Measuring host rock volume changes during magma emplacement

Aaron S. Yoshinobu[a, 1], Gary H. Girty[b]

[a]*Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, U.S.A.*
[b]*Department of Geological Sciences, San Diego State University, San Diego, CA 92182, U.S.A.*

Abstract

We use a technique to evaluate volume strains in contact aureoles during magma emplacement based on geochemical mass balance calculations. Dynamothermal contact metamorphism adjacent to the Emigrant Gap composite pluton, Sierra Nevada, California, produced an ~1 km wide thermal/structural aureole consisting of an outer andalusite ± cordierite zone and an inner potassium feldspar ± sillimanite zone. Mass balance calculations using Al as an immobile reference frame element in metapelites inside and outside of the aureole indicate that the percentage change in total rock mass between chlorite-grade rocks outside of the thermal effects of the pluton and the aureole is −11.1% ± 1.4%. Mass balance calculations indicate that Si was the major rock forming element depleted (~ − 16%) from the aureole during contact metamorphism. Mass balance calculations and density measurements yield volume strains associated with mass transfer during contact metamorphism of −12.4%. These data, in conjunction with field relationships, are interpreted to suggest that (a) element mobility during contact metamorphism is not restricted to volatiles, and (b) volume losses within the contact aureole occur during magma emplacement and may contribute to the 'space-making' process during magma emplacement if intrusion spans the period necessary to engage hydrothermal circulation in the host rocks. © 1998 Elsevier Science Ltd. All rights reserved.

1. Introduction

Magma emplacement in arc settings involves the transfer of large quantities of heat and material into and through the crust. Studies of pluton–host rock systems have demonstrated that contact aureoles are zones where dramatic changes occur over geologically rapid time scales (e.g. Barton et al., 1991). Two linked processes that may occur during magma emplacement and contact metamorphism are chemical mass transfer and associated volume strain (Labotka et al., 1984; Nabelek et al., 1984). During contact metamorphism fluids emanating from igneous intrusions flow through permeable networks (Morrison and Hoisch, 1994) and may remove chemical species from the aureole and deposit them outside of the aureole. Thus, the contact aureole surrounding the intrusion has undergone a net loss of material. Such volume changes may contribute to the space-making process during pluton emplacement (Paterson et al., 1991).

Large volume losses during regional metamorphism have been documented using a variety of techniques (Ague, 1991, 1994; Gresens, 1967; Wright and Henderson, 1992). Ague (1991) used major and trace element geochemical data in assessing the roles that mass transfer and volume strains may play in cleavage formation during regional metamorphism. Based on this data, as much as 30% of the mass and volume of metapelites was removed during regional, prograde metamorphism (Ague, 1991).

In this study, we apply similar techniques to metapelites in the contact aureole of the Emigrant Gap composite pluton, northern Sierra Nevada, California, to evaluate the effect of chemical mass transfer and volume strain during contact metamorphism and magma emplacement. Based on geochemical, structural, and field data, we contend that transfer of silica in metapelites is the primary cause of significant volume strains in the contact aureole during cleavage formation associated with contact metamorphism. Together with field and geochronological evidence of multiple magmatic events, these data are used to suggest that during emplacement of successive batches
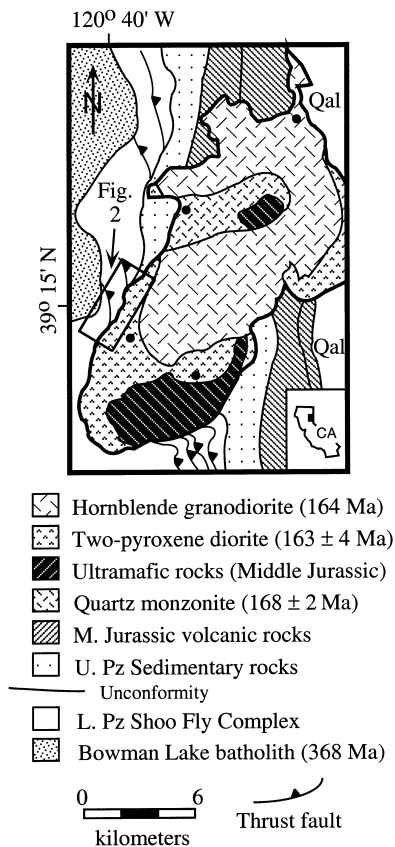
[1] e-mail: yoshinob@earth.usc.edu

