Long-term geochemical variability of the Late Cretaceous Tuolumne Intrusive Suite, central Sierra Nevada, California

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Abstract: This study investigates the internal anatomy and petrogenesis of the Tuolumne Intrusive Suite (TIS), which comprises metaluminous, high-potassium, calc-alkaline granitoids typical of the Sierra Nevada batholith. Although the TIS has often been cited as an example of a large magma chamber that cooled and fractionated from the margins inward, its geochemistry is inconsistent with closed-system fractionation. Most major elements are highly correlated with SiO2, but the scattered nature of trace elements and variations of initial Sr and Nd isotopic ratios indicate that fractional crystallization is not the predominant process responsible for its chemical evolution. Isotopic data suggest mixing between melts of mantle-like rocks and a granitic melt similar in composition to the highest-silica TIS unit. Monte Carlo models of magma mixing confirm that such processes can reproduce the observed variations in major elements, trace elements and isotopic ratios. Thermobarometry suggests emplacement at depths near 6 km and crystallization temperatures ranging from 660 to 750 °C. Feldspars, hornblende, biotite and magnetite exhibit evidence of extensive low-temperature subsolidus exsolution. The TIS as a whole trends toward more evolved isotopic compositions and younger U–Pb zircon ages passing inward. This pattern indicates a general increase in the proportion of felsic, crustally derived melt in the mixing process, which may have resulted from net accumulation of heat added to the lower crust by intrusion of mantle-derived mafic magma. However, the bulk geochemical and isotopic compositions of the equigranular Half Dome Granodiorite, the porphyritic Half Dome Granodiorite and the Cathedral Peak Granodiorite overlap one another and the contacts between them are commonly gradational. We interpret these map units to represent a single petrological continuum rather than distinct intrusive phases. The textural differences that define the units probably reflect thermal evolution of the system rather than distinct intrusive events.

Normally zoned intrusive suites are common in the plutonic record and characteristically have mafic margins that grade toward a felsic core (Buddington 1959; Pitcher 1993). The origin of the zonation is interpreted to reflect either inward-progressing fractional crystallization (e.g. Bateman & Chappell 1979; Walawender et al. 1990) or magma mixing between end members represented by marginal and core facies (e.g. Reid et al. 1983; Kistler et al. 1986). The notion that all plutons and intrusive suites were largely molten at one time so that fractional crystallization and mixing could operate throughout has recently been challenged, and is at odds with geophysical observations and a growing set of geochronological data (e.g. Deniel et al. 1987; Glazner et al. 2004). Consequently, the origin of petrographic and geochemical variation in zoned suites must be reexamined.

The Tuolumne Intrusive Suite (TIS) of the Sierra Nevada batholith (SNB), California, is a particularly well-studied and well-exposed example of a zoned intrusive suite and was originally interpreted to reflect inward fractional crystallization (Frey et al. 1978; Bateman & Chappell 1979). However, subsequent work by Kistler et al. (1986) revealed isotopic variation across the suite, and a mixing origin for the petrological and chemical variation in the TIS became widely accepted. More recently, Coleman et al. (2004) demonstrated a regular age variation across the TIS and, most problematically for the mixing hypothesis, a difference of at least 8 Ma in the ages of the outermost mafic (>93 Ma) and innermost felsic (c. 85 Ma) members of the suite. These authors argued that the age difference was too large for the two magmas to ever have been molten at the same time and, therefore, an origin involving mixing between the exposed units was discredited.

Here, we return to the TIS and build on an already large petrographic, chemical, isotopic

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and geochronological dataset in an attempt to understand the origin of chemical variation in the suite. Data include major-element, trace-element and isotopic data, as well as the first comprehensive set of mineral analyses published for the TIS. Mineral compositions were originally measured to test the fractional crystallization and mixing hypotheses; however, as our work progressed, we realized that these options were not tenable. A full discussion of the data and the evolution of thought regarding the TIS are found in Gray (2003). This work is based on analysis of approximately 120 samples; additional datasets and thermal modelling are in Gray (2003).

**Geological setting**

The TIS is one of a number of zoned plutonic bodies emplaced along the eastern Sierra Nevada during the Late Cretaceous (Stern et al. 1981; Chen & Moore 1982). Related nested plutonic suites include the John Muir and Mount Whitney Intrusive Suites to the south and the Sonora plutonic complex to the north (Fig. 1). Together these bodies comprise over 2500 km² of exposed rock that is among the youngest in the Mesozoic SNB and that varies in composition from gabbro to granite. Magmatism that created the SNB occurred in three major episodes from approximately 220 to 80 Ma (Stern et al. 1981; Bateman 1992). The largest volume was emplaced during the middle to Late Cretaceous (c. 120 to 80 Ma, Stern et al. 1981; Chen & Moore 1982; Coleman & Glazner 1997) along the present axis of the batholith. The TIS was emplaced over a period of approximately 8 Ma, with concordant zircon U–Pb ages decreasing from approximately 93 Ma at its margins to 85 Ma near its centre (Coleman et al. 2004; Matzel et al. 2005). It intruded between older Cretaceous granitoid rocks (intrusive suite of Yosemite Valley, Sentinel Granodiorite) to the west and south, and Paleozoic to Jurassic metasedimentary and metavolcanic rocks to the north and east (Fig. 1).

The TIS is a concentrically zoned suite consisting of five mapped units (Calkins 1930; Bateman et al. 1983, 1988; Bateman 1992). From the margins inward the units are: (1) the granodiorite of Kuna Crest; (2) the equigranular Half Dome Granodiorite; (3) the porphyritic Half Dome Granodiorite; (4) the Cathedral Peak Granodiorite; and (5) the Johnson Granite Porphyry (Fig. 1). The rocks are predominantly medium- to coarse-grained, except the Johnson Granite Porphyry, which has a highly variable, but generally aplitic to alaskitic, texture. The TIS contains a consistent suite of minerals, but abundance and grain size varies among the units. The primary mineralogy is plagioclase (andesine to oligoclase), K-feldspar (microcline perthite), quartz, hornblende and biotite, with accessory titanite, magnetite, zircon, apatite and allanite (Bateman & Chappell 1979). In general, the proportions of mafic minerals and corresponding color indices decrease from the margins inward. Hornblende and biotite together constitute approximately 20% of the granodiorite of Kuna Crest, but less than 1% of the Johnson Granite Porphyry. The largest decrease occurs in traverses across the Kuna Crest and equigranular Half Dome Granodiorite (Bateman & Chappell 1979). Modal layering of mafic minerals is commonly observed in the granodiorite of Kuna Crest and at the outer margins of both the equigranular Half Dome and Cathedral Peak granodiorites, but is generally sparse elsewhere. Mafic magmatic enclaves are common in the Kuna Crest and Half Dome granodiorites.

