Birth of the Sierra Nevada magmatic arc: Early Mesozoic plutonism and volcanism in the east-central Sierra Nevada of California

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ABSTRACT

Granitic and volcanic rocks in the east-central Sierra Nevada, western United States, record the earliest stages of magmatism in the eastern Sierra Nevada magmatic arc, allowing us to examine magma sources and connections between plutonic and volcanic processes in the initial stages of arc construction. The Scheelite Intrusive Suite is one of the largest in the Sierra Nevada region, and is composed of the Wheeler Crest Granodiorite, granite of Lee Vining Canyon, and Pine Creek Granite. The Pb/U zircon ages from each unit of the suite suggest assembly between 226 and 218 Ma. The Scheelite Intrusive Suite is a high-K calcic or calc-alkalic suite, compositionally broadly similar to the nearby Late Cretaceous Tuolumne and John Muir Intrusive Suites, though plutons of the Scheelite Intrusive Suite are consistently Ca and Fe rich and lower in Na. Although Triassic granodiorites are isotopically quite similar to nearby Late Cretaceous intrusive suites, the trend toward more isotopically primitive granites is in contrast to the constant or more whole-rock radiogenic Sr trends observed in younger intrusive suites. Along the western margin of the Scheelite Intrusive Suite, the basal Mesozoic volcanic section in the Saddlebag Lake pendant includes silicic volcanic rocks that are in part coeval and potentially comagmatic with Triassic plutonic rocks. Widespread quartz-phyric ash-flow tuffs of Black Mountain, Saddlebag Lake, and Greenstone Lake yield Pb/U zircon ages of 232, 224, and 219 Ma, indicating that felsic ignimbrite volcanism commenced earlier and continued during emplacement of the 226–218 Ma Scheelite Intrusive Suite. Ash-flow tuffs are hydrothermally altered but have high field strength element abundances and Nd isotopic compositions, suggesting affinity to the relatively felsic parts of the Wheeler Crest Granodiorite and the granite of Lee Vining Canyon.

INTRODUCTION

The northwest-trending Mesozoic Cordilleran orogenic belt was constructed across the preexisting northeast-trending Paleozoic continental margin of the western United States. Evolution of the Mesozoic Cordillera was marked by long-lived magmatism driven by subduction of Pacific basin oceanic lithosphere, accretion of crustal elements, and by the dispersion of components of the margin by orogen-parallel shear (Bateman, 1992; Miller et al., 1992; Saleeby et al., 1992; Saleeby and Busby, 1993; Schweickert and Lahren, 1993). The timing of magmatic arc initiation and the nature of the lithospheric components that contributed to plutonism and volcanism are fundamental to understanding both the initiation and the subsequent development of the orogen across its structurally complex and compositionally diverse substrate.

The Sierra Nevada batholith, its satellite plutonic rocks in eastern California and western Nevada, and its framework rocks are key components for understanding the formation of the northwest structural grain of the Cordilleran orogen. Pendants along the east side of the batholith preserve strata that record Neoproterozoic to Paleozoic passive margin sedimentation, Paleozoic accretionary orogenic events along the older, northeast-trending margin (Schweickert and Lahren, 1987; Greene et al., 1997a; Stevens et al., 1997; Stevens and Greene, 2000; Fig. 1), and the initiation of arc volcanism. This early Mesozoic volcanism and associated pluton emplacement are key constraints on tectonic models for subduction initiation at the western edge of North America, which reflects the transition to the northwest-trending Cordilleran margin. In this study we provide geochronologic and geochemical data on the initiation of arc magmatism in the east-central Sierra Nevada from both volcanic rocks that stratigraphically overlie units correlated with Paleozoic allochthons, and the earliest Mesozoic plutonic rocks that intrude them.

Precise geochronologic data for early Sierran arc volcanic and plutonic rocks are also fundamental to understanding the secular evolution of Cordilleran arc magmatism in the Sierra Nevada. While existing data make it clear that volcanism was spatially associated with plutonism (Busby-Spera, 1984; Schweickert and Lahren, 1987, 1999; Saleeby et al., 1990; Fiske and Tobisch, 1994; Sorensen et al., 1998; Proffett and Dilles, 2008), difficulties with geochronology in volcanic rocks and limited geochemical data for older plutons and volcanic rocks limit our understanding of the long-term petrologic evolution of the arc system (e.g., Glazner, 1991; Bateman, 1992). In this study we extend the work of Kistler (1993) and Schweickert and Lahren (1999, 2006) by describing the petrogenesis of felsic volcanic rocks associated with batholithic magmatism in the earliest stages of evolution of the arc in the east-central Sierra Nevada and adjacent parts of eastern California. These data for the early Mesozoic batholithic rock suite and

its contemporaneous and spatially associated volcanic cover provide a baseline for comparison to older accreted arcs (Wyld, 1991; Miller et al., 1992), contemporaneous parts of the arc constructed on much older crustal substrates in southern California (Miller et al., 1995; Barth et al., 1997), and younger plutonic and volcanic parts of the Mesozoic Cordilleran arc.

GEOLOGIC SETTING

Framework Rocks of the East Sierran Arc

The oldest granitic rocks in east-central California were grouped as the Scheelite Intrusive Suite (SIS) by Bateman (1992), and constitute the earliest record of Mesozoic plutonism in the Sierra Nevada and ranges immediately to the east (Fig. 2). Early Mesozoic volcanic rocks exposed along the west side of the SIS in the Saddlebag Lake pendant were mapped and described by Brook (1977), Keith and Seitz (1981), Kistler and Swanson (1981), and Bateman et al. (1983). Studies by Schweickert and Lahren (1993, 1999, 2006) and Kistler (1993) described the volcanic section in more detail and linked explosive volcanism in the pendant to contemporaneous SIS plutons. Schweickert and Lahren (1999) proposed the existence of the Tioga Pass caldera as a Triassic volcanic center related to the SIS. Thus a linked plutonic and volcanic system is exposed in the study area, one that allows us to examine lithospheric magma sources and connections between plutonic and volcanic processes in the initial stages of evolution of the Sierran Mesozoic magmatic arc.

At the inception of magmatism in the study area, plutonic rocks of the SIS intruded, and volcanic rocks were deposited across, an imbricated section of allochthonous and parautochthonous sedimentary rocks (Fig. 1). This imbricated section comprises a complex crustal host-rock assemblage that obscures the nature of the deeper lithosphere. Parautochthonous rocks include deformed Neoproterozoic to Permian platform to continental slope units exposed along the west side of the SIS in the Pine Creek, Mount Morrison, and Ritter Range pendants, and along the east side of the SIS in the Benton Range (Stevens and Greene, 2000; Stevens and Stone, 2005). These parautochthonous units were interleaved by folding and thrusting in the east-vergent Sierra Nevada–Death Valley thrust system, which was interpreted by Stevens and Stone (2005) to have been active during the Late Permian Morrison orogeny; however, Dunne and Walker (2004) viewed many of the thrusts in this region to be Triassic or Jurassic in age. The Sierra Nevada–Death Valley thrust system is composed of three main structural plates, from structurally lowest to highest, the White-Inyo, Nevahbe, and Morrison plates. The SIS intrudes deformed rocks of the White-Inyo plate in the Benton Range, and intrudes folded rocks of the Nevahbe plate in the Mount Morrison and southern Ritter Range pendants (Fig. 1; Stevens and Greene, 2000). The timing of intrusion of the SIS therefore provides a younger limit on the timing of east-vergent Sierra Nevada–Death Valley thrusting.

