New insights into migration of the Cretaceous Sierran arc using high-precision U-Pb geochronology

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ABSTRACT

COURTNEY L. BECK: New insights into migration of the Cretaceous Sierran arc using high-precision U-Pb geochronology
(Under the direction of Drew S. Coleman)

A compilation of 254 U-Pb zircon and K-Ar and Ar-Ar biotite ages for the central Sierra Nevada batholith, CA, shows no record of monotonic west-to-east migration of magmatism during the Cretaceous. Rather, spatial age variation in the central Sierra Nevada batholith is dominated by 1) a stepwise shift of the locus of magmatism 2) a west-to-east migration to the end of magmatism and 3) patterns within intrusive suites that reflect local crustal deformation. The step in magmatism was contemporaneous with the beginning of the Sierra Crest magmatic event and beginning of deformation along ductile shear zones in the eastern Sierra. At ~102 Ma, a laterally extensive shear zone formed along the eastern margin of the Cretaceous batholith and was localized and dissected by Sierra Crest plutons. Central Sierran biotite ages cluster between ~78 and 90 Ma and may reflect batholith-wide exhumation or cooling related to waning of local magmatism.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

Table

NEW INSIGHTS INTO MIGRATION OF THE CRETACEOUS SIERRAN ARC USING HIGH-PRECISION U-PB GEOCHRONOLOGY

INTRODUCTION

The Sierra Nevada batholith formed as a result of subduction related arc magmatism along the western boundary of North America during the Mesozoic. Early geochronologic data suggested that intrusive rock ages throughout the western United States decrease regularly from west to east, a pattern attributed to inland migration of the magmatic focus from 120-80 Ma (Coney and Reynolds, 1977). The first comprehensive geochronologic studies of the central Sierra Nevada batholith comprised 62 U-Pb zircon ages of Stern et al. (1981) and 82 U-Pb zircon ages of Chen and Moore (1982). A compilation of these ages suggested that the Cretaceous Sierran arc migrated inland at ~2.7 mm/a (Chen and Moore, 1982). Arc migration was thought to have occurred in response to flattening of the subducting slab, eventually culminating in the Laramide orogeny (Coney and Reynolds, 1975; Livaccari et al., 1981).

In the past several decades, the database of Sierran geo-and-thermochronology has expanded significantly. Until recently, a single U-Pb age from a map unit was thought to represent the intrusive age of the entire unit. However, high-precision geochronology studies of plutonic rocks reveal that individual plutons are emplaced incrementally over several million years, rather than as large batches of magma (Coleman et al., 2004; Matzel et al., 2006; Michel et al., 2008; Tappa et al., 2011; Davis et al., 2012). Within the Sierra Nevada batholith, for example, the Half Dome Granodiorite of the Tuolumne Intrusive suite and Lamarck Granodiorite of the John Muir Intrusive Suite were assembled over at least 3 Ma (Coleman et al., 2004; Davis et al., 2012). New, high-precision geochronology in the central Sierra Nevada generally supports the pattern of older rocks in the west and younger rocks in the east; however, spatial age variation is more complex than the linear age decrease suggested by early geochronologic data. In light of new high-precision ages and new understanding of how plutons are assembled in the upper crust, it is worthwhile to revisit the question of spatial age variation in the Sierra Nevada batholith.

Whereas individual plutons and intrusive suites in the eastern Sierra Nevada are well dated by high-precision U-Pb zircon and Ar-Ar biotite geochronology (Coleman et al., 2004; Davis et al., 2012), few high-precision, high sample density studies have been conducted in the suites of the western Sierra Nevada (e.g., Fine Gold and Shaver intrusive suites). Recently, Lackey et al. (2012) obtained LA-ICPMS zircon ages for rocks of the Fine Gold Intrusive Suite in the western Sierra that provide the first modern attempt to date these rocks.

Obtaining high-precision U-Pb zircon ages for intrusive suites of the western Sierra Nevada would provide a complete transect of modern ages for Cretaceous intrusive rocks across the central part of the batholith. Herein, I present new thermal annealing-chemical abrasion-isotope dilution thermal ionization mass spectrometry (TA-CA-ID TIMS) ages for Cretaceous intrusive rocks of the western Sierra Nevada. I also compile published U-Pb zircon and biotite Ar-Ar and K-Ar ages from the Sierra Nevada batholith and revisit the question of spatial age variation in the central Sierra Nevada batholith.

GEOLOGIC SETTING

Mesozoic Tectonics of Western North America

The Sierra Nevada batholith extends approximately 600 km through eastern California, exposing over 40,000 km^2 of plutonic rock (Kistler, 1990; Bateman, 1992). Formation of the dominantly granite, granodiorite and tonalite batholith occurred throughout the Mesozoic as a result of oceanic plate subduction under the North American continent (Bateman, 1992). Previous work demonstrates that the batholith was assembled during three main magmatic pulses that took place between ~225–195 Ma, 180–165 Ma and 102–85 Ma (Stern et al., 1981; Chen and Moore, 1982; Coleman and Glazner, 1997; Ducea, 2001). The majority of the exposed batholith was intruded at depths of 4-19 km, and intrusion depths are somewhat shallower in the eastern Sierra (Ague and Brimhall, 1988). The end of regional magmatism is associated in time and space with the end of the Sierra Crest magmatic event, the period of voluminous magmatic activity from ~98-86 Ma (Coleman and Glazner, 1997). Sierra Crest plutons of the eastern Sierra include the Mount Givens Granodiorite and Tuolumne John Muir and Mount Whitney intrusive suites (Coleman and Glazer, 1997).

Early Sierran geochronologic data were interpreted to define a linear, west-to-east decrease in age. This spatial age distribution was interpreted to reflect slow, monotonic inland migration of the locus of magmatism from 120-80 Ma (Chen and Moore, 1982). For the central (36-38˚N) Sierra Nevada batholith, the geochronologic data were used to infer an inland arc migration rate of 2.7 mm/a (Stern et al., 1981; Chen and Moore, 1982). Chen and Moore (1982) interpreted the slow, steady rate of arc migration and the linear spatial age distribution to reflect flattening of the subducting slab. Termination of Sierran plutonism at ~80 Ma was interpreted to be a result of increased flattening of the subducting slab, perhaps in response to increased convergence rates between the eastern Pacific and North American plates (Coney, 1972; Coney and Reynolds, 1977; Chen and Moore, 1982).

Since Chen and Moore (1982) proposed their interpretation of plutonism in the Sierra Nevada batholith, the Sierran geo-and-thermochronology database has expanded to include more data from the batholith's northern, southern and central reaches. This study focuses on Cretaceous high-precision U-Pb zircon geochronology data from the central Sierra Nevada batholith (Table 1). New laboratory techniques, such as thermal annealing and chemical abrasion (Mundil et al., 2004; Mattinson, 2005), provide ages with higher precision than ages determined in early Sierran geochronology studies. Additionally, modern geochronology studies report ages derived from analyses of only a few individual zircons, or fragments of zircon, in contrast to analyses of large zircon populations (~50-100 grains). Whereas single-grain analyses can account for problems such as Pb-loss and inheritance, analyses of large zircon populations provide average ages that are impacted by these complications.

Geology of the Plutonic Rocks of the Eastern Sierra Nevada Batholith

The Cretaceous rocks in the eastern Sierra Nevada batholith include the Whitney, John Muir and Tuolumne intrusive suites, and the Mount Givens Granodiorite. Plutons of the eastern Sierra formed during the Sierra Crest magmatic event, between ~98-86 Ma, and are generally more silicic than plutons of the western portions of the batholith (Coleman and Glazner, 1997). High-precision U-Pb zircon geochronology shows that plutons of the John Muir and Tuolumne intrusive suites accumulated over at least 10-12 Ma (Coleman et al., 2004; Memeti et al., 2010; Davis et al., 2012). The 1500 km^2 Mount Givens Granodiorite is exposed east of the Shaver Intrusive Suite and a single published age of 90 +3/-4 exists for the northern portion of the pluton (Tobisch et al., 1993). New high-precision U-Pb zircon geochronology indicates that the Mount Givens was emplaced over ~7 Ma, from 97.9-90.9 Ma (Frazer, 2013). Rocks in the southern portion of the pluton are generally younger than those of the north; however, more high-precision geochronologic data are necessary to fully document spatial age variation in the Mount Givens Granodiorite (Frazer, 2013).

The 1200 km^2 Tuolumne Intrusive Suite varies from mafic granodioritic outer margins to a more felsic granitic-granodioritic core (Bateman, 1992; Coleman et al., 2004). Plutons of the Tuolumne are older at the margins and younger in the center, ranging from ~95-85 Ma (Kistler and Fleck, 1994; Coleman et al., 2004; Memeti et al., 2010). South of the Tuolumne Intrusive Suite, the John Muir Intrusive Suite ranges in composition from monzodiorite to granite (Bateman, 1992; Davis et al., 2012). Plutons of the Muir Intrusive Suite decrease in age and become more felsic from south to north (Bateman, 1992; Mahan et al., 2003; Davis et al., 2012). High-precision U-Pb zircon ages indicate that the Muir was assembled over 12 Ma, from ~83-95 Ma (Mahan et al., 2003; Davis et al., 2012). Biotite Ar-Ar ages for rocks from the Muir range from 87.5-82.1 Ma and cluster near the youngest zircon ages of rocks from the suite (Davis et al., 2012). This pattern is interpreted to reflect post-magmatic cooling (Davis et al., 2012) which may be associated with the end of the Sierra Crest magmatic event. The ~1200 km^2 Mount Whitney Intrusive Suite includes three nested granitic plutons south of the Muir Intrusive Suite (Moore and Sisson, 1978). The margins of the Mount Whitney suite are older and more mafic than the central pluton, and published U-Pb zircon ages suggest that the suite was emplaced from 88-83 Ma (Chen and Moore, 1982; Kylander-Clark et al., 2005; Mattinson, 2005; Saleeby et al., 1990; Hirt, 2007; Davis, 2010).

Cretaceous Tectonics of the Eastern Sierra Nevada Batholith

At ~100 Ma, a system of dextral reverse (±normal)-sense shear zones formed in Cretaceous and Jurassic plutons in the eastern Sierra Nevada (Tobisch et al., 1995). Table 2 summarizes the style and timing of deformation along these shear zones. Published mapping and U-Pb zircon and Ar-Ar hornblende and biotite ages indicate that the shear zones generally young from west to east (Table 2). These shear zones are interpreted to preserve evidence of a transition from an extensional to a transpression-dominated regime at ~90 Ma (Tobisch et al., 1995).

The oldest and westernmost shear zones include the Quartz Mountain, Kaiser Peak, Courtright and Bench Canyon (Tobisch et al., 1995). These shear zones were mapped and dated by Tobisch et al. (1995) and interpreted to record reverse ductile shear. The Sawmill Lake shear zone deforms Jurassic and Late Cretaceous intrusives of the southern John Muir Intrusive Suite, including the McDoogle pluton (Fig. 1; Mahan et al., 2003). Reverse ductile shear along this shear zone began by at least 95 Ma and persisted until 92 Ma (Mahan et al., 2003). The 300 km Sierra Crest shear system records dextral deformation along the eastern boundary of the Sierra Nevada batholith (Fig. 1; Tikoff, 1994). The Cascade Lake, Gem Lake and Rosy Finch shear zones are structurally continuous and comprise the northern portion of this regional shear system (Tikoff and Saint Blanquat, 1997). Movement along these shear zones began at 88 Ma (Table 2).

