Nd isotope disequilibrium during crustal anatexis: A record from the Goat Ranch migmatite complex, southern Sierra Nevada batholith, California

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ABSTRACT

Geological and geochemical studies of a pelitic migmatite complex within the Isabella pendant of the southern Sierra Nevada batholith, California, suggest that the leucosomes represent the products of partial melting of the metapelite host driven by the emplacement of the adjacent Goat Ranch pluton ca. 100 Ma. The leucosomes preserve a record of large-magnitude Nd isotope disequilibrium with respect to their pelitic source. The leucosomes have a wide range of $\varepsilon_{Nd(100\ Ma)}$ from −6.0 to −11.0, as compared to −8.7 to −11.3 for the source. They can be subdivided into two groups based on their major elements and Sr and Nd isotope geochemistry. Group I leucosomes have higher P_2O_5 contents and $\varepsilon_{Nd(100\ Ma)}$ values than those of group II. The $\varepsilon_{Nd(100\ Ma)}$ values of group I leucosomes are significantly higher than those of metapelites and migmatites by two to four epsilon units, suggesting that group I leucosomes are in Nd isotope disequilibrium with their sources. Correlations among P_2O_5 contents, $\varepsilon_{Nd(100\ Ma)}$ values, and Sm/Nd ratios in the leucosomes suggest that apatite or monazite has played a dominant role in fractionating Sm from Nd and generating Nd isotope disequilibrium. Dissolution of apatite or monazite might play a critical role in regulating the behavior of the Sm-Nd isotope systems and thus the Nd isotope compositions of melts generated during crustal anatexis, especially in metasedimentary protoliths.

Keywords: Nd isotope disequilibrium, migmatite, crustal anatexis, leucosome, Sierra Nevada batholith.

INTRODUCTION

An increasing number of experimental and geochemical observations have suggested that Sr, Nd, and Pb isotope disequilibrium may develop under some conditions (Watson and Harrison, 1984; Peucat, 1986; Hogan and Sinha, 1991; Hammouda et al., 1996; Tomomasini and Davies, 1997; Ayres and Harris, 1997; Knesel and Davidson, 1999, 2002). In crustal anatexis, melts with Sr disequilibrium characteristics are well documented from field and experimental data (e.g., Kaczor et al., 1988; Sawyer, 1991; Barbero et al., 1995; Knesel and Davidson, 1999, 2002). For metasedimentary rocks, Rb and Sr are hosted by major rock-forming minerals, but accessory phases dominate the Sm and Nd budgets (Gromet and Silver, 1983; Sawyer, 1991; Sevigny, 1993; Bea et al., 1994; Bea, 1996a, 1996b). The principal carrier phases for Sm and Nd are apatite and monazite, which also dominate the phosphorus budget of these rocks. Theoretically, it is possible to generate melts that are not in equilibrium with their source's Nd isotopic ratios by differential dissolution of apatite or monazite. In contrast with monazite, apatite has high time-integrated Sm/Nd ratios and hence high $^{143}Nd/^{144}Nd$ ratios. Enhanced dissolution of apatite into the melts is likely to elevate their P_2O_5 contents, ε_{Nd} values, and Sm/Nd ratios simultaneously. However, observations documenting Nd isotope disequilibrium in mantle- or crustal-derived melts are still lacking. Nd isotope disequilibria in anatectic melts have been inferred mainly from geochemical observations in either migmatite complexes or leucogranite bodies (Barbero et al., 1995; Ayres and Harris, 1997; Whittington and Treloar, 2002).

Unlike leucogranites, whose sources cannot be identified unambiguously, leucosomes preserved within migmatites provide the best opportunity to study the radiogenic isotope geochemistry of anatectic products and evaluate the magnitude of isotope disequilibrium. Because most granitoids contain some crustal components derived from assimilation of melts from crustal rocks, understanding the Sr-Nd isotopic systematics of anatectic melts is critical to discuss the Sr-Nd systematics of granitoids and to formulate and test various petrogenesis models for the formation of granitoids. Migmatite zones occur in several of the deeper-level pendants of the Triassic–Jurassic metasedimentary framework rocks in the Sierra Nevada batholith (Saleeby, 1990; Saleeby and Busby, 1993). They commonly formed as a result of partial melting of the relatively fertile metapelite units within the proximity of granitic plutons (Pickett and Saleeby, 1994; Saleeby, 1999; Zeng, 2003). Therefore, geochemical observations on the leucosomes may yield key information to evaluate factors affecting the elemental and isotope characteristics of anatectic melts. The Goat Ranch migmatite complex, one of the best-preserved migmatite complexes throughout the southern Sierra Nevada, formed as a result of partial melting of the upper metapelite unit of the Isabella pendant; the partial melting was driven by the emplacement of Goat Ranch pluton ca. 100 Ma (Saleeby, 1999; Zeng, 2003). Here we report Sr and Nd isotope