In the northern Ritter Range and Saddlebag Lake pendants (Fig. 1), structurally higher eugeoclinal units of the Roberts Mountains and Golconda allochthons are above parautochthonous units of the Sierra Nevada–Death Valley thrust system: these higher allochthons are interpreted to have been emplaced by east- to southeast-vergent thrust faulting during the Mississippian Antler and Permian–Triassic Sonoma orogenies, respectively (Schweickert and Lahren, 1987, 2006; Greene et al., 1997a). The temporal transition between this southeast-vergent shortening associated with emplacement of the Golconda and Roberts Mountains allochthons and development of the east-vergent Sierra Nevada–Death Valley thrust system is not completely understood, but indicates final truncation of the North American continental margin that set the stage for initiation of east-directed Mesozoic subduction (Walker, 1988; Stone and Stevens, 1988; Stevens and Stone, 2005). Both eugeoclinal allochthons are intruded by granodiorite or granite of the SIS, and are unconformably overlain by early Mesozoic volcanic rocks;
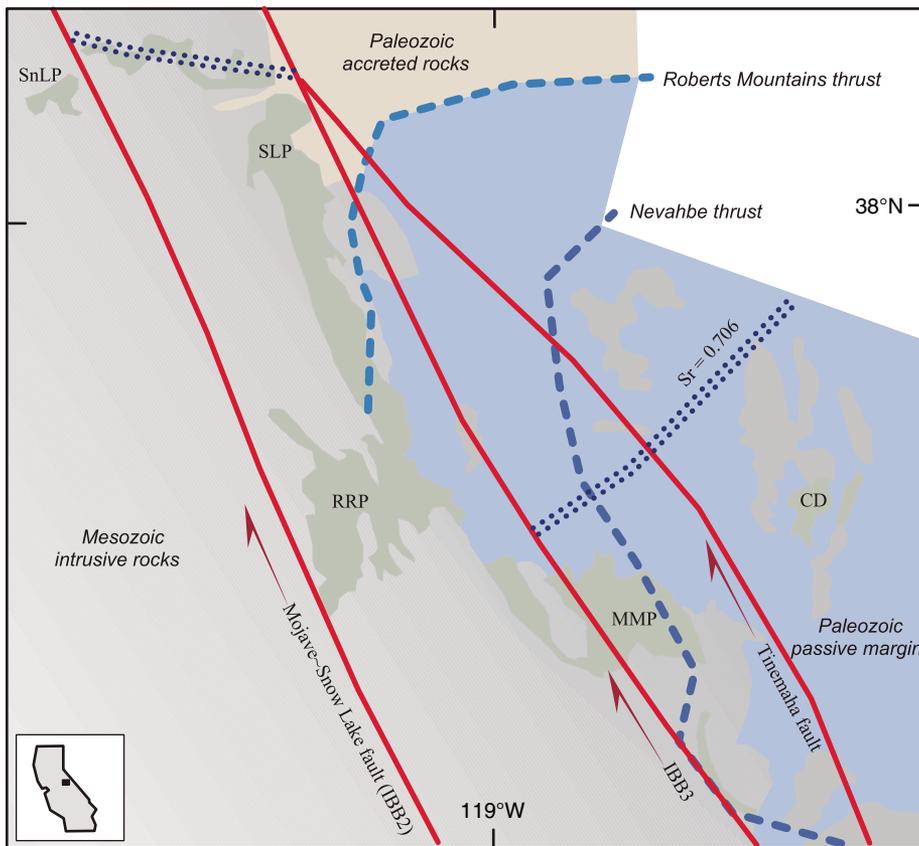
Figure 1. Tectonic sketch map showing pendants (green), Mesozoic intrusive rock outcrops (gray), and major inferred structural features in the east-central Sierra Nevada and Mono Basin–northern Owens Valley region, adapted from Kistler (1993), Greene et al. (1997a), and Stevens and Greene (2000). Mesozoic intrusive rocks were emplaced into an imbricated upper crustal section of shelf and slope sedimentary rocks (blue shades) and accreted rocks of the Roberts Mountains and Golconda allochthons (tan). Contrasting stratigraphic sections in pendants and differences among older plutons may record Permian–Triassic dextral slip on the Tinemaha fault and/or Mesozoic dextral slip on intrabatholithic breaks (IBB2, IBB3). CD—Casa Diablo pendant, MMP—Mount Morrison pendant, RRP—Ritter Range pendant, SLP—Saddlebag Lake pendant, SnLP—Snow Lake pendant. Inset: Black rectangle shows location of map in California.
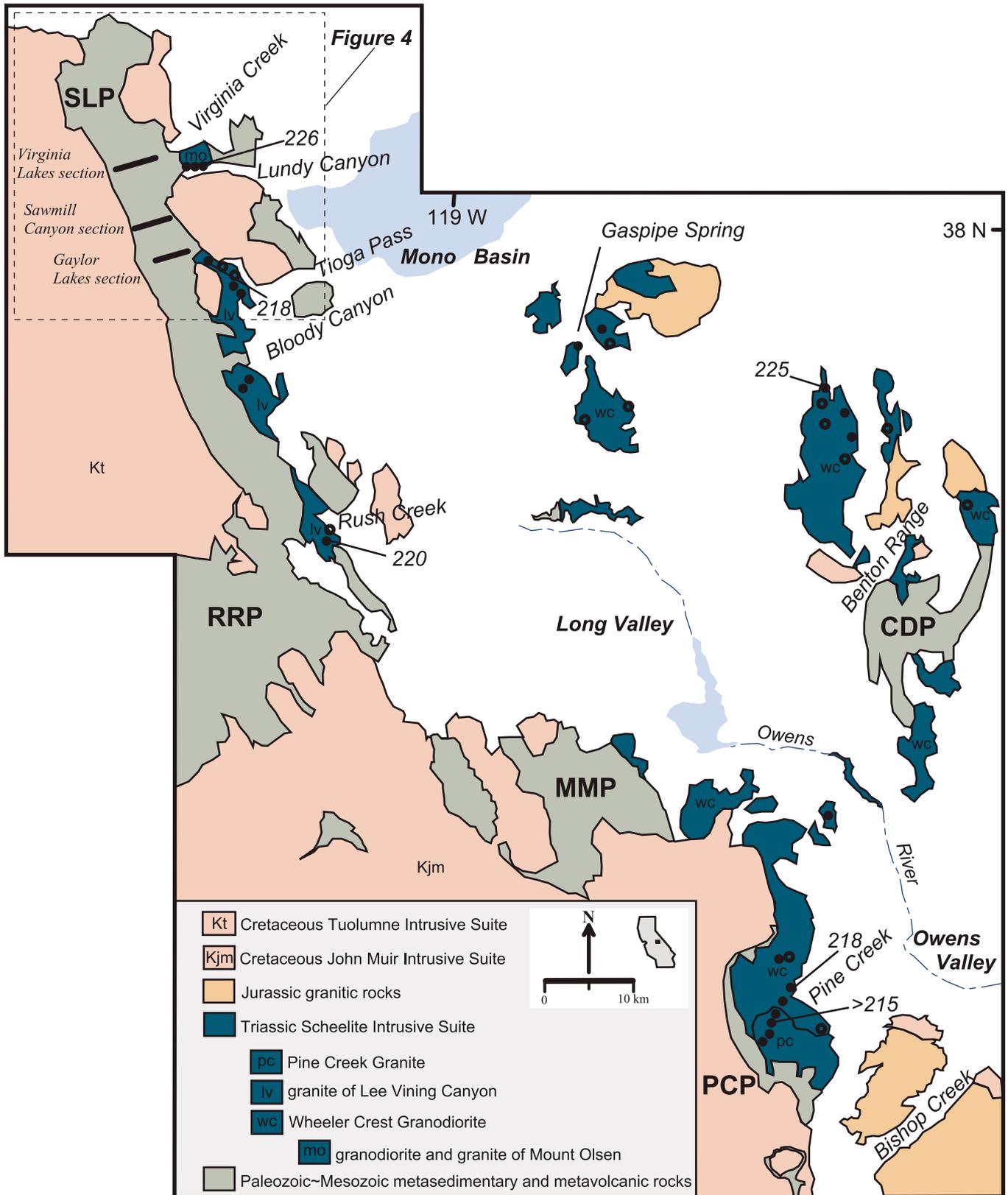
Figure 2. Geologic map showing plutons of the Scheelite Intrusive Suite in the east-central Sierra Nevada and Mono Basin–northern Owens Valley region, adapted from Rinehart and Ross (1957), Bateman (1965, 1992), Huber and Rinehart (1965), Kistler (1966a), Crowder et al. (1972), Krauskopf and Bateman (1977), Bailey (1989), and Schweickert and Lahren (1999). Filled black circles show geochemistry sample localities, with ages (in Ma) labeled on geochronology sample localities. Open black circles are additional whole-rock samples from Bateman et al. (1984). CDP—Casa Diablo Pendant, MMP—Mount Morrison pendant, PCP—Pine Creek pendant, RRP—Ritter Range pendant, SLP—Saddlebag Lake pendant. Inset: Black rectangle shows location of map in California.

the chronology of plutonism and volcanism in the northern Ritter Range and Saddlebag Lake pendants thus may provide key constraints on the structural juxtaposition of miogeoclinal and eugeoclinal units over a wide region in east-central California (Schweickert and Lahren, 1987, 2006; Greene et al., 1997a).

Imbricated Paleozoic rocks, as well as plutons of the SIS and early Mesozoic volcanic sections, may have been offset by large-magnitude strike-slip faults in or near the east-central Sierra Nevada. Such faults could also have juxtaposed compositionally distinct deeper parts of the lithosphere reflected in compositional patterns of magmatic rocks. Kistler (1993) proposed the existence of a major intrabatholithic dextral strike slip fault (intrabatholithic break 3, or IBB3;

Fig. 1) that truncated the Sr 0.706 isopleth and offset it ~65 km, and offset western and eastern parts of the SIS. A similar line of reasoning led Saleeby and Busby (1993) to propose their eastern intrabatholithic break, which coincides with the proposed IBB3. Alternatively, Schweickert and Lahren (2006) argued that key lithostratigraphic and structural units in the Saddlebag Lake pendant tie together across the proposed trace of IBB3. Although much of the proposed trace of IBB3 is obscured by middle to Late Cretaceous plutons, Kistler (1993) equated it in part to the northwest-trending Laurel-Convict fault in the Mount Morrison pendant. However, this fault has been shown to record sinistral shear and is cut by a 225 ± 16 Ma dike (Greene et al., 1997b). Dextral separation in the study area

may also have occurred along the hypothetical Tinemaha fault beneath northern Owens Valley (Fig. 1), inferred to record ~65 km dextral slip east of Mount Morrison pendant without offsetting the SIS (Stevens and Greene, 2000).

