The Fine Gold Intrusive Suite: The roles of basement terranes and magma source development in the Early Cretaceous Sierra Nevada batholith

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ABSTRACT

The Fine Gold Intrusive Suite is one of the largest (>2000 km²) and oldest intrusive complexes in the Sierra Nevada batholith (California, USA), and therefore contains a wealth of information about nascent magmatic processes in a convergent margin arc. Because the suite intrudes both accreted oceanic and/or island-arc terranes and continental crust, it provides perspective on how convergent margin magmatism recycles existing crust versus reworking of fringing island arcs into continental crust. Such insight informs our understanding of how continental crust formation may have operated in the Phanerozoic as compared to earlier in Earth history.

New zircon U-Pb geochronology shows that the largely tonalitic suite was emplaced over ~19 m.y. (124–105 Ma), in three pulses that young from west to east. The most recent domain is nested within the previous ones, such that lobes of magma protruding from the main bodies of the Bass Lake Tonalite (the primary member of the Fine Gold Intrusive Suite) are older than interior areas. Zircon δHf (6.1‰–8.0‰) and εHf (–4.7 + 6.4) show temporal trends indicating that early magmas were source mixtures of mantle with as much as 45% Paleozoic to Mesozoic oceanic and/or arc rocks, whereas later magmas contain greater inputs (to 50%) of Proterozoic North American crust. Older domains in the suite were likely generated from isolated sources, including initial high Sr/Y (to ~90), high Na₂O magmas consistent with garnet-bear bearing sources inferred to be relatively deep.

Higher ε⁸⁷Sr/⁸⁶Sr, lower εHf, and higher Rb/Sr values in younger plutons show a source that tipped greater proportions of North American crust and was presumably more organized and larger, given its more homogeneous isotopic and trace element traits. Our findings also show that expression of the ε⁸⁷Sr/⁸⁶Sr = 0.706 isoploth in arc magmas may be delayed until magma sources are sufficiently vigorous to melt and incorporate aged continental crust. Therefore, Sr, values of older spotting plutons may better record the position of discrete terrane boundaries, whereas younger plutons will record the magmatically average position of terrane boundaries. Although the Fine Gold Intrusive Suite is comparable to the Late Cretaceous voluminous intrusive suite of eastern Sierran suites in terms of duration and age zoning of magmatism, the influence of preexisting basement compositions and differing degrees of organization of the magma sources with age is more pronounced. In addition, the findings show that recycling of fringing arc terranes into continental crust is relatively rapid and that estimates of the growth of Phanerozoic continental crust from such preprocessing should be revised upward.

INTRODUCTION

The tempo and modes of global crustal growth are unresolved. This is particularly true of convergent margin batholith settings, like the Sierra Nevada batholith (California, USA; Fig. 1), where the balance of new crustal growth versus recycling of preexisting crust, including juvenile island-arc terranes that are accreted onto continental margins (e.g., Lee et al., 2008), is uncertain. Apart from the need to resolve crustal mass balance in magmatic arc systems, continued studies are necessary to understand arc volatile fluxes (e.g., H₂O, CO₂), which influence climate and control the formation of economically valuable metals and minerals.

Recent studies in the Sierra Nevada have revolutionized our understanding of the dynamics of magmatism in these settings, especially concerning the processes and rates by which magmas generate plutons and batholiths. High-precision geochronology, single crystal studies, and detailed field and geochemical investigations show spectra of ages in crystal populations from individual rocks (Coleman et al., 2004; Miller et al., 2007; Memeti et al., 2010; Davis et al., 2012), and intricate textural records of magma, crystal, and volatile interaction (Žák et al., 2007; Moore and Sisson, 2008; Paterson et al., 2008; Solgadi and Sawyer, 2008; Paterson, 2009). Most of these findings show that over protracted periods, individual magma systems, including magma sources, plumbing systems, and their plutonic and volcanic products, are prone to recycling magmas and crystals from previous magmatic episodes. Moreover, the newly documented longevity of these magma systems shows that thermal and volatile fluxes from these magma systems are much more complex than previously envisioned.

Most of these recent discoveries concerning pluton assembly stem from detailed studies of the Late Cretaceous Tuolumne Intrusive Suite, which is one of the largest eastern Sierran magmatic centers and is representative of the last, most voluminous gasp of arc magmatism (Coleman and Glazner, 1997). In contrast, other workers have taken a broad view, emphasizing the importance of long-term links between regional tectonics and magmatic flare-ups in the Sierra Nevada and other Cordilleran arcs (Ducea and Barton, 2007; DeCelles et al., 2009). Specifically, DeCelles et al. (2009) attributed observed oscillations in magma productivity and associated isotopic signatures to cyclic patterns of lithospheric-scale thrusting.
Figure 1. Simplified geologic map of the Sierra Nevada. Red box indicates the location of the Fine Gold Intrusive Suite and associated wall rocks (detailed in Fig. 2). The Sherman Thomas borehole into garnet-bearing trondhjemite is shown west of the field area (map after Lackey et al., 2008).

in the retroarc. Although there is much to be learned about convergent margin systems from both single pluton and Cordilleran-wide studies, there is a clear need to bridge these small- and large-scale perspectives. There is ample evidence for magmatic periodicity (Stern et al., 1981; Chen and Moore, 1982) as well as interplay of magmatism and tectonism (Glazner, 1991; Tobisch and Cruden, 1995; Saleeby et al., 2003; Nadin and Saleeby, 2008) in the Cretaceous Sierran arc, suggesting that intermediate-scale feedbacks between tectonics and magmatism operated in the Cretaceous, and perhaps exerted first-order controls on recycling and generation of new crust.

In an effort to build a whole-arc (tectonomagmatic) perspective and address the controls of magmatic periodicity during the Cretaceous, we have turned our attention to the western Sierra Nevada. Here, the Fine Gold Intrusive Suite, one of the largest exposed Cretaceous intrusive suites in the Sierra (Bateman, 1992), is at the transition between the Sierra Nevada and 140–115 Ma granitoid batholith rocks that have recently been recognized in accreted basement terranes beneath the San Joaquin Valley (Saleeby, 2007; Saleeby et al., 2010). The Fine Gold Intrusive Suite also intrudes across several continuous belts of metamorphic wall rocks on its northeastern margin (Figs. 1 and 2), presenting an optimal setting to evaluate the role of wall-rock assimilation in magma diversification.

In this paper we present new U-Pb single grain zircon ages that allow us to revise the temporal and spatial record of the construction of the Fine Gold Intrusive Suite. Combined O and Hf isotopic analyses of zircon and whole-rock geochemistry reveal progressive changes in the magma source of the suite that reflect changes in basement composition and the degree of organization of magma sources. We use these data to appraise different reservoirs contributing to the magma sources and have applied mass balance, mixing, and assimilation–fractional crystallization (AFC) models to evaluate budgets of these reservoirs in the magmas, as well as potential secondary contamination effects.

**FINE GOLD INTRUSIVE SUITE**

**Granitoid Rocks**

The Fine Gold Intrusive Suite is at the transition from the more southern Sierran batholith, which is dominated by Cretaceous plutonic rocks with interspersed metamorphic wall rock, to a northern domain where prebatholithic rocks are volumetrically more abundant and locally punctured by Jurassic and Early Cretaceous plutons (Fig. 1). It comprises the voluminous Bass Lake Tonalite (BLT), which extends over at least 2000 km² (Fig. 2), and includes smaller bodies of the Knowles Granodiorite, Ward Mountain Trondhjemite, and stocks of the granodiorite of Arch Rock. The BLT has abundant plagioclase feldspar, low color index, and is pervasively deformed. Foliations are defined by deformed mafic enclaves (Fig. 3A) and aligned biotite and hornblende crystals (Fig. 3B). Where exposed, pluton–wall rock contacts are sharp (Fig. 3C).

Although the entirety of the unit is named a tonalite, the BLT varies in composition from gabbro to high-silica granodiorite and exhibits distinct variations in hornblende and biotite abundances. Locally, it displays magma mingling textures that are similar to those widely described elsewhere in the Sierra Nevada (Barbarin, 1991; Bateman, 1992), and that are perhaps best exemplified by the complex enclaves swarms exposed near locality 12 (Fig. 3D). The mafic enclaves show evidence of reaction with the former tonalite magma, on the basis of diffuse boundaries and abundant, large (10–30 cm long; Figs. 3E, 3F) hornblende crystals at the interface of the two magmas. These observations suggest fluid exchange during mingling of the magmas that caused crosing of hornblende grains at the site of mingling.

**Previous Ages**

Bateman (1992) adopted an average age of 114 Ma for the BLT based on patterns of discordance from individual age determinations. In detail, however, original bulk zircon U-Pb ages ranged from 105 to 124 Ma ($\pm 12$). Stern et al. (1981) suggested that younger ages (108 and 105 Ma) recorded in the BLT east of the Coarsegold roof pendant (Fig. 2) were from a younger zone of the BLT, which they called the Oakhurst pluton. In addition, the Ward Mountain Trondhjemite and Knowles Granodiorite were dated as 115 and 112 Ma, respectively, and one of the stocks of the granodiorite of Arch Rock yielded a U-Pb age of 116 Ma (Bateman, 1992). The 134 Ma tonalite of Millerton Lake is the oldest pluton in the area (Bateman, 1992).