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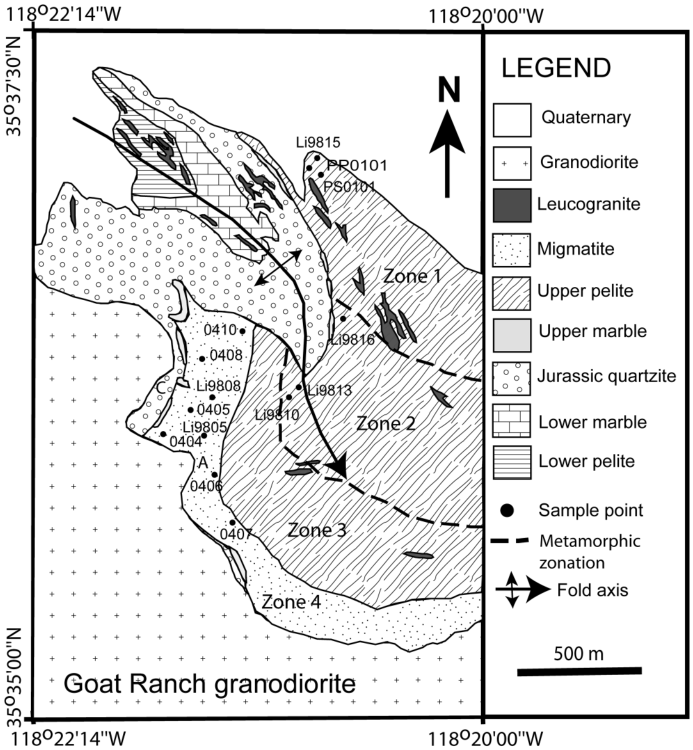

Figure 1. Geologic map of Goat Ranch migmatite complex, Lake Isabella area, southern Sierra Nevada, California, showing sample locations and metamorphic zones 1 through 4 within upper pelite unit of Isabella pendant.

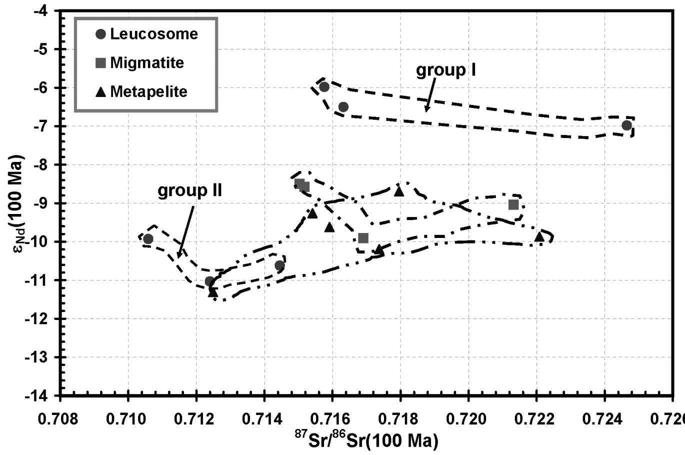

Figure 2. Nd and Sr isotope covariation diagram showing Sr-Nd systematics of leucosomes, migmatites, and metapelites. Leucosomes can be subdivided into two groups. Group I leucosomes have higher $\varepsilon_{Nd(100\ Ma)}$ values than those of either metapelites or migmatites, suggesting Nd isotope disequilibrium during partial melting. Symbol sizes are larger than analytical errors.

and major element compositional data collected from the Goat Ranch migmatite complex to (1) characterize the Sr and Nd systematics of leucosomes, migmatites, and nonmigmatitic metapelites and (2) discuss the role of nonmodal partial melting and dissolution of apatite or monazite in shaping the Sr-Nd isotopic systematics in the leucosomes.