Scheelite Intrusive Suite

Bateman (1992, p. 27) grouped all the granitic terrane of the Sierra Nevada range as the Sierra Nevada batholith, and used a hierarchy of terms to arrange granitic rocks that constitute the batholith; in this hierarchy, an intrusive suite is the broadest term, incorporating a group of granitic rocks with "true age differences of no more than a few million years" that display textural and compositional changes like those of
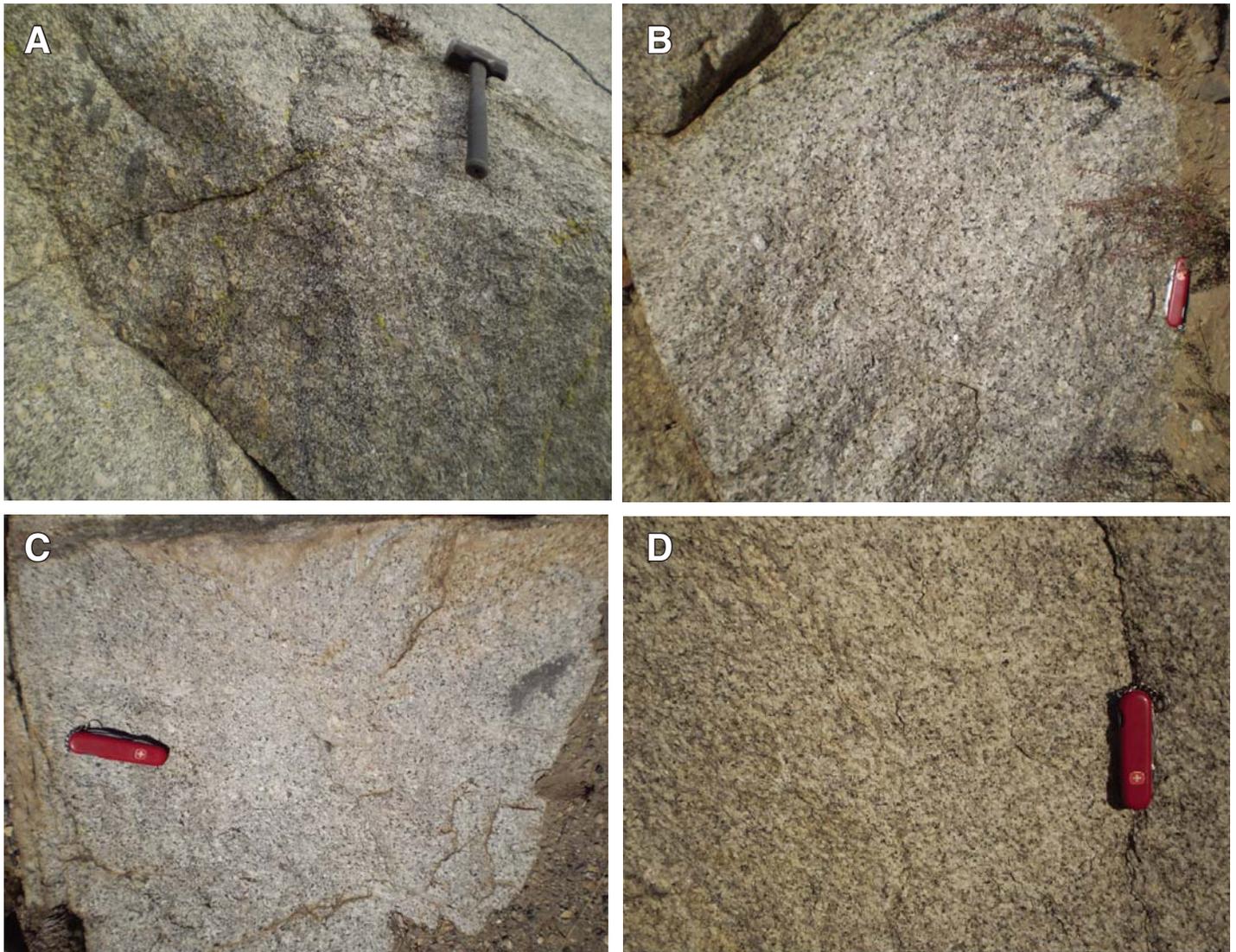
Figure 3. Field photos of granitic rocks of the Scheelite Intrusive Suite. (A) Porphyritic Wheeler Crest Granodiorite in Pine Creek, with moderately well-developed phenocryst and enclave shape fabric. (B) Porphyritic granite of Mount Olsen in Lundy Canyon. (C) Weakly porphyritic granite of Lee Vining Canyon east of Tioga Pass. (D) Seriate granite of Pine Creek.

well-exposed, clearly nested or zoned intrusions. In this sense, Bateman (1992) assigned early Mesozoic granodioritic to granitic rocks along the east-central Sierra Nevada range front and in adjacent ranges to the SIS (Fig. 2), composed of three intrusive units; Wheeler Crest Granodiorite, the granite of Lee Vining Canyon, and Tungsten Hills Granite. Most of the plutons included in this definition of the SIS have yielded Triassic or Jurassic K-Ar and/or U-Pb ages (Evernden and Kistler, 1970; Stern et al., 1981; Chen and Moore, 1982). The Wheeler Crest Granodiorite includes porphyritic, hornblende biotite granodiorite to biotite granite in the Pine Creek region, and texturally similar granodiorite in the Benton Range region (see also Rinehart and Ross, 1957; Bailey, 1989); and was extended northward to include the porphyritic granodiorite and granite of Mount Olsen by Huber et al. (1989; see also Kistler, 1993). North of Long Valley, the equigranular to porphyritic granite of Lee Vining Canyon is exposed along the east side of the Ritter Range and Saddlebag Lake pendants from near Rush Creek north to Tioga Pass. The seriate to weakly porphyritic Tungsten Hills Granite includes four isolated granite masses; the northern Pine Creek mass intrudes the Wheeler Crest Granodiorite, and texturally similar masses are exposed to the south along, and south of, Bishop Creek. New geochronologic data suggest that this third intrusive unit is composite, and it is redefined herein (see following). Much of the SIS is apparently concealed beneath Pliocene to Holocene volcanic rocks in northern Owens Valley and Long Valley. Bateman (1992) estimated that the SIS underlies an area of ~3000 km² in the eastern Sierra Nevada range front and adjacent areas to the east, making it both one of the oldest and largest Mesozoic intrusive suites in the Sierra Nevada region.

Four geographically isolated bodies compose the Wheeler Crest Granodiorite: the granodiorites of the Benton Range, Gaspipe Spring, and Wheeler Ridge, and the granodiorite to granite of Mount Olsen. The Wheeler Crest Granodiorite is mostly a weakly to moderately foliated, seriate to porphyritic, sphene hornblende biotite granodiorite, with tan to pinkish tan, blocky, poikilitic potassium feldspar phenocrysts as much as 6 cm in long dimension (Fig. 3A). Moderate to steeply dipping enclave shape fabric paralleled by aligned potassium feldspar phenocrysts is particularly well developed along the western margin of the suite, in contact with the Cretaceous John Muir Intrusive Suite and metamorphic rocks of the Pine Creek pendant. The Mount Olsen body is composed of leucocratic, porphyritic biotite granodiorite to granite with light gray potassium feldspar phenocrysts as much as 3 cm in long dimension in a seriate granitic matrix

(Fig. 3B). Where best exposed in Lundy Canyon, it lacks recognizable planar fabric.

The granite of Lee Vining Canyon is a seriate to weakly porphyritic biotite granite, locally with blocky tan potassium feldspar phenocrysts as much as 1.5 cm in long dimension set in a seriate granitic matrix (Fig. 3C). The matrix of the granite often contains distinctive subhedral to euhedral quartz crystals ranging from 4 to 8 mm across, set in a finer grained matrix of feldspar, quartz, and minor biotite.

The Wheeler Crest Granodiorite is intruded by the granite of Pine Creek, seriate biotite granite that has a weak planar fabric defined by aligned biotite (Fig. 3D) that is subparallel to the fabric in the adjacent granodiorite. Texturally similar granites in the Tungsten Hills, Bishop Creek, and Shannon Canyon masses (sensu Bateman, 1965, 1992) have yielded Jurassic U-Pb ages (Stern et al., 1981; this study). The third intrusive unit of the SIS is therefore redefined here as Pine Creek Granite (Fig. 2), composed of equigranular to seriate porphyritic biotite granite of Triassic age (Stern et al., 1981; this study). Pine Creek Granite is best exposed in the Mount Morgan 7.5′ quadrangle along the northwest side of Pine Creek, near the abandoned mining town of Scheelite. Pine Creek Granite intrudes the Wheeler Crest Granodiorite along its northern and western margins, and along its western margin intrudes metavolcanic rocks of the Pine Creek septum (see also mapping by Bateman, 1965, 1992 [modified]). It is intruded by diorite of unknown age and by mafic dikes.

Koip Sequence Volcanic Rocks, Saddlebag Lake Pendant

Metamorphosed volcanic rocks unconformably overlying Paleozoic metasediments in the eastern Sierra Nevada were named the Koip sequence by Kistler (1966b; see also Bateman, 1992). Further work indicated that the sequence, as originally envisioned, contains Triassic, Jurassic, and minor Cretaceous volcanic and volcaniclastic rocks, and subsequently, workers have limited the term Koip sequence to the basal, Triassic part of the Mesozoic volcanic section in the range. The basal metavolcanic section that overlies Paleozoic to Early Triassic metasedimentary rocks in the Saddlebag Lake pendant belongs to the lower part of the Koip sequence as defined by Keith and Seitz (1981), Kistler and Swanson (1981), and Bateman et al. (1983). We studied these rocks principally in the central and southern part of the pendant between Virginia Creek and Tioga Pass, where they were identified as the Koip sequence, mapped, and described in detail in Schweickert and Lahren (1999, 2006; Figs. 4 and 5). All units in this pendant are meta-

morphosed and deformed, and most outcrops contain prominent cleavage or foliation; for brevity, we omit the prefix "meta" and refer to protoliths where they can be determined. The Koip sequence in this area includes volcanic and volcaniclastic units that disconformably overlie Early Triassic siliciclastic strata of the Candelaria Formation. The Koip stratigraphic sequence is repeated in five principal thrust plates; our geochronology samples come from the second-highest plate, and rock geochemistry is based on samples from all but the lowest thrust plate. The stratigraphically lowest silicic volcanic unit recognized in the pendant is the tuff of Black Mountain (Fig. 6A), which locally disconformably overlies deformed sandstone and siltstone of the Candelaria Formation. Tuff of Black Mountain is a light gray, relatively pumice poor ash-flow tuff with feldspar and quartz phenocrysts. The tuff of Black Mountain is overlain by the conglomerate of Cooney Lake; where the Black Mountain tuff is not present, conglomerate of Cooney Lake unconformably overlies the Candelaria Formation. The Cooney Lake unit is predominantly conglomerate with clasts of quartzite, chert, argillite, and sparse intrusive and extrusive igneous clasts, interlayered with sandstone. Concordantly overlying this conglomerate is the tuff of Saddlebag Lake (Fig. 6B), a very light tan to light gray ash-flow tuff with dark gray flattened pumice as much as 15 cm long, and phenocrysts of a mafic mineral, feldspar, and quartz. The tuff of Saddlebag Lake is overlain by a heterogeneous, primarily volcaniclastic unit composed of matrix-supported tuff breccia with angular to subrounded clasts of aphanitic to porphyritic basalt and andesite (Fig. 6C), and sparse basalt and andesite flows. Schweickert and Lahren (2006) reported a pillowed andesite flow in this unit. The volcaniclastic unit is overlain by the tuff of Greenstone Lake (Fig. 6D), a tan and usually pumice-poor ash-flow tuff with biotite(?), feldspar, and quartz phenocrysts. This tuff marks the top of the Koip sequence, where it is concordantly overlain by Jurassic(?) volcaniclastic sedimentary rocks and volcanic rocks, informally named the Sawmill Canyon sequence by Schweickert and Lahren (2006).