A moderately strong margin-parallel foliation is present, as indicated by the preferred alignment of mafic minerals and flattened mafic enclaves (Bateman 1992; Zak et al. 2007). Evidence for solid-state deformation is locally marked by elongated quartz grains and the wispy appearance of linear disaggregated hornblende and biotite. The Half Dome Granodiorite is easily recognized by euhedral hornblende phenocrysts up to 20 mm long, and large (typically up to 4 mm and locally larger) euhedral titanite crystals. The porphyritic Half Dome Granodiorite is also distinguished by the presence of abundant K-feldspar phenocrysts and rare megacrysts (crystals >50 mm in length). K-feldspar megacrysts also are abundant in the Cathedral Peak Granodiorite, but they are typically larger (up to 100 mm in length) and more blocky than in the adjacent porphyritic Half Dome Granodiorite (Johnson et al. 2006). The Johnson Granite Porphyry is characterized by a nearly equal mixture of fine-grained sodic plagioclase, K-feldspar and quartz, with minor biotite and a general absence of hornblende. Locally it contains miarolitic cavities and sparse spherical blobs, typically 10–20 cm across, of K-feldspar megacrysts surrounded by Cathedral Peak-like matrix (Titus et al. 2005). Concentric zonation and gradational contacts led early workers to hypothesize that emplacement occurred in three separate pulses, each successive pulse having intruded into the still molten previous one, which was still mobile enough to be pushed out of the way without forming a significant solid-state fabric (Evernden & Kistler 1970; Frey et al. 1978; Bateman & Chappell 1979). As envisioned by Bateman & Chappell (1979), the Kuna Crest was emplaced first, followed by the Half Dome Granodiorite, then the Cathedral Peak Granodiorite and
Fig. 1. Geology of the TIS, central Sierra Nevada, California (after Bateman 1992) and plutons comprising the Late Cretaceous Sierra Crest event (Coleman & Glazner 1997). The TIS is one of a number of compositionally zoned pluton suites intruded along the Sierra crest during the Late Cretaceous.
Johnson Granite Porphyry. Diapiric rise and shouldering of wall rocks was considered the most likely emplacement scenario for the early units, with subsequent units emplaced by stretching of partially crystallized outer margins (ballooning), as evidenced by foliation in the Kuna Crest and progressive weakening of foliation inward (Bateman et al. 1983; Bateman & Chappell 1979).

Contacts between units vary from sharp to gradational and dip moderately to steeply away from the centre of the suite (Bateman 1992; Coleman et al. 2006). Contact orientations are difficult to determine in many places owing to broad, gradational contacts. The contact between the inner Johnson Granite Porphyry and Cathedral Peak Granodiorite is generally sharp (Titus et al. 2005), whereas contacts between the Cathedral Peak, equigranular and porphyritic Half Dome and Kuna Crest are typically gradational over tens to hundreds of metres (Johnson et al. 2006). The steeply dipping margin-parallel foliation, so pronounced in the outer gradoniorite of Kuna Crest, becomes progressively weaker inward and is scarcely visible in the Johnson Granite Porphyry (Bateman 1992; Zak et al. 2007).

Petrology of the Tuolumne Intrusive Suite

Methods

Mineral analyses were performed by wavelength-dispersive X-ray spectrometry using the Cameca CAMEBAX electron microprobe at Duke University. X-ray intensities were corrected utilizing the methods and correction factors of Bence & Albee (1968). All analyses were performed using an accelerating voltage of 15 kV and a sample current of 15 nA. A beam diameter of 20 μm was used in each analysis except during K-feldspar analyses, during which a beam diameter of 50 μm was used to better average exsolution lamellae. Where applicable, concentrations of Na, Cl and F were determined first to minimize the effect of volatile loss and element migration. Mineral compositions are reported in weight-percent oxides and represent the average of at least five analyses of each mineral grain.

Analysis for major and trace elements used a combination of fusion ICP, total digestion ICP, ICP-MS and INAA techniques. Approximately 1–2 kg of material was collected at each location and reduced to powder in a steel jaw crusher and alumina shatterbox. Based on replicate analyses of two samples, analytical precision is estimated to be approximately ±2% for major oxides and trace elements, and ±3% for rare earth elements.

For isotope analyses, a single dissolution was used with 500 mg of powdered sample loaded into Teflon® bombs with a mixture of HF + HNO₃, and placed in an oven at 180 °C for 5 days. After dissolution, the solution was dried, dissolved in hydrochloric acid and separated into three aliquots for Sr, Nd and Pb isotope analysis. Each aliquot was then dried and re-dissolved in the appropriate starting acid solution for ion exchange chemistry. The aliquots were then subjected to ion-exchange chromatography followed by analysis using a Micromass VG Sector 54 thermal ionization mass spectrometer (TIMS) at the University of North Carolina. Strontium isotopic measurements were normalized to 86Sr/88Sr = 0.1194, and Nd isotopes to 144Nd/144Nd = 0.7219. Six replicate analysis of standards during the study period yielded a mean 87Sr/86Sr = 0.710257 ± 0.000022 (2σ) for NBS 987, a mean 143Nd/144Nd = 0.512112 ± 0.000011 (2σ) for JNd-1, and a mean 206Pb/207Pb = 1.0940 ± 0.0003 (2σ) for NBS 981 with a mean fractionation correction of 0.098 ± 0.008% per amu. Isotopic ratios were corrected to the mean age of the host rock (Coleman et al. 2004).

All data tables (mineral analyses, whole-rock major- and trace-element analyses, and Sr, Nd and Pb isotope analyses) are available online at http://www.geolsoc.org.uk/SUP18320.

Mineral chemistry

Fifteen polished thin sections representing all units of the TIS and two mafic enclaves were analysed to determine representative mineral compositions. Feldspar, titanite, biotite and hornblende molecular proportions were calculated on the basis of 8, 4, 22 and 24 oxygens, respectively. All iron in feldspar, titanite and biotite was assumed to be Fe³⁺, whereas Fe²⁺ was calculated in hornblende from charge balance by the method of Cosca et al. (1991). Hornblende normalization to 24 oxygens was chosen over the more traditional 23 oxygens because the latter scheme has been shown to overestimate Fe³⁺. In addition, normalization to 24 oxygens is the recommended procedure for hornblende and plagioclase thermobarometry (Blundy & Holland 1990; Holland & Blundy 1994; Anderson & Smith 1995).

The K-feldspars measured in this study are potassium-rich and vary only from Or₈₆ to Or₉₀ (Fig. 2; see also Kerrick 1969; Johnson et al. 2006). Orthoclase content does not correlate with whole-rock silica or location within the intrusive suite. Anorthite and iron concentrations are uniformly low, less than 0.3 and 0.1 mol%, respectively.

Plagioclase occurs as both optically zoned and unzoned grains, the zoned grains displaying both
normal and oscillatory zoning. Anorthite content in unzoned grains decreases systematically inward across the TIS from approximately An 50 in the marginal granodiorite of Kuna Crest to An 15 in the Johnson Granite Porphyry (see also Bateman & Chappell 1979). Average An content in the zoned plagioclase grains is similar, but ranges to higher An values. Plagioclase Or content is less than 2.5 mol% in all grains analysed. Iron content is slightly higher than that observed in the K-feldspars, reaching 0.22 mol% in one sample (HD01-6). Textural evidence for relict grains (resorbed and embayed edges, overgrowths, etc.) and cumulate grains is generally lacking. However, synneusis and boxy-cellular texture (Hibbard 1995) are common.