Geology of the Plutonic Rocks of the Western Sierra Nevada Batholith

The 3000 km^2 Fine Gold Intrusive Suite is exposed at the western edge of the Sierra Nevada batholith (Fig. 1; Bateman, 1992). The largest mapped intrusion of the suite is the 2000 km^2 Bass Lake Tonalite. The Fine Gold Intrusive Suite also includes the smaller

Knowles Granodiorite, Ward Mountain Trondhjemite, and the granodiorite of Arch Rock (Bateman, 1992). The majority of the Bass Lake Tonalite is an equigranular hornblende-biotite tonalite that varies from gabbro to granodiorite (Bateman, 1992). The pluton intrudes metamorphic wallrocks and is cut by rocks of the Shaver and Yosemite Valley intrusive suites (Bateman, 1992). Previously, the age of the Bass Lake Tonalite was thought to be approximately 114 Ma, as estimated by an average of thirteen U-Pb zircon ages spanning from 124 to 105 Ma (Stern et al., 1981; Bateman, 1992). Modern laser ablation U-Pb zircon ages for the Bass Lake Tonalite confirm that the age range from 121 to 105 Ma (average 2σ uncertainties of ± 2 Ma; Lackey et al., 2012) records the assembly of the complex pluton. These authors clustered the plutonic rocks into three age groups: old (121-115 Ma), intermediate (114-110 Ma), and young (108-105 Ma), which correlate roughly with geographic position within the pluton, generally younging from west to east (Lackey et al., 2012).

The Shaver Intrusive Suite is exposed directly east of the Fine Gold Intrusive Suite (Fig. 1) and contains several granodioritic and granitic bodies, the largest of which is the 600 km^2 Dinkey Creek Granodiorite (Bateman, 1992). The majority of the Dinkey Creek pluton is equigranular, with megacrystic facies cropping out in the north and along the margins of the southwestern lobe. Alkali feldspar megacrysts in a medium-grained groundmass define the megacrystic facies, which ranges in composition from granite to granodiorite (Bateman, 1992). The medium-grained equigranular facies contains mafic enclaves, which are generally ellipsoidal and composed of hornblende and biotite (Bateman, 1992; Dorais et al., 1990). Two U-Pb zircon ages for the Dinkey Creek Granodiorite include a discordant 104 Ma age (Stern et al., 1981) and a concordant 102 ± 1 Ma age (Tobisch et al., 1993).

METHODS

U-Pb Zircon Geochronology

Six whole rock samples were collected from fresh surfaces throughout the Bass Lake Tonalite and the Dinkey Creek Granodiorite (Fig. 1). Zircons were obtained by mechanical separation (jaw crusher, disk mill and water table) of whole rock samples. Denser minerals ($\rho > 3.3$ g/cm^3) were isolated using a separation funnel and methyl iodide. Zircons were further isolated using a Frantz magnetic separator and hand-picked in ethanol under a binocular microscope. Selected grains were thermally annealed at 950° C for 48 hours and chemically abraded in an HF+HNO_3 solution for 16 hours at 180°C in order to eliminate radiation-damaged fractions and inclusions (Mattinson, 2005). Grains were dissolved with a mixed ^{205}Pb-^{233}U-^{236}U UNC spike in an HF+HNO_3 solution over five days and converted from a nitrate salt to chlorides in 6M HCl (Parrish and Krough, 1987; Krough, 1973; Parrish, 1987). Chloride salts were passed through HCl anion-exchange columns to isolate U and Pb (Krough, 1973). Uranium fractions were loaded on 99.98% Re filaments in either graphite solution or colloidal silica gel, whereas lead fractions were loaded on 99.998% Re filaments in colloidal silica gel.

Mass analyses were performed using the Daly detector of the VG Sector-54 thermal ionization mass spectrometer at the University of North Carolina-Chapel Hill. Mass fractionation for U was calculated by measuring the ^{233}U/^{236}U ratio of the spike and Pb fractionation was assumed to be 0.15%/amu. The majority of U samples analyzed were loaded with silica gel and ionized as UO_2 in order to raise ionization efficiencies and minimize run variability caused by inconsistencies in the graphite solution. There are no systematic differences between oxide and metal analyses that could affect how U is measured and samples analyzed as U-oxides were corrected for oxygen isotope ratios. All samples were assumed to have no initial Pb and all common Pb was attributed to lab blank. The data were corrected for Th/U disequilibrium according to the procedures outlined by Schmitz and Bowring (2001). Dinkey Creek samples were corrected using a Th/U ratio of 4, an average of three Th/U ratios reported for Dinkey Creek samples in Bateman et al. (1984). Bass Lake samples were corrected using a Th/U ratio of 2.4, an average of Th/U data reported for Bass Lake samples in Truschel (1997) and Lackey et al. (2012). Raw data were processed and reduced with Tripoli and Redux (Bowring et al., 2011; McLean et al., 2011).

Compilation of Ages

A total of 254 U-Pb zircon and K-Ar and Ar-Ar biotite ages were used in this study to reevaluate spatial age distribution and arc migration rates in the central Sierra Nevada batholith (Table 1). These data were collected either from the original publication or from NAVDAT (North American Volcanic and intrusive rock DATabase; www.navdat.org). NAVDAT search criteria are listed in Appendix 1.

RESULTS

U-Pb Zircon Geochronology

Thorium-corrected analyses of zircon samples from the Dinkey Creek Granodiorite and Bass Lake Tonalite spread along an interval of concordia. Ranges or weighted-mean averages of ^{206}Pb-^{238}U ages are reported for two samples from the Dinkey Creek Granodiorite and four samples from the Bass Lake Tonalite. All analyses are of single-grain fractions. Analytical results are reported in table 3.

Two samples were collected from the equigranular unit of the Dinkey Creek Granodiorite: DCP11-01 from the northeastern portion of the pluton, near the contact with the Mount Givens Granodiorite, and DCP11-02 from the southern lobe. Both Dinkey Creek samples are equigranular granodiorites rich in plagioclase, quartz and prismatic hornblende. DCP11-02 also includes minor amounts of visible titanite. Two analyses of DCP11-01 yield ^{206}Pb-^{238}U ages of 100.61 and 100.68 Ma. These zircon fractions are concordant and overlap within uncertainty. A third fraction is reversely discordant and provides a ^{206}Pb-^{238}U age of 101.04 Ma. Two single-grain fractions from DCP11-02 yield ^{206}Pb-^{238}U ages of 101.09 and 101.36 Ma.

Four samples were collected along an approximately N-S transect through the Bass Lake Tonalite. There is a scatter of ages beyond analytical uncertainty for all Bass Lake samples. The Bass Lake Tonalite is described by Bateman (1992) as a medium-grey, medium-grained equigranular tonalite; however, samples collected in this study displayed a range of compositions and grain sizes.

A hornblende-biotite tonalite (BLT11-01) collected from the southern Bass Lake Tonalite, near Prather, CA, yields three concordant fractions. Two of the concordant fractions overlap within uncertainty and provide ^{206}Pb-^{238}U ages of 107.6 ± 0.23. The ages of all three fractions range from 105.83-108.01 Ma.

Sample BLT11-02, collected south of Millerton Lake, is biotite-rich and dominantly composed of alkali and plagioclase feldspar. This sample yields a spread of ages along concordia from 103.9-135.39 Ma.

A quartz, plagioclase and hornblende-rich tonalite (BLT11-03) was collected from the central portion of the Bass Lake Tonalite in a unit mapped as Cretaceous or Jurassic gabbro (Bateman and Busacca, 1982). Analyses of six single-grain zircon fractions yield a range of ages from 103.8-252.84 Ma.

A quartz, plagioclase and biotite-rich tonalite (BLT11-04) was collected from the northern portion of the Bass Lake Tonalite yields two discordant and one concordant fraction that cluster around 110 Ma. Ages of the three concordant fractions range from 109.12-110.14 Ma.

Compilation of Ages

Geochronologic coverage of the Sierra Nevada batholith has vastly increased since Chen and Moore (1982) presented the idea of inland arc migration. Their study used approximately 88 Cretaceous central Sierran U-Pb zircon ages to analyze spatial age variation. In the three decades since their study, approximately 90 U-Pb zircon ages have been published for the central Sierra (Table 1). A total of 182 U-Pb zircon ages compiled from the NavDat database were used to reevaluate spatial age variation in the central Sierra Nevada batholith. The majority of K-Ar Sierran biotite ages were determined in large-scale studies by Evernden and Kistler (1970) or du Bray and Dellinger (1988). Modern Ar-Ar biotite ages have been determined for the eastern Sierra Nevada in studies by Tobisch et al. (1995), Memeti et al. (2010), and Davis et al. (2012). Biotite data are generally sparse in the western part of the Sierra Nevada (including the Bass Lake Tonalite). A total of 72 K-Ar and Ar-Ar biotite ages for the central Sierra Nevada batholith were used to evaluate spatial variation (Table 1).

Central Sierran U-Pb zircon ages range from 75.8 to 123.9 Ma. Age coverage is widespread throughout the central Sierra Nevada, particularly in the Tuolumne and John Muir intrusive suites (Fig. 1). The precision of published ages varies greatly based on the method used and when the study was conducted. Older TIMS studies, such as Stern et al. (1981) and Chen and Moore (1982), do not report 2σ errors. Modern TIMS studies report ages with average errors that range from 0.1 to 1 Ma (Coleman et al., 1995; Tobisch et al., 1995; Coleman et al., 2004; Gray et al., 2004; Memeti et al., 2010; Davis et al., 2012). Ages determined by LA-ICPMS generally have larger 2σ errors that range from ~1-4 Ma (Lackey et al., 2012).

Central Sierran biotite K-Ar and Ar-Ar ages range from 69 to 126 Ma. The majority of published K-Ar and Ar-Ar biotite ages were determined for rocks of the eastern Sierra, including those of the Tuolumne, John Muir, and Mount Whitney intrusive suites (Tobisch et al., 1995; Memeti et al., 2010; Davis et al., 2010). Studies by Evernden and Kistler (1970) and du Bray and Dellinger (1988) provide ages for granodioritic plutons south of the Mount Whitney intrusive suite. Few widespread biotite studies have been done in the western extents of the batholith; however, eight ages are published for plutons of the Shaver and Fine Gold intrusive suites (Noyes et al., 1983; Tobisch et al., 1995). The three oldest biotite ages are in the far western portion of the batholith; from west to east, these ages are 126 ± 4 Ma, 103 ± 3 Ma (Naeser et al., 1971) and 101.5 ± 3.5 Ma (Bateman et al., 1983). The oldest biotite ages, 126 ± 4 Ma and 103 ± 3 Ma, were determined from borehole samples at depths of 3 and 485 m, respectively (Naeser et al., 1971). These boreholes are located in the western extent of the central Sierra Nevada batholith and were sampled as part of a USGS heat flow study.

The errors of central Sierran biotite ages vary depending on which method was used. Ages determined in modern studies by the Ar-Ar method, such as those by Tobisch et al. (1995), Memeti et al. (2010) and Davis et al. (2010), are less than 1 Ma. Ages determined by the K-Ar method (Evernden and Kistler, 1970; Naeser et al., 1971; Bateman et al., 1983; du Bray and Dellinger, 1988) have errors that range from 1-9 Ma.