ANALYTICAL METHODS

The data set for this study includes 45 new whole-rock analyses (Supplemental Table 1¹),

and incorporates 14 whole-rock major element analyses of intrusive rocks reported by Bateman et al. (1984). Whole-rock samples were crushed in a two-step jaw crushing procedure and ground in a WC-lined mixer mill. X-ray fluorescence (XRF) analyses for major and Rb, Sr, and Zr were performed on fused glass disks at Michigan State University using a Bruker spectrometer. Additional trace element analyses were completed on the same whole-rock glasses with a Micromass inductively coupled plasma–mass spectrometer (ICP-MS) at Michigan State University. In-run precision was monitored using JB-1a basalt and JA3 andesite rock standards, and is better than 1% for most major elements and trace elements present in abundances >100 ppm analyzed by XRF, and 2%–5% for trace elements analyzed by ICP-MS.

Sr and Nd whole-rock isotope ratios were measured on the VG Sector mass spectrometer at the University of Kansas. Samples were total spiked for Nd and Sm and dissolved using microwave dissolution vessels. Separation of Sr and rare earth element (REE) group elements was done using standard cation exchange techniques. The method of White and Patchett (1984) was used for separation of Sm and Nd. Analyses for Sm were done on single Ta filaments; Sr was run on single Re filaments. Analyses of Sr and Nd were completed in dynamic multicollector mode with $^{88}Sr = 4V$ and $^{144}Nd = 1V$; Sm was analyzed in static multicollector mode with $^{149}Sm = 500$ mV. Analytical blanks were <100 pg for all elements. Strontium isotopic compositions are normalized for $^{86}Sr/^{88}Sr = 0.1194$ and referenced to NBS-987 $^{87}Sr/^{86}Sr = 0.710250$. Reproducibility of Sr values is bet-

ter than ±0.000020 based on replicate runs of NBS-987. Neodymium isotopic compositions are normalized to $^{146}Nd/^{144}Nd = 0.7219$ and referenced for La Jolla $^{143}Nd/^{144}Nd = 0.511850$. Epsilon values for Nd at crystallization are calculated using $(^{143}Nd/^{144}Nd)_{(CHUR, 0 Ma)} = 0.512638$ and $^{147}Sm/^{144}Nd_{(CHUR, 0Ma)} = 0.1967$ (CHUR—chondritic uniform reservoir). Reproducibility of Nd values is ~0.20 epsilon units based on replicate analyses of in-house standards. Correction to crystallization age values for Sr was done using XRF elemental analyses; Nd initial values were computed using the isotope dilution values from mass spectrometry.

Zircons were separated from whole-rock samples by gravimetric techniques, mounted in epoxy, and polished for examination using a cathodoluminescence detector on a scanning electron microscope. Cathodoluminescence images were used to guide selection of analysis points. Elemental concentrations and isotopic ratios were measured on the U.S. Geological Survey SHRIMP-RG (sensitive high-resolution ion microprobe–reverse geometry) at Stanford University, using analytical and data analysis procedures described in Barth and Wooden (2006). Isotopic ratios were standardized against Braintree Complex zircon R33 (419 Ma; Black et al., 2004). Errors on ages of individual grains are reported at one sigma, and errors on calculated crystallization ages of rocks are reported at the 95% confidence level (Supplemental Table 2[2]).

ZIRCON GEOCHRONOLOGY

Intrusive Rocks

Previous zircon geochronologic data from rocks of the SIS (Stern et al., 1981; Chen and Moore, 1982) indicated complex isotopic systematics with both discordant and reversely discordant ages, but estimated ages were in broad agreement with initial K-Ar studies that indicated a probable Triassic age for this intrusive suite (Evernden and Kistler, 1970). Pb/U ages for individual bulk fractions in both of these earlier studies range from 185 to 217 Ma, but $^{207}Pb*/^{206}Pb*$ ages reported by Chen and Moore (1982) are generally older, ranging from 220 to 244 Ma. Chen and Moore (1982) inferred that older xenocryst zircons were present in their
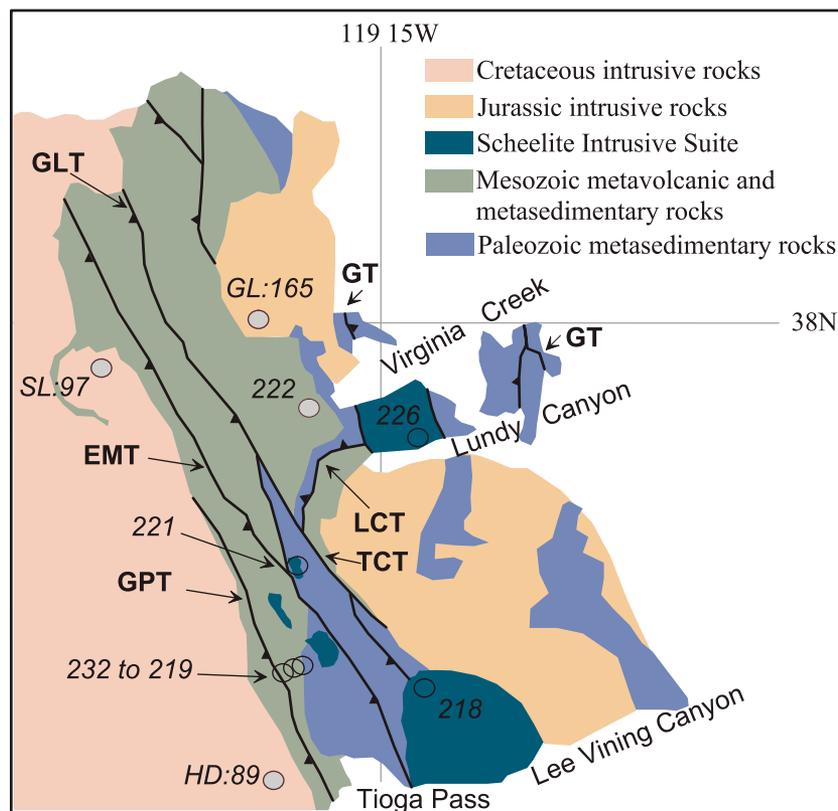
Figure 4. Simplified geologic sketch map of the Saddlebag Lake pendant (modified from Schweickert and Lahren, 2006). Unfilled circles are U-Pb zircon sample localities of Triassic rock units from this study (ages in Ma). Previous published ages for these units are described in the text. Gray circles are U-Pb zircon sample localities for adjacent rock units; Jurassic Green Lakes (GL) pluton and Cretaceous Soldier Lake (SL) pluton localities are from Mundil et al. (2004) *in* Memeti et al. (2010). Cretaceous Half Dome (HD) granodiorite age is from Coleman et al. (2004), Virginia Creek locality is age of tuff of Saddlebag Lake cited by Schweickert and Lahren (1999). EMT—Excelsior Mountain thrust, GLT—Glenberry Lake thrust, GPT—Gaylor Peak thrust, GT—Golconda thrust, LCT—Lundy Canyon thrust, TCT—Tioga Crest thrust.
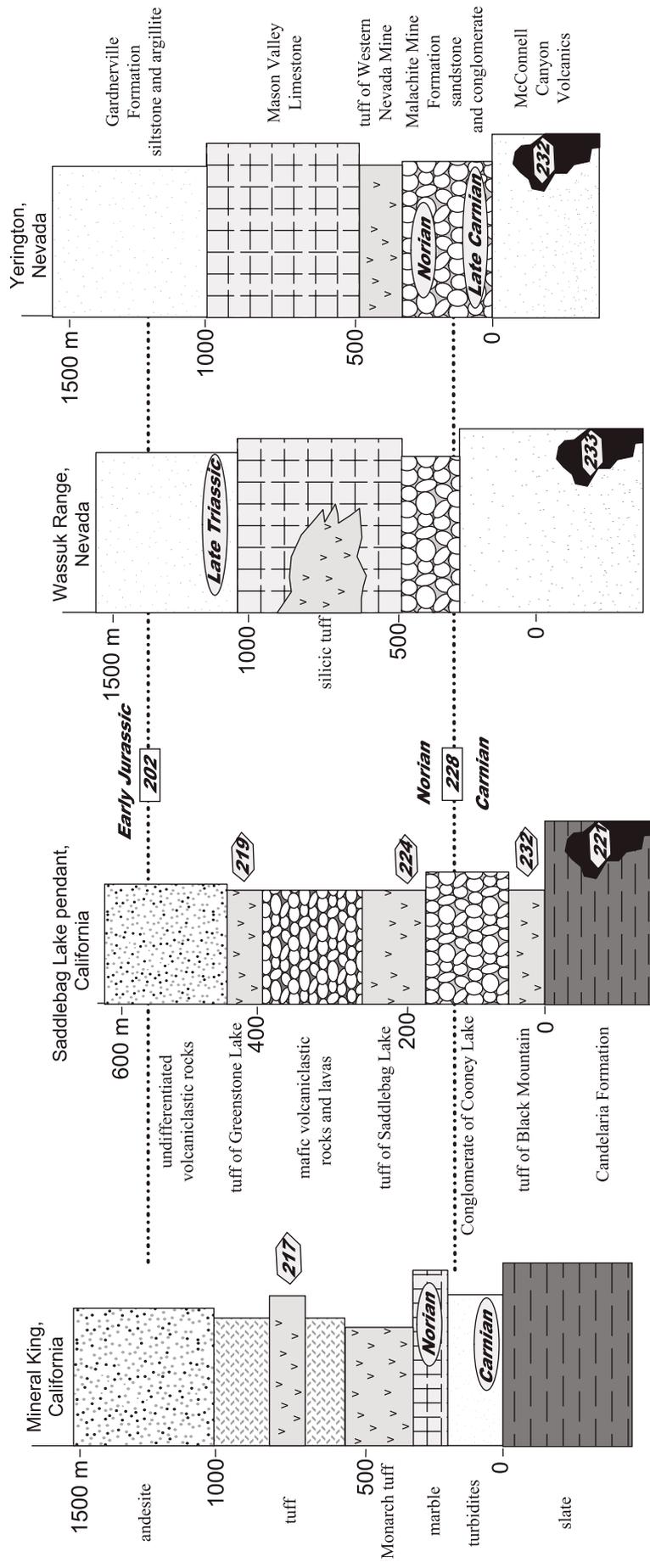
Figure 5. Stratigraphic column for least-deformed volcanic rocks of the Koip sequence in the Virginia Creek section, Saddlebag Lake pendant. For comparison, time-correlated stratigraphic columns are shown for the Triassic section in Mineral King pendant, southern Sierra Nevada (Busby-Spera, 1984, 1986; Saleeby and Busby, 1993), and Late Triassic sections in the Wassuk Range and Yerington District, western Nevada, from Proffett and Dilles (2008). Ellipses within columns locate intervals with fossil ages. Numbers to the right of each column locate intervals with U-Pb zircon ages. Ages of the Carnian-Norian and Triassic-Jurassic boundaries are from Walker and Geissman (2009).

samples, and that magmatic zircons were probably affected by loss of radiogenic Pb during later reheating associated with emplacement of Late Cretaceous granitic rocks, and concluded that the likely crystallization age of the SIS was ca. 210 Ma (Chen and Moore, 1982). This age was inferred to be consistent with Rb/Sr whole-rock isotopic results (R.W. Kistler, 1979, written commun., *in* Stern et al., 1981).