Hornblendes are calcic and plot in the magnesiohornblende to actinolite fields on the classification diagram of Leake (1978). Although hornblende SiO2 generally increases with host-rock SiO2, the increase is not systematic and considerable variability is observed within individual TIS units. FeO generally decreases with host-rock SiO2, similar to the trend observed for whole-rock FeO, but hornblende MgO increases, contrary to the whole-rock trend. Other oxides show no correlation with host-rock chemistry, consistent with a previous study of central SNB hornblendes (Dodge et al. 1968). Hornblende Fe/(Fe + Mg) correlates negatively with whole-rock SiO2, decreasing from approximately 0.42 in the granodiorite of Kuna Crest to 0.30 in the Cathedral Peak Granodiorite (the Johnson Granite Porphyry contains no appreciable hornblende). Fluorine and chlorine are present in only minor amounts, typically less than 0.3 wt%. Except for the Kuna Crest Granodiorite, hornblende Ti contents are not correlated with Ti in biotite from the same rock (Fig. 3).

Biotite contains nearly constant molecular abundances of Fe and Mg, resulting in a narrow range of Fe/(Fe + Mg) ratios (approximately 0.48–0.41) that decrease with whole-rock SiO2. Variations with whole-rock chemistry mimic those of hornblende, but each oxide varies by no more than 1 wt% over the full range of whole-rock SiO2 (55–74 wt%). Only in the Johnson Granite Porphyry does F content exceed 1 wt%; in all other units, F content is typically less than 0.25 wt%. Chlorine is present in only trace amounts. In contrast to the other minerals, titanite major-element concentrations vary between samples by less than 0.6 wt%, and are uncorrelated with host-rock chemistry.

**Fig. 2.** Feldspar compositions in the TIS do not agree with the experimentally determined compositions of Elkins & Grove (1990), and suggest pervasive subsolidus modification. Pressure and temperature estimates for crystallization of the TIS from this study. See text for discussion.

**Fig 3.** Titanium (Ti) compositions of the TIS hornblende and biotite. Lack of correlation in Ti composition is thought to indicate subsolidus re-equilibration (Ague & Brimhall 1988).
A significant aspect of hornblende and biotite chemistry is the decreasing Fe/(Fe + Mg) with whole-rock SiO₂, which indicates crystallization under increasing fO₂ conditions (Czamanske & Wones 1973; Czamanske et al. 1981). Elevated fO₂ is consistent with the assemblage magnetite + titanite + quartz (Wones 1989). Wones (1989) estimated that the reaction hedenbergite + ilmenite + oxygen = titanite + magnetite + quartz lies about 2 log units above the Ni–NiO buffer.

Thermobarometry

Estimates of pressure and temperature at the time of crystallization were made by simultaneous solution of the plagioclase–amphibole thermometer of Blundy and Holland (Blundy & Holland 1990; Holland & Blundy 1994), and the temperature-dependent Al-in-hornblende barometer of Anderson & Smith (1995). Estimated plagioclase temperatures vary from approximately 750 ± 40 °C in the granodiorite of Kuna Crest and mafic enclaves, to approximately 700 ± 40 °C in the Cathedral Peak Granodiorite (Fig. 4). Zircon saturation temperatures (Watson & Harrison 1983) range from 710 to 770 °C, in general agreement with the plagioclase thermometry and suggesting late-magmatic crystallization of zircon. Although estimated pressures range from 0.35 to 0.03 GPa, the majority of samples indicate pressures from 0.1 to 0.2 GPa, with an average of 0.17 GPa (corresponding to a depth of 6 km), consistent with previous estimates for central Sierra Nevada plutons (Bateman 1992). Ague & Brimhall (1988) also obtained pressures of 0.05–0.23 GPa for two Cathedral Peak Granodiorite samples from Al-in-hornblende barometry. The estimated temperatures resemble experimentally determined solidus temperatures for synthetic granites and granodiorites (Whitney 1988) and natural dacite melts (Scaillet & Evans 1999) at 0.2 GPa confining pressure. At these temperatures and pressures, hornblende on the solidus suggests an H₂O content of at least 4 wt% (Scaillet & Evans 1999).

TIS samples have plagioclase and hornblende compositions well-matched to the compositions used in the thermobarometric calibrations. In addition, the mineral assemblage assumed by Anderson & Smith (hornblende + biotite + plagioclase + quartz + alkali feldspar + magnetite or ilmenite) is identical to that found in the TIS. However, hornblendes in the TIS display lower Fe/(Fe + Mg), which decreases with whole-rock SiO₂. A decreasing Fe/(Fe + Mg) – SiO₂ trend, combined with a high Mg content, indicates an elevated oxidation state in the hornblende (Wones & Gilbert 1982; Wones 1989). Progressive oxidation of the hornblende decreases its total Al content, resulting in a potential underestimate of pressure (Anderson & Smith 1995). Thus, the calculated pressures for the TIS may be slightly low.

Major- and trace-element geochemistry

New major-oxide and trace-element data are presented for 56 samples collected from locations within all units of the TIS, as well as three mafic enclaves and one aplite dyke. Rocks of the TIS are metaluminous, high-potassium, calc-alkaline granitoids, similar to many other plutonic suites within the SNB (Bateman 1992). The TIS displays a broad compositional range, with SiO₂ content varying from approximately 59 wt% in the marginal granodiorite of Kuna Crest, to 75 wt% in the central Johnson Granite Porphyry. Compositional variability within individual units is more restricted, except for the equigranular Half Dome Granodiorite in which compositions overlap all other units except the Johnson Granite Porphyry (Fig. 5). A small compositional gap exists between the Johnson Granite and the older units, and the major and trace-element contents of the Johnson closely approach the composition of the aplite dyke (Fig. 5).

Major oxides are well-correlated with SiO₂, except Na₂O and K₂O, possibly the result of low-temperature re-equilibration (see Discussion).
However, most trace elements display little or no correlation with SiO$_2$ (Fig. 6). Notable exceptions include the transition metals (V, Co, Ni and Sc) and Sr, which display strong negative correlations. Zr and Hf display weak negative correlations, and Rb displays a weak positive correlation. However, considerable scatter is observed in these plots. When plotted against each other, most incompatible trace elements show only weak correlations. However, strong correlations exist for Zr–Hf (Zr–Hf is nearly constant across all units) and Nb–Ta, as is expected from their similar chemical behaviour.