DISCUSSION

U-Pb Zircon Geochronology

Two samples from the Dinkey Creek Granodiorite (DCP11-01 and DCP11-02; Fig. 2) are identical in age within error at 100.75 and 101.21. Sample DCP11-02 is approximately 3 Ma younger than a nearby sample of Stern et al. (1981). Analyses of zircons from Dinkey Creek samples do not show evidence of inherited grains.

Analyses of samples from the Bass Lake Tonalite show significant evidence of an inherited component and indicate a complex magmatic history for the area. Grains that are much older (several million years) than the majority of a sample's zircon population are interpreted to be inherited grains, or xenocrysts (Miller et al., 2007). Ages of zircons from samples BLT11-02 and BLT11-03 spread along a large interval of concordia; therefore, it is impossible to interpret a precise magmatic age from these data. Inherited grains in these samples are generally early Cretaceous in age, ranging from ~112 to ~137 Ma. However, two grains in sample BLT11-03 yielded Triassic ages of 220.62 Ma and 252.84 Ma. These inherited grains are much older than any granitic rocks exposed in the area. This sample was collected near units mapped as metamorphosed Jurassic and Triassic rocks, a possible source for these inherited Triassic grains. The inheritance seen in Bass Lake Tonalite samples is consistent with inheritance seen in published ages of four samples from the Fine Gold Intrusive Suite (Lackey et al., 2012).

Samples BLT11-01 and BLT11-04 show no evidence of inherited grains. I interpret approximate ages of ~107 Ma and ~110 Ma, respectively. These approximate ages are consistent with those provided by Lackey et al. (2012). Two published Bass Lake Tonalite ages near sample BLT11-01 are similar to this sample's interpreted age, at 105 ± 2.4 Ma and 107.5 ± 3.5 Ma (Lackey et al., 2012). A Bass Lake sample located ~9 km northwest of sample BLT11-04 is 110.6 ± 1.3 Ma and a nearby Hogan Mountain sample is 118.4 ± 1.3 Ma (Lackey et al., 2012).

Spatial Age Variation in the Central Sierra Nevada Batholith

A compilation of 254 U-Pb zircon ages, including the new data presented here, for rocks from the central Sierra Nevada batholith does not define a linear west-to-east migration across the central Sierran arc. Rather, spatial age variation in the central Sierra is defined by three patterns: a regional shift in magmatism, a west-to-east migration of the end of magmatism, and internal age variation within individual intrusive suites (Figs. 3 and 4). No spatial age patterns are observed among K-Ar and Ar-Ar biotite ages in the central Sierra, other than a regional cluster of ages around 78-90 Ma (Fig. 5).

Eastward Migration of the Cretaceous Sierran Arc?

The new U-Pb data suggest that the migration of Cretaceous magmatism was stepwise, rather than progressive. Both the western and eastern Sierra preserve cycles whereby magmatism is widespread at the onset and concentrates eastward through time. These cycles are separated by a lull in magmatism.

From 125 to 105 Ma, magmatism was concentrated in the western portion of the batholith (Figs. 3, 6). Magmatism initiated across the entire western region and gradually concentrated along the eastern edge of this part of the batholith (Fig. 6). Magmatic activity persisted along the eastern edge of this region from the onset at 125 Ma until the end of the western cycle at 105 Ma (Fig. 6; Movie 1; Appendix 2).

After final emplacement of the Bass Lake Tonalite in the western batholith at ~ 105 Ma, magmatism apparently waned until the emplacement of Dinkey Creek Granodiorite at ~101 Ma. The Dinkey Creek pluton was the only pluton intruded in this interval and limited geochronologic data suggest it was assembled quickly. Another brief hiatus occurred after the emplacement of the Dinkey Creek Granodiorite, and that lull was followed by the onset of the Sierra Crest magmatic event at 98 Ma (Coleman and Glazner, 1997).

Magmatism in the eastern Sierra began at 98 Ma with the beginning of emplacement of the Mount Givens Granodiorite (Frazer, 2013) and was widespread throughout the eastern Sierra at the onset. As for the earlier, western Sierra event, over time, magmatism concentrated eastward, until the end at ~84 Ma. Also similar to the earlier western episode, magmatism occurred along the eastern edge of the region throughout the entire cycle (Fig. 11).

The west-to-east decrease in age observed by Chen and Moore (1982) is still present among the new high-precision U-Pb data for the central Sierra Nevada batholith (Fig. 6; Movie 1). However, this pattern is not a function of the onset of magmatism at any given longitude. Rather, it is a function of the regular, eastward progression of the end of magmatism at any longitude. The onset of magmatism at any given longitude is a step function and is dominated by two major magmatic cycles, in the western and eastern regions of the batholith.

Hypotheses Accounting for the Patterns in Magmatism

There are several hypotheses that could explain the eastward step in the concentration of magmatism in the Sierra Nevada batholith (Fig. 7). Flat-slab subduction is the original model used to explain the eastward decrease in age of central Sierran plutonic rocks (Coney and Reynolds, 1977; Chen and Moore, 1982). This hypothesis predicts that as the subducting slab flattens, the locus of magmatism migrates inland, creating a pattern of older rocks near the coast and younger rocks further inland (Fig. 7B).

A second hypothesis for the cause of eastward concentration of magmatism is the effect of subduction erosion (Fig. 7C). The Andean margin of northern Chile is a sediment-starved margin, and thought to be tectonically similar to the subduction system that formed the Sierra Nevada batholith. Since the early Jurassic, the axis of arc volcanism in northern Chile has migrated ~200 km inland, perhaps in response to subduction erosion (Rutland, 1971; von Huene and Scholl, 1991). Thrusting at the deformation front can occur at convergent margins and cause shortening. Shortening that occurs without decrease the dip of the subducting slab results in an inland migration of the locus of magmatism. Western magmatism ceases and older arc material moves trenchward.

Both flat-slab subduction and subduction erosion can explain the shift observed in the locus of magmatism between ~105 and 98 Ma, but neither can account for the internal pattern of the widespread magmatism at the onset with a progressive narrowing of the locus of magmatism toward the eastern margin. I propose that this pattern is driven by magma supply dynamics induced by magma flow in the mantle (Ducea, 2001; Glazner et al., 2005; Fig. 7D). Mantle circulation is fertile at the onset, providing widespread fluxes of magma. Over time, mantle being fed to the western part of the arc is depleted as a result of driving magmatism in the east. At the same time, the eastern side of the arc is constantly being fed a "fresh" supply of mantle; consequently, the locus of magmatism focuses toward the east. I suggest that this hypothesis is the most favorable of the three presented here to account for the internal age variation in both the older (western) and younger (eastern) cycles; however either flattening of the slab or subduction erosion may account for the step in the locus of magmatism between 105 and 98 Ma.

Internal Age Patterns

Although the plutons of the western Sierra Nevada lack the detailed geochronologic coverage present in the eastern Sierra, recently published data for the Bass Lake Tonalite suggest an eastward decrease in age for this area. Lackey et al. (2012) divided the Bass Lake Tonalite into three spatiotemporal domains. These domains show a general eastwardly younging trend, which is consistent with the original interpretations of Chen and Moore (1982). However, rocks that fall within the central domain age range (109-114 Ma) are exposed along the eastern geographic boundary of the Bass Lake Tonalite, suggesting some component of concentric zoning (Lackey et al., 2012). Two samples from this study, BLT11-01 and BLT11-04, were collected from the eastern domain, which includes rocks ranging in age between 108 and 105 Ma. Sample BLT11-01 (~107 Ma) falls within this age range, whereas BLT11-04 (~110 Ma) falls within the central domain age range. The boundary between the eastern and central domains is uncertain in the area near the location of BLT11-

04, and this sample's age may draw this boundary further to the east. Alternatively, the domains outlined by Lackey et al. (2012) may not be robust.

The new data provided for the Dinkey Creek granodiorite, in conjunction with published data for that area, do not define any spatial age patterns. The four concordant ages from the Dinkey Creek are all ~101 Ma (Tobisch et al., 1995; Lackey et al., 2012). More data are necessary, particularly from the central and southeastern lobe of the Dinkey Creek Granodiorite, to fully understand how age varies in this area. However, the preliminary data suggest the ~1500 km^2 pluton may have been assembled anomalously rapidly relative to other well-dated plutons (e.g., Coleman et al., 2004; Matzel et al., 2006; Michel et al., 2008; Davis et al., 2012). This possibility is worthy of investigation.

Although the Sierra Crest plutons were intruded over the same time period between approximately 98 and 85 Ma, each preserves a different spatial age variation and no batholith-scale trend is evident. For example, the Tuolumne Intrusive Suite preserves a well-documented concentrically zoned age pattern (Evernden and Kistler, 1970; Coleman et al., 2004; Figs. 4, 8). The Tuolumne progresses from older, mafic granodiorite on the outer margins to younger, more felsic granodiorite or granite in the center (Evernden and Kistler, 1970; Coleman et al., 2004).

The Mount Givens Granodiorite and John Muir Intrusive Suite were intruded adjacently from ~98-84 Ma (Davis et al., 2012; Frazer, in progress; Fig. 3). No linear, west-to-east age progression is preserved in either pluton. The oldest rocks of the Mount Givens Granodiorite, ~98-95 Ma, are in the northwest part of the pluton and the youngest rocks, ~92-91 Ma, are in the southeast portion of the pluton (Frazer, 2013). Thus, the spatial age variation in the Mount Givens Granodiorite is largely dominated by a decrease in age to the southeast (Frazer, 2013). In contrast, the oldest rocks of the John Muir Intrusive Suite are in the southwest part of the pluton and age progressively decreases to the northwest from ~96-84 Ma (Davis et al., 2012). Although the Mount Givens pluton and the John Muir Intrusive Suite were assembled during the same time period, they preserve opposite-trending spatial age variations.

The lack of batholith-scale migration patterns, at least in the eastern Sierra Nevada, suggests that spatial age variation is not controlled by arc-scale mechanisms. Some component of inland arc migration may be preserved in the eastwardly-younging Bass Lake Tonalite; however, additional data are necessary to fully understand spatial age variation in this area.

Coleman et al. (2012) interpreted the spatial age pattern in the Tuolumne Intrusive Suite to reflect pluton emplacement processes; specifically, doming of the roof over a top-down, incrementally assembled laccolith (Coleman et al., 2012; Fig. 8). Further south, the Mount Whitney Intrusive Suite displays a similar spatial age variation of older, more mafic outer margins. The model of Coleman et al. (2012) is essentially identical to the model proposed for assembly of the Mount Whitney Intrusive Suite (Hirt, 2007).

The intrusive patterns of the John Muir Intrusive Suite and Mount Givens Granodiorite are more complex. Tikoff and Teyssier (1992) interpreted all of the Sierra Crest plutons to have been assembled over 5-10 Ma in tensional bridges within a batholith-scale right lateral shear zone. Consistent with this suggestion, Davis et al. (2012) interpreted at least part of the John Muir Suite to have been assembled as a sheeted dike complex. Both of these interpretations suggest that the spatial age variations in the John Muir Intrusive Suite and the Mount Givens Granodiorite reflect local intrusion styles and tectonics.