We analyzed spots within individual zircons from seven samples of the SIS. All samples show a range of measured grain ages in excess of analytical errors but usually contain a single dominant population of grains (Supplemental Table 2 [see footnote 2]). This observation indicates that Pb loss has affected some zircons in all samples, and that some samples contain older premagmatic and/or antecrystic (i.e., magmatic grains inherited from an earlier phase of the same magma system; e.g., Bacon and Lowenstern, 2005) zircons. Inferred crystallization ages for rock units are based on interpretation of these zircon data arrays, and most crystallization age estimates are based on the oldest well-defined population of grains preserved in a given sample.

We analyzed two samples of the Wheeler Crest Granodiorite (Figs. 2 and 7), both of which show evidence for three main age groups of zircons. The sample from the Benton Range yielded 2 zircons with an age of ca. 232 Ma, and a main population of 12 grains yielding an age of 225 ± 2 Ma (mean square of weighted deviates, MSWD = 2.9). One younger grain with an age of ca. 217 Ma is inferred to have lost some radiogenic Pb and was excluded from this calculation. The sample from the Wheeler Ridge - Pine Creek area has a similar bulk composition, and its zircons are relatively enriched in Th and U but show similar Th/U to the zircons in the Benton Range sample. The Wheeler Ridge sample also yielded a minor population of older grains; in this case three grains ca. 225 Ma that are identical in age to the main population of grains in the Benton Range sample. The predominant population of eight grains is younger, however, and yields a crystallization age of 218 ± 1 Ma (MSWD = 1.4), excluding four younger grains with ages
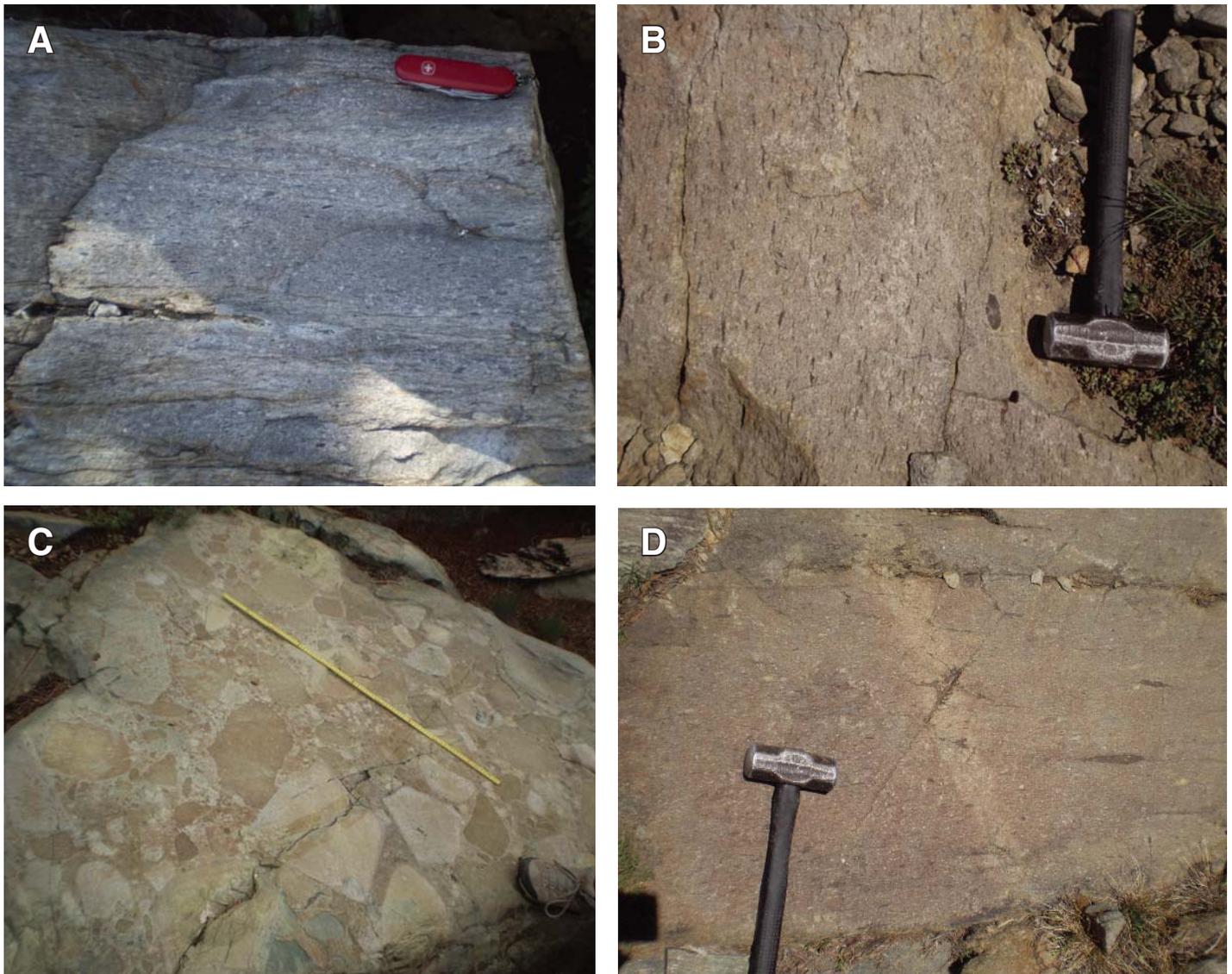
Figure 6. Field photos of Saddlebag Lake pendant volcaniclastic units of the Koip sequence. (A) Foliated tuff of Black Mountain. (B) Tuff of Saddlebag Lake with well-developed pumice fabric. (C) Matrix-supported mafic volcanic breccia at Frog Lakes, with angular to subrounded clasts, lacking fabric. Measuring tape is 1 m in length. (D) Tuff of Greenstone Lake with well-developed pumice fabric.
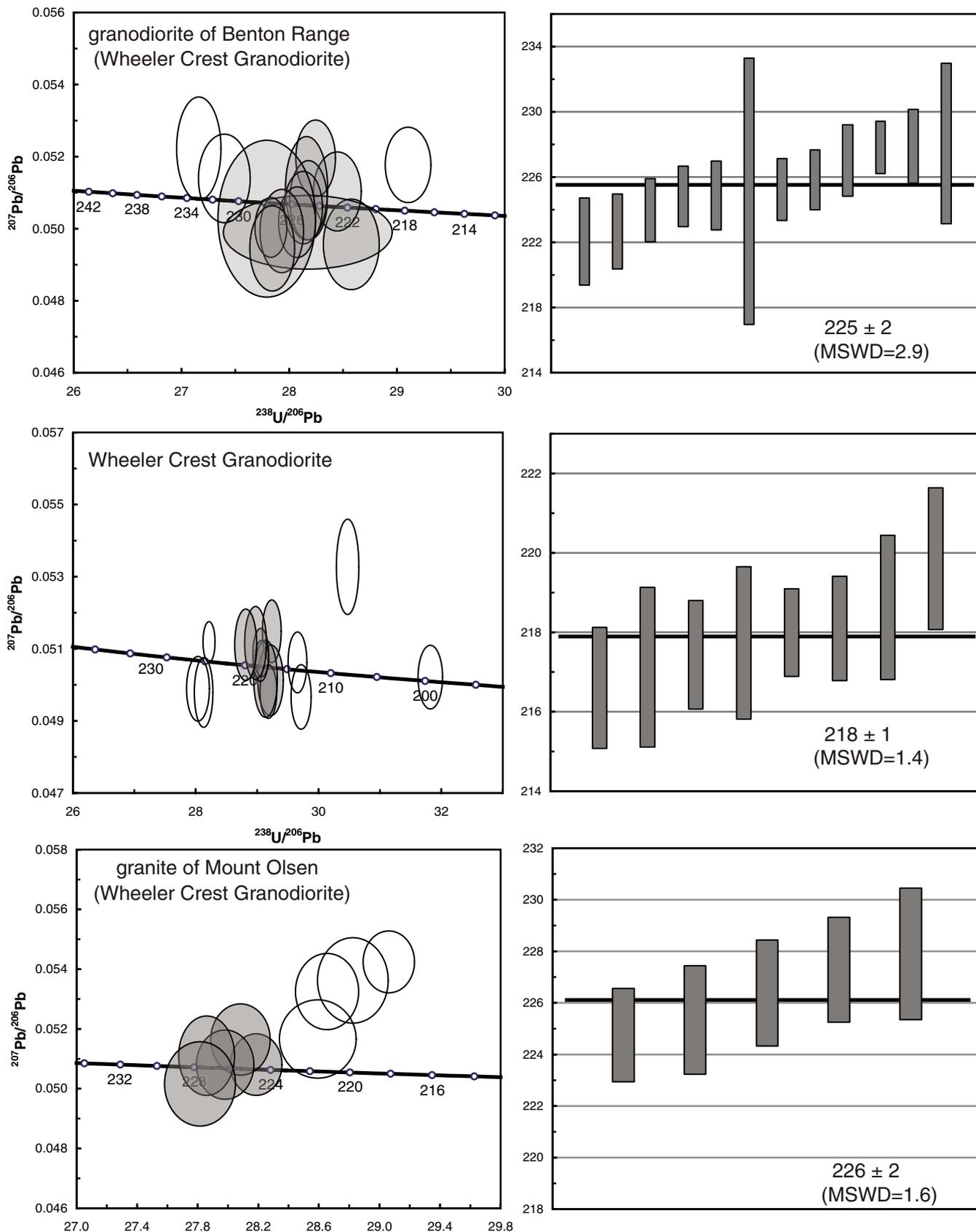
Figure 7. Tera-Wasserburg concordia diagrams and weighted mean $^{206}Pb*/^{238}U$ ages for zircons from rock units of the Wheeler Crest Granodiorite, Scheelite Intrusive Suite. All measured zircons are plotted on concordia diagrams at left; zircon analyses plotted with unshaded symbols were excluded from calculation of weighted mean crystallization age shown at right. See text for discussion. MSWD—mean square of weighted deviates.

as low as 200 Ma that are inferred to have lost some radiogenic Pb.