The regional homogeneity of the BLT and the continuity of foliations that can be traced over...
many kilometers are the primary features that led Bateman (1992) to consider the BLT a single unit, despite significant variations of age. Although breaks in foliation were proposed to indicate possible internal contacts between magma bodies (Bateman, 1992), lack of continuous outcrop prevents confident recognition of such contacts. The homogeneity within the BLT clearly was paradoxical to Bateman and his colleagues, who employed isotopic and magnetic susceptibility methods to try to recognize cryptic internal contacts in the BLT. They also sought to understand how emplacement of the Ward Mountain Trondhjemite magma, supposedly as a mushy, semisolid magma, caused deformation in older parts of the BLT (Bateman et al., 1983). Although sparingly cited in the literature, both studies show some of the earliest deliberations on the complexities of pluton assembly in the Sierra Nevada.

Previous Work on Magma Petrogenesis

Prior geochemical study of the Fine Gold Intrusive Suite accompanying U.S. Geological Survey mapping of 15° quadrangles was summarized by Bateman (1992), and including some prior isotopic analyses of strontium (Kistler and Peterman, 1973; Kistler, 1990; Bateman et al., 1991) and oxygen isotopes (Masi et al., 1981; Lackey et al., 2006, 2008). Truschel (1996)
studied the overall petrogenesis of the Fine Gold Intrusive Suite with a battery of O, Sr, Nd, and Pb isotope analyses, which yielded initial \(^{87}\text{Sr}/^{86}\text{Sr}\) (Sr\(_i\)) values similar to those of previous workers (Kistler and Peterman, 1973; Kistler, 1990; Bateman et al., 1991). In general, Sr\(_i\) was found to be low (0.704) in western parts of the suite, and to increase eastward to ~0.706. Nd and Pb isotope ratios tracked with Sr\(_i\), suggesting a mixture of Proterozoic continental crust and a younger (Paleozoic), low Sr\(_i\) (0.704), high \(\varepsilon\text{Nd}\) (+8) reservoir. The unusually high \(\delta^{18}\text{O}\) of the Fine Gold Intrusive Suite (Masi et al., 1981; Lackey et al., 2008), but correspondingly low Sr\(_i\), led to the proposal (Lackey et al., 2008) that this high \(\delta^{18}\text{O}\) reservoir is a mixture of mantle-derived magmas and altered Paleozoic to Mesozoic ocean crust or equivalent age volcanicogenic sedimentary rocks.

**Metamorphic Wall Rocks**

The northern margin of the BLT truncates regionally southeast-striking metamorphic wall rocks of the Shoo Fly, Calaveras, and Triassic–Jurassic arc terranes, which are diverse packages of accreted arc rocks with lithologies that include ophiolitic mélangé, slate, quartzite, argillite, and marble (Snow and Scherer, 2006). The steeply dipping Melones fault zone bounds these terranes, which, based on scattered roof pendants and sepa in the BLT (Fig. 2), show a preintrusive southward trend (Fig. 2). South of the BLT, wall rocks of the Kings River ophiolite and Kings Sequence abut the BLT (Fig. 2); however, contacts of these units are poorly exposed.

In a broad sense, ages of the wall rocks young to the west. Western belt rocks are dominantly Late Triassic to Early Jurassic arc volcanicogenic rocks deposited on Paleozoic ophiolitic mélangé and mafic basement generated during abyssal magmatism during the Early Ordovician and Carboniferous–Permian (Saleeby, 2011). To the east, Calaveras rocks are a Permian to Late Triassic subduction mélangé chert-argillite sequence containing blocks of limestone, amphibolite, greenschist, and basalt (Ernst et al., 2008). Detrital zircon grains as young as Late Triassic are found in Calaveras Complex rocks on the east side of the Coarsegold pendant (S. Paterson, 2011, written commun.). The Shoo Fly Complex, which crops out northeast of the Fine Gold Intrusive Suite (Fig. 2), is composed of late Paleozoic quartzite, pelite, marble, and calc-silicate rocks, and includes scattered Devonian orthogneiss bodies (Schweickert et al., 1988).

Sediments comprising Calaveras and Shoo Fly rocks show a preponderance of North American continental detritus based on both Sr\(_i\) values and detrital zircon populations (Grasse et al., 2001; Ernst et al., 2008). Western volcaniclastic rocks have lower Sr\(_i\) values (0.703–0.706; Kistler and Peterman, 1973; DePaolo, 1981a) than those to the east (0.707–0.715), which are interpreted to have been derived from older sediments on average. All formations have high whole rock (WR) \(\delta^{18}\text{O}\) value (10‰–23‰; Boehlke and Kistler, 1986; Bateman et al., 1991); the highest values are from chert-argillite mélange protoliths (e.g., Lackey et al., 2006). Negative correlation of Sr\(_i\) and \(\delta^{18}\text{O}\) in the BLT east of the Melones fault was therefore attributed to greater proportions of Calaveras Complex rock in magma sources or as a contaminant.

**METHODS**

Representative intrusive rocks, sampled both close to and far from wall rocks, were collected throughout the mapped extent of the BLT (Fig. 2). One sample each from the Knowles Granodiorite and the Dinkey Creek Granodiorite were also collected. Zircon was concentrated by standard crushing, density, and magnetic...
separation techniques, with least magnetic fractions being isolated with a Frantz separator. A binocular microscope was used to purify zircons further and select single grains for U-Pb and Hf isotope analysis. Table 1 provides the latitude and longitude of sample locations.

**Coupled U-Pb Geochronology and Hf Isotope Analytical Methods**

Zircon separates from 26 samples were mounted, along with appropriate U-Pb and Hf zircon standards, in 1 in (2.54 cm) epoxy disks. The mounts were imaged and grain maps were produced. We first ablated 40-μm-diameter pits on 25–35 individual zircon grains from each sample for U-Pb analysis. After completion of all U-Pb analyses for a sample, Hf isotope measurements were then made via ablation on top of the preexisting U-Pb pits. Because the data are acquired sequentially and not simultaneously, it is possible that the successive pits drilled for U-Pb and Hf measurement are sampling different crystal depth domains (Kemp et al., 2009). Given the apparent homogeneity of most zircons from the Fine Gold Intrusive Suite, as seen in cathodoluminescence (CL) images (Fig. 4), and the lack of significant changes in Hf isotopic ratios during the 60 s of data acquisition, we assume that measured Hf values can be confidently linked to previously measured U-Pb ages from the same spot.

U-Pb and Hf isotope data were collected using a New Wave 193 nm ArF laser ablation system coupled to a Nu Plasma HR inductively coupled plasma–mass spectrometer at the University of Arizona (for additional information, see http://sites.google.com/a/laserchron.org/laserchron/). Laser ablation was done using a 40-μm-diameter spot and a hit rate of 7 Hz. The laser was run in constant energy mode with output energy of 8 mJ/pulse, which corresponds to an energy density of ~2 J/cm<sup>2</sup> and an estimated drill rate of 0.7 μm/s. The U-Pb analytical routine consisted of a 15 s on-peak background measurement with the laser off, followed by 15 s of peak measurement performed at 1 s integration times with the laser firing. This results in an analysis pit of ~15 μm depth. Hf analyses were performed in the same way, but with a 40 s on-peak background measurement with the laser off, followed by 60 s of on-peak measurement with the laser firing. This results in an additional ~35 μm of excavation from the preexisting U-Pb pit. Additional details of the methods used to generate and reduce U-Pb data can be found in Gehrels et al. (2008); details of combined U-Pb and Hf analytical methodology can be found in Cecil et al. (2011).

Figure 4. Representative cathodoluminescence (CL) of Bass Lake Tonalite zircons. CL traits are similar among grains in a population. Among samples, however, there are a variety of textures ranging from oscillatory (e.g., 3, 5, 8, 20) to sector (24, 29) to mixed (36) zoning. Mixed and discontinuous zoning in 36 suggests inherited cores, but the sample has a simple age distribution among grains. Scale bars are 100 μm for all samples.
The samples are generally characterized by simple, prismatic zircons, with internal oscillatory zoning and rare inherited components or younger growth rims (Fig. 4). For each sample, CL images were made for all individual crystals and 20–30 measurements were made on chosen zircons or identified zircon domains. Only 1 sample (IS94) had zircons with rims and cores that were clearly distinguishable in CL images and of variable age. For that sample, multiple analyses (2–5 spots at 40 μm per spot) were performed on some individual crystals to target the distinct core and rim domains. Weighted mean ages were then determined for each component, and a magmatic age was assigned based on the interpreted igneous domain. Uncertainties for reported 206Pb/238U ages are 1–2% (2σ) and include both a systematic error (typically 1–2%) and an error associated with the scatter and precision of a set of measurements for a given sample (≤1%; 2σ; see Gehrels et al., 2009, for details of error analysis).