Fig. 1. Geologic map of the Emigrant Gap composite pluton and host rocks. Note that deflected host rock markers along the southern half of the pluton are truncated, and the strongly discordant nature of the northern half of the pluton. Bold dots are locations of U–Pb zircon analyses.

of magma, volume losses in the aureole due to fluid-hosted mass transfer may be a contributing factor to the space-making process.

1.1. Geological setting

The Emigrant Gap composite pluton (EGCP) is a large (147 km^2) composite body consisting of an outer two-pyroxene diorite phase (163 $\pm$ 4 Ma), an inner bio-tite–hornblende granodiorite phase (164 Ma), an older core consisting of 168 $\pm$ 2 Ma quartz monzonite, and two co-magmatic ultramafic bodies (Fig. 1; all ages U/Pb zircon from Girty et al., 1993a). The composite intrusion was emplaced into argillites, sandstones, and limestones of the Lower Paleozoic Shoo Fly Complex, Upper Paleozoic epiclastic rocks, and Jurassic volcanic rocks. Temperature and pressure estimates based on contact metamorphic mineral assemblages described below range from 625–675°C 2.2–3.0 Kb, respectively (Girty et al., 1993b). These estimates are consistent with aluminum-in-hornblende determinations from the pluton yielding pressures of crystallization of 2.1 $\pm$ 0.3 Kb (Skinner, 1994).

Host rocks display a variation in deformation style associated with magma emplacement from southwest to northeast. In the southwestern half of the pluton, the host rocks consist of argillites, sandstones, and minor carbonate units of the Shoo Fly Complex meta-morphosed to chlorite-grade during an older regional metamorphism (Fig. 1). Outside of the aureole these rocks contain a weak, northwest-trending foliation defined by biotite, chlorite, quartz, and white mica and associated thrust faults and folds of Paleozoic age (Girty et al., 1990). Approaching the pluton contact, these structures and lithologic contacts are deflected to north-northeast strikes (Figs. 1 and 2). Within the structural aureole, the older foliation is transposed and coarsened into a strong schistosity with a northeast strike along the western and eastern margins of the pluton and is overgrown by andalusite and cordierite porphyroblasts. In the southern half of the intrusion, these deflected structures are truncated at the pluton contact. To the north, the pluton is strongly discordant and intrudes Upper Paleozoic epiclastic rocks and Jurassic volcanic rocks. Contact metamorphism along the northern margin of the pluton produced a hornfel-sic texture and no contact-parallel foliation. Lithologic contacts and older foliations in the host rocks can be traced into the structural aureole of the intrusion with virtually no deflection at the pluton contact (Fig. 1).

To evaluate the role of mass transfer and volume change during contact metamorphism, we undertook a study of the major- and trace-element chemistry of metapelites within an argillite–sandstone belt of the Shoo Fly Complex (Fig. 2). Twenty-six samples were selected from the Shoo Fly Complex in a traverse across a well studied portion of the ∼1 km wide con-tact aureole of the EGCP. At this locality, the contact aureole is composed of (a) an outer andalusite $\pm$ cor-dierite belt ($n = 17$), and (b) an inner potassium feld-spar $\pm$ sillimanite belt ($n = 9$) (Girty et al., 1993b) (Fig. 2). The chemistry of samples from the belts was then compared with 13 pelitic mudstone samples selected from outside the contact aureole which rep-resent the protolith of metapelites within the contact aureole.