Regional Biotite Ar Age Patterns

Central Sierran biotite ages define no clear east-west or north-south age patterns. The majority of biotite ages of plutonic rocks in the central Sierra Nevada batholith fall between 78 and 90 Ma, independent of the corresponding intrusive age (Fig. 5). Few ages fall outside this cluster and the three ages that are older than 100 Ma are located in the far western Sierra. In general, the older biotite ages are located further west, in the Shaver Intrusive Suite and Mount Givens Granodiorite (Tobisch et al., 1995). However, biotite data for the western Sierra is too limited to determine whether any east-west trends are present.

Figure 9 shows the relationships between zircon and biotite ages in three different areas of the central Sierra. Each point in Figure 9 represents a single sample for which there are both biotite and zircon data (Table 4). For all three suites, there is a positive correlation between crystallization age and Tz-Tb, and a tendency of biotite ages to cluster near the youngest zircon ages of the suite.

Two main hypotheses exist regarding the relationship between zircon and biotite ages in the central Sierra Nevada batholith: biotite ages reflect cooling related to a regional (batholith-wide) event, or biotite ages reflect cooling related to a local (intrusive suite) event. Regional events could include a rapid batholith-wide exhumation that occurred ca. 85-95 Ma (e.g., Renne et al., 1993; Saleeby et al., 2008) or conductive cooling (e.g., Dumitru et al. 1991; Saleeby, 2003). Unroofing is thought to have progressed eastward, following the eastward migration of magmatism (Nadin and Saleeby, 2008), although the present study suggests this was more likely a step to the east rather than a steady migration. Stratigraphic evidence for this rapid unroofing event includes a record of fore-arc sedimentation in the Great Valley sequence and an increase in sedimentation rate in deep-sea fan deposits (Mansfield, 1979; Renne et al., 1993). Biotite age patterns may also be explained by a regional conductive cooling event caused by subduction (Dumitru et al., 1991; Saleeby, 2003). This event may be coincident with the beginning of shallow-angle subduction (Dumitru et al., 1991) The second hypothesis is that biotite ages reflect cooling related to the end of local magmatism (Davis et al., 2012). These authors suggest that, in the John Muir Intrusive Suite, biotite ages are determined by the onset of post-magmatic cooling.

The proposed batholith-wide unroofing event and waning of the Sierra Crest magmatic event are essentially contemporaneous; therefore, it is difficult to discern whether the regional cluster of biotite ages around 80-90 Ma reflects regional cooling related to exhumation, or to the end of Cretaceous magmatism, or some combination of both. If central Sierran biotite ages are governed by post-magmatic cooling, biotite ages should increase westward. The new U-Pb zircon data for the Bass Lake Tonalite should be supplemented with Ar-Ar biotite ages to rigorously test this hypothesis in the westernmost Sierra Nevada batholith.

Regional Deformation in the Eastern Sierra and Migration of the Sierran Arc

From 90-80 Ma, deformation in the eastern Sierra Nevada batholith was predominantly transpressional extensional and transitioned to mainly dextral transpressional at ~90 Ma (Tikoff and Teyssier, 1992; Tobisch et al., 1995). Tobisch et al. (1995) interpreted deformation in the central Sierra Nevada batholith to progress from west to east on the basis of eastwardly younging U-Pb crystallization and Ar-Ar cooling ages of rocks in the shear zones. New geo-and thermochronologic data suggest these interpretations should be refined. For example, new high-precision U-Pb zircon data refine the emplacement age of the Mount Givens Granodiorite from 90 +3/-4 to an emplacement range of 97.9-90.9 Ma (Frazer, 2013). Additionally, the new interpretation of central Sierran spatial age variation presented here suggests the monotonic eastward decrease in age interpreted from early geochronology studies is not present in the central Sierra.

The temporal step in magmatism within the Cretaceous central Sierran arc is associated spatially with these well-developed shear zones. Movement along the Courtright, Quartz Mountain and Kaiser Peak shear zones, which define the eastern margin of the 101 Ma Dinkey Creek pluton, began at ~102 Ma (Tobisch et al., 1995). Movement along the Bench Canyon shear zone also began at ~102 Ma (Tobisch et al., 1995). To the east, movement along the Rosy Finch, Gem Lake and Cascade Lake shear zones began later, at ~88 Ma (Tobisch et al., 1995; Tikoff and Saint Blanquat, 1997; Tikoff and Greene, 1994; Green and Dutro, 1991; Sharp et al., 1993; Greene and Schweickert, 1995; Davis, 1995). Further east, Mahan et al. (2003) demonstrated that deformation associated with the Sawmill Lake shear zone, along the eastern margin of the Sierra Crest plutons, predated the onset of Cretaceous magmatism in that area (pre-95 Ma). Therefore, it is possible that movement along the Rosy Finch, Gem Lake and Cascade Lake shear zones began earlier than local magmatism.

Nadin and Saleeby (2008) demonstrate that spatial age variation of U-Pb zircon ages in the southern Sierra Nevada batholith is disrupted by deformation along the southern extent of the proto-Kern Canyon fault. Disruption in the southern Sierra is contemporaneous with the magmatic shift and onset of shearing in the central Sierra. The sharp step in ages reflects

~10 Ma of missing plutonic activity along the southern proto-Kern Canyon fault between ca. 100 and 90 Ma, and is attributed to east-west crustal shortening across the shear zone (Nadin and Saleeby, 2008). These authors did not recognize a similar pattern of disruption caused by the Sierra Crest shear system; however, the more complete dataset used in this study demonstrates that this pattern continues to the north (Fig. 6). Thus, there appears to be a batholith-scale event that is reflected in rocks assembled along at least 250 km of arc length and throughout approximately 15 km of crustal thickness (Saleeby, 2003; Nadin and Saleeby, 2008).

I propose that by ~102 Ma, a laterally extensive shear zone was established along the eastern margin of the Cretaceous batholith (Fig. 10). I propose that deformation was focused along the eastern boundary of the batholith as a result of concentration of young plutons, such as the Dinkey Creek Granodiorite and the youngest Bass Lake Tonalite. Following a short hiatus, magmatism resumed and from 98-95 Ma, the Sierra Crest magmatic event was focused along and began to dissect the regionally extensive shear zone. Individual strands of the shear zone may have been inactivated and new portions of the shear zone (e.g., the Rosy Finch Shear Zone) that are contained entirely within younger (post-95 Ma) plutons may have developed at this time.

The spatial age variation in the Mount Givens Granodiorite and John Muir Intrusive Suite may directly reflect deformation in this shear zone. Bends along the Rosy Finch shear zone may have permitted the formation of dilational jogs that permitted intrusion of magmas (Fig. 11). The spatial age patterns preserved in the Mount Givens Granodiorite and John Muir Intrusive Suite are consistent with incremental pluton growth along a releasing bend in the Rosy Finch shear zone (Fig. 11).

Emplacement of silicic magmas along dilational jogs in an extensional environment can be sustained by typical continental crustal extension rates (Hanson and Glazner, 1995). Half extension rates for continental crust are ~10-20 mm/a and displacement rates along strike-slip faults in transpressive environments average ~30 mm/a (Hanson and Glazner, 1995; Jarrad, 1986; Paterson and Tobisch, 1992). Using the distance from the oldest (~95 Ma) samples in the Mount Givens Granodiorite (north) and John Muir Intrusive Suite (south) to an 88.8 Ma sample near the Rosy Finch shear zone yields a half extension rate of ~8-9 mm/a. The half extension rate of ~10 mm/a required is thus comparable to typical continental crustal extension rates. However, this hypothesis should be rigorously tested with additional geochronologic data. This hypothesis is a modification of the P-shear hypothesis of Tikoff and Teyssier (1992) and both processes of magma localization may be important in the problem of pluton emplacement.

Correlation of late Cretaceous magmatism and development of batholith-down shear zones has also been attributed to late-stage sinking of the batholith (Glazner et al., 2003). According to this hypothesis, movement along the shear zones reflects settling of plutons and the volcanic pile into the heated deeper crust. Whereas some of the latest stage of motion along the Cretaceous shear zones may reflect such a process, it seems difficult to reconcile the regional cooling of the plutonic rocks recorded in the biotite ages with contemporaneous sinking if that cooling is tectonic. Instead, if the cluster of biotite ages reflects relaxation of the geothermal gradient associated with the end of Sierra Crest magmatism (Davis et al., 2012), then there could be a more significant component of batholith sinking preserved in the shear zones.

CONCLUSIONS

Compilation of U-Pb zircon and K-Ar and Ar-Ar biotite ages for the central Sierra Nevada batholith does not support a steady inland migration of the Cretaceous arc. Individual intrusive suites of the central Sierra Nevada preserve unique spatial age patterns, which I interpret to reflect local intrusion processes and regional tectonics. A regional magmatic shift from west to east occurred at ~100 Ma, contemporaneous with the onset of deformation along ductile shear zones in the eastern Sierra. Sierran magmatism is characterized by two cycles during which magmatism initiates across a region of the batholith and concentrates eastward over time. This pattern is not likely to reflect either flattening of the slab or subduction erosion alone. Instead, I hypothesize that one of these processes, combined with progressive depletion on mantle supplied from east to west above the subducting slab, accounts for the spatio-temporal variation in magmatism.

Central Sierran biotite cooling ages may reflect a rapid, batholith-wide unroofing event or cooling related to the waning of local magmatism. Cretaceous K-Ar and Ar-Ar biotite ages in the central Sierra Nevada batholith preserve a cluster of ages between ~78 and 90 Ma, which may reflect either hypothesis. This pattern should be tested rigorously with additional data from the Bass Lake Tonalite and the eastern Sierra shear zones.

At ~102 Ma, a laterally extensive shear zone formed along the eastern margin of the Cretaceous batholith. I propose that this shear zone was localized and dissected by plutons of the Sierra Crest magmatic event at ~98 Ma. Movement began along the Courtright, Kaiser Peak, Quartz Mountain and Bench Canyon shear zones by ~102 Ma, which predates intrusion of the Sierra Crest plutons. Similarly, movement along the Sawmill Lake shear zone pre-dated Cretaceous magmatism in the area. These interpretations suggest that movement along the Rosy Finch, Cascade Lake and Gem Lake shear zones should be refined using additional Ar-Ar biotite data. I hypothesize that the spatial age patterns preserved in the Mount Givens Granodiorite and John Muir Intrusive Suite reflect deformation along the Rosy Finch shear zone; however, this hypothesis should be rigorously tested with additional geochronologic data.