Hf isotopic measurements were made using 176Hf/177Hf for mass bias corrections and an exponential mass bias function was used in all calculations. The 171Yb and 173Yb, which are interference free, were monitored during the Hf analysis in order to calculate Yb mass bias (βy) and the contribution of Yb to the measurement of 176Hf (Hf + Lu + Yb). The Lu correction was performed by monitoring 176Lu and using 176Lu/177Lu = 0.02653 (Patchett, 1983) and 179Hf/177Hf for mass bias corrections and an exponential mass bias function was used in all calculations. The 176Lu decay constant calculations. The 173Yb and 171Yb, which are

\[\text{from zircon by laser fluorination at the University of Oregon Stable Isotope Lab using a 35 W New Wave Co2 infrared laser to heat samples in the presence of BrF5 reagent (Bindean, 2008). Oxygen was cryogenically cleaned, pumped through Hg to capture excess F2, and converted to CO2 with a hot carbon rod before analysis. Isotope ratios were measured with a Finnigan MAT 253 mass spectrometer and measured values were corrected to the Gore Mountain Garnet standard ( UWG-2) analyzed throughout the session using the accepted δ18O value of 5.80%e (Valley et al., 1995). The average raw δ18O of UWG-2 for 3 days of analyses (n = 18) in this study is 5.63%e ± 0.25%e [1 standard deviation, SD; standard error, 1σ = 1 SD/n; (n) is ±0.02%e]. Average day-to-day precision of UWG-2 is ±0.08%; 15% of zircon analyses were replicated and showed precision of ±0.04%; an overall 2 SD uncertainty of 0.15% is adopted for zircon analyses based on day-to-day precision of UWG-2.

Whole-Rock Geochemistry

Major elements and selected trace elements were determined for 29 samples by X-ray fluorescence (XRF; Table 2) at Pomona College (n = 20) and Washington State University (WSU; n = 9). Methodology and error analysis were adapted from Johnson et al. (1999) for samples analyzed at WSU, with a similar analytical protocol at Pomona. Representative whole-rock powders were prepared in a Rocklabs tungsten carbide head and mill. Powdered sample and flux were mixed in a 2:1 ratio, typically 3.5 g powder to 7.0 g dilithium tetraborate (Li2B4O7). The vortexer-blended mixture was to the age of 116 Ma for the Sawmill Mountain body of the Arch Rock reported by Stern et al. (1981). Our analysis of the granite of Shuteye Peak yielded an age of ca. 114 Ma, which is considerably older than a prior concordant age of 102 Ma, likely from a different body within the Shuteye Peak (Stern et al., 1981). An enclave and host sample of Dinkey Creek granodiorite near the Dinkey Creek type locality (Fig. 2) yielded statistically identical ages of ca. 101 Ma that are comparable, within error, to a previously published concordant 102 ± 1 Ma age on the eastern side of the Dinkey Creek pluto (Tobisch et al., 1993).

Revised Ages of the BLT

Overall, the new ages expand the intrusion period of the BLT from the range given by Stern et al. (1981), and often are older or younger than the previously determined ages. Older portions of the BLT occupy lobes in the northwest corner of the tonalite. Gradually decreasing ages from 121 to 115 Ma are found within the easternmost parts of the exposed

Oxygen Isotopes

Zircons were prepared for δ18O analysis by sequentially cleaning bulk aliquots in HNO3, HF, and HCl to remove mineral impurities and radiation-damaged domains from the crystals (Lackey et al., 2008). Oxygen was liberated

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1Supplemental File. PDF file of 52 figures showing SiO2 variation diagrams of major and trace elements and 1 table providing U-Pb and Hf isotope analyses. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00745.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.
tonalite (Fig. 2). Intrusions belonging to an intermediate age group (114–109 Ma) show similar decreasing age patterns, and are more centrally located within the BLT, surrounding the Coarsegold pendant and adjacent to the 124 Ma Ward Mountain Trondhjemite. It is notable that some of the intermediate ages are on the eastern and southeastern sides of the BLT, suggesting a component of concentric inward-younging in age. The youngest identified magmatic episode ranges in age from 108 to 105 Ma and defines the eastern exposures of the BLT, from Oakhurst to the south as Prather (Fig. 2). We note that some of the largest discrepancies in age from this study and previous bulk thermal ionization mass spectrometry ages are in this youngest section of the BLT. For example, the 105 Ma age at locality 10 (Fig. 2) is from a lobe of the BLT that was originally dated as 116 Ma (Stern et al., 1981).

### Zircon Inheritance

In most samples, U-Pb age populations are uniform, as expected from the homogeneous CL properties of the crystals. Of the 24 samples that were dated, however, 4 (11S33; 11S49; 3, 8) show evidence of zircon inheritance (i.e., 1–5 grains with ages distinctively older than the rest; see Fig. 5 and the Supplemental File [see footnote 1]). These older ages correspond to identifiable zircon cores in the CL images in one case (Fig 5G). Inherited crystals zircons are nearly all Early Cretaceous (ca. 145–116 Ma; Fig. 5), and the older the interpreted magmatic age of a sample, the older the age of the inherited zircons contains it. For example, the Ward Mountain Trondhjemite (11S33) has several xenocrysts ranging from 135 to 140 Ma, and a single 17 Ma grain (Supplemental File [see footnote 1]); the Knowles Granodiorite has rims with a mean age of 113.6 Ma that overgrow partially resorbed inherited zircon grains with a mean age of ca. 136 Ma (Figs. 5A, 5G); samples 3 and 8 have mean ages of 115.6 and 108.4 Ma, with inherited cores of ca. 124–128 and 117 Ma, respectively (Figs. 5B, 5C). Although xenocrysts in younger members of the Fine Gold Intrusive Suite may be reworked from unexposed plutons or magma conduits from previous episodes of magmatism in the suite, xenocrysts older than the 134 Ma tonalite of Millerton Lake have no exposed sources in the region, and are younger than the Jurassic depositional age of the youngest metasedimentary wall rocks. The xenocryst ages are coeval with magmatic ages of the Great Valley batholith (Saleeby, 2007), which ranges in age from 140 to 115 Ma, as determined on granitoid rocks sampled in drill cores from the San Joaquin Valley (Saleeby et al., 2010).

### Oxygen Isotopes

Oxygen isotope ratios of zircon ([8216O]zircon) are 5.8‰–8.0‰ among all samples studied (Table 1; Fig. 6A), and range from 6.1‰ to 8.0‰ in the Fine Gold Intrusive Suite (Fig. 6). These zircon values are considerably higher than those from most Sierra Nevada granitoid rocks with the exception of the southern Sierra Nevada (Lackey et al., 2005), and are similar to earlier values reported (Lackey et al., 2008) for the Fine Gold Intrusive Suite. By contouring all [delta]18O values, a broad area of high [delta]18O is discernible in the western and southwestern domains of the BLT (Fig. 7A). The high [delta]18O values extend to near the western boundary of the Coarsegold pendant and are similar to those in the Knowles and Ward Mountain plutons. The ca. 117 Ma Arch Rock plutons have notably lower [delta]18O (6.3‰–6.8‰) than the younger BLT rocks surrounding them. Similarly, older rocks in the eastern part of the BLT (121–115 Ma) have lower values relative to younger (108–115 Ma) adjacent rocks (Figs. 2 and 7A).

### Hafnium Isotopes

Hafnium isotope ratios vary by 16.5 epsilon units (4.7 ± 11.8; Table 1). The range of eHf in the Fine Gold Intrusive Suite, exclusive of the Academy pluton sample, is 11.4 units (4.7–6.4; Fig. 6B). Similarly large ranges of eHf are reported in other Cretaceous batholiths, such as the central Coast Mountain Batholith, British Columbia (eHf = +1–13; Cecil et al., 2011), and the Separation Point plutonic suite, New Zealand (eHf = -4 to +12; Bolhar et al., 2008). In contrast to the Fine Gold Intrusive Suite, eHf from the eastern Sierra Nevada are typically more evolved and less variable (−9 to −1;
Lackey et al., 2011), suggesting a greater average age of the sources in the eastern Sierra. Unlike δ¹⁸O, ε⁵⁷⁷ values generally decrease eastward (Fig. 7B). They also show notable differences between adjacent intrusions; for example, sample 16 (Fig. 2) has a higher ε⁵⁷⁷ signature than the younger BLT rocks immediately surrounding it. For comparison, published ⁸⁷Sr/⁸⁶Sr ratios were recalculated for new ages in the BLT, and are compared to O and Hf (Fig. 6C). Sr values increase with each younger episode of magmatism and there is an upward shift in their baseline values (Fig. 6C).

Major and Trace Element Geochemistry

Whole-rock compositions from this study (Table 2) are comparable with previously published values for the ranges of major, minor, and trace elements (e.g., Bateman, 1992; Truschel, 1996), but fill in a number of gaps in the coverage from previous studies. Broadly, rocks of the suite have similar geochemistry to that of other Phanerzoic tonalite, trondhjemite, and granodiorite suites (Drummond and Defant, 1990), in that they have high Al (Al₂O₃ > 15 wt% at 70 wt% SiO₂; Table 2), and low Rb, Rb/Sr, and Y (Figs. 6D, 6E, 6G). The Ward Mountain Trondhjemite has high Na₂O (>4 wt%, and Na/Rb; Fig. 6F) and Sr/Y (>40 and as high as 92) values (Fig. 6G), indicative of magmas derived from small degrees of partial melting in sources that were sufficient deep to be garnet bearing, and likely eclogitic in composition (Petford and Atherton, 1996; Tulloch and Kimbrough, 2003). Such high Sr/Y values are also recorded in Truschel’s (1996) analyses of samples from the 126 Ma Sherman Thomas garnet-bearing trondhjemite that was sampled in the drill core to the west of the field area (Fig. 1).