2. Volume changes during contact metamorphism

2.1. Mass balance methodology and analysis

In order to successfully utilize mass balance to deter-mine the relative gains and losses of various rock-forming elements, two requirements must be met: (1) the average bulk composition of pelitic rock assem-blages existing prior to contact metamorphism must be shown to be uniform; and (2) a low solubility, im-mobile reference species must be selected to gauge the
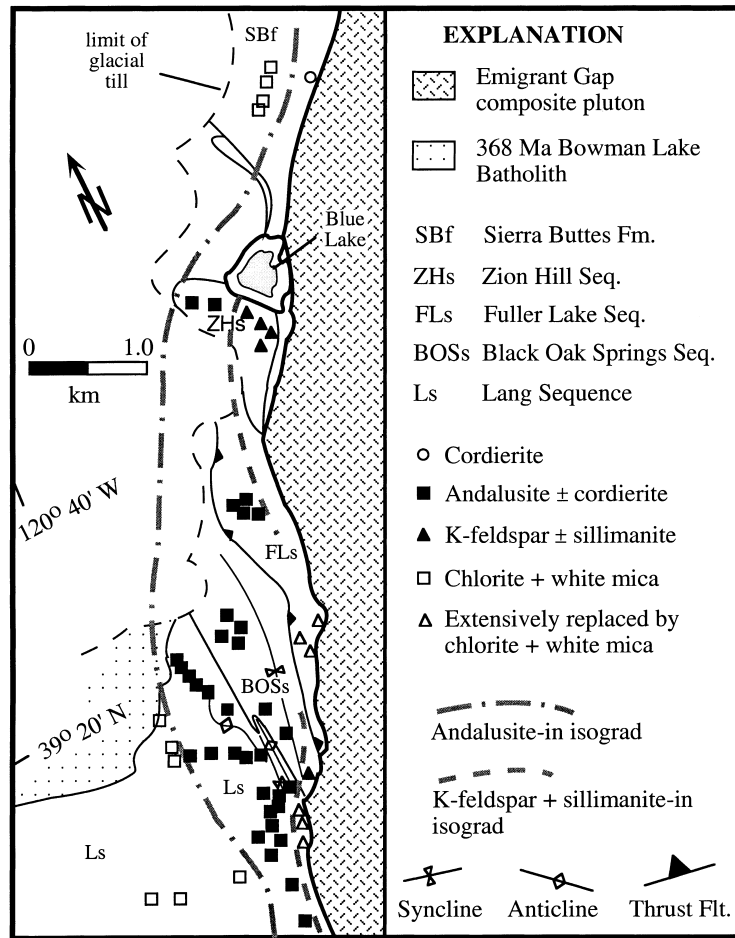
Fig. 2. Detailed geologic map of the western margin of the pluton showing map-scale host rock lithologies, deflections of host rock markers, contact metamorphic isograds, and sample locations for *P–T* analysis and geochemical analyses.

relative increase and decrease of more mobile species. Once these requirements are met, the mass balance formulations of Brimhall et al. (1988) and Ague (1991) can be applied to analyzed sample means from various petrographically defined zones within a contact metamorphic aureole to estimate possible gains or losses of major rock-forming elements.

The most fundamental parameter that can be calculated is the total percentage mass change (*T*) from some initial to some final state, based on a reference-frame element *i* (Ague, 1991):

$$T_i = \left[(C_i^0/C_i') - 1 \right] \times 100, \tag{1}$$

where C_i^0 and C_i' are the concentrations (in ppm) of the reference-frame element *i* in a belt of rocks outside and inside a contact aureole, respectively. Assuming that the chosen reference-frame element is immobile, negative values for T_i indicate that the sample has undergone mass loss. Following Brimhall et al. (1988), Eq. (1) can be extended to describe the mass changes in percent (*τ*) of a specific mobile species *j* relative to a

fixed, immobile species *i* through the formulation:

$$\tau_i^j = \left[(C_i^0/C_i') \times (C_j'/C_j^0) - 1 \right] \times 100, \tag{2}$$

where C_j^0 and C_j' are the concentrations of the mobile species *j* in a belt of rocks outside and inside a contact aureole, respectively. Negative values for τ_i^j indicate that element *j* has undergone mass loss between some initial and final state, whereas positive values indicate mass gain.