All units of the TIS are depleted in heavy rare earth elements (REE) relative to light REE (Fig. 7). Light REE abundances are similar in all units and overlap in normalized plots, but heavy REE abundances decrease systematically from the margins inward and correlate negatively with SiO$_2$. Correlation of REE abundance with whole-rock SiO$_2$ changes with atomic number: light REE display no significant correlation, middle
REE are strongly negatively correlated and heavy REE are weakly negatively correlated. Although the depletion of heavy and middle REE relative to light REE could be explained by ubiquitous removal of zircon or titanite, evidence from the TIS is mixed. Both Zr and Hf decrease in the more felsic units, but for other trace elements commonly associated with these minerals, namely U, Th and Y, such trends are not apparent. The similarity of TIS REE patterns to those of the mafic enclaves may suggest significant inheritance of these patterns from the source, especially if garnet is present.

The absence of pronounced Eu anomalies, except in isolated cases, is a ubiquitous feature of the TIS. Minor Eu anomalies occur in a few samples of the granodiorite of Kuna Crest and Johnson Granite Porphyry, but are absent in the other units. It is most significant that the one aplite sample does not show the Eu anomaly that might be expected in this highly differentiated rock (Glazner et al. 2008).

Fig. 6. Plots of representative trace elements v. SiO₂. All symbols as in the first panel. Most trace elements display weak to no correlations with SiO₂. Notable exceptions include the transition metals and Sr.
Radiogenic isotope geochemistry

Twenty-six samples were analysed to determine whole-rock Sr, Nd and Pb isotopic compositions. Rocks of the TIS display considerable variability in whole-rock Sr and Nd isotopic composition with a negative correlation between initial Sr ratio and \( \varepsilon_{\text{Nd}}(t) \). Initial \( ^{87}\text{Sr} / ^{86}\text{Sr} \) varies from 0.7056 to 0.7073 and \( \varepsilon_{\text{Nd}}(t) \) varies from approximately -3 to -8 (Fig. 8a). Data from the granodiorite of Kuna Crest, equigranular Half Dome Granodiorite and Johnson Granite Porphyry plot in distinct and separate fields that do not overlap with other units. However, there is a continuous variation in the isotopic compositions of the suite as a whole, and the isotopic compositions of the porphyritic Half Dome and Cathedral Peak granodiorites are similar and plot within a common region. The negative trend shown by the Kuna Crest samples is less pronounced than the rest of the TIS and resembles the trend defined by adjacent and older intrusive rocks on the west side of the TIS (Sentinel Granodiorite and intrusive suite of Yosemite Valley; Kistler et al. 1986; Ratajeski et al. 2001; Fig. 8b). With the exception of one porphyritic Half Dome sample, the remaining units appear to share a common but more negative trend. At present it is unclear whether the composition of this one sample is anomalous or can be explained by mixing between potential source rocks or melts (see the section below on Source of Isotopic Variability).

Considerable variability was also observed in initial Pb isotopic compositions with \( ^{206}\text{Pb} / ^{204}\text{Pb} \) varying from 18.8 to 19.3, \( ^{207}\text{Pb} / ^{204}\text{Pb} \) from 15.5 to 15.8, and \( ^{208}\text{Pb} / ^{204}\text{Pb} \) from 38.2 to 38.9.
These compositions plot within the same general field as other SNB granitoids and close to the composition of primitive island-arc lavas (Doe & Zartman 1979; Chen & Tilton 1991; Ratajeski et al. 2001). Linear regression of $^{206}\text{Pb}/^{204}\text{Pb}$ v. $^{207}\text{Pb}/^{204}\text{Pb}$ results in a slope of 0.1208 ± 0.018, equivalent to a $^{207}\text{Pb}/^{206}\text{Pb}$* age of 1.96 ± 0.24 Ga, consistent with ages calculated from previous Pb isotopic studies, and is interpreted as the mean age of a lithospheric component beneath the SNB (Doe & Delevaux 1973; Chen & Tilton 1991). On a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$, the different trends displayed by samples from the granodiorite of Kuna Crest and the other TIS units are again apparent.

(Fig. 8c). These compositions plot within the same general field as other SNB granitoids and close to the composition of primitive island-arc lavas (Doe & Zartman 1979; Chen & Tilton 1991; Ratajeski et al. 2001). Linear regression of $^{206}\text{Pb}/^{204}\text{Pb}$ v. $^{207}\text{Pb}/^{204}\text{Pb}$ results in a slope of 0.1208 ± 0.018, equivalent to a $^{207}\text{Pb}/^{206}\text{Pb}$* age of 1.96 ± 0.24 Ga, consistent with ages calculated from previous Pb isotopic studies, and is interpreted as the mean age of a lithospheric component beneath the SNB (Doe & Delevaux 1973; Chen & Tilton 1991). On a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$, the different trends displayed by samples from the granodiorite of Kuna Crest and the other TIS units are again apparent.

Scattered possible mixing trends are observed in all isotopic systems. The trend is most apparent on plots of $\varepsilon_{\text{Nd}}(t)$ v. $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 8a),
Evidence for subsolidus mineral modification is apparent from the mineral chemistry. Feldspar compositions do not agree with the experimental equilibrium compositions of Elkins & Grove (1990) and suggest pervasive subsolidus modification (Fig. 2; Johnson et al. 2006). Although plagioclase An contents are consistent with equilibrium between hornblende and biotite Ti content in all units except the Kuna Crest Granodiorite also suggests subsolidus modification (Fig. 3). Ague and Brimhall (1988) found a similar relationship among other SNB granitoids and argued for low-temperature re-equilibration. Thus, TIS hornblende, biotite, magnetite and feldspar chemistry are all consistent with significant re-equilibration at temperatures below the solidus. This suggests that P–T estimates derived from the hornblende–plagioclase system should be viewed with caution, at least in long-lived, slowly cooled systems.

Spatial and temporal variations in composition

The spatial distribution of major and trace elements was examined using data from three traverses across some or all of the TIS (Fig. 9). The data reveal a progressive increase in SiO₂ from the margins inward. All other major elements except Na₂O and K₂O also correlate with position, reflecting their well-defined correlations with SiO₂. Trace element correlations are mixed. Rubidium shows the strongest correlation, with an almost linear increase inward across the TIS, followed by the transition metals that decrease in abundance from the margins inward. The remaining trace elements show weak to no correlation with position, again reflecting their lack of correlation with SiO₂.

In contrast to the trace elements, there is a clear relationship between the isotopic composition and location within the TIS (Fig. 9). Overall, ⁸⁷Sr/⁸⁶Sr increases and εNd(t) decreases from the margins inward, reaching maximum and minimum values, respectively, in the Johnson Granite Porphyry. Because age decreases continuously inward (Coleman et al. 2004), this correlation is linked to the variation in age. This conclusion contrasts with an earlier study of Chen & Tilton (1991), who found no correlation between age and isotopic composition of rocks elsewhere in the central Sierra Nevada. However, they based this conclusion on a single age from each pluton sampled and did not examine variation within individual plutons.