We follow Huber et al. (1989) and correlate the granodiorite and granite of Mount Olsen with the Wheeler Crest Granodiorite based on its texture and whole-rock composition. Our sample from this unit (Figs. 2 and 7) yielded zircons with Th and U concentrations and Th/U quite similar to those of our sample of Wheeler Crest Granodiorite from the Benton Range. An array of nine grains from this sample with ages as young as 217 Ma is suggestive of Pb loss, and the oldest population of five grains yields a best estimate crystallization age of 226 ± 2 Ma (MSWD = 1.6), which is identical in age to the granodiorite in the Benton Range. Schweickert and Lahren (1987) cited a zircon age of 219 ± 2 Ma for this pluton, collected at the same locality. Although no data were presented, their age was presumably based on the analysis of one or more multimilligram zircon fraction(s). If their sample underwent Pb loss similar to our sample, then a 219 Ma age is a reasonable average age for zircons at his locality. We therefore propose that the 226 Ma age reported here, identical to the age of the Wheeler Crest Granodiorite in the Benton Range, is a firmer estimate of the crystallization age of the Mount Olsen pluton.

We analyzed two samples of the granite of Lee Vining Canyon (Figs. 2 and 8). The zircons in both samples show similar overall ranges in Th and U concentrations and Th/U, though relatively Th and U enriched zircons are more common in the more felsic sample from Lee Vining Canyon. The first sample, from Rush Creek, is the more coherent; excluding 1 analysis with a relatively large analytical error and 1 younger grain, 10 magmatic grains yield a crystallization age of 220 ± 2 Ma (MSWD = 2.9). The weighted mean age for this sample also excludes one analyzed concordant older grain at 226 Ma. The second sample, collected from near Tioga Pass, indicates both inheritance of older premagmatic and antecrystic zircon and Pb loss. Premagmatic grains are slightly discordant but suggest crystallization ages of ca. 612 and 1650 Ma. The oldest coherent group of five magmatic grains yields a minimum crystallization age of 218 ± 2 Ma (MSWD = 4), excluding a single older concordant Triassic grain with an age of 225 Ma. Our 220 and 218 Ma crystallization ages for the granite of Lee Vining Canyon are consistent with a whole-rock Rb/Sr isochron age of 217 Ma (see following) and the 212 ± 5 Ma Rb-Sr whole-rock isochron age of R.W. Kistler (1979, written commun., *in* Stern et al., 1981) (reported as 212 ± 8 Ma by Kistler and Swanson [1981], 212 ± 11 Ma by Kistler [1993], and 216 ± 5 Ma by Kistler and Fleck

[1994]). We thus interpret the older 225 and 226 Ma individual grains in these two samples as antecrystic zircons incorporated in this granite along with Proterozoic premagmatic grains, an inference supported by zircon Pb/U ages from the Wheeler Crest Granodiorite described here, and the associated silicic volcanic rocks described in the following.

We analyzed two samples of the Tungsten Hills Granite of Bateman (1965, 1992). The first sample, from the Pine Creek Granite as defined herein (Fig. 2), has U-enriched zircons similar in composition to the Lee Vining Canyon granite samples, and shows comparably disturbed isotopic systematics; 12 analyzed zircons yielded a 15 m.y. range of Pb/U ages and a Pb loss array (Fig. 8). The oldest population of grains suggests a minimum crystallization age for this sample of ca. 215 Ma. The second sample, from the Bishop Creek mass of the Tungsten Hills Granite, yielded a well-defined crystallization age of 149 Ma (our data). These results, when coupled with whole-rock elemental and isotopic data, indicate that the Tungsten Hills and Bishop Creek masses of the Tungsten Hills Granite (sensu Bateman, 1965, 1992) are Jurassic in age. Stern et al. (1981) presented a highly discordant Jurassic single fraction zircon age from the Shannon Canyon mass south of the area shown in Figure 2 (their sample 56 west of Warren Lake), so we conclude that the central and southern parts of the Tungsten Hills Granite of Bateman (1965, 1992) include one or more plutons of Jurassic age, and pending further geochemical work should not be included in the Triassic SIS.

The monzonite of Saddlebag and Odell Lakes of Bateman et al. (1983) is a group of comparatively mafic satellite plutons that intrudes Paleozoic metasedimentary rocks in the Saddlebag Lake pendant west of the SIS. Of 10 zircon grains from a sample of monzodiorite from the pluton at Odell Lake, 9 scatter just slightly in excess of analytical errors (Fig. 9), yielding a crystallization age of 221 ± 2 Ma (MSWD = 3.1), excluding an older grain at 226 Ma; this is our current best estimate of crystallization age, but the actual age could be closer to 222 ± 2 Ma if the younger grains underwent minor loss of radiogenic Pb. Schweickert and Lahren (2006) reported a zircon age of ca. 220 Ma for this pluton, which is in good agreement with the age reported here.

Ash-Flow Tuffs

Previous geochronologic data indicate that mafic and felsic volcanic rocks contemporaneous with the SIS are exposed along its western flank, in the Saddlebag Lake pendant (Fig. 4).

Kistler and Swanson (1981) reported an Rb-Sr whole-rock isochron age of 224 ± 14 Ma (recalculated as 228 ± 7 Ma by Kistler [1993] and 229 ± 5 by Kistler and Fleck [1994]) for volcanic rocks in the pendant in and south of our study area. Mafic volcanic rocks in or near our study area, probably correlative with the mafic volcaniclastic unit (Fig. 5), yielded Rb-Sr data collinear with this isochron (R.W. Kistler, 1980, personal commun., *in* Keith and Seitz, 1981). Schweickert and Lahren (2006) cited ages from ash-flow tuffs in the Saddlebag Lake pendant, described further in stratigraphic context herein.

We analyzed spots within individual zircons from three felsic tuffs in the Sawmill Canyon section of the northern Saddlebag Lake pendant. The zircons in these samples have Th and U concentrations and Th/U similar to zircons in granitic rocks of the SIS. All samples yielded zircons with a range of ages in excess of analytical errors, very similar to what we observe in the plutonic rocks, indicating that Pb loss affected some zircons in all samples, and in addition that some samples contain older antecrystic zircons. Eruption ages for these tuff samples are based on interpretation of data arrays, and usually are based on the oldest well-defined population of grains preserved in a given sample.

Our sample of the tuff of Greenstone Lake, collected at the top of the Koip sequence in Sawmill Canyon, indicates possible minor inheritance and moderate Pb loss, with measured ages of individual grains as young as 185 Ma (Fig. 10). The oldest coherent group of six magmatic grains yields a reasonably precise crystallization age of 219 ± 1 Ma (MSWD = 1.2), excluding the five younger grains that we infer underwent Pb loss due to reheating by the immediately adjacent Late Cretaceous Tuolumne Intrusive Suite (Fig. 4). A single older grain, concordant at 226 Ma, is similar in age and Th and U concentrations to magmatic grains in the underlying tuff of Saddlebag Lake, and so is inferred to be inherited from an older part of the magmatic system. Schweickert and Lahren (2006) cited a multigrain zircon U-Pb age of ca. 211 Ma for this tuff, which may represent an average age for zircons with substantial Pb loss.