Fig. 1

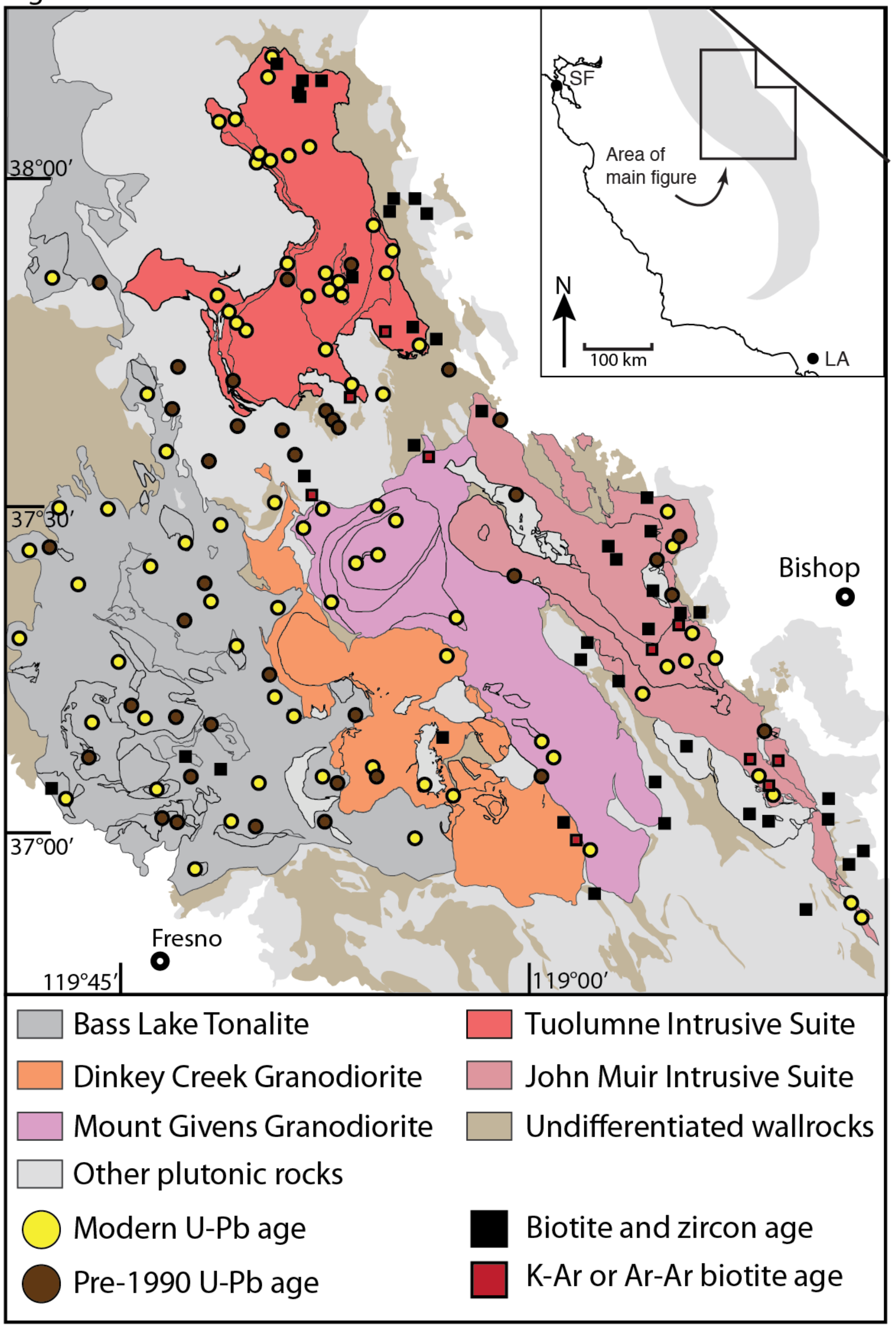

Figure 1: Geology of central Sierra Nevada batholith. Map showing locations of U-Pb zircon and K-Ar and Ar-Ar ages for the central Sierra Nevada batholith. Only main intrusive suites of the central Sierra Nevada batholith are shown here. Sample locations are approximate. See text and Table 1 for age sources. Map after Bateman (1992); Coleman et al. (2004); Cruden et al. (1999); Lackey et al. (2008).

Figure 2

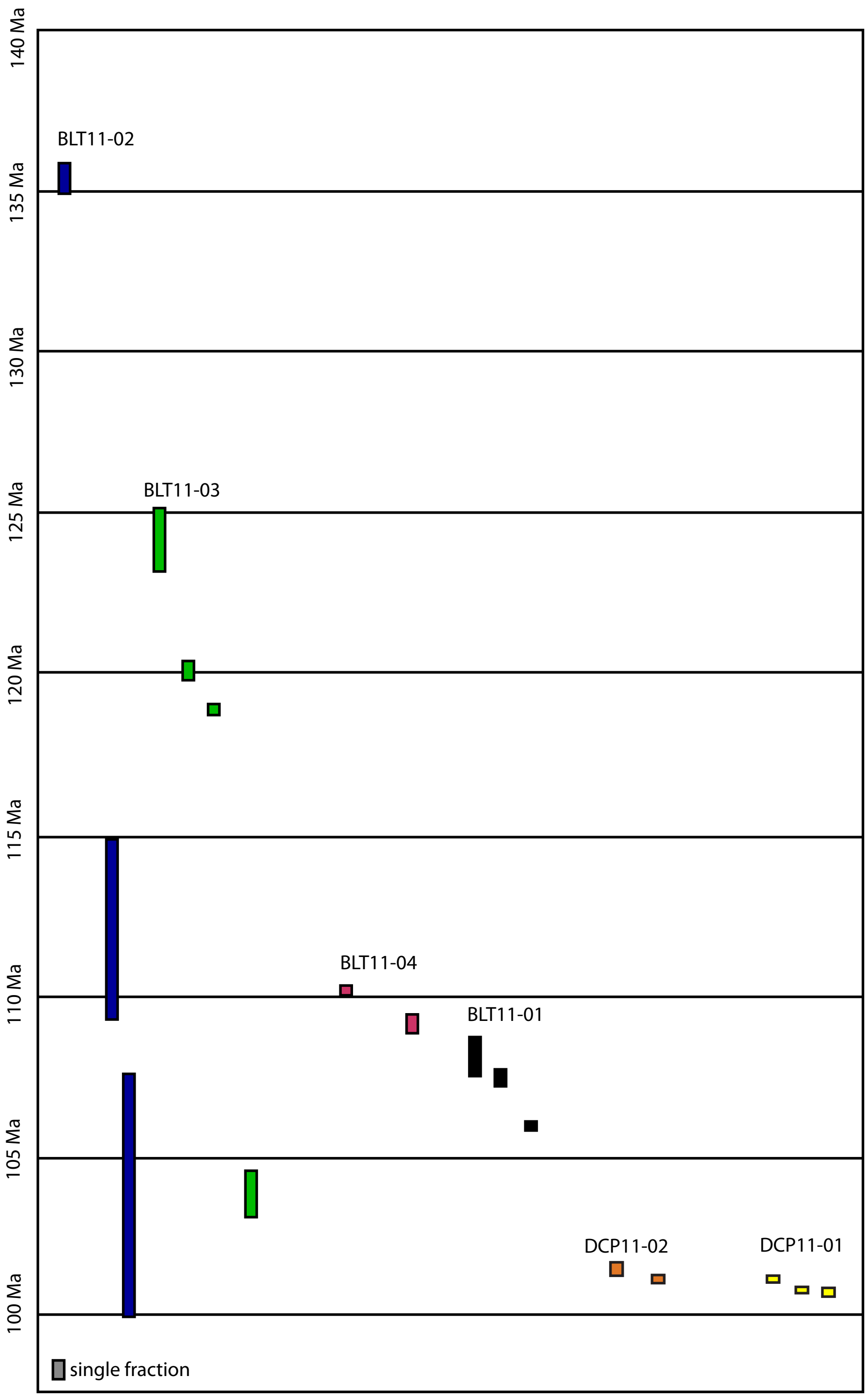

Figure 2: Crystallization ages of Bass Lake Tonalite and Dinkey Creek Granodiorite. Compilation of $^{206}Pb/^{238}U$ ages for individual zircon fractions from the Bass Lake Tonalite and the Dinkey Creek Granodiorite. Vertical length of box represent 2-sigma uncertainties. Ages of inherited grains (older than 200 Ma) from BLT11-03 are not included in this figure.

Fig. 3

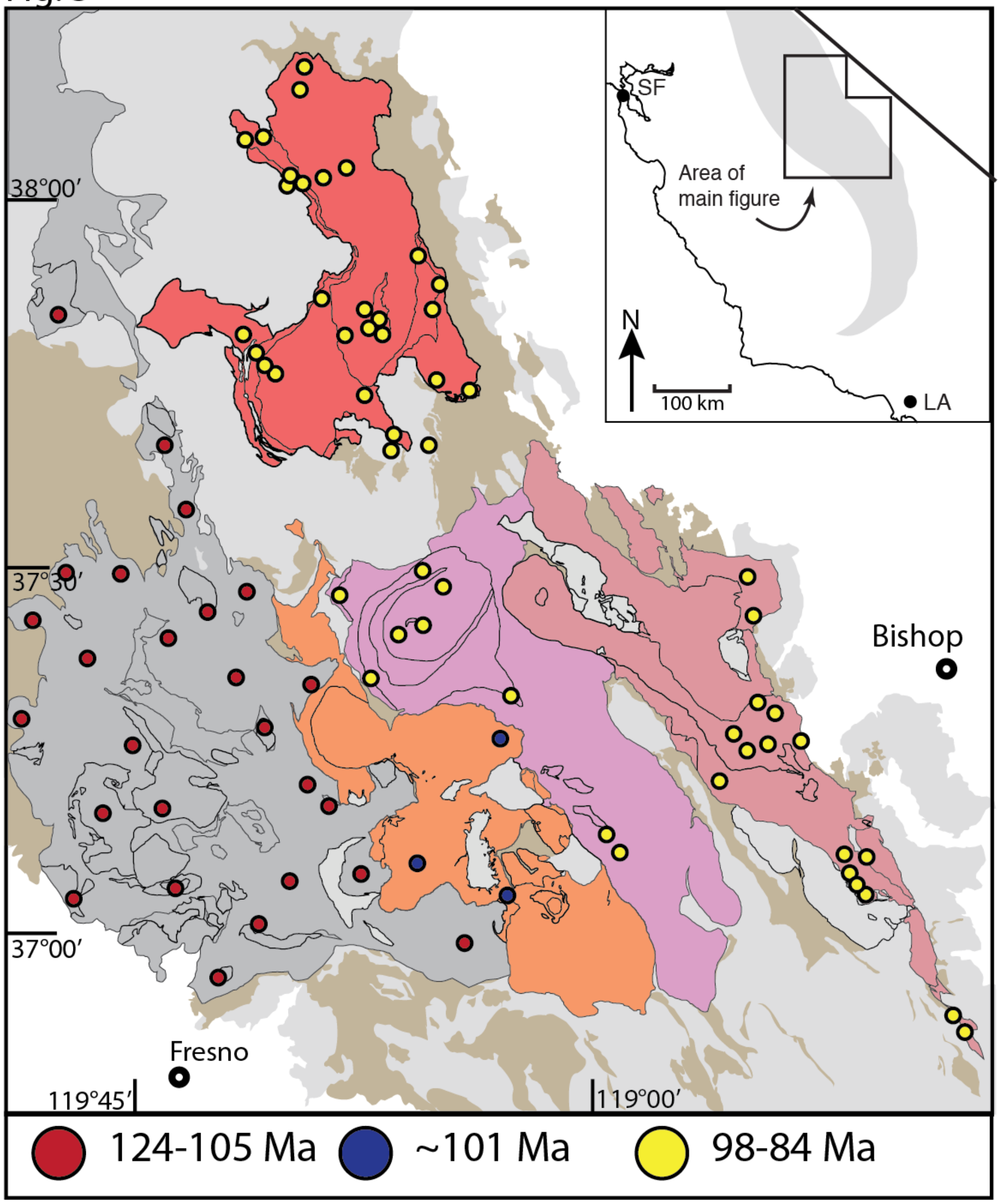

Figure 3: Cretaceous Magmatic shift. Map showing ~100 Ma shift in magmatism. Map unit designations same as Figure 1.Shift in magmatism coincides spatially and temporally with the beginning of movement along ductile shear zones in the eastern Sierra Nevada batholith.