**Figure 5.** Age and Hf isotope analyses from selected representative samples. (A–C) Individual crystal ages and mean U-Pb ages for samples 1S94, 8S03, and 8S08. Red bars are accepted concordant analyses that are used in mean age determinations. Blue bars represent crystal ages not used to determine mean magmatic sample age, and commonly indicate older, inherited cores. In the case of sample 1S94, the blue bars not interpreted as inherited core ages likely reflect mixing via laser ablation of magmatic and inherited zircon domains. Mean age is the weighted arithmetic mean with associated analytical uncertainty only, whereas the given age includes both systematic and analytical uncertainty at the 2σ level. MSWD—mean square of weighted deviates. (D–F) Individual Hf analyses and mean ε⁵⁷⁷ isotopic composition of the same samples as in A–C. Hf measurements were made in the previously ablated U-Pb laser pit. The mean ε⁵⁷⁷ given is a weighted mean of individual measurements with analytical uncertainties at the 1σ level. (G) U-Pb and ε⁵⁷⁷ variations in xenocryst-bearing zircon population of the Knowles Granodiorite. Note bright CL cores that are older and higher ε⁵⁷⁷ compared to rims.
Figure 6. Temporal variation of geochemistry in the Fine Gold Intrusive Suite. (A) Oxygen isotope values. (B) Hafnium isotope values. (C) Published Sr isotope values. Values are color coded for the three age domains of the Bass Lake Tonalite and affiliated intrusions. Note that $\delta^{18}O$ of samples that were not dated are assigned an assumed age according to ages of their nearest neighbor samples. Previously determined values of $\delta^{18}O$ (zircon) (from Lackey et al., 2008) are included for the Ward Mountain Trondhjemite, Knowles Granodiorite, and Dinkey Creek granodiorite. Published Sr values (Masi et al., 1981; Bateman et al., 1991; Kistler and Fleck, 1994; Truschel, 1996) and those of R.W. Kistler (2001, written commun.) are recalculated using new ages that are assigned according to sample location. Note that many of the younger values are from a 15-km transect east of the Coarsegold pendant (Bateman et al., 1991). (D) Rb. (E) Rb/Sr. (F) Na/Rb. (G) Sr/Y. Values in D–E are for samples from this study and legacy data (see text for sources). Gray arrows on graphs are drawn to highlight progressive change of geochemical indices.
Figure 7. The Bass Lake Tonalite contoured for various geochemical and isotopic characteristics (Zrc—zircon). Grayed portions are major bodies of preplutonic metamorphic rocks that were excluded from contouring. VSMOW—Vienna standard mean ocean water. Other Cretaceous intrusions of the Fine Gold Suite are: K—Knowles Granodiorite; W—Ward Mountain Trondhjemite; A—granodiorite of Arch Rock. West to east compositional zoning is most apparent in the spatial distribution of $\delta^{18}$O (E) and $\varepsilon$Hf (F) values, and can also be observed in most contour maps of select major and trace elements and ratios (C–F). Contouring protocol is described in the text (see Methods discussion).
Table 1: Major, Minor, and Trace Element Compositions of the Fine Gold Intrusive Suite

<table>
<thead>
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<th>Sample unit</th>
<th>8S03</th>
<th>8S05</th>
<th>8S06</th>
<th>8S07</th>
<th>8S08</th>
<th>8S10</th>
<th>8S11</th>
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Note: Major oxides (in wt %) are totalized pseudosilicate based on determination of initial loss on ignition (LOI) in first analysis. Total Fe is reported as Fe₂O₃ for measurements at Pomona College and as FeO at Washington State University. Typical analytical uncertainty for Pomona analyses (in wt %) of major elements measured by fusion of ducal powders, is 0.15% (SiO₂); 0.06-0.07% (Fe₂O₃, Al₂O₃); 0.02-0.05% (Na₂O, K₂O, MgO, CaO); <0.004% (TiO₂, MnO, P₂O₅). Trace element (ppm) uncertainties at ±20 ppm vary, with most trace elements reproducible at better than ±2 ppm. (Cu, Ga, Nb, Pb, Rb, Th, U, V, Zr). Others are reproducible at ±3 ppm (Cr, Sc, Sr, V), and a handful have higher uncertainties, in parentheses in ppm: Ce (4); Zn (6); Ni (7); Ba (40). bdl—below detection limit. Dash indicates not analyzed. For plutonic unit abbreviations, see Table 1.

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Like the isotope data, the whole-rock geochemical indices show that increasing or decreasing variability of isotopes in the Fine Gold Intrusive Suite occurs in trace element and elemental ratios indices as well (Figs. 6D–6G). To determine if differentiation of magmas was a factor in controlling trace element trends, we cast the sample data versus SiO$_2$ (wt%), but found no correlations between differentiation and trace elements (see the Supplemental File [see footnote 1]). With decreasing age, most elements decrease in their ranges of values, particularly in the transition from the intermediate to the youngest episode of magmatism. For example, Rb increases in younger samples, with the smallest amount of variation in the youngest domain of the BLT (Fig. 6D). In contrast, average Na$_2$O/Rb decreases with increasing age, most elements decrease in their ranges of values, particularly in the transition from the intermediate to the youngest episode of magmatism. For example, Rb increases in younger samples, with the smallest amount of variation in the youngest domain of the BLT (Fig. 6D). Contouring SiO$_2$ concentrations does not show a regional pattern, but rather localized variations that suggest that plutonic lobes of magma are compositionally zoned, similar to what has been described in the Tuolumne Intrusive Suite (Fig. 7C; Economos et al., 2010; Memeti et al., 2010). For example, the domain to the east of the Coarsegold pendant appears to be zoned because it has SiO$_2$ values that are intermediate near the pendant, but become higher to the east (Fig. 7C). This compositional shift coincides with the location of the proposed Oakhurth pluton of Stern et al. (1981), the existence of which is also supported by new ages in this study (Fig. 2). Unlike SiO$_2$, the concentration of Na$_2$O shows a broad regional pattern. It is higher in western areas of the BLT than to the east; areas of high Na$_2$O also have lower Rb/Sr and higher Na$_2$O/Rb than areas to the east (Fig. 7D) that are inferred to be derived from older crustal basement or sediments thereof, as shown by Sr values (Fig. 6C). When whole-rock geochemical data are divided according to age, older rocks show greater ranges and variability, whereas rocks become less variable in the intermediate age group and most homogeneous in the youngest group (Fig. 6). The group of intermediate age rocks shows an intriguing pattern of Rb bimodality and some of the highest Rb concentrations of any of the rocks analyzed (Fig. 6D). The highest Rb group borders the youngest BLT rocks, generally east of the Coarsegold pendant.

**DISCUSSION**

In the following, we integrate new age, isotopic, and geochemical data to evaluate the tempo and mode of emplacement of the Fine Gold Intrusive Suite. We address the causes of geochemical variation within the suite, and characterize the sources of the magmas, including the influences of wall rocks and preexisting conduits. In our discussions we refer to magma “sources” as sites at the base of the arc where magma is amassed, noting that the development of sources involves a complex array of processes (e.g., Hildreth and Moorbath, 1988). We use “conduits” to refer to the feeder networks that relay magma from sources to the sites where the magmas crystallize as plutons; “reservoirs” to denote preexisting large-scale masses of the crust and mantle that melt and contribute to magma sources; “components” to refer to possible rocks composing a reservoir; and “contamination” to refer to superimposed modification of magmas by wall rocks. In our discussions of the Fine Gold Intrusive Suite, we attempt to relate our findings to the larger interpretation of the Sierran arc as a whole, considering the Fine Gold Intrusive Suite to be one of a series of magma systems reflecting changing magmatic styles, changing source compositions, and changing tectonic configuration of the arc.

**Emplacement of the Fine Gold Intrusive Suite**

New U-Pb ages indicate that emplacement of the Fine Gold Intrusive Suite was incremental, with transitional ages between the oldest and youngest units. We designate three age groups, however, according to their spatial distributions. Breaks between these age domains are assigned according to discordances in foliation, changes in bulk chemistry, $\delta^{18}$O values, or steep changes of magnetic susceptibility in the BLT that were interpreted by Bateman et al. (1991) to be internal contacts. Furthermore, because roof septa commonly define boundaries between plutons in the Sierra (Bateman, 1992), metamorphic wall rocks scattered throughout the BLT and the bodies of the granodiorite of Arch Rock may define some contacts. Figure 8 shows the proposed distribution of the three major north-northwest–elongate age domains in the suite. The orientations of these belts of rock are consistent with the broad orientation of maximum elongation direction, or plutonic grain, of the Sierra Nevada batholith (see fig. 3 of Lackey et al., 2008). A formal name is not proposed here; rather we informally refer to the belts of similar aged BLT as the western, central, and eastern domains, to emphasize the observed spatiotemporal patterns in the U-Pb data. The eastern domain includes the Oakhurst pluton of Stern et al. (1981). In calling these domains, we note that the age variations in these belts suggest that they are not single plutons intruded as discrete batches of magma. Instead, they are likely to be composed of multiple plutons, or else show age progressions like the members of the Tuolumne (Memeti et al., 2010) and John Muir (Davis et al., 2012) Intrusive Suites.