GEOLOGIC SETTING

The study area is located along the axial part of the southern Sierra Nevada batholith within the northwest-trending belt of I-type, strongly contaminated and reduced plutons as defined by Ague and Brimhall (1987). The Goat Ranch migmatite complex consists of the Goat Ranch granodiorite pluton and the adjacent migmatite zone in the upper metapelite unit of the Isabella pendant. The gross structure of the pendant consists of a large, steeply plunging, isoclinal anticline with strong, steep, stretching lineations and smaller folds in a sequence of carbonates, quartzites, and pelites (Fig. 1). Nonmigmatitic metapelite in zone 1 consists of andalusite, biotite, quartz, plagioclase, K-feldspar, muscovite ($<$5%), and minor sillimanite. Zones 2 and 3 are characterized by widespread sillimanite and the loss of andalusite; zone 3 also is characterized by the appearance of local leucosomes. Within the principal migmatite zone (zone 4), the leucosomes associated with the finely laminated migmatite mainly consist of quartz, K-feldspar, and plagioclase, and have a granoblastic texture (Data Repository Fig. DR1[1]). In contrast, the melanosomes mainly consist of biotite (as much as 60%) and sillimanite with subordinate quartz, plagioclase, K-feldspar, and local garnet. Generally, quartz, plagioclase, and K-feldspar in the leucosomes are substantially coarser than those in the mesosomes or melanosomes. In thin section, some of the leucosomes have trace amounts of apatite located at the boundaries of quartz and plagioclase. Apatite also occurs as a minor phase in zones 1 through 4.

RESULTS

We have carried out major element and Sr and Nd isotope analysis on a suite of leucosomes, finely laminated migmatites, and metapelites from the Isabella pendant. Migmatites containing leucosomes thicker than 1 cm were selected for separation of the leucosomes for major element and Sr-Nd isotope analyses. The analytical results are given in Table DR1 (see footnote 1). Rb, Sr, Sm, and Nd elemental and isotope (calculated at 100 Ma) compositions of the leucosomes, migmatites, and nonmigmatitic metapelites are summarized in Table DR1 (see footnote 1). The $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values of the leucosomes range from 0.71059 to 0.72465 and from -6.0 to -11.0, respectively. The pelite and migmatites have initial $^{87}Sr/^{86}Sr$ ratios of 0.71715–0.72970 and 0.71664–0.72211, respectively. The initial ε_{Nd} values in the upper metapelites and migmatites range from -8.7 to -11.3 and from -8.5 to -9.9, respectively. Based on their Sr and Nd isotopic ratios, the leucosomes can be divided into two groups. Group I leucosomes have $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values ranging from 0.71576 to 7.2465 and from -6.0 to -7.0, respectively. In contrast, in the group II leucosomes, $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values range from 0.71059 to 0.71445 and from -9.9 to -11.0, respectively. The group I leucosomes have $\varepsilon_{Nd(100\ Ma)}$ values significantly higher, by two to four epsilon units, than the upper metapelites or migmatites (Fig. 2). The group I and II leucosomes also have distinct major element geochemistry (Zeng and Saleeby, 2002): (1) group I has trondhjemite-like compositions, whereas group II has granitic compositions; and (2) P_2O_5 in group I leucosomes is much higher than in group II leucosomes. It appears that the $\varepsilon_{Nd(100\ Ma)}$ values of the leucosomes are correlated with their respective P_2O_5 content (Fig. 3A). Group I leucosomes have Sm/Nd ratios between 0.23 and 0.33, as compared to Sm/Nd ratios between 0.11 and 0.25 in group II. The migmatites and upper pelites have Sm/Nd ratios between 0.15 and 0.32 and between 0.16 and 0.21, respectively. Despite the large scatter in Sm and Nd concentrations in the metapelite, the $\varepsilon_{Nd(100\ Ma)}$ values of the leucosomes appear to be correlated with their Sm/Nd ratios (Fig. 3B).

DISCUSSION

The observed Sr and Nd systematics of the leucosomes (Fig. 3) can be understood by examining the partial-melting reactions and dissolution behavior of accessory phases in a metasedimentary source.