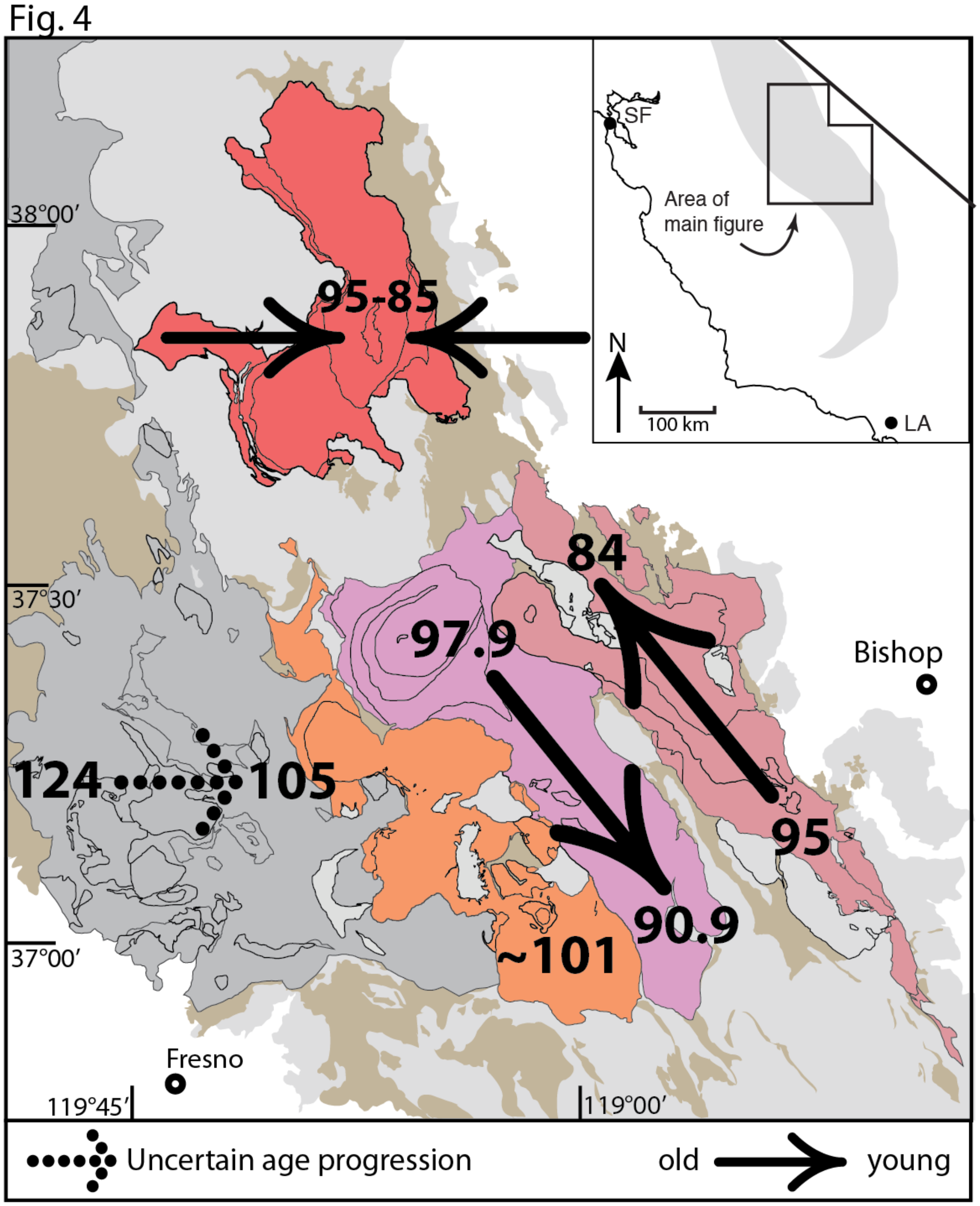

Figure 4: Age patterns within central Sierran intrusive suites. Map showing spatial age patterns of the main intrusive suites of the central Sierra Nevada batholith. Arrows point towards younger ages. Listed ages indicate age range of each intrusive suite. All ages are in Ma. Map unit designations same as Figure 1.

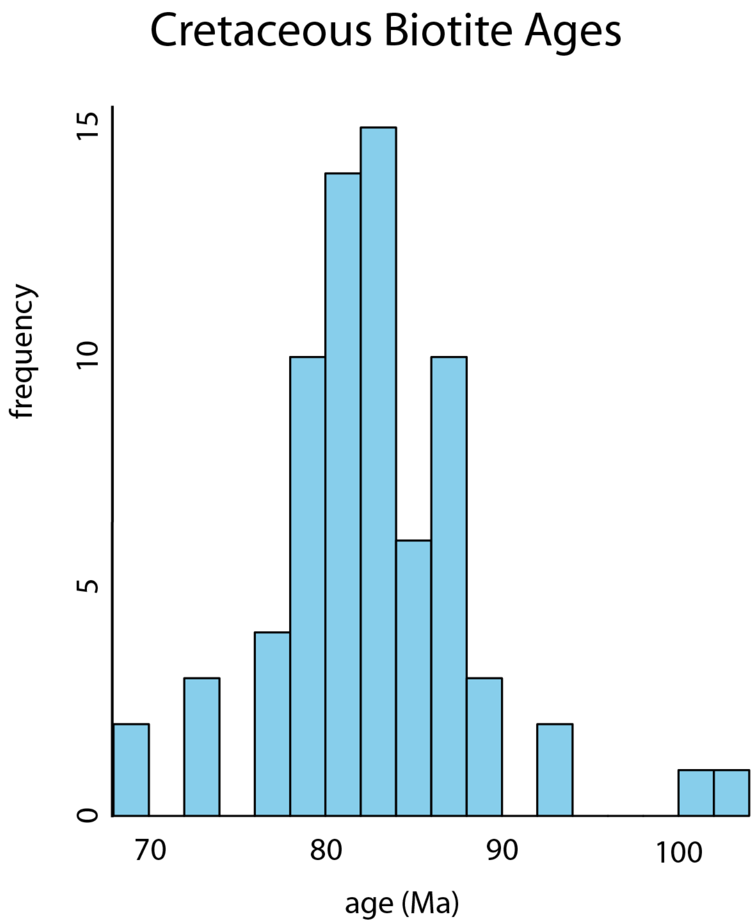

Figure 5: Histogram of Cretaceous K-Ar and Ar-Ar biotite ages in the central Sierra Nevada batholith. Central Sierran biotite ages cluster between ~78 and 90 Ma.

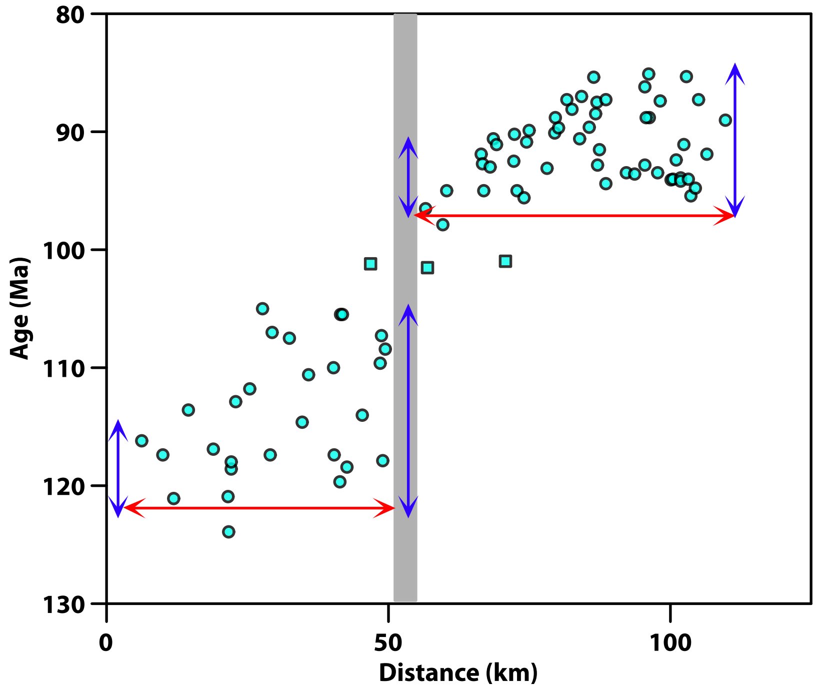

Figure 6: Central Sierran age profile. Profile of modern (post-2000) U-Pb zircon ages between 37° and 38° N; ages from this study; Coleman et al. (2004); Matzel et al. (2005); Matzel et al. (2006); Bracciali et al. (2008); Burgess and Miller (2008); Memeti et al. (2010); Lackey et al. (2012); Davis et al. (2012); and Frazer (2013). Ages are projected on to a line perpendicular to the axis of the batholith. Gray area represents location of Courtright shear zone. Squares represent location of the Dinkey Creek Granodiorite, which are in the gap between the eastern and western parts of the batholith. Red arrows highlight widespread magmatism at the onset of the pre- and post- 101 Ma events. Blue arrows indicate consistent magmatism in easternmost areas of each region, and short periods of magmatism at the westernmost area in each region. Positive slope in age across the batholith indicates eastward progression of the cessation of arc magmatism.