If mass changes have occurred in any significant amount, it is possible to deduce changes in rock dimensions (e.g. volume strain) that may attend contact metamorphism using the volume strain equation from Brimhall and Dietrich (1987; see also Ague, 1991):

$$\varepsilon_i = \left[(\rho^0/\rho')(C_i^0/C_i') - 1 \right] \times 100, \tag{3}$$

where ρ^0 and ρ', and C_i^0 and C_i' are the average sample density and concentration of a reference element in a belt of rocks outside and inside a contact

Table 1
Mean values of major oxide abundances in weight percent*

	Chlorite-grade	Andalusite ± cordierite belt	Potassium feldspar ± sillimanite belt	Aureole†
	Mean ($n = 13$)	Mean ($n = 17$)	Mean ($n = 9$)	Mean ($n = 26$)
SiO_2	63.4 ± 2.53	59.7 ± 1.69	59.7 ± 3.11	59.9 ± 1.40
Al_2O_3	20.0 ± 1.59	22.7 ± 0.98	22.5 ± 2.72	22.5 ± 0.99
TiO_2	0.92 ± 0.09	1.04 ± 0.05	1.02 ± 0.13	1.02 ± 0.05
FeO‡	6.41 ± 0.73	7.23 ± 0.96	6.14 ± 0.54	6.90 ± 0.63
MnO	0.07 ± 0.02	0.08 ± 0.02	0.08 ± 0.02	0.08 ± 0.02
CaO	0.57 ± 0.23	0.39 ± 0.10	0.82 ± 0.58	0.52 ± 0.19
MgO	2.21 ± 0.30	2.15 ± 0.24	2.55 ± 0.58	2.26 ± 0.24
K_2O	4.68 ± 1.14	5.89 ± 0.28	6.01 ± 0.52	5.87 ± 0.26
Na_2O	1.56 ± 1.32	0.66 ± 0.17	1.07 ± 0.32	0.78 ± 0.15
P_2O_5	0.12 ± 0.02	0.16 ± 0.05	0.14 ± 0.02	0.15 ± 0.03
Bulk density§	2.59	2.63	2.62	2.63

*Average compositions were normalized on a volatile- and LOI-free basis. †Student's t test indicates no difference between the andalusite ± cordierite and potassium feldspar ± sillimanite belts with the exception of Na_2O; therefore data were combined ($n = 26$) for the aureole mean and standard error of the mean at the 95% confidence level. Student's t test comparing the aureole data and the chlorite-grade data (outside of the aureole) indicate a significant difference in the composition of SiO_2 at the 95% confidence interval. ‡Total FeO. §Bulk density measured in g/cc. Uncertainties given as the standard error of the mean at the 95% confidence level.

aureole, respectively. Negative values for ε_i indicate volume losses, whereas positive values indicate volume gains.

2.2. Analytical methods and major element results

Major- and trace-elements were analyzed at the GeoAnalytical Laboratory of Washington State University, Pullman, Washington following conventional procedures. All 39 samples were analyzed for major- and trace-elements by standard X-ray fluorescence (XRF) techniques on an automatic Rigaku 3370 spectrometer. Each elemental analysis was fully corrected for line interference and matrix effects. Loss-on-ignition was not determined. Repeated analysis of well-characterized standards suggests that precisions for major-element data are < 1 relative weight percent, whereas precisions for trace-element data analyzed by XRF are less than ~5–20 relative weight percent depending on the particular trace element and its concentration. Density measurements for the strain analyses were conducted using standard procedures for bulk density analysis. Table 1 is a summary of the major-element chemistry from the three sampled belts.

In reviewing Table 1, the most striking change in average major oxide weight percent between the chlorite-grade rocks and the various belts in the contact aureole is the decrease in SiO_2 at the 95% confidence interval. In contrast, Al_2O_3 increases in relative concentration from the chlorite-grade rocks to the aureole, implying that aluminum was enriched during contact metamorphism (by depletion of mobile species). However, because there is some overlap in the uncertainties of the data, a statistical analysis is necessary to