We analyzed a sample of the tuff of Saddlebag Lake, collected immediately above the conglomerate of Cooney Lake in the Sawmill Canyon section. Twelve grains define a coherent compositional group in terms of Th and U concentrations and Th/U, and yielded a Pb loss array (Fig. 10), with grains as young as 216 Ma, but the oldest coherent group of eight grains yields a well-defined crystallization age of 224 ± 1 Ma (MSWD = 1.7). Schweickert and Lahren (1999) cited a zircon age of 222 ± 5 Ma,
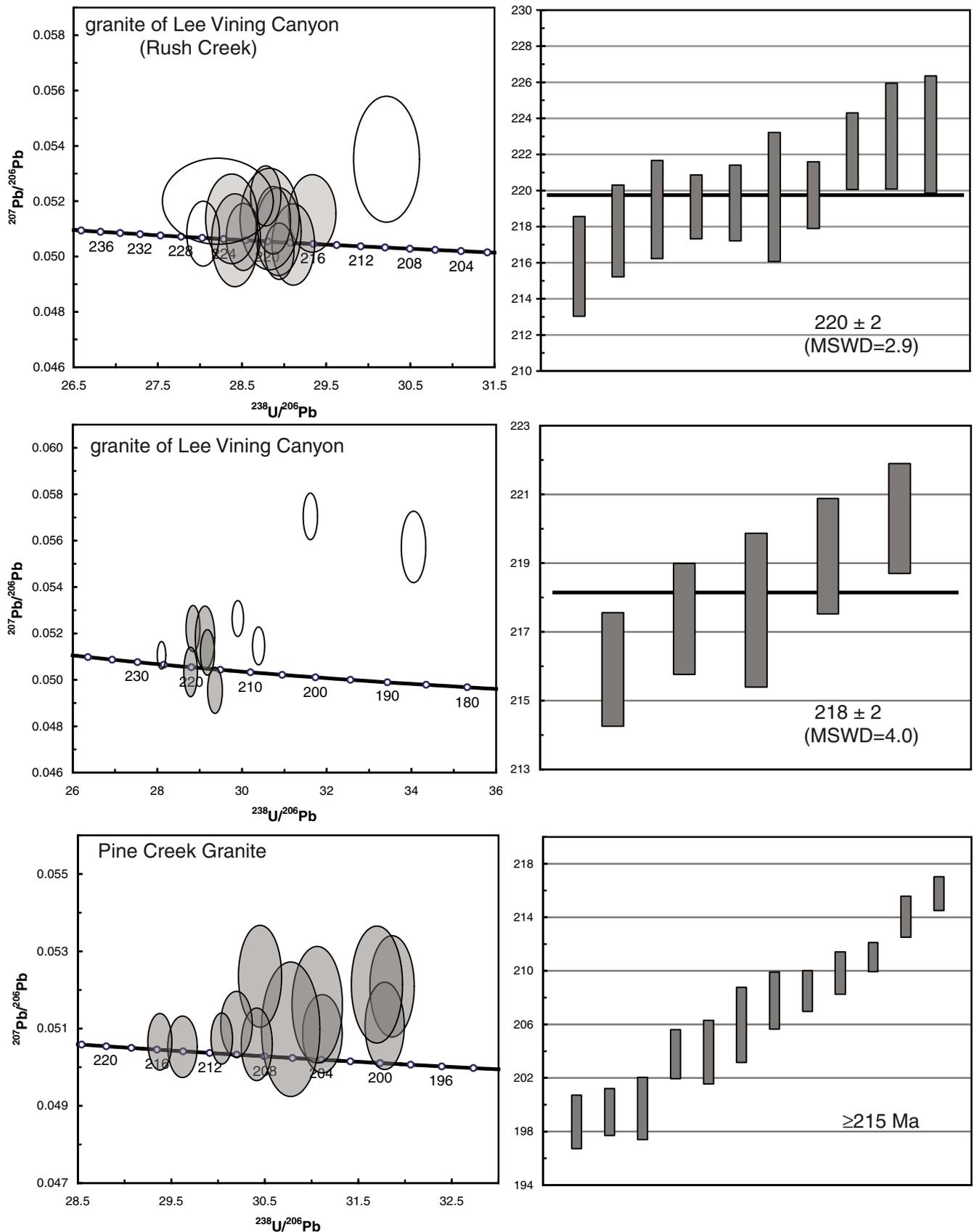
Figure 8. Tera-Wasserburg concordia diagrams and weighted mean $^{206}Pb*/^{238}U$ ages for zircons from samples of the granite of Lee Vining Canyon and Pine Creek Granite, Scheelite Intrusive Suite. All measured zircons are plotted on concordia diagrams at left; zircon analyses plotted with unshaded symbols were excluded from calculation of weighted mean crystallization age shown at right. MSWD—mean square of weighted deviates. See text for discussion.

recalculated from the 222 ± 4 Ma age reported by Schweickert and Lahren (1987), for this tuff from a correlated exposure in the Virginia Creek section (Fig. 4), in agreement with our results.

We analyzed a third sample of tuff, from the tuff of Black Mountain at the base of the Koip sequence in the Sawmill Canyon section. The sample of tuff yielded zircons with comparatively simple U-Pb systematic (Fig. 10). A single coherent group of seven magmatic grains yields a well-defined crystallization age of 232 ± 2 Ma (MSWD = 2.2). A single older grain that is concordant at 236 Ma is similar in Th/U to most other magmatic grains in this sample, and so we interpret it to be antecrystic, inherited from an older but as yet unidentified part of this magmatic system.

Geochronologic Summary

Our best estimate of ages of plutonism associated with construction of the SIS is Late Triassic, older than 215 Ma, and mostly likely from 226 to 218 Ma. Our redefinition of the SIS herein, in keeping with the use of the term intrusive suite as envisioned by Bateman (1992), includes those granitic rocks that are texturally and compositionally similar and appear to have crystallization ages separated by no more than ~8 m.y. Granodiorite and granite plutons emplaced at this time were contemporaneous with intrusion of mafic satellite plutons, including the monzodiorite pluton at Odell Lake. Assembly of the SIS was also broadly contemporaneous with eruption and deposition of mafic and silicic metavolcanic rocks of the Koip sequence exposed in the Saddlebag Lake pendant between Tioga Pass and Virginia Creek, indicating that the SIS intruded the basement of its own volcanic cover. Explosive silicic volcanism commenced prior to emplacement of any recognized volume of plutonic rock, and both mafic and silicic explosive volcanism continued during assembly of the SIS. The oldest volcanism yet recognized in this region (tuff of Black Mountain) suggests that volcanism had begun by ca. 232 Ma. Antecrystic zircon appears to be present in most tuffs and suggests magmatism may have commenced in the east-central Sierra Nevada region as early as Middle Triassic time, ca. 236 Ma.

PETROLOGIC OBSERVATIONS

### Whole-Rock Major and Trace Element Chemistry

The SIS is composed of metaluminous to weakly peraluminous, high-K granodiorite and granite (see Supplemental Table 1 [see footnote 1]), broadly compositionally similar to younger middle to Late Cretaceous intrusive suites of the Sierra Nevada batholith. Silica contents range from 62% to 77%, and most other major elements exhibit sublinear negative correlations with silica, with the exception of potassium, which correlates positively with silica, and sodium, which shows no discernible variation across this compositional range (Fig. 11). Three samples of mafic porphyritic granodiorite from the granodiorite of the Benton Range collected in the vicinity of Gaspipe Spring are Al and Ba enriched and plot off these trends, in a sense consistent with accumulation of alkali feldspar, and are excluded from further discussion. The SIS is a calc-alkalic suite, in the sense that it lacks iron enrichment (e.g., Miyashiro, 1974; Arculus, 2003), but is calcic rather than calc-alkalic in the sense of Peacock (1931). The SIS shows major element covariations remarkably similar to those of the Late Cretaceous Tuolumne and John Muir Intrusive Suites, which crop out immediately to the west (Fig. 2), but both Ca and Fe are consistently relatively enriched and Na depleted in granodiorites and mafic granites in the SIS, compared to these nearby, classically calc-alkalic suites.