[1]GSA Data Repository item 2005008, Table DR1, Sr and Nd isotope ratios and P_2O_5 contents, and Figure DR1, field photograph of migmatites, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

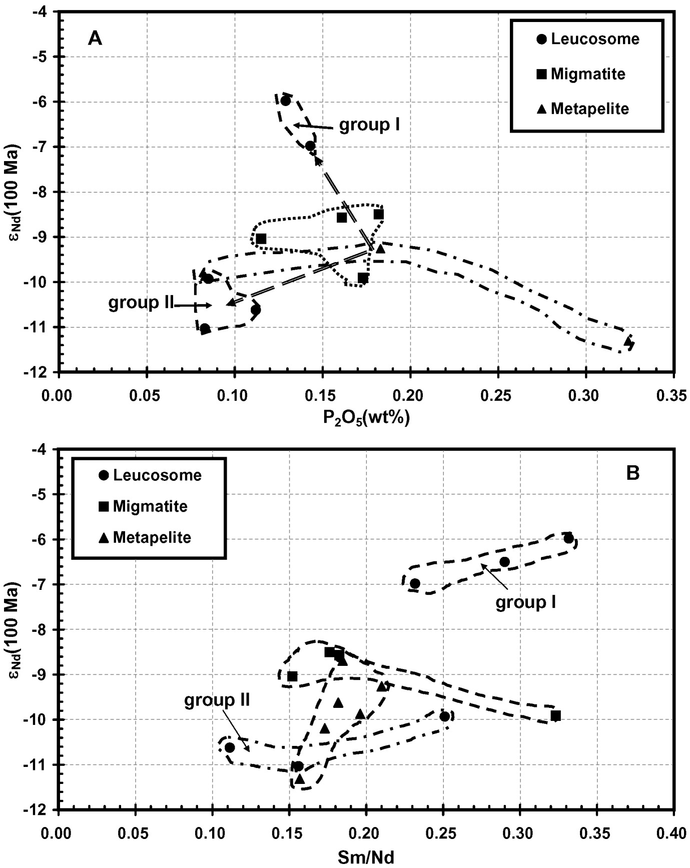

Figure 3. Plots of Nd isotope compositions of leucosomes, migmatites, and metapelites from upper pelite unit vs. (A) their P_2O_5 contents and (B) Sm/Nd ratios, illustrating potential effect of apatite dissolution in development of Nd isotope geochemistry of metasedimentary rock–derived melts. In general, leucosomes with high P_2O_5 contents have high $\varepsilon_{Nd(100\ Ma)}$ values, which can be attributed to larger quantity of apatite dissolved into melt. Symbol sizes are larger than analytical errors.

Zeng et al. (2001) showed that the $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values of the leucosomes, migmatites, and metapelites are distinct from those of the Goat Ranch granodiorites. Major and trace element data (Zeng and Saleeby, 2002; Zeng, 2003) demonstrate that the leucosomes resulted from the nonmodal partial melting of the metapelite in a water-present condition through the following alternative reactions:

$$\text{quartz} + \text{plagioclase} + H_2O \rightarrow \text{melt} \quad (1)$$

$$\text{quartz} + \text{plagioclase} + \text{muscovite} + H_2O \rightarrow \text{melt} + \text{biotite}. \quad (2)$$

Furthermore, the leucosomes were not derived from melts of a composition similar to the Goat Ranch granodiorite or deeper-level metapelites, and the leucosomes show light rare earth element (LREE) enrichment similar to that of the metapelites.