verify the changes noted in the compositional data between the different belts (see Ague, 1994). Applying a student's t test (see Comrey, 1975) indicates no significant difference in major oxide concentrations between the andalusite ± cordierite and potassium feld-
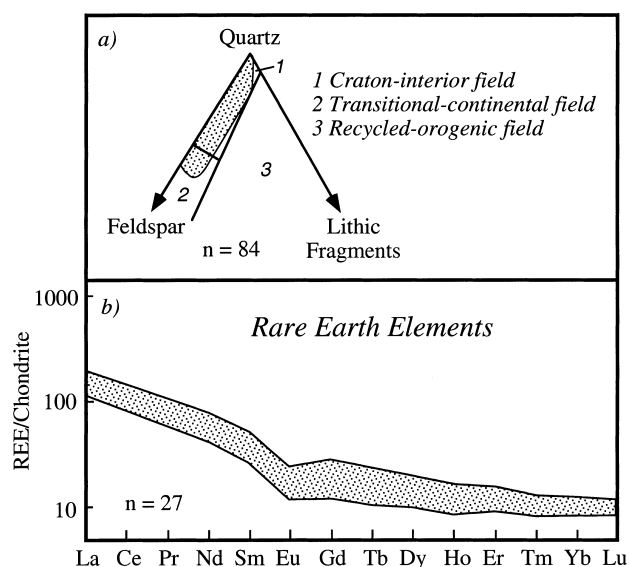

Fig. 3. Two data sets used to constrain initial uniform composition of the host rock protolith prior to contact metamorphism. (a) Point-count data (dotted pattern) derived from sandstones interstratified with pelitic mudstones within the Shoo Fly Complex plotted on the provenance-discrimination diagram of Dickinson et al. (1983). 1 = Craton-interior provenance field, 2 = Transitional-continental provenance field, 3 = Recycled-orogenic provenance field (G.H. Girty, unpublished data). (b) Chondrite-normalized REE plot showing 1 σ standard deviation envelope (dotted pattern) for pelitic mudstones within the argillite-sandstone belt of Shoo Fly Complex (data from Girty et al., 1993b, and unpublished).

spar $\pm$ sillimanite belts with the exception of Na_2O. Therefore, the data were combined to obtain the aureole mean which was used in the mass balance calculations below. Importantly, applying the same statistical test to the chlorite-grade data and the aureole data for SiO_2 indicates a significant difference at the 95% confidence interval. A more detailed statistical analysis of mass changes using the techniques of Woronow and Love (1990) yields similar results (Garrison et al., 1997). In summary, the statistical analyses clearly indicate that mass loss of major oxides such as SiO_2 accompanies contact metamorphism.

3. Discussion

The use of this technique rests on the assumption that Al is an immobile reference element that can be used to gauge increases and/or decreases in other species, and that the bulk composition of the protolith was uniform prior to contact metamorphism. Due to the low solubility of Al in water-rich fluids commonly found in pelitic rocks (Ague, 1991), and based on statistical modeling of Al behavior in these pelites (Garrison et al., 1997), we assume Al to be immobile during contact metamorphism. We infer that the bulk composition of the protolith within the Shoo Fly Complex was uniform prior to contact metamorphism based on two data sets. First, 84 samples of sandstones interstratified with the pelitic mudstones plot mostly in the craton-interior provenance field on the provenance-discrimination diagram of Dickinson et al. (1983) (Fig. 3a). If the interstratified argillites which we sampled represent the finer grained silt- to clay-sized detritus derived from source rocks similar to those supplying sand-sized detritus to the sandstones, then the argillites should display chemistries indicative of a well mixed continental source (Girty et al., 1993b; McClennan, 1989). As shown in Fig. 3(b), and as discussed by Girty et al. (1993b), argillites from the Shoo Fly Complex have a tightly clustered uniform REE distribution pattern that is characteristic of well mixed sediment shed from a continental source. Thus, it is likely that the composition of the protolith argillites in the Shoo Fly Complex was uniform prior to contact metamorphism.