**Western Domain**

The oldest belt of BLT rocks (121–115 Ma) stitch across the Melones fault zone, showing that simultaneous intrusion of magmas occurred into both Triassic–Jurassic wall rocks and Calaveras metamorphic wall rocks (Fig. 8). Isolated lobes in the westernmost part of this domain have the oldest ages (ca. 121 Ma; Fig. 8), suggesting an eastward (inward) younging of ages during this earliest magmatic episode. Stocks of the granodiorite of Arch Rock, although more widespread, appear to be temporally associated with the western domain. The revised age of the Ward Mountain Trondjhemite to ca. 124 Ma makes this unit the oldest intrusion in the suite and forces a revision of the model of Bateman et al. (1983). Because the Ward Mountain Trondjhemite predates the BLT, it cannot be called upon as a mushy magma that intruded into, and deformed BLT rocks in the western domain. Instead, the Ward Mountain magmas, like the Arch Rock stocks, intruded as solitary bodies. Deformation in the Ward Mountain plutons is therefore likely to be a secondary solid-state feature, imparted during subsequent magmatism. Considering the revised age of the Ward Mountain Trondjhemite, we attribute the associated foliation in the BLT to magmatic flow alignment of grains and enclaves as the BLT was emplaced around the Ward Mountain plutons.

**Central Domain**

The intermediate age group (114–109 Ma) occupies much of the center of the field area, typically has strongly developed foliations, and encloses or bounds most of the larger roof pendants (Fig. 8). Thus, it appears that this stage of magmatism preferentially engulfed or trapped pendants and septa of wall rocks. In addition to the central portion of the study area, rocks of similar age are found along the southern and eastern margins of the BLT (Fig. 8), and include the 113 Ma tonalite of Ross Creek (Bateman, 1992) and the ca. 114 Ma granite of Shutey Peak (this study). Inclusion of the granite of Shutey Peak in the Fine Gold Intrusive Suite suggests that the central domain (as defined by ca. 114–109 Ma ages) had either once been continuous to the east, or intruded as a separate magma and later warped into a corrugated shape by emplacement of younger BLT plutons or Late Cretaceous magmas even further to the east (Fig. 2).

Some of the major cryptic internal contacts that Bateman et al. (1983) proposed are associated with the central domain. For example, they proposed that the elongate protrusion of the
The geochronologic and geochemical data from rocks of the Fine Gold Intrusive Suite point to changes in magma system behavior between the earliest and latest magmatic stages. The high Na and Sr/Y values but low Rb and Rb/Sr values of older magmas, including the Ward Mountain, Arch Rock, and Knowles plutons, are consistent with minimal input of continental crust. This is supported by these samples defining two arrays in Hf-O isotopic space: western domain samples trend toward high δ18O, high εHf defining an arc recycling trend; younger samples define a negative crustal trend toward high δ18O and low εHf (Fig. 9A). The Goat Mountain sample of the granodiorite of Arch Rock and BLT samples 29 and 33 intrude the eastern domain (Fig. 2). Collectively, their low to intermediate δ18O values and intermediate εHf show that early magmas in the eastern domain contained lower proportions of continental crust than the main 108–105 Ma pulse of magmas. The two BLT samples are included on the low δ18O side of the crustal array (Fig. 9A). The Dinkey Creek granodiorite sample plots low on the array, an expected result given its more eastward position in the batholith. The two arrays we identify are discussed in the following in terms of bulk isotopic character of the reservoirs (O.C. and C.C. in Fig. 9A).

**Characterizing Crustal Reservoirs**

Proterozoic North American continental crust is inferred to have underlain the Sierran arc before batholith construction, according to previous Sr, Nd, Pb, and Os isotopic studies of Sierran plutons and xenoliths from the base of the arc (e.g., Kistler and Peterman, 1973; DePaolo, 1981a; Kistler et al., 1986; Chen and Tilton, 1991; Lee et al., 2000). Model ages determined by these workers define typical mixing arrays, and isochron bounds on large data sets (e.g., Kistler et al., 1986) yield Proterozoic (1.7–2.0 Ga) value (Fig. 6E), and thus has a distinctly more primitive source. This intrusion is the northernmost in a narrow belt of coeval ring dike complexes exposed in the western Sierra Nevada (Clemens-Knott and Salebye, 1999) that also have mantle-like Nd, Sr, and O isotope ratios (Clemens-Knott, 1992; Lackey et al., 2008). The sample from the tonalitic margin of the pluton (2 in Fig. 2) was not dated by us, but is inferred to have a ca. 114 Ma age based on a U-Pb zircon age by Mack et al. (1979). Its higher δ18O (Fig. 6A) and younger age suggest a different source or increased magma contamination, and highlight the Academy Pluton as a promising location to study crustal contamination in a small-scale intrusive complex.

**Continental Reservoir**

The youngest domain in the BLT (108–105 Ma) is comparable in area to the central domain, contains several small roof pendants, generally has weak to randomly oriented foliation, and contrasts geochemically with earlier magmas. Within and adjacent to the younger rocks of the eastern domain are older Arch Rock, Goat Mountain, and Hogan Mountain stocks (Fig. 2), which have δ18O and εHf values that are in contrast to those of the young BLT. For example, the εHf of the Goat Mountain body (+4.8) is considerably higher than the −2 to −4.5 values of the eastern domain. Thus, it appears that the eastern domain is chemically more evolved than magmas that were emplaced 10–15 m.y. earlier at equivalent positions relative to prebatholithic wall-rock terranes.

Overall, the domains in the BLT show both a general progression of magmatism from west to east, as recognized by early geochronology (Stern et al., 1981; Chen and Moore, 1982), as well as a component of internally inward-younging ages. Such a pattern is consistent with the extended emplacement history of intrusive suites of this size, such as the Tuolumne (Coleman et al., 2004; Memeti et al., 2010) and John Muir Intrusive Suites (Davis et al., 2012), although these eastern Sierra suites show that magma emplacement may have been largely centered at the same position in response to favorable tecotectonically controlled conduits for magma flow (Glazner, 1991; Tikoff and Teyssier, 1992).

**Academy Pluton**

Although coeval with western domain BLT rocks, the 118 Ma interior sample (1 in Fig. 2) of the Academy Pluton has high εHf and low δ18O, approaching a Mesozoic depleted-mantle
Figure 9. Isotope and trace element evaluation of magma sources and contamination. (A) Oxygen versus hafnium correspondence for different Bass Lake age groups and associated intrusions. Arrays of O-Hf isotope values for older samples versus those in the eastern domain project to high δ¹⁸O (zircon) values consistent with input from Paleozoic to Mesozoic (εHf 8–11) and Proterozoic (εHf < –14 to –30) crustal reservoirs, respectively. See text for discussion of δ¹⁸O zircon estimates and model age calculations for reservoirs. δ¹⁸O mass balance scales, graduated in 20% increments, connect from the centers of reservoir ranges to account for uncertainty and heterogeneity. The depleted mantle value for Early Cretaceous time from the mantle curve of Kemp et al. (2006), western mafic complex Hf data (vertical pink bar) from Clemens-Knott et al. (2011), and Mojave crustal εHf from Goodge and Vervoort (2006). VSMOW—Vienna standard mean ocean water; C.C.—continental crust; O.C.—ocean crust. (B) Published Sr vs. δ¹⁸O (whole rock, WR) show distinct arrays of older western and central domains compared to the eastern domain. Reference data from the Dinkey Creek granodiorite and Tuolumne Intrusive Suite define arrays, the mutual intersection of which at low δ¹⁸O, low Sr is adopted as the eastern domain mantle reservoir (see Table 3). Note poor fit of assimilation–fractional crystallization (AFC) model between the Calaveras Complex and Mariposa Formation. Sources of δ¹⁸O-Sr data of granitoid rocks are Masi et al. (1981), Kistler et al. (1986), Bateman et al. (1991), Kistler and Fleck (1994), and Truschel (1996). For clarity, reservoir averages are shown as boxes that are smaller than actual variations. Average Sr and δ¹⁸O values of reservoirs are discussed in the text and given in Table 3, as are model parameters for the AFC and simple mixing models that are shown. DSr—solid: melt partition coefficient of an AFC curve. SN Basalt—Farmer (2004) SN alkali basalt; Mesozoic Basalt—Condie (1993) Mesozoic basalt. (C) Sr/Y versus Y. (D) Sr/Y versus Rb/Sr. Note characteristic asymptotic array connecting high Sr/Y to high Y and Rb/Sr values. The high Sr/Y values of the Ward Mountain Trondhjemite project toward estimated Sr/Y values for melts from garnet-bearing eclogite residues of the Sierran magmas (Lee et al., 2007). Simple mixing curves between high Sr/Y melts and selected metamorphic wall rocks show no conclusive evidence of contamination.
model ages. Previous geochronology also shows widespread inheritance of Proterozoic zircons in magmas of the central Sierra Nevada (Steen et al., 1981; Chen and Moore, 1982). Uncertainty in $^{176}$Lu/$^{176}$Hf isotope ratios of the crust (e.g., Vervoort and Patchett, 1996; Vervoort et al., 2000) make Hf model age calculations approximate at best, although values $\epsilon$Hf down to $\sim$30.0 are reported for 1.7–1.8 Ga Joye basement (Goodget and Vervoort, 2006). Measured $\epsilon$Nd values of $\sim$10 to $\sim$15 for 1.7 to 2.0 Ga Proterozoic North American continental crust (e.g., DePaolo, 1981), are equivalent to $\epsilon$Hf values $\sim$14.2 to $\sim$22.0 using the crustal $\epsilon$Nd-$\epsilon$Hf array of Vervoort et al. (2011), and are consistent with $\epsilon$Hf values for measured in zircon from granites in the Idaho batholith (Gashgini et al., 2008). We adopt the $\sim$30.0 Mojave value of Goodge and Vervoort (2006) as the lower limit of crustal $\epsilon$Hf values. Using the intercepts of the $\epsilon$Hf values on the envelope defined by the two sides of our Crustal Trend $\epsilon$Hf-$\delta^{18}O$ array, we define an average $\delta^{18}O$(Zrc) value for the crustal reservoir of 10.2‰ (Fig. 9A).