Origin of chemical variation in the Tuolumne Intrusive Suite

The obvious concentric textural and compositional zoning, gradational contacts between the units, linear major-element trends on SiO₂ plots, systematic changes in mineral compositions and whole-rock isotopic compositions, and the trend toward more felsic compositions inward noted in this and previous studies (Bateman & Eaton 1967; Frey et al. 1978; Bateman & Chappell 1979; Reid et al. 1983; Kistler et al. 1986; Coleman & Glazner...
1997) led earlier researchers to consider the TIS an example of emplacement followed by fractional crystallization, magma mixing or some combination thereof. However, Coleman et al. (2004) and Glazner et al. (2004) noted that these processes cannot be the sole processes at work because the outer units of the suite are at least 8 Ma older than the inner units, and thermal modelling indicates...
that even large magma bodies will cool to the solidus in a matter of hundreds of thousands of years. Consequently, a new model that is consistent with geochemical, isotopic and geochronologic data is needed. Any model for formation of the TIS must incorporate the regular temporal and spatial trends observed, but also account for the apparent linear trends in major-element and scatter in trace-element data.

One model that could explain the observations is simply derivation of the various units from an evolving partial-melting zone (hot zone) in the deeper crust (Ratajeski et al. 2005; Annen et al. 2006). If the source region evolves via thermal maturation, progressive movement (upward?) and depletion of source materials, then the overall geochemical evolution of the suite and lack of correlation among trace elements could simply be a result of changes in the source region. In this admittedly ad hoc model the various magmas are related only in that they were derived from nearby areas during the same long-term thermal event and came to freeze in the same general part of the upper crust.

An alternative process that honours a stronger genetic relation among the components of the TIS and can produce the observed correlations (and lack thereof) is mixing of partial melts. Sisson et al. (2005) demonstrated that partial melting of Sierran gabbros and diorites can produce a range of melt compositions from gabbro to granite. They also found a nearly linear relationship between partial melt fraction and the major-oxide content of the resulting melt for most oxides. Starting with two partial melt fractions (F) and the proportion of the first melt in the resulting mixture, the model generates three uniformly distributed random numbers drawn from [0 1] to represent the random mixing model the various magmas are related only in that they were derived from nearby areas during the same long-term thermal event and came to freeze in the same general part of the upper crust.

The model assumes a two-step process in which melting of a mafic metagneous crustal rock is followed by mixing of the partial melts thus produced. Major-element, trace-element and isotopic compositions are calculated using Monte Carlo methods. The model assumes a two-step process in which melting of a mafic metagneous crustal rock is followed by mixing of the partial melts thus produced. Major-element, trace-element and isotopic compositions are calculated using Monte Carlo methods. The model generates three uniformly distributed random numbers drawn from [0 1] to represent the random nature of the mixing process also produces decoupling of the incompatible elements from one another owing to different values of partition coefficients. A comparison of model predictions with major- and trace-element data from the TIS reveals that this process is consistent with the observed data (Fig. 10e–h). Thus, the partial melt and random mixing model predicts trace-element scatter comparable to the TIS, while preserving the relative linearity of the major-element trends. We emphasize that we are not trying to reproduce observed trends with this model, but to explore processes that can explain the features of these trends.

**Source of isotopic variability**

Although the observed major- and trace-element trends can be reproduced by randomly mixing partial melts from a single source rock, isotopic data clearly require at least one additional source to reproduce the isotopic trends (Fig. 8). From a study of initial Sr and Nd isotopic ratios, Kistler et al. (1986) argued that mixing between mafic and felsic end members is the most plausible...
explanation for the range of intermediate compositions observed in the TIS. Although liquid-crystal fractionation may have been active on a local scale, its signature is masked by the more predominant mixing process. Kistler et al. (1986) argued that covariation of initial Sr and Nd ratios could be modelled by simple mixing of basalt with 48 wt% SiO₂, \( \frac{\text{Sr}}{\text{Si}} \) = 0.7047 and \( \frac{\text{Nd}}{\text{Si}} \) = 0.51269 with a granitic magma with 73.3 wt% SiO₂, \( \frac{\text{Sr}}{\text{Si}} \) = 0.7068 and \( \frac{\text{Nd}}{\text{Si}} \) = 0.51212.

**Fig. 10.** Monte Carlo partial melting and mixing model predictions compared to data from the TIS. Model predictions are shown as solid circles, data from the TIS shown as open circles. (a) Predicted major-oxide compositions after partial melting and random mixing. Owing to the linear nature of the partial melt composition v. SiO₂ relationship (see text), final mixed compositions are confined to a line. (b) Model predictions for CaO compared with TIS data. (c) Monte Carlo batch melting model predicts curvilinear trends for incompatible and compatible trace elements. Random mixing of any two melt compositions produces scatter away from the melting trends. \( \frac{C_m}{C_o} \) is the ratio of the concentration of an element in the melt to its composition in the source rock. (d) Predicted compositions after random mixing of partial melts (incompatible elements shown as solid circles, compatible elements shown as solid triangles). Model predictions for Rb (e), Ta (f), Sr (g) and Zr (h) compared with TIS data. Assumed model starting compositions: Rb = 25 ppm, Ta = 0.15 ppm, Sr = 850 ppm and Zr = 325 ppm.
Whether these two hypothetical compositions represent realistic source magmas for the TIS is difficult to assess, as neither corresponds to any specific rock unit presently observed in the SNB. Although Kistler’s granitic composition is similar to the Johnson Granite Porphyry, the basaltic composition lies considerably off the overall TIS trend (Fig. 8b). Studies of peridotite xenoliths from Cenozoic volcanic rocks suggest that the mantle beneath the SNB at the time of TIS emplacement possessed on average a higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than proposed by Kistler and his coworkers (Beard & Glazner 1995; Coleman & Glazner 1997; Ducea & Saleeby 1998). Thus, Kistler’s basalt may not be the best candidate for the isotopically less-evolved end member (Fig. 8b).

Another possible candidate for the less-evolved end member are melts derived from sub-Sierran peridotite. With $^{87}\text{Sr}/^{86}\text{Sr} = 0.7058$ to 0.7062 and $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.5122 to 0.5125, the xenoliths plot near the middle of the TIS trend (Fig. 8b). Mixing of Kistler’s granitic end member with peridotite melts could explain the trend between the Half Dome Granodiorites, Cathedral Peak Granodiorite and Johnson Granite Porphyry, but cannot account for the granodiorite of Kuna Crest.

This opens the possibility that three different magmas were mixed to produce the TIS. Underplating by basaltic liquids similar in isotopic composition to the peridotite xenoliths melted the older Sentinel and Yosemite Valley rocks that then mixed to produce the granodiorite of Kuna Crest. Mixing one or several Kuna Crest compositions with the crustal granitic melt produced the remaining TIS units. However, all components would have been molten at the same time, and it seems unlikely that cross trends (scatter away from the mixing line) could have been avoided. A more likely scenario is basaltic underplating that melted the Sentinel and Yosemite Valley rocks, followed by mixing of the components to produce the granodiorite of Kuna Crest. A later but less-intense pulse of basaltic underplating mixed with partial melts of dioritic to gabbroic lower crust (of varying SiO$_2$ content; Reid et al. 1993; Ratajeski et al. 2005) producing the remainder of the TIS. To date the identities of source magmas responsible for the TIS (and the SNB as a whole) remain largely a topic of speculation and controversy.

