, Group III: open circles), CMG (open squares), Somesville granite (filled squares), and mafic dikes and chilled gabbros (open triangles). In (f) and (h), dashed lines enclose area of possible binary mixtures.