A whole-rock $\delta^{18}O$ conversion can be made using the right regular variation of $\delta^{18}O$ of zircon and whole-rock values with silica content (see Lackey et al., 2008). Partial melts of most rock types are 70–75 wt% SiO$_2$ (Patinou Douce, 1999), thus a whole-rock $\delta^{18}O$ of a partial melt derived from this crustal component should be $\sim$2‰ greater than the zircon value, or 11.1‰. Although this value is higher than the estimated average $\delta^{18}O$ of 8.9‰ for continental crust (Simon and Lécuyer, 2005), that estimate includes mafic crustal compositions and older Archean terranes with lower $\delta^{18}O$ than Proterozoic and younger crustal rocks (Valley et al., 2005).

### Arc-Oceanic Reservoir

The array projecting toward a high $\epsilon$Hf reservoir suggests mixing of depleteted mantle with components of young hydrothermally altered oceanic rocks and volcaniclastic sedimentary rocks. Given the shallow slope of this array, we have used an estimated $\delta^{18}O$ value for typical rocks to intercept the array and deduce and range of $\epsilon$Hf values for this reservoir. A mixture of such rocks should have average $\delta^{18}O$(WR) values that are generally $\sim$$12$‰ ($\sim$10‰ for equivalent $\delta^{18}O$ zircon), assuming that additional sedimentary input and volcaniclastic rocks will have similar to higher $\delta^{18}O$ values (Magaritz and Taylor, 1976; McCulloch et al., 1980; Staudigel et al., 1995; Muehlenbachs, 1998). The $\delta^{18}O$ value forms an intercept of the O-Hf array at $\epsilon$Hf values of $\sim$9–12. To compare our $\epsilon$Hf values to other studies in the western Sierra Nevada, the oceanic island basalt–mid-oceanic ridge basalt (MORB) mantle $\epsilon$Hf-$\epsilon$Nd array (Chauvel et al., 2008) was used to determine equivalent $\epsilon$Nd values of this reservoir. Values of $\epsilon$Nd are $\sim$4.8–6.7 and broadly consistent with a reservoir of arc-related rocks, yet $\epsilon$Nd values are lower than $\epsilon$Nd values of $\sim$9.0–11.0 from exposed ophiolitic rocks in the western and northern Sierra Nevada (Shaw et al., 1987; Saleeby et al., 1989). Even when corrected for minor radiogenic ingrowth between the Paleozone and 125 Ma maximum age of the Fine Gold Intrusive Suite, the ophiolitic values are higher than typical $\sim$8.8 values common for MORB (Chauvel et al., 2008); thus, other rocks are clearly present in the arc terrane reservoir. A 9 rock composite sample of Jurassic volcaniclastic rocks from the Mariposa Formation has an $\epsilon$Nd of $\sim$4.6 (DePaolo, 1981a), illustrating that volcaniclastic rocks will act to lower the bulk $\epsilon$Nd of an arc terrane compared to contemporary basaltic ocean crust. Subducted oceanic sediments, with initial $\epsilon$Nd and $\epsilon$Hf value of $\sim$8.9 and $+2$, respectively, can also reduce the radiogenic isotope ratios of the bulk reservoir further (Chauvel et al., 2008), and the introduction of a component of continental crust is possible. We characterize the average reservoir of accreted oceanic and/or arc lithosphere as having $\epsilon$Hf of $\sim$9–12, with a minimum $\delta^{18}O$(WR) of $\sim$10‰.

### $\delta^{18}O$ Mass Balance

Despite considerable uncertainty about the average isotopic compositions of crust, mantle, and any intermediate reservoirs that contributed to the magmas of the Fine Gold Intrusive Suite, $\delta^{18}O$ mass balance calculations do not have the same pitfalls that affect radiogenic isotope systems in which variable trace element concentrations profoundly affect initial ratios. In contrast, zircon, magma, and silicate rocks contain roughly equal amounts of oxygen ($\sim$50 wt%). Thus, $\delta^{18}O$ values of crustal end members can be compared to the measured BLT values, and a theoretical mantle component, to provide a reasonably informative sense of the crustal input of the two reservoirs into magma sources. A binary calculation of $\delta^{18}O$ values takes the form:

$$
\delta^{18}O \text{ magma}_{\text{final}} = \delta^{18}O \text{ crust} \times (X) + \delta^{18}O \text{ magma}_{\text{initial}} \times (1 - X),
$$

where $X$ is the fraction (0–1) of the reservoir relative to initial magma input (mantle). In our calculation, the mantle end member is chosen as the 5.8‰ value of the Academy Pluton, the $\delta^{18}O$ zircon of which is only slightly elevated above mantle values. Mass balance mixing lines, graduated in 20% increments (Fig. 9A), show arc-oceanic crustal input for the 30%–45% of samples from the western domain; input of Proterozoic crust in the eastern domain rocks is calculated to be $\sim$5%–50%. Both are maximum estimates because some of the components in the reservoirs contributing to these magmas likely had higher $\delta^{18}O$ values. The calculated inputs are well above levels that are possible by simple wall-rock assimilation (e.g., Glazner 2007); thus we conclude that reservoir mixing in magma sources is the primary control of the bulk isotopic variation of the Fine Gold Intrusive Suite.

### Wall-Rock Contamination

Even if source mixing imparted much of the isotopic character of the Fine Gold Intrusive Suite, the numerous roof pendants and exposures of pluton–wall rock boundaries in the field area (Fig. 2) show potential for crustal contamination caused by assimilation of wall rocks. In evaluating for possible crustal contamination here, we focus on $\delta^{18}O$, Rb/Sr, and $^{87}$Sr/$^{86}$Sr (Sr$_{i}$) ratios, noting that all three tracer measures are especially sensitive to detect upper crustal contamination. Available $\delta^{18}O$ and Sr$_{i}$ for the Fine Gold Intrusive Suite, surrounding wall rocks, mafic complexes in the western foothills, and the Tuolumne and Shaver Intrusive Suites (Masi et al., 1981; Clemens-Knott, 1992; Kistler and Fleck, 1994; Truschel, 1996) show variable distinct trends in O-Sr space for the western and central domain samples, versus those in the eastern domain (Fig. 9B). The western foothills samples and the Shaver and Tuolumne Intrusive Suites also show distinct O-Sr arrays that help to compare the data from the Fine Gold Intrusive Suite to the rest of the Sierran arc.

To evaluate if the Fine Gold rocks record contamination, we used simple mixing and AFC (DePaolo, 1981b) models. Model parameters are given in Table 3. The mixing model adopts the western primary O-Sr isotopic values of the Academy Pluton, which is approximately the average for other foothills mafic complex samples (Fig. 9B). Rb and Sr concentrations for this end member are the average of foothills mafic complex analyses of Clemens-Knott (1992) between 45 and 60 wt% SiO$_2$. When compared to western domain magmas, an AFC trend toward Mariposa Formation values trends below the main array of plutonic samples (Fig. 9B). In contrast, the simple mixing model between the mantle reservoir and altered ocean crust shows a reasonable fit of the lower limit of the western domain BLT samples, a confirmation of source mixing. An AFC model approach to this same pair of reservoirs using a high D$_{O}$ (3.5; solid:mel coefficient of an AFC...
Magma evolution of the Fine Gold Intrusive Suite