We used the end-member isotopic compositions estimated by Kistler et al. (1986) to determine how well the random mixing model fared in producing the observed variability. Kistler et al. did not estimate the Nd concentration in the end members, and therefore we used typical values from the granodiorite of Kuna Crest and Johnson Granite Porphyry of 24 and 19 ppm, respectively, in model calculations.

In our model (Fig. 11), although the isotopic compositions of the two end members are fixed, the Sr and Nd concentrations of melts vary in accordance with the trace-element systematics described earlier. For simplicity, the major- and trace-element composition of the basaltic liquid is held constant although, in reality, local fractionation and assimilation would probably modify this composition as well.

The model indicates that this partial melting and mixing process can create scatter about two-component isotopic mixing trends without requiring additional source components (Fig. 11a). If Sr–Nd ratios of the end members were constant, a mixing hyperbola with no cross-trend variability would
result, but if Sr/Nd ratios in the melts are modified by partial melting, the curvature changes and random mixtures plot away from the main trend. Thus, partial melting followed by random mixing can create significant isotopic scatter even with only two end members. The amount of scatter predicted by the model is not as great as that observed in the TIS (Fig. 11b), but a small amount of variability in the crustal end member would increase the scatter.

**Time-space patterns of geochemical variation**

Major- and trace-element modelling suggests that both partial melting and mixing are required to explain the chemical evolution of the TIS because neither process alone can account for all of the observed trends. However, although clear trends are absent from individual units, the TIS as a whole becomes more felsic inward. Further, initial Sr and Nd isotopic compositions are systematically more evolved passing inward. Thus, the magma mixtures which formed the interior units contained progressively larger proportions of a crustal, felsic and isotopically evolved end member. The TIS also systematically decreases in age inward (Coleman et al. 2004), and therefore the proportion of the crustal component increased with time (Gray 2003). This pattern is difficult to reconcile with a purely random mixing model, and therefore the emplacement process may not have been as random as implied by the modelling.

We propose that individual melt aliquots were generated in the upper mantle and lower crust and buoyantly separated from their sources; mantle- and crust-derived components were then mixed at the crustal source and/or during ascent to the upper crust, and incrementally assembled and consolidated in the upper crust. The systematic increase with time of a crustal magmatic component may reflect progressive heating of the lower-crustal source region by prolonged, repeated injection of mantle-derived mafic magma (Kemp et al. 2007). Heat accumulation in the lower-crustal magma source would cause later mafic injections to raise an increasing volume of surrounding lower crust above its solidus, and thus make an increasing volume of crustal melt available to mix and mingle with the mantle-derived component (Annen et al. 2006).

**Significance of mapped plutonic units**

The porphyritic facies of the Half Dome Granodiorite is geochemically and isotopically nearly identical to the Cathedral Peak Granodiorite, and Kistler & Fleck (1994) argued that the two therefore should be reassigned to the same rock unit. However, the geochemical and isotopic properties of the equigranular Half Dome also overlap both of those units such that the only consistent differences between the three units are textural (Johnson et al. 2006). Further, contacts between all three rock units are commonly gradational in the field, and geochronologic evidence indicates progressive assembly of the three units over a period of several Ma (Coleman et al. 2004; Matzel et al. 2005).

We therefore infer that the porphyritic Half Dome shares petrological properties with the equigranular Half Dome and the Cathedral Peak units because the three form a single evolutionary continuum. Mapping such a continuum as three distinct rock units arises from imposition of the discrete rock unit definitions needed for field mapping onto a continuous range of petrological variation produced by a protracted incremental process. Such arbitrary unit definitions are routinely used as heuristic tools for mapping continuously variable rocks of all sorts, but it is vitally important not to confuse mapping conventions with actual geological phenomena. The question of whether the porphyritic Half Dome would be better assigned to the same rock unit as the Cathedral Peak thus appears to have little fundamental significance other than field convenience.

Nonetheless, the anomalously large feldspar grains in a rock that otherwise resembles typical Half Dome Granodiorite is intriguing. One possible explanation is that the porphyritic facies represents a mixture between the equigranular Half Dome and Cathedral Peak Granodiorites, a hypothesis based largely on the presence of both K-spar megacrysts characteristic of the Cathedral Peak and euhedral hornblende crystals characteristic of the equigranular Half Dome (Wallace & Bergantz 2002). This alternative is contradicted both by geochronological data indicating that the granodiorites differ in age sufficiently that they never were molten at the same time, and by the observation that rocks with megacrysts lack most of the smaller crystals that are present in non-megacrystic units. Textural coarsening offers an alternative explanation (Higgins 1999; Johnson et al. 2006). Heating of inner parts of the Half Dome Granodiorite by emplacement of the adjacent Cathedral Peak Granodiorite, and flushing the system with water released during crystallization of water-rich magmas (Sisson & Layne 1993; Carmichael 2002), may have resulted in textural coarsening of adjacent Half Dome Granodiorite. Another related alternative is that the textural changes that define the transitions from equigranular Half Dome to porphyritic Half Dome to Cathedral Peak represent thermal evolution over time (Coleman et al. 2006). The equigranular Half Dome contains kilometre-scale lithological cycles that we interpret to record an
earlier evolutionary stage during which the magma system periodically froze up to a significant degree; the megacrystic Cathedral Peak seems to lack lithological cycles and probably represents a later stage when intergranular melt was continuously present. In this interpretation, the textural features that define the three mapped units reflect the evolving thermal state of the TIS and do not relate directly to intrusive events that assembled the TIS.

Summary

Rocks of the TIS are metaluminous, high-potassium, calc-alkaline granitoids, identical to many other plutonic suites within the SNB. Mineralogy and thermobarometry indicate hornblende – plagioclase and zircon saturation temperatures of 660–770 °C at c. 6 km depth. Evidence of low-temperature subsolidus exsolution is observed in compositions of feldspars, hornblende, biotite and magnetite. Although most major elements display strong linear trends with SiO₂, scatter of trace-element data and variability of initial Sr and Nd isotopic ratios are inconsistent with fractional crystallization as the predominant process responsible for its chemical evolution. Monte Carlo simulation of randomly mixed melts derived by varying degrees of partial melting of a mafic crustal source indicates that such a mixing process could produce the observed major- and trace-element trends.

Isotopic data, however, suggest mixing between melts of mantle-like rocks and a granitic melt similar in composition to the Johnson Granite Porphyry. The sources cannot be identified with certainty, but potential candidates include mantle peridotite, lower crustal diorite and older granitoids including the Sentinel Granodiorite and intrusive suite of Yosemite Valley. Isotopic data from the granodiorite of Kuna Crest are distinct from other TIS units and plot on a trend that corresponds to the Sentinel Granodiorite and intrusive suite of Yosemite Valley. This suggests that (1) the Kuna Crest is isotopically more closely related to these rocks than to other units of the TIS, or (2) more than two magma sources were involved in the chemical evolution of the TIS. The remaining units appear to share a common but more negative Sr–Nd isotopic trend more consistent with two-component mixing. The general temporal trend toward more evolved isotopic compositions may result from thermal maturation of the source region (Annen et al. 2006).