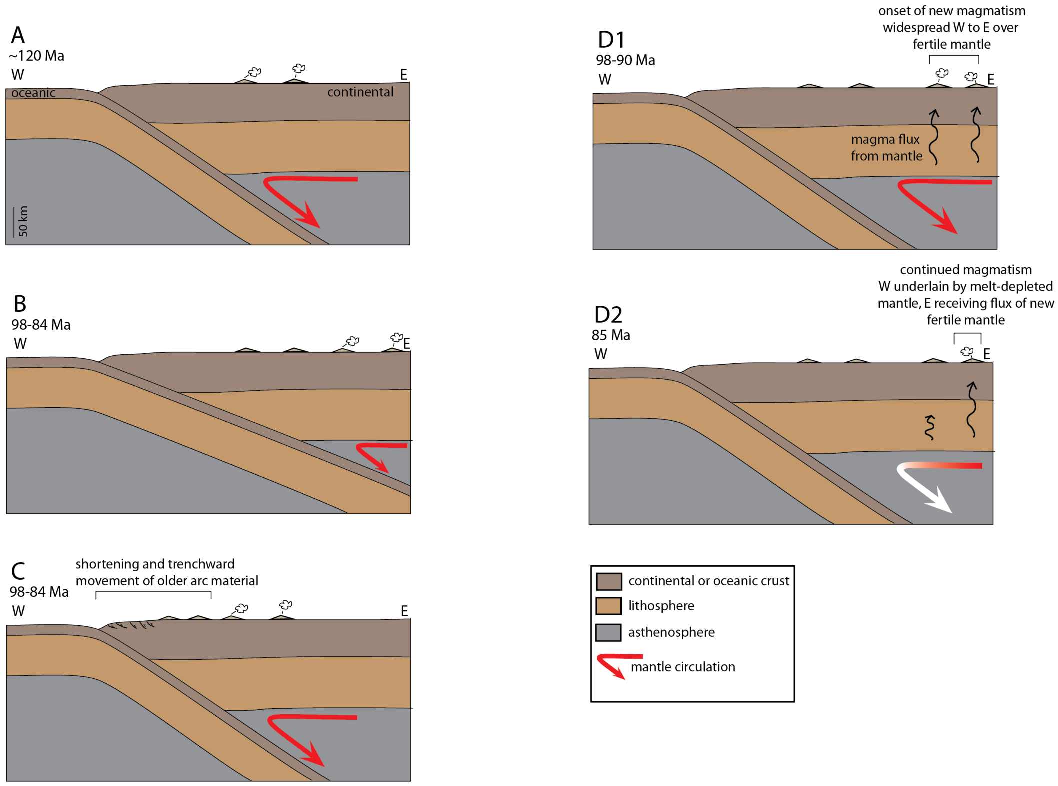

Figure 7.:Hypotheses for cause of inland migration of the end of magmatism. Large red arrows show mantle circulation. Continental/oceanic designations and scale same for A-D.(A) Schematic model of Cretaceous arc magmatism at ~120 Ma. Magmatism is widespread across the batholith at the onset. (B) Flat-slab hypothesis. Shallow angle subduction causes the subducting slab to flatten. Flattening of the subducting slab causes the locus of magmatism to migrate inland, and western magmatism ceases in response. (C) Subduction erosion hypothesis. Thrust faults can occur at the deformation front in a subduction zone and cause shortening. If shortening occurs without a change in the dip of the subducting slab, the locus of magmatism migrates inland. Older arc material moves trenchward over time. (D1) Mantle depletion hypothesis. Melting is widespread from west to east as magma mantle underlying the entire region is fertile. (D2) Magmatism during waning period. Size of melt arrows is proportional to amount of melt; lighter color indicates increasing melt depletion. While the eastern portion of the area continues to receive an influx of fertile mantle, the mantle source becomes progressively depleted westward, causing melting to decrease. This progressive depletion of magma may cause the eastward concentration of magmatism in the central Sierra Nevada batholith. The cycle depicted in D1 and D2 also occurred in the western Sierra, from 120-105 Ma.

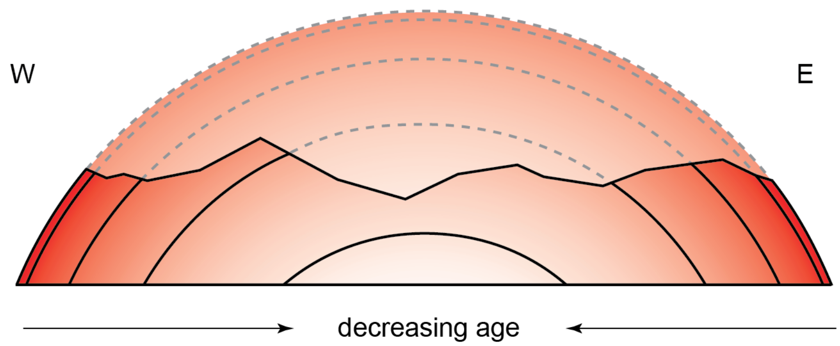

Figure 8: Emplacement model for Tuolumne Intrusive Suite simplified from Coleman et al., 2012. Darker shades indicate older magmas. The Tuolumne Intrusive Suite is interpreted to have been constructed as a top-down series of magmas in an inflating laccolith. Highly schematic present level of exposure is indicated. This interpretation predicts the concentric pattern of old intrusive rocks on the external margin of the suite, becoming progressively younger inward.

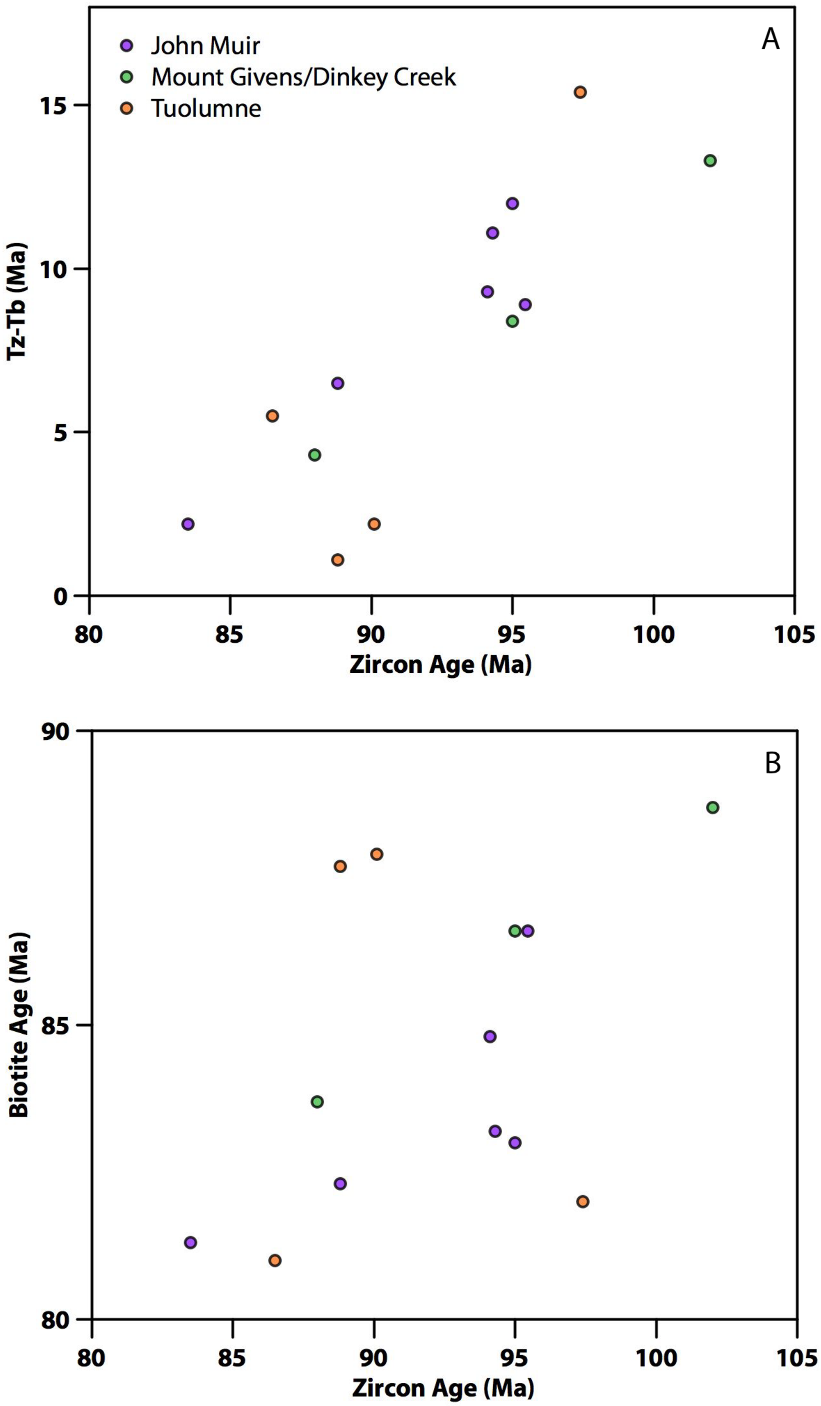

Figure 9: Relationships between biotite and zircon ages for the John Muir and Tuolumne intrusive suites and Mount Givens and Dinkey Creek granodiorites. Panel A shows zircon age plotted against the difference between zircon and biotite age (Tz-Tb) and panel B shows zircon age plotted against biotite age. Each point represents a single sample for which both biotite and zircon ages are published. Older rocks display a larger difference between biotite and zircon age. Note that this positive trend in data is present in all three areas of the eastern Sierra.

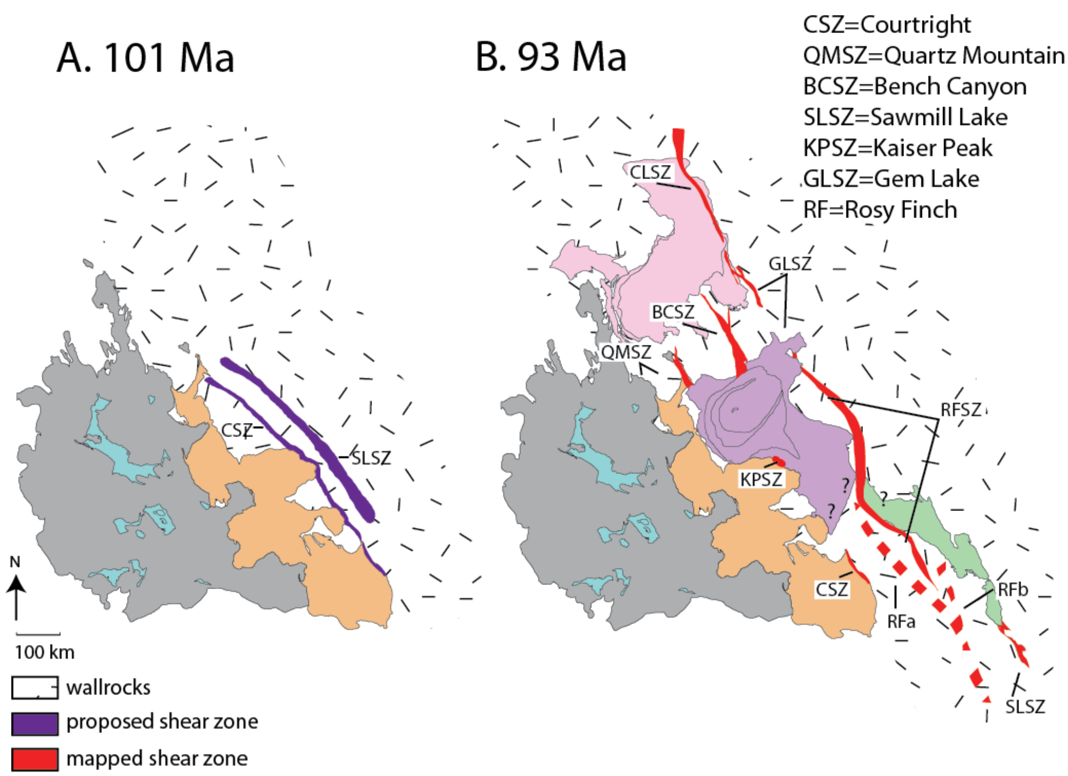

Figure 10: Cretaceous eastern Sierra shear zone model. See Figure 4 for map symbol explanation, shear zone names and present-day location of plutons and shear zones. (A) Model showing location of proposed shear zones at ~101 Ma. Courtright shear zone was once laterally extensive on the eastern margin of the Cretaceous batholith. Sawmill Lake shear zone was laterally extensive in older wall rocks. (B) By ~98 Ma shear zones were localized and dissected at ~98 Ma by Sierra Crest plutons. Shapes and location of Mount Givens Granodiorite and John Muir Intrusive Suite and nearby shear zones are inferred. Intrusion of Sierra Crest plutons continued to dissect the shear zone until magmatism stopped at ~ 85 Ma, leaving the present configuration of plutons and shear zones (Fig. 3).