TABLE 3. MIXING AND ASSIMILATION–FRACTIONAL CRYSTALIZATION PARAMETERS USED IN OXYGEN–STRONGIUM ISOTOPE MODELS

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>δ18O (WR)</th>
<th>Initial Sr</th>
<th>Pb ppm</th>
<th>Sr ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continental crust</td>
<td>11.1(10)</td>
<td>0.7068(1)</td>
<td>49(2)</td>
<td>320(2)</td>
</tr>
<tr>
<td>Altered ocean crust</td>
<td>11.8(10)</td>
<td>0.7052(3)</td>
<td>19(2)</td>
<td>169(3)</td>
</tr>
<tr>
<td>Mariposa Formation</td>
<td>13.0(7)</td>
<td>0.7046(3)</td>
<td>26(2.3)</td>
<td>184(2.3)</td>
</tr>
<tr>
<td>Calaveras Complex</td>
<td>15.0(6)</td>
<td>0.7125(6)</td>
<td>72(9)</td>
<td>169(3)</td>
</tr>
<tr>
<td>Eastern primary magma</td>
<td>6.5(3)</td>
<td>0.7049(2)</td>
<td>29(7)/60(7)</td>
<td>280(7)/2223(7)</td>
</tr>
<tr>
<td>Western primary magma</td>
<td>7.1(2)</td>
<td>0.7038(2)</td>
<td>21(9)</td>
<td>350(9)</td>
</tr>
</tbody>
</table>

Note: WR—whole rock. Kd of ~ 0 based on average Kd for Sr in basalt from GERM (Geochemical Earth Reference Model; http://earthref.org/GERM) Database; values of 3.5 used for strongly fractionating scenario (Fig. 8B). Ratios of assimilant to fractionally crystallized magma were iteratively varied from 0.2 to 0.3 to obtain closest approach to assimilant with assimilation–fractional crystallization (AFC) path. Data sources: 0—this study; 1—Kistler et al. (1986); 2—Rudnick and Gao (2003); 3—Staudigel et al. (1995); 4—Boehlke and Kistler (2004); 5—Kistler and Fleck (1994) CL-1 of Academy Pluton; 6—Clemens-Knott (1992).

TABLE 4. MAJOR, MINOR, AND TRACE ELEMENT COMPOSITIONS OF MARIPOSA FORMATION AND CALAVERAS COMPLEX WALL ROCKS

<table>
<thead>
<tr>
<th>Sample Unit</th>
<th>Lithology</th>
<th>Phyllic pelite</th>
<th>Phyllic pelite</th>
<th>Phyllic pelite</th>
<th>Phyllic pelite</th>
<th>Phyllic pelite</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Srcc</td>
<td>Jm</td>
<td>Jm</td>
<td>Tncc</td>
<td>Tncc</td>
</tr>
<tr>
<td>Latitude (°N)</td>
<td></td>
<td>37°17'11.40&quot;</td>
<td>37°07'08.98&quot;</td>
<td>37°20'07.12&quot;</td>
<td>37°35'45.71&quot;</td>
<td>37°16'27.26&quot;</td>
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<tr>
<td>Longitude (°W)</td>
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<td>119°55'50.70&quot;</td>
<td>119°58'00.08&quot;</td>
<td>119°50'48.80&quot;</td>
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<td>MgO</td>
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<tr>
<td>CaO</td>
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<tr>
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<tr>
<td>Pb</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Tm</td>
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<tr>
<td>Yb</td>
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<tr>
<td>Lu</td>
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<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Note: Analytical details are given in Table 1. LOI—loss on ignition. Pelitic rock samples are typically biotite-muscovite pelites. Formations: Jm—Mariposa Formation; Tncc—Calaveras Complex. Dashes indicate not analyzed; bdl—below detection limits.

curve) to simulate high degrees of fractional crystallization suggests that this process could account for some of the scatter of samples above the simple mixing line (Fig. 9B).

Eastern domain samples cannot be modeled assuming the same mantle value as rocks in the western domain. This finding is consistent with previous studies suggesting that the mantle component in the Sierra Nevada has higher Sr, to the east (Kistler et al., 1986; Chen and Til-
ton, 1991). Moreover, eastern domain samples and the Tuolumnie and Shaver Intrusive Suites appear to fan away from a common mantle end member, which we adopted for the purpose of this approach. This end member was inferred by Kistler et al. (1986) to have δ18O = 6.0‰ and Sr = 0.704. Our extrapolation of linear fits to the data suggests a mantle component with δ18O = 6.0‰, Sr = 0.705. The crustal δ18O(WR) of ~11‰ from our study is higher than that of the continental crust reservoir and have modeled these as a simple mixing array. The crustal contamination AFC array for the high Sr, high δ18O wall rocks of the Calaveras Complex (Table 3) shows no indication of crustal contamination in the eastern domain, but a simple mixing array between continental crust and the eastern domain magma produces a good fit to the data array. Simple source mixing trajectories of Sr-O arrays confirm source mixing of reservoirs, but are incompatible with crustal contamination.

**Trace Elements**

Trace elements were also evaluated to assess potential crustal contamination (Fig. 9C). This second approach allows us to consider a larger number of samples, including published data and new measurements of wall-rock compositions (Table 4). Sr/Y versus Rb/Sr values were used, given the link of high Sr/Y ratio to deep crustal origin (Drummond and Defant, 1990), and the Rb/Sr ratio to crustal contamination. Simple mixing lines between potential crustal rocks, and a high Sr/Y melt value for Sierran eclogitic xenoliths (Fig. 9D), project through...
the Ward Mountain Trondhjemite data, but are largely mismatched with potential wall rocks. Instead, the main array of samples of the Fine Gold Intrusive suite is fringed by wall-rock samples, without clear deviations off the main igneous elemental trends to indicate wall-rock contamination.

Revisiting the Ilmenite Series Classification of the BLT

The rocks of the Fine Gold Intrusive Suite were classified as ilmenite series granitoids by Ishihara and Sasaki (1989) when they compared the Sierran arc to the magnetite-ilmenite series rocks in Japan. Their work showed low sulfur isotope ratios ($\delta^{34}S < -2.3\%$e) in two BLT samples compared to higher (>1.6%) values across the Sierra Nevada. High (>280 ppm) concentrations of noncarbonate carbon in the rocks and low $\delta^{13}C$ values were attributed to either a reduced magma source or interaction with carbon-charged wall rocks. Given the sparse evidence of wall-rock contamination we report, it appears that the low $\delta^{34}S$ values in the Fine Gold Intrusive Suite are controlled in the source and not by carbon-charged metavolcanic wall rocks. Moreover, the two samples that Ishihara and Sasaki (1989) analyzed were from the small, isolated stocks of BLT that intrude the Coarsegold pendant 15 km north of locality 31 (Fig. 2). Such samples are likely to overemphasize the effects of wall-rock contamination in the BLT.

Summarizing Source and Contamination History

The combined geochemical isotope record from the Fine Gold Intrusive Suite confirms considerable input (to 45%) of Paleozoic accreted arc terranes, with late-stage magmas of the eastern domain showing similar content of North American continental crust in their source. That there is no significant crustal contamination in an intrusive suite that would appear primed for contamination because of myriad pendants and wall rocks is consistent with other recent findings. For example, Sr and Nd isotopic analyses of plagioclase from migmatic complexes in the lower crustal exposures of the southern Sierra record contamination to at most 100 m into the pluton (Saleeby et al., 2008). The $\delta^{18}O$ analysis of rocks emplaced at mid-crustal levels in the central Sierra Nevada record similarly thin (50 m) veneers of contamination at pluton margins (Lackey et al., 2006). Contamination halos resulting from partial melting of metamorphic screens in the shallowly emplaced Tuolumne Intrusive Suite are undetectable in the pluton at distances >1 m from the screen (Mills et al., 2009).

Evolving Styles of Magmatism

A summary petrotectonic model for the emplacement of the Fine Gold Intrusive Suite is presented in Figure 10 and used to frame discussion of the ramifications of the geochemical data in time and space. In this model, the pre-BLT framework of accreted terranes is shown to transition to a crystalline North American continental crust (Fig. 10A). The transition may be gradual, or sharp, with the truncated continental margin acting as a backstop against which Paleozoic to Jurassic terranes were accreted (Ernst et al., 2008). The ultimate suture of oceanic and continental terranes remains uncertain and has been elusive, but the most recent interpretation assigns this boundary to the foothills suture between the Calaveras Complex and Shoo Fly terrane (Saleeby, 2011). Given the eastward dips of the Melones (Paterson et al., 1989; Paterson and Wainger, 1991) and Shoo Fly faults (Merguerian and Schweickert, 1987), we interpret the boundary between the accreted terranes and continental affinity rocks of the Shoo Fly and Snow Lake blocks to also dip eastward. This creates a crustal section that is layered, with younger rocks of island arc or ocean crust affinities at the base and older, crustally derived packages of continental margin sediments and potentially crustal fragments to the east (Fig. 10A).

Initial Magmatism

The emplacement of the Ward Mountain Trondhjemite was the first major episode of magmatism in the Fine Gold Intrusive Suite, and was soon followed by more voluminous and widely distributed pulses of magmatism in the western and northern reaches of the suite (Figs. 8 and 10A). The low Rb/Sr but unusually high Sr/Y values (Fig. 8D), in conjunction with low Sr, and high $\delta^{18}O$ values of the Ward Mountain Trondhjemite, point to a unique origin of this magma. In particular, the new data presented here suggest that arc magmatism initiated at depths great enough to be garnet bearing, but that later magmas would not reflect such melting conditions. The deep origin of these magmas was possibly at the base of a tectonically thickened arc crust. Such a configuration suggests that the low Sr and high $\delta^{18}O$ values of the Ward Mountain magma (Truschel, 1996; Lackey et al., 2006, 2008) perhaps sampled an enriched or contaminated mantle domain. It is possible that some mass derived from melting of altered ocean crust on top of the Farallon plate.