3.1. Volume strain estimates

We now apply the mass balance equations to the mean values of major-element data to compare mass gains/losses and associated volume strains. Comparison of the chlorite-grade rocks with those collected from the contact aureole yield T_i values (Eq. (1)) of $T_{Al} = -11.1\% \pm 1.4\%$ indicating that rocks sampled from the contact aureole have undergone ap-

proximately 11% mass loss based on the immobile reference-frame element chosen. Applying Eq. (2), the data give τ_i^j values of $\tau_{Al}^{Si} = -15.9\% \pm 1.0\%$ which indicate that a significant amount of SiO_2 has been transferred out of the aureole during contact metamorphism. Given minimal density changes of $\sim 2\%$ (Table 1), volume strain estimates within the contact aureole obtained from Eq. (3) give values of $\varepsilon_{Al} = -12.4\%$. There is virtually no change in volume strain values between the two contact metamorphic zones. Our preliminary data indicate a -12% volume strain of metapelites during emplacement of the various phases of the EGCP. Conventional, constant volume strain analyses of regional lithologic markers, which have been deflected (rotated) in the map plane by the pluton indicate shortening strains of approximately -21% within the contact aureole (Yoshinobu et al., 1994). Thus, the bulk shortening in the contact aureole occurs by both host rock deflections and volume losses.

Two obvious questions follow from the above analysis. First, what is the nature of the source of the fluids and the 'sink' to which the mobile species migrated? Mapping in the outer margins of the aureole in the Shoo Fly Complex has documented large outcrops of pelites with networks of quartz veins that likely represent the sinks of migrating fluids. Analysis of the stable isotopic composition of the veins would be one way of testing the source and composition of the fluids they represent (e.g. Morrison and Hoisch, 1994). Second, do the volume strains help to make 'space' during magma emplacement? Volume losses in the contact aureole may provide further space for a pluton if it can be shown that intrusion spans the time necessary to construct a vigorous hydrothermal circulation system in the contact aureole (~ 100 ka, Marsh, 1989), so that mass transfer, volume losses, and foliation development can accommodate continued magma emplacement. Mapping of internal igneous phase contacts, geochemical data, and U–Pb (zircon) crystallization ages indicates that construction of the EGCP occurred over at least 4 Ma (Fig. 1). Therefore it is likely that periodic hydrothermal circulation systems had sufficient time to be generated and influence contact metamorphism during subsequent magma emplacement. However, we are cautious in directly linking volume losses to the space-making process without further knowledge of the rates and durations of foliation development, magma transport and intrusion.

4. Conclusions

Based on field mapping and major element geochemistry from the contact aureole of the EGCP we make the following conclusions: (a) mass balance equations

using the low-solubility reference element Al demonstrate that major-element mass transfer may occur during contact metamorphism, (b) decreases in mass of major rock-forming elements such as Si (−16%), indicate that contact metamorphism of pelitic rocks is not an entirely isochemical process, a result that is well substantiated in studies of skarns (e.g. Barton et al., 1991), and (c) mass transfer and density changes attending contact metamorphism yield volume strains of approximately −12% during emplacement of the EGCP. The transfer of major rock forming elements and subsequent volume loss may contribute to the 'space-making' process, if the intrusion spans the period necessary to engage hydrothermal circulation in the host rocks. Further work in other contact metamorphic environments should occur to test and refine this technique.

Acknowledgements

References

Ague, J.J., 1991. Evidence for major mass transfer and volume strain during regional metamorphism of pelites. Geology 19, 855–858.

Ague, J.J., 1994. Mass transfer during Barrovian metamorphism of pelites, south-central Connecticut. I: Evidence for changes in composition and volume. American Journal of Science 294, 989–1057.

Barton, M.D., Staude, J.M., Snow, E.A., Johnson, D.A., 1991. Aureole Systematics. Mineralogical Society of America Reviews in Mineralogy 26, 723–847.

Brimhall, G.H., Dietrich, W.E., 1987. Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis. Geochimica et Cosmochimica Acta 51, 567–587.

Brimhall, G.H., Lewis, C.J., Ague, J.J., Dietrich, W.E., Hampel, J., Teague, T., Rix, P., 1988. Metal enrichment in bauxites by deposition of chemically mature aeolian dust. Nature 333, 819–824.

Comrey, A.L., 1975. Elementary Statistics. Dorsey Press, Homewood, Illinois.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knapp, R.A., Lindberg, F.A.,

Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geological Society of America Bulletin 94, 222–235.