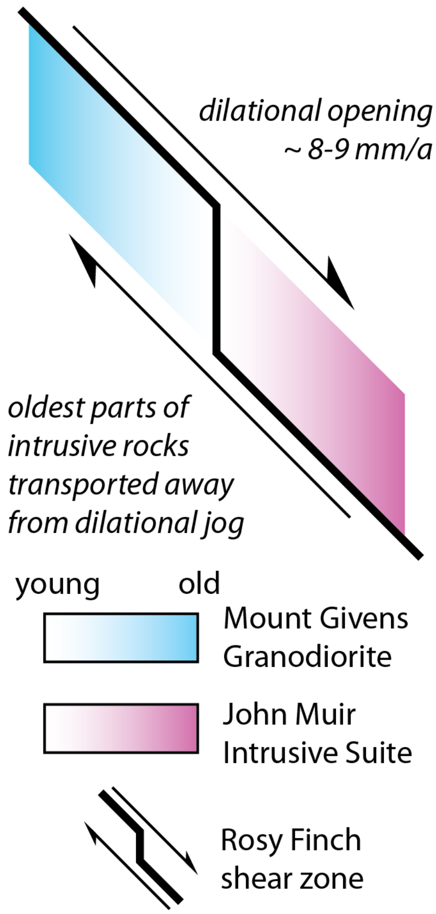

Figure 11: Mount Givens Granodiorite and John Muir Intrusive Suite emplacement model. Highly schematic model of pluton growth along a dilational opening in the Rosy Finch shear zone at ~93 Ma. Darker colors represent older and more mafic rocks; lighter colors represent younger and more felsic rocks. See text for discussion.

TABLE 1. GEOCHRONOLOGIC DATA SOURCES

Author	Year	Method	Number of Ages
Beck	2012	U/Pb zircon TIMS	4
Bateman et al.	1983	K/Ar biotite	1
Bracciali et al.	2008	U/Pb zircon TIMS	1
Burgess and Miller	2008	U/Pb zircon TIMS	2
Chen and Moore	1982	U/Pb zircon TIMS	48
Coleman and Glazner	1997	U/Pb zircon TIMS	3
Coleman et al.	1995	U/Pb zircon TIMS	3
Coleman et al.	2004	U/Pb zircon TIMS	8
Davis	2010	Ar/Ar biotite	6
Davis et al.	2012	Ar/Ar biotite	7
Davis et al.	2012	U/Pb zircon TIMS	10
du Bray and Dellinger	1988	K/Ar biotite	19
Evernden and Kistler	1970	K/Ar biotite	27
Frazer	In progress	U/Pb zircon TIMS	10
Lackey et al.	2012	U/Pb zircon LA-ICPMS	28
Mahan et al.	2003	U/Pb zircon TIMS	2
Matzel et al.	2005 or 2006b	U/Pb zircon TIMS	7
Memeti et al.	2010	U/Pb zircon TIMS	8
Memeti et al.	2010	Ar/Ar biotite	2
Naeser et al.	1971	K/Ar biotite	2
Noyes et al.	1983	K/Ar biotite	2
Stern et al.	1981	U/Pb zircon TIMS	40
Tobisch et al.	1993	U/Pb zircon TIMS	2
Tobisch and Cruden	1995	U/Pb zircon TIMS	1
Tobisch et al.	1995	Ar/Ar biotite	6
Tobisch et al.	1995	U/Pb zircon TIMS	5

TABLE 2. TIMING OF MOVEMENT ALONG SIERRAN SHEAR ZONES

Shear Zone	Shear Sense	Age (Ma) Max	Min	Reference
Quartz Mountain	reverse	102*	87*	Tobisch et al. (1995)
Courtright	reverse	102*	89*	Tobisch et al. (1995)
Kaiser Peak	reverse	102*	91†	Tobisch et al. (1995)
Bench Canyon	reverse	95*	90*	Tobisch et al. (1995)
Cascade Lake	dextral	88*	80*	Davis (1995); Tikoff and Greene (1994)
Gem Lake	dextral	88*	84†	Greene and Dutro (1991); Tikoff and Greene (1994); Greene and Schweickert (1995); Tobisch et al. (1995)
Rosy Finch	dextral	88*	84†	Tikoff and Greene (1994); Tobisch et al. (1995); Tikoff and de Saint Blanquat (1997)
Sawmill Lake	reverse	≥95*	92*	Mahan et al. (2003)

*Evidence from cross-cutting relationships
†Evidence from Ar/Ar ages of metamorphic minerals within shear zone

TABLE 3. U-PB DATA FOR BASS LAKE AND DINKEY CREEK ROCKS

sample	U (ppm)	Pb* (pg)	Th†/U	$^{206}Pb/^{204}Pb$§	$^{206}Pb/^{238}U$#	Error (%)	$^{207}Pb/^{235}U$#	Error (%)	$^{207}Pb/^{206}Pb$#	Error (%)	ages (Ma)** $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Corr. coef.	Total†† common Pb (pg)
DCP11-01 (311527, 4126909)															
F2	1570	45.2	0.41	793	0.01573	0.14	0.10431	0.71	0.04809	0.65	100.61	100.74	104.0	0.494	3.7
F3	2757	105	0.39	3862	0.01580	0.11	0.10433	0.36	0.04709	0.27	101.04	100.76	94.3	0.885	1.7
F10	1077	40.6	0.35	1744	0.01574	0.10	0.10453	0.34	0.04817	0.29	100.68	100.95	107.5	0.636	1.5
DCP11-02 (294356, 4107424)															
F2	968	28.2	0.44	492	0.01581	0.13	0.10528	0.77	0.04831	0.68	101.09	101.63	114.0	0.704	3.7
F3	1449	27.9	0.40	970	0.01585	0.42	0.10480	1.1	0.04798	0.31	101.36	101.20	98.3	1.382	1.9
F12	4606	22.7	0.43	161	0.01612	0.14	0.10840	1.7	0.04878	1.6	103.05	104.50	137.0	0.743	10
BLT11-01 (276318, 4102096)															
F3	708	117	0.35	1187	0.01656	0.11	0.109719	0.37	0.048073	0.30	105.83	105.71	102.90	0.655	6.4
F11	165	84.1	0.40	1328	0.01680	0.23	0.111614	0.48	0.048176	0.40	107.42	107.44	107.90	0.548	4.0
F12	542	92.5	0.39	1452	0.01690	0.57	0.112320	0.67	0.048215	0.29	108.01	108.09	109.80	0.902	4.1
BLT11-02 (263441, 4097129)															
F7	926	7.8	0.51	628	0.01623	3.63	0.109258	4.0	0.048822	1.7	103.79	105.29	139.30	0.910	0.8
F8	502	11.8	0.38	210	0.02123	0.34	0.157030	5.2	0.053659	4.9	135.39	148.10	356.80	0.797	3.9
F10	258	9.5	0.36	99	0.01753	2.50	0.119880	13	0.049608	12	112.00	114.96	176.70	0.408	7.5
BLT11-03 (269498, 4119576)															
F4	268	8.9	0.44	208	0.01623	0.67	0.111200	2.0	0.049683	1.7	103.80	107.06	180.18	0.583	2.9
F5	368	74.9	0.21	366	0.04000	0.24	0.271085	1.9	0.491507	1.8	252.84	243.56	155.02	0.593	14.0
F10	845	7.8	0.28	189	0.01881	0.21	0.127713	2.6	0.049253	2.5	120.11	122.04	159.91	0.785	3.0
F13	245	5.5	0.51	68	0.01944	0.80	0.131522	14	0.049068	13	124.14	125.46	150.62	0.945	6.8
F17	612	36.9	0.29	691	0.01861	0.11	0.125901	0.55	0.049060	0.49	118.88	120.41	150.72	0.672	3.6
F19	423	17.4	0.25	75	0.03482	0.26	0.245083	2.0	0.051055	3.7	220.62	222.57	243.30	0.836	10.0
BLT11-04 (267257, 4138786)															
F2	1109	66.6	0.27	557	0.01707	0.27	0.112725	0.58	0.047889	0.47	109.12	108.45	93.8	0.589	8.1
F5	3250	33.0	0.29	661	0.01723	0.10	0.114460	0.68	0.048170	0.63	110.15	110.04	107.6	0.543	3.3

Note: sample locations are in WGS84, UTM zone 11

* Total mass of radiogenic Pb

† Th contents calculated from radiogenic ^{208}Pb and the $^{207}Pb/^{206}Pb$ date of the sample, assuming concordance between U-Th and Pb systems

§ Measured ratio corrected for fractionation and spike contribution only

Measured ratios corrected for fractionation, tracer and blank

** Th-corrected isotopic dates calculated using the decay constants $\lambda_{238} = 1.55125E^{-10}$ and $\lambda_{235} = 9.8485E^{-10}$ (Jaffey et al. 1971)

†† Total mass of common Pb

Pb blank ratios: $^{206}Pb/^{204}Pb = 18.864 \pm 0.25$; $^{207}Pb/^{204}Pb = 15.630 \pm 0.25$; $^{208}Pb/^{204}Pb = 38.193 \pm 0.50$ (1-sigma)

TABLE 4. BIOTITE AND ZIRCON DATA (TZ-TB MODEL)

Zircon Age (Ma)	Biotite Age (Ma)	Tz-Tb (Ma)
John Muir Intrusive Suite		
83.5	81.3	2.2
88.8	82.3	6.5
94.1	84.8	9.3
94.3	83.2	11.1
95.0	83.0	12.0
95.45	86.6	8.9
Mount Givens and Dinkey Creek		
88.0	83.7	4.3
95.0	86.6	8.4
102.0	88.7	13.3
Tuolumne Intrusive Suite		
86.5*	81.0*	5.5
88.8†	87.7†	1.1
90.1	87.9	2.2
97.4	82.0	15.4

Note: John Muir data from Davis et al. (2012); Mount Givens/Dinkey Creek data from Tobisch et al. (1995); Tuolumne data from Memeti et al. (2010)
*Data from Matzel et al. (2005) or (2006b)
†Zircon age from Coleman et al. (2004)

APPENDICIES

Appendix 1: NavDat Search Criteria

Age: Cretaceous. 145.5-65.5.

Location: between latitudes 39°N and 34.5°N, and longitudes 120.5°W and 118°W. State: California. Excluded samples located outside the SNB.

Rock type: Names from paper. Igneous. Plutonic.

Age method: Pb206-U238, U-Pb Concordia, K-Ar, Ar-Ar.

Age material: mineral

Age mineral: zircon or biotite

Excluded: regional correlation, unknown age technique/mineral, whole rock, personal communication, samples with multiple same ages for various locations, Pb-Pb ages

Appendix 2: Summary of Eastward Migration Animation

Movie 1: Animation of Cretaceous Sierran magmatism in 4 Ma time steps, from 125-84 Ma. Red dots represent sample ages that fall within the noted time boundary; blue dots represent sample ages that are older than the noted time boundary. From 120-110 Ma, magmatism is widespread across the western part of the Sierra. At the end of the western cycle, 109-105 Ma, magmatism is concentrated along the eastern boundary of the area. The Dinkey Creek Granodiorite was emplaced at ~101 Ma, during the hiatus that occurred between the western and eastern magmatic episodes. Magmatism is widespread throughout the eastern Sierra from 99-90 Ma, and concentrates eastward by 89 Ma. By 84 Ma, magmatism in the central Sierra Nevada batholith ceased.

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