The petrochemical and isotopic properties of the equigranular Half Dome Granodiorite, porphyritic Half Dome Granodiorite and Cathedral Peak Granodiorite largely overlap one another and their texturally defined contacts are generally gradational. We thus interpret these map units to represent a single petrological continuum rather than distinct intrusive phases. The textural features that define the map units may reflect thermal evolution of the system rather than indicating distinct intrusive events during its assembly.

The TIS shares time – space – composition features common to most large zoned intrusive suites. Consequently, it seems likely that processes responsible for the generation of the TIS may have operated in other systems as well. If geochronological data from other zoned suites reveal long (millions of years) intrusive histories, traditional ideas regarding the evolution of such suites will need to be abandoned in favour of geologically plausible scenarios.

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References

AGUE, J. J. & BRIMHALL, G. H. 1988. Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California. Geological Society of America Bulletin, 100, 891–911.

ALLEN, C. M. 1991. Local equilibrium of mafic enclaves and granitoids of the Turtle Pluton, Southeast California; mineral, chemical, and isotopic evidence. American Mineralogist, 76, 574–588.

ANDERS, E. & GREVESSE, N. 1989. Abundances of the elements; meteoritic and solar. Geochemica et Cosmochimica Acta, 53, 197–214.

ANDERSON, J. L. & SMITH, D. R. 1995. The effects of temperature on the Al-in-hornblende barometer. American Mineralogist, 80, 549–559.

ANNEN, C., BLUNDY, J. D. & SPARKS, R. S. J. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. Journal of Petrology, 47, 505–539.

BARBARIN, B. 1991. Enclaves of the Mesozoic calc-alkaline granitoids of the Sierra Nevada batholith, California. In: DIDIER, J. & BARBARIN, B. (eds) Enclaves and Granite Petrology. Elsevier, New York, 135–153.

BATEMAN, P. C. 1992. Plutonism in the Central Part of the Sierra Nevada Batholith, California. US Geological Survey Professional Papers, 1483.

BATEMAN, P. C. & CHAPPELL, B. W. 1979. Crystallization, fractionation, and solidification of the Tuolumne
intrusive series, Yosemite National Park, California. *Geological Society of America Bulletin*, 90, 465–482.

Bateman, P. C. & Eaton, J. P. 1967. Sierra Nevada batholith. *Science*, 158, 1407–1417.

Bateman, P. C., Chappell, B. W., Kistler, R. W., Peck, D. L. & Busacca, A. J. 1988. Tuolumne Meadows Quadrangle, California; analytic data. *US Geological Survey Bulletin*, 1819, 43.

Bateman, P. C., Kistler, R. W., Peck, D. L. & Busacca, A. J. 1983. Geologic Map of the Tuolumne Meadows Quadrangle, Yosemite National Park, California. US Geological Survey Map GQ-1570, scale 1:62,500.

Beard, B. L. & Glazner, A. F. 1995. Trace element and Sr and Nd isotopic composition of mantle xenoliths from the Big Pine volcanic field, California. *Journal of Geophysical Research*, 100, 4169–4179.

Bence, A. E. & Albee, A. L. 1968. Empirical correction factors for the electron microanalysis of silicates and oxides. *Journal of Geology*, 76, 382–403.

Blundy, J. D. & Holland, T. J. B. 1990. Calcic amphibole equilibria and a new amphibole – plagioclase geothermometer. *Contributions to Mineralogy and Petrology*, 104, 208–224.

Brown, W. L. & Parsons, I. 1989. Alkalifeldspars: ordering rates, phase transformations and behavior diagrams for igneous rocks. *Mineralogical Magazine*, 53, 25–42.

Buddington, A. F. 1959. Granite emplacement with special reference to North America. *Geological Society of America Bulletin*, 70, 671–747.

Calkins, F. C. 1930. *The Granitic Rocks of the Yosemite Region*. US Geological Survey Professional Papers, 160, 120–129.

Carmichael, I. S. E. 2002. The andesite aqueduct; implications for normalizations, calculated H2O activities, and thermobarometry. *Contributions to Mineralogy and Petrology*, 108, 472–484.

Czamanske, G. K. & Wones, D. R. 1973. Oxidation during magmatic differentiation, Finnmarka Complex, Oslo Area, Norway; Part 2, the mafic silicates. *Journal of Petrology*, 14, 349–380.

Czamanske, G. K., Ishihara, S. & Atkin, S. A. 1981. Chemistry of rock-forming minerals of the Cretaceous – Paleocene batholith in southwestern Japan and implications for magma genesis. *Journal of Geophysical Research*, 86, 10 431–10 469.

Deneil, C., Vidal, P., Fernandez, A., Fort, P. & Peucat, J.-J. 1987. Isotopic study of the Manaslu granite (Himalaya, Nepal): inferences on the age and source of Himalayan leucogranites. *Contributions to Mineralogy and Petrology*, 96, 78–92.

DePaolo, D. J. 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular ranges, California. *Journal of Geophysical Research*, 86, 10 470–10 488.

DePaolo, D. J. & Wasserburg, G. J. 1979. Petrogenetic mixing models and Nd–Sr isotopic patterns. *Geochimica et Cosmochimica Acta*, 43, 615–627.

Dodge, F. C. W., Papike, J. J. & Mays, R. E. 1968. Hornblends from granitic rocks of the central Sierra Nevada batholith, California. *Journal of Petrology*, 9, 378–410.

Doe, B. R. & Delevaux, M. H. 1973. Variations in lead–lead isotopic compositions in Mesozoic granitic rocks of California: a preliminary investigation. *Geological Society of America Bulletin*, 84, 3513–3526.

Doe, B. R. & Zartman, R. E. 1979. Plumbotectonics, the Phanerozoic. *In: Barnes, H. L. (ed.) Geochemistry of Hydrothermal Ore Deposits*. Wiley-Interscience, New York, 22–70.

Ducea, M. N. & Saleeb, J. B. 1998. The age and origin of a thick mafic–ultramafic keel from beneath the Sierra Nevada batholith. *Contributions to Mineralogy and Petrology*, 133, 169–185.

Elkins, L. T. & Grove, T. L. 1990. Ternary feldspar experiments and thermodynamic models. *American Mineralogist*, 75, 544–559.

Evernden, J. F. & Kistler, R. W. 1970. *Chronology of Emplacement of Mesozoic Batholithic Complexes in California and Western Nevada*. US Geological Survey Professional Papers, 623.

Frey, F. A., Chappell, B. W. & Roy, S. D. 1978. Fractionation of rare-earth elements in the Tuolumne Intrusive Series, Sierra Nevada batholith, California. *Geology*, 6, 239–242.