Garrison, K.M., Bradbury, L.M., Sanders, J.C., Hanson, W.E., Gallarano, C.S., Ash, J.W., Waite, R.A., Girty, G.H., 1997. Estimating β and power for the student's t test: implications for elemental mass change in a Middle Jurassic contact metamorphic aureole. In: Girty, G.H., Hanson, R.E., Cooper, J.D., (Ed.). Geology of the Western Cordillera: Perspectives from Undergraduate Research, 82. Pacific Section Society of Economic Paleontologists and Mineralogists, pp. 123–135.

Girty, G.H., Gester, K.C., Turner, J.B., 1990. Pre-Late Devonian geochemical, stratigraphic, sedimentologic, and structural patterns, Shoo Fly Complex, northern Sierra Nevada, CA. In: Harwood, D.S., Miller, M.M., (Ed.). Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada, Klamath Mountains, and related terranes, 255. Geological Society of America Special Paper, pp. 43–56.

Girty, G.H., Yoshinobu, A.S., Wracher, M.D., Girty, M.S., Bryan, K.A., Skinner, J.E., McNulty, B.A., Bracchi, K.A., Harwood, D.S., Hanson, R.E., 1993a. U–Pb zircon geochronology of the Emigrant Gap composite pluton, northern Sierra Nevada, CA: Implications for the Nevadan orogeny. In: Dunne, G., McDougall, K., (Ed.). Paleogeography of the Western united States—II Mesozoic. Pacific Section Society of Economic Paleontologists and Mineralogists, pp. 323–332.

Girty, G.H., Hanson, A.D., Yoshinobu, A.S., Knaack, C., Johnson, D., 1993b. Provenance of Paleozoic mudstones in a contact metamorphic aureole determined by rare earth element, Th, and Sc analyses, Sierra Nevada, CA. Geology 21, 363–366.

Gresens, R.L., 1967. Composition–volume relationships of metasomatism. Chemical Geology 2, 47–65.

Labotka, T.C., White, C.E., Papike, J.J., 1984. The evolution of water in the contact-metamorphic aureole of the Duluth Complex, northeastern Minnesota. Geological Society of America Bulletin 95, 788–804.

Marsh, B.D., 1989. Magma chambers. Annual Reviews in Earth and Planetary Sciences 17, 439–474.

McClennan, S.M., 1989. Rare earth elements in sedimentary rocks: Influences of provenance and sedimentary processes. Mineralogical Society of America Reviews in Mineralogy 21, 169–200.

Morrison, J., Hoisch, T.D., 1994. Upward flow of magmatic fluids from the Old Woman granodiorite, Old Woman Mountains, southeastern California. Journal of Geophysical Research 99, 9469–9476.

Nabelek, P.I., Labotka, T.C., O'Neil, J.R., Papike, J.J., 1984. Contrasting fluid/rock interaction between Notch Peak granitic intrusions and argillites and limestones in western Utah: Evidence from stable isotopes and mineral assemblages. Contributions to Mineralogy and Petrology 86, 25–34.

Paterson, S.R., Vernon, R.H., Fowler, T.K., 1991. Aureole tectonics. Mineralogical Society of America Reviews in Mineralogy 23, 673–722.

Skinner, J.E. 1994. Aluminum-in-hornblende barometry, amphibole–plagioclase thermometry, geochemistry, and petrology of the Middle Jurassic Emigrant gap composite pluton. M.S. thesis. San Diego State University.

Woronow, A., Love, K.M., 1990. Quantifying and testing differences among means of compositional data suites. Journal of Mathematical Geology 22, 837–852.

Wright, T.O., Henderson, J.R., 1992. Volume loss during cleavage formation in the Meguma Group, Nova Scotia, Canada. Journal of Structural Geology 14, 281–290.

Yoshinobu, A.S., Skinner, J.E., Girty, G.H., 1994. Ductile to brittle wall rock response during pluton emplacement, Emigrant Gap composite pluton (EGCP), northern Sierra Nevada, CA. Geological Society of America Abstracts with Programmes 26, 106.