Unlike muscovite or biotite dehydration melting in dry conditions, both the water-present melting reactions lead to melts with relatively low Rb/Sr ratios (Inger and Harris, 1993). The leucosomes have Rb/Sr ratios ranging from 0.03 to 0.48, indicative of melts resulting from such reactions. For a typical metapelite, micas and feldspars are the hosts of Rb and Sr, respectively. Micas commonly have much higher time-integrated Rb/Sr ratios and hence $^{87}Sr/^{86}Sr$ ratios than those in either feldspars or bulk rock. If the differences in Sr isotope ratios for different phases persist until the onset of melting, it is conceivable that melts from both melting reations will develop isotope ratios different from those of their source. The Sr isotope ratios of such melts depend on the proportions of phases that enter the melt. Consequently, such melts will not be in equilibrium with their source in terms of Sr isotope geochemistry. The Nd isotope geochemistry of anatectic melts also can be understood in a similar fashion. Instead of being controlled by the rock-forming phases, accessory phases (e.g., apatite and monazite) dominate the behavior of the Sm-Nd isotope system during crustal anatexis (Sawyer, 1991; Ayres and Harris, 1997; Whittington and Treloar, 2002; Zeng, 2003). For a metasedimentary source, water content and temperature are the key parameters that determine the melting reaction (Vielzeuf and Holloway, 1988; Patiño Douce and Harris, 1998). Experimental results (Harrison and Watson, 1984; Watson and Harrison, 1984; Rapp and Watson, 1986; Pichavant et al., 1992; Montel, 1993) have shown that monazite dissolution overwhelms the dissolution of apatite under wet and low-temperature conditions. In contrast, dry and high-temperature conditions favor apatite dissolution. For a mica-bearing metasedimentary source, the presence of water will lower the melting temperature significantly (Wyllie, 1977; Patiño Douce and Beard, 1996; Patiño Douce and Harris, 1998), and partial melting proceeds through the water-fluxing melting reactions in which neither muscovite nor biotite plays a significant role. Under water-absent conditions, however, muscovite or biotite dehydration melting proceeds at a significantly higher temperature (Clemens and Vielzeuf, 1987; Le Breton and Thompson, 1988; Dardien et al., 1995; Johannes and Holtz, 1996). Therefore, the coupling between melting reactions and dissolution of accessory phases in crustal anatexis results in the formation of melts with distinctive Sr and Nd isotope systematics: (1) Some melts have relatively high $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values relative to their source because of a combination of dry, high-temperature conditions favoring mica breakdown and apatite dissolution. (2) Some have relatively lower $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values than their source owing to a combination of wet, low-temperature conditions favoring mica stability, slower apatite dissolution, and perhaps faster monazite dissolution. (3) There may be other melts that have $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values close to their sources because of closer approach to equilibrium or intermediate water and temperature conditions.

Previous studies (Sawyer, 1991; Sevigny, 1993) have shown that crustal anatexis can generate melts with a strong LREE-depleted signature when monazite remains in the residue. Although the group II leucosomes have elevated Sm/Nd ratios relative to the metapelite, our data demonstrate LREE enrichment in all the leucosomes (Zeng and Saleeby, 2002). This observation, together with the Nd isotope data for the leucosomes, strongly argues against a strong monazite influence on the leucosome geochemistry. Instead, increasing dissolution of apatite into the melts is likely to have led to the elevated P_2O_5 contents, $\varepsilon_{Nd(100\ Ma)}$ values, and Sm/Nd ratios that characterize the group I leucosomes. The occurrence of apatite along the grain boundaries between quartz, K-feldspar, and plagioclase in some of the leucosomes also supports this interpretation.

Although temperature and water content are the primary factors that determine the melting reactions and accessory phase dissolution, which in turn control the Sr and Nd isotope systematics of the melts, other factors—e.g., rates of melt production, melt segregation and migration, accessory phase dissolution, and strain (Sawyer, 1994; Watt et al., 1996; Rushmer, 2001)—also will affect the magnitude of deviation of the $^{87}Sr/^{86}Sr_{(100\ Ma)}$ and $\varepsilon_{Nd(100\ Ma)}$ values in the melts from those of their sources. In particular, the melt-extraction rate plays an important role (Sawyer, 1991; Watt and Harley, 1993; Watt et al., 1996; Zeng, 2003). Under high strain rates, deformation may enhance melt extraction and help to preserve the early formed Sr or Nd isotope disequilibrium signature. How deformation-enhanced melt extraction affects the elemental and isotope geochemistry of anatectic melts deserves further detailed examination.

CONCLUSIONS

The major element and Sr and Nd isotope compositional data presented in this study demonstrate that the leucosomes in the Goat

Ranch migmatite complex fall into two groups. Group I leucosomes have higher initial ε_{Nd} values than those in group II. The Nd isotopic ratios of the group I leucosomes suggest that they preserve a high degree of Nd isotope disequilibrium (two to four epsilon units) but weak Sr isotope disequilibrium with respect to either metapelites or migmatites. Favorable dissolution of apatite into the melts at relatively dry, higher-temperature conditions is thought to have been responsible for producing such a high degree of Nd isotope disequilibrium, which is supported by the observed correlation between the P_2O_5 contents and initial ε_{Nd} values for the leucosomes. The complexity in the Sr-Nd isotope systematics of anatectic melts as in this study requires extreme care in interpreting batholithic Sr-Nd systematics.

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