Glazner, A. F., Bartley, J. M., Coleman, D. S., Gray, W. & Taylor, R. Z. 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today*, 14, 4–11.

Glazner, A. F., Coleman, D. S. & Bartley, J. M. 2008. Tenuous connection between high-silica rhyolites and granodiorite plutons. *Geology*, 36, 183–186.

Gray, W. M. 2003. *Chemical and thermal evolution of the Late Cretaceous Tuolumne Intrusive Suite, Yosemite National Park, California*. PhD thesis, University of North Carolina at Chapel Hill, NC.

Hibbard, M. J. 1995. * Petrography to Petrogenesis*. Prentice-Hall, Englewood Cliffs, NJ.
Higgins, M. D. 1999. *Origin of Megacrysts in Granitoids by Textural Coarsening: a Crystal Size Distribution (CSD) Study of Microcline in the Cathedral Peak Granodiorite, Sierra Nevada, California*. Geological Society Special Publications, 168, 207–219.

Holland, T. J. B. & Blundy, J. 1994. Non-ideal interactions in calcic amphiboles and their bearing on amphibole – plagioclase thermometry. *Contributions to Mineralogy and Petrology*, 116, 433–447.

Johannes, W. 1989. Melting of plagioclase – quartz assemblages of 2 kbar water pressure. *Contributions to Mineralogy and Petrology*, 103, 270–276.

Johnson, B. R., Glazner, A. F. & Coleman, D. S. 2006. Significance of K-feldspar Megacryst Size and Distribution in the Tuolumne Intrusive Suite, California. Geological Society of America Abstracts with Programs, 38, 93.

Kemp, A. I. S., Hawkesworth, C. J. *et al*. 2007. Magmatic and crustal differentiation history of granitic rocks from HF–O isotopes in zircon. *Science*, 315, 980–983.

Kerrick, D. M. 1969. K-feldspar megacrysts from a porphyritic quartz monzonite, central Sierra Nevada, California. *American Mineralogist*, 54, 839–848.

Kistler, R. W. & Fleck, R. J. 1994. *Field Guide for a Transect of the Central Sierra Nevada, California: Geochronology and Isotope Geology*. US Geological Survey Open File Report, 94-0267.

Kistler, R. W., Chappell, B. W., Peck, D. L. & Bateman, P. C. 1986. Isotopic variation in the Tuolumne intrusive suite, central Sierra Nevada, California. *Contributions to Mineralogy and Petrology*, 94, 205–220.

Leake, B. E. 1978. Nomenclature of amphiboles. *American Mineralogist*, 63, 1023–1052.

Matzel, J., Mundil, R., Paterson, S., Renne, P. & Nomade, S. 2005. Evaluating Pluton Growth Models using High Resolution Geochronology: *Tuolumne Intrusive Suite, Sierra Nevada, California*. Geological Society of America Abstracts with Programs, 37, 131.

Pin, C., Binon, M., Belin, J. M., Barbarin, B. & Clemens, J. D. 1990. Origin of microgranular enclaves in granitoids: equivocal Sr-Nd evidence from Hercynian rocks in the Massif Central (France). *Journal of Geophysical Research*, 95, 17 281–17 828.

Pitcher, W. S. 1993. *The Nature and Origin of Granite*. Chapman & Hall, London.

Ratajeski, K. 1999. *Field, Geochemical and Experimental Study of Mafic to Felsic Plutonic Rocks Associated with the Intrusive Suite of Yosemite Valley, California*. PhD thesis, University of North Carolina at Chapel Hill, NC.

Ratajeski, K., Glazner, A. F. & Miller, B. V. 2001. Geology and geochemistry of mafic and felsic plutonic rocks in the Cretaceous intrusive suite of Yosemite Valley, California. *Geological Society of America Bulletin*, 113, 1486–1502.

Ratajeski, K., Sisson, T. W. & Glazner, A. F. 2005. Experimental and geochemical evidence for derivation of the El Capitan Granite, California, by partial melting of hydrous gabbroic lower crust. *Contributions to Mineralogy and Petrology*, 149, 713–734.

Reid, J. B., Evans, O. C. & Fates, D. G. 1983. Magma mixing in granitic rocks of the central Sierra Nevada, California. *Earth and Planetary Science Letters*, 66, 243–261.

Scaillet, B. & Evans, B. W. 1999. The 15 June 1991 eruption of Mount Pinatubo. I. Phase equilibria and pre-eruption P–T–fO2–fH2O conditions of the dacite magma. *Journal of Petrology*, 40, 381–411.

Sisson, T. W. & Layne, G. D. 1993. H2O in basalt and basaltic andesite glass inclusions from four subduction-related volcanoes. *Earth and Planetary Science Letters*, 117, 619–635.

Sisson, T. W., Ratajeski, K., Hankins, W. B. & Glazner, A. F. 2005. Voluminous granitic magmas from common basaltic sources. *Contributions to Mineralogy and Petrology*, 148, 635–661.

Stern, T. W., Bateman, P. C., Morgan, B. A., Newell, M. F. & Peck, D. L. 1981. Isotopic U–Pb Ages of Zircons from the Granitoids of the Central Sierra Nevada. US Geological Survey Professional Papers, 1071.

Titus, S. J., Clark, R. & Tikoff, B. 2005. Geologic and geophysics investigation of two fine-grained granites, Sierra Nevada Batholith, California; evidence for structural controls on emplacement and volcanism. *Geological Society of America Bulletin*, 117, 1256–1271.

Walogwader, M. J., Gastil, R. G. *et al*. 1990. Origin and Evolution of the Zoned La Posta-type Plutons, Eastern Peninsular Ranges Batholith, Southern and Baja California. Geological Society of America Memoirs, 174, 1–18.

Wallace, G. S. & Bergantz, G. W. 2002. Wavelet-based correlation (WBC) of zoned crystal populations and magma mixing. *Earth and Planetary Science Letters*, 202, 133–145.

Watson, E. B. & Harrison, T. M. 1983. Zircon saturation revisited; temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters*, 64, 295–304.

Whitney, J. A. 1988. The origin of granite: the role and source of water in the evolution of granitic magmas. *Geological Society of America Bulletin*, 100, 1886–1897.

Wones, D. R. 1989. Significance of the assemblage titanite + magnetite + quartz in granitic rocks. *American Mineralogist*, 74, 744–749.

Wones, D. R. & Gilbert, M. C. 1982. Chapter 3, Amphiboles in the igneous environment; Introduction. In: Veblen, D. R. & Ribbe, P. H. (eds) *Amphiboles: Petrology and Experimental Phase Relations (Reviews in Mineralogy 9B)*, Mineralogical Society of America, Washington, DC, 355–357.

Zak, J., Paterson, S. R. & Memeti, V. 2007. Four magmatic fabrics in the Tuolumne batholith, central Sierra Nevada, California (USA): implications for interpreting fabric patterns in plutons and evolution of magma chambers in the upper crust. *Geological Society of America Bulletin*, 119, 184–201.