Early Source Complexity

As emplacement of western and central domain BLT proceeded, younger magmas intruded the complex of older plutons of the Ward Mountain Trondhjemite and engulfed stocks of the granodiorite of Arch Rock as well as roof pendant screens and septa, and possibly displaced previously emplaced rocks such as the granite of Shutey Peak. We hypothesize that the more variable isotopic and trace element compositions of the western and central domains (Figs. 6 and 9), as well as the older Ward Mountain and Arch Rock magmas (Fig. 10B, I and II), reflect lateral and vertical mixing of rocks that were simultaneously being melted at localized sources, commonly at small volumes, and relayed to the site of emplacement by separated conduits (Fig. 10B, III).

Even if early-stage BLT magmas came from dispersed sources, the calculated input of arc–oceanic terrane rocks, 30%–45% of their mass, signifies an efficient process of refinement of accreted rocks into granitic crust. If such magmas are produced over 10 m.y. in the western domain, or 25% of the full duration of Cretaceous magmatism in the Sierra Nevada, then 7.5%–11.3% of Sierran granitic magmas are derived from recycled arc terrane. This is a minimum estimate. Magma production was not at a constant rate, and compiled age data show apparent lulls in productivity (Lackey et al., 2008). Moreover, if similar levels of production occurred in the concealed Great Valley batholith (Saleeby et al., 2010), the duration and volume of such recycling would be 50% greater.

Refinement of accreted terranes into ocean crust may also be underestimated in other arcs, because of a paucity of combined oxygen and radiogenic isotope studies (Lackey, 2011), although recent Hf studies in the Coast Ranges (Cecil et al., 2011) and Separation Point (Bolhar et al., 2008) batholiths commonly show high $\varepsilon^{18}O$ values in Cretaceous granitic crust, implying similar recycling of oceanic and/or arc rocks into granitic crust. We propose that crustal growth by refinement of fringing island arcs (e.g., Lee et al., 2007) is underestimated in Cordilleran batholiths.

Mature Late-Stage System

As shown in Figures 6 and 8, the eastern domain has more restricted ranges of $\delta^{18}O$ and $\varepsilon^{18}O$ than older BLT rocks. The absence of lower $\delta^{18}O$ values suggests diminished transfer of mantle melts into the arc crust. Precursor BLT (samples 29, 33, 35; Figs. 2 and 10) and Arch Rock magmas in the same belt were more primitive or had a greater mantle component, although mechanisms for changing magma sources at that time are not clear from our current data set. In effect, the entire Fine Gold magma system appears to have shifted from one that was variably mixing mantle and crustal reservoirs, to one that was established, tapping
Proterozoic crust and also homogenizing isotopic differences among reservoirs (Fig. 10C). A trend toward greater isotopic homogeneity would be expected for a subarc MASH (magma assimilation, storage, and homogenization) zone (Hildreth and Moorbath, 1988), which is inferred to have operated at the base of the Sier- rarian arc (Ducea, 2002; Saleeby et al., 2003). Isotopic records from eclogitic and pyrox- enite xenolith samples of that MASH zone, which were erupted from beneath the Shaver Intrusive Suite at Big Creek and Chinese Peak (Fig. 2), suggest such homogenization. For example, the pyroxenite and eclogitic rocks have relatively uniform Sr (0.7056 ± 0.0006, 1 SD; Ducea, 2002), and δ18O (7.3‰ ± 0.9‰, 1 SD; Ducea, 2002; Lackey et al., 2005) because they were produced by a blend of reservoirs. Companion xenoliths of refractory crustal rocks and plagioclase granulites presumed to have survived at or above the MASH zone are much more isotopically variable (Sr = 0.7088 ± 0.0033; δ18O = 10.3‰ ± 2.9‰; Ducea, 2002), recording the mixture of crustal components entering the MASH zone. Although they are from the next younger episode of magmatism, the eclogitic and pyroxenite residuals indicate the kind of MASH processing envisioned to produce the eastern domain of the BLT.

Temporal Development of the 0.706 Line
The significance of the initial 87Sr/86Sr = 0.706 isopleth (0.706 line; Fig. 8) is considered here given that its occurrence in the Fine Gold Intrusive Suite is manifested in the Bass Lake domain of the BLT. Considered the magmatic expression of the boundary in the prebatholith arc between accreted arc terranes and Protero- zoic North American continental crust (Kistler...
and Peterman, 1973; Kistler, 1990), the previously published location of the 0.706 line in the Fine Gold Intrusive Suite cuts across domains in the eastern BLT (Fig. 8), and its location is largely fixed by samples in the Dinkey Creek granodiorite (for sample locations and values, see Bateman et al., 1991; Kistler and Fleck, 1994). Because Sr values increase in a stepwise fashion with new episodes of magmatism (Fig. 6C), it appears that individual magmatic episodes are more important in determining the location of Sr isopleths in the Fine Gold Intrusive Suite than a specific structural break. Therefore, the 0.706 line can be viewed as a discrete area or zone within the eastern domain. Such a zone resolves the problem of having the 0.706 line cross age domains (Fig. 8), and it provides an important indication of when the Fine Gold magma source began to tap crustal material. Similar zoning toward higher Sr values is present in younger members of the Tuolumne Intrusive Suite (Kistler et al., 1986), and is consistent with a lag between the initiation of an intrusive center and the onset of crustal melting. Overall, these results suggest that the geochemistry of early and spatially dispersed magmas, like those of the granodiorite of Arch Rock, provide the best record of preexisting terrane boundaries.

Implications for the Dynamics of Evolving Sources

Besides prebatholithic architecture, magma production will be controlled by an array of transient processes including variable subduction rate with correspondingly variable mantle melting, shortening and deformation of the arc, and growth and foundering of the residual arc root, all of which may cause transitions of magma sources, and potentially episodicity of magmatism (Ducea, 2001; Saleebey et al., 2003; Ducea and Barton, 2007; DeCelles et al., 2009). Although current findings cannot resolve such processes, they hint at characteristics of the nascent stages of magmatism in the Sierran arc. For example, the crust and complementary eclogitic to pyroxenite root of an arc thickens as the arc melts and efficiently hybridized with other magmas (Dufek and Bergantz, 2005). This finding raises the question of whether arcs melt crust from the bottom upward, potentially remelting underplated hydrous mafic cumulates (e.g., Rapp and Watson, 1995; Sisson et al., 2005; Ratasek et al., 2005). Alternatively, does melting proceed throughout the lower crust with intrusive complexes composed of sills (Ammen et al., 2006), or dikes (Dufek and Bergantz, 2005), allowing simultaneous melting at different levels in the lower crust, and coalescence of melts at higher level mixing zones? In this latter case, the geochemical lag might reflect the time required to thermally mature sources and the arc to the point that continental crust will melt and efficiently be hybridized with other magmas (Dufek and Bergantz, 2005). The Dufek and Bergantz (2005) model also predicts that systems initially have low mantle and crustal melts occurring in isolated domains of mantle and crustal melts, a situation that may be encapsulated by the other stocks of the granodiorite of Arch Rock as well as small mafic bodies in the western and central domains. Such domains may hold further details on the changing styles of magmatism in the suite to further resolve our understanding of early-stage Sierran magmatism, and to help tune tectonomagmatic models of Cordilleran batholiths.

CONCLUSIONS

New U-Pb ages and oxygen and hafnium isotope geochemistry for the Fine Gold Intrusive Suite show a pronounced evolution of magmatism over its life span of ~19 m.y. The emplacement time scale of the Fine Gold Intrusive Suite is approximately twice that observed in the intrusive suites of the eastern Sierran arc, but the exposed areas of this and the eastern Sierra Nevada suites suggest a similar magma production rate. The combined O-Hf isotope record from the Fine Gold Intrusive Suite confirms maximum input of as much as 45% of Paleozoic accreted oceanic and/or arc terranes; in contrast, late-stage magmas on the east side of the suite show the first significant incorporation of North American continental crust. The transition of sources of the Fine Gold Intrusive Suite was controlled by basement architecture, and source mixing, with minimal crustal contamination. Large variations of isotope and trace element composition in older magmas, in the western and central domains of the suite, suggest that early magmas were produced in isolated sources. The youngest episode of magmatism, in the eastern domain of the suite, is more geochemically uniform, suggesting the transition to a magma source that was larger and well mixed, and more typical of the voluminous intrusive suites of the eastern Sierran arc. New ages also show that the 87Sr/86Sr = 0.706 line, the geochemical tracer of the boundary between accreted terranes and continental North American crust, was only expressed during eastern domain magmatism. Therefore, the 0.706 line represents a highly averaged record of this boundary; regional isotopic discontinuities recorded in older and smaller intrusions that intruded the domain may provide more accurate records of this boundary in other Sierra Nevada settings. The Fine Gold Intrusive Suite also shows that recycling of accreted island arc and/or oceanic terranes into granitic continental crust can be accomplished efficiently and at high volume in Cordilleran-type batholiths; thus, Phanerozoic crustal growth may be underestimated.

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Magma evolution of the Fine Gold Intrusive Suite


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