Whole-rock samples suggest consistent compositional differences among SIS plutonic units, and suggest important differences both within the SIS and when comparing the SIS to adjacent Late Cretaceous suites. Wheeler Crest Granodiorite comprises granodiorite to relatively mafic granite with silica contents from 62% to 74% (Fig. 12). The Pine Creek Granite and the granite of Lee Vining Canyon largely overlap the more felsic end of the major element compositional spectrum of the Wheeler Crest Granodiorite, and extend it to silica contents of nearly 77%. Transition metal and high field strength minor and trace element abundances show good negative correlations with silica. All SIS units
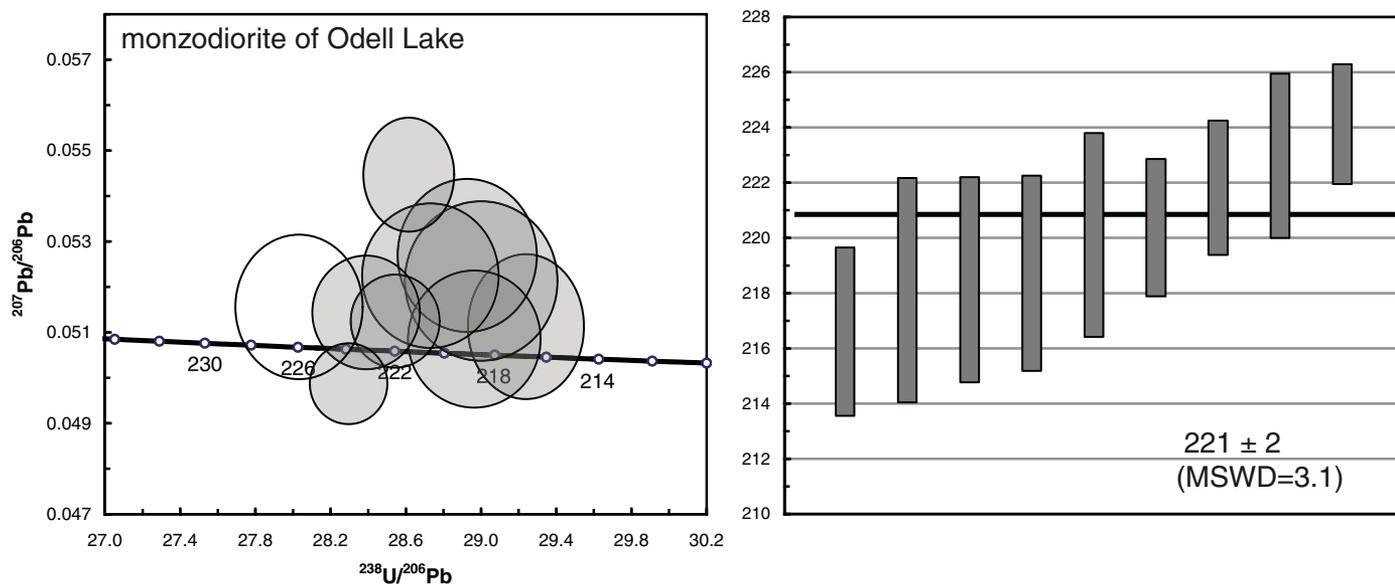
Figure 9. Tera-Wasserburg concordia diagram and weighted mean ^{206}Pb*/^{238}U age for zircons from monzonite of Odell Lake. All measured zircons are plotted on concordia diagram at left; zircon analysis plotted with unshaded symbol was excluded from calculation of weighted mean crystallization age shown at right. MSWD—mean square of weighted deviates. See text for discussion.
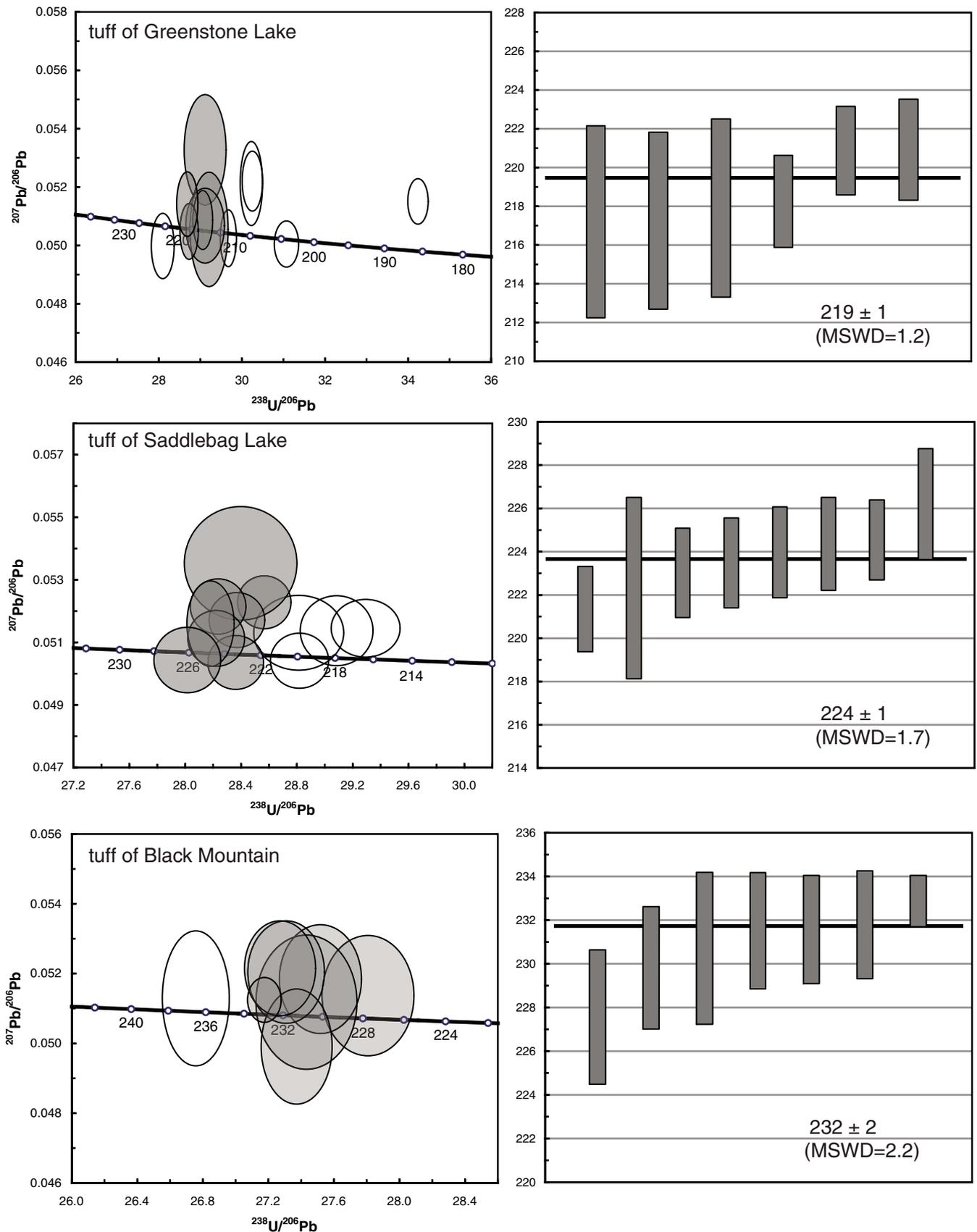
Figure 10. Tera-Wasserburg concordia diagrams and weighted mean $^{206}Pb*/^{238}U$ ages for zircons from ash-flow tuffs of the Koip sequence, Saddlebag Lake pendant. All measured zircons are plotted on concordia diagrams at left; zircon analyses plotted with unshaded symbols were excluded from calculation of weighted mean crystallization age shown at right. MSWD—mean square of weighted deviates. See text for discussion.
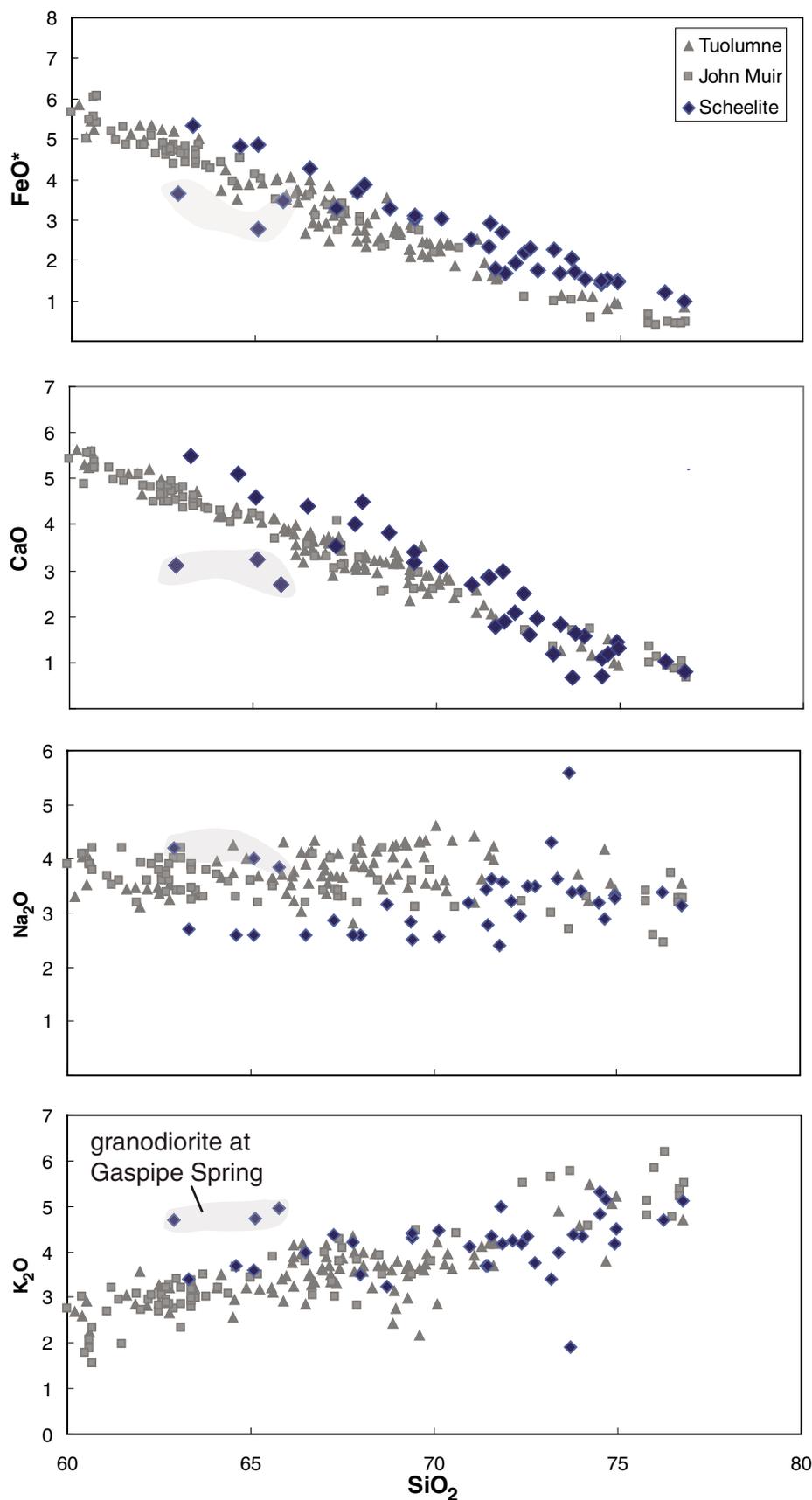
are enriched in light relative to heavy REEs (Fig. 13). Chondrite-normalized (CN) light REEs in granodiorites are enriched relative to heavy REEs, with La/Yb$_{CN}$ ~ 10–20; superimposed on these trends are very weak negative Eu anomalies of ~0.7–0.9. Granites are similarly light REE enriched and have modestly greater Eu anomalies of ~0.5–0.8. Trace element ratios indicate consistent geochemical differences between the SIS and Late Cretaceous suites. The SIS is relatively enriched in monovalent lithophile elements and depleted in Sr, resulting in consistently lower Sr/Y and La/Yb and higher Rb/Sr and Ba/Zr compared to the Tuolumne and John Muir Intrusive Suites (Fig. 14).

Major and trace element abundances suggest a geochemical affinity between SIS units and Triassic ash-flow tuffs in the Saddlebag Lake pendant, consistent with their geographic proximity and close similarity in U-Pb ages. Silica contents of the tuffs range from 70% to 74%, indicating that the tuffs are broadly dacitic to rhyolitic in bulk composition. Sodium scatters toward very low values and Ca sympathetically to high values in comparison to intrusive rocks of similar silica content, suggesting that most of these volcanic rocks underwent alkali element hydrothermal alteration. Disturbance of alkali element abundances due to both hydrothermal alteration and contact metamorphism has been documented in this region (Sorensen et al., 1998). However, the tuffs in the Saddlebag Lake pendant exhibit good linear trends with increasing silica for transition metals and oxides of high charge elements, indicating a major element compositional affinity of the tuffs to the relatively felsic parts of the Wheeler Crest Granodiorite and the granite of Lee Vining Canyon (Wonderly et al., 2009; Fig. 12).

Whole-Rock Radiogenic Isotope Chemistry

The Rb/Sr and Sr isotope ratios support the ages of rock units in the SIS calculated from zircon U-Pb systematics, but suggest some variation in initial Sr isotopic ratios. The 31 samples from this study and that of Kistler (1993) that yield a whole-rock Rb-Sr isochron age of 211 ± 10 Ma (initial $^{87}Sr/^{86}Sr$ = 0.7061 ± 3), broadly

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Figure 11. Geochemistry of low charge major elements in whole rocks from units of the Scheelite Intrusive Suite (additional analyses from Bateman et al., 1984). Compositions of adjacent Late Cretaceous John Muir and Tuolumne Intrusive Suites shown for comparison (Frost, 1987; Bateman and Chappell, 1979; Gray et al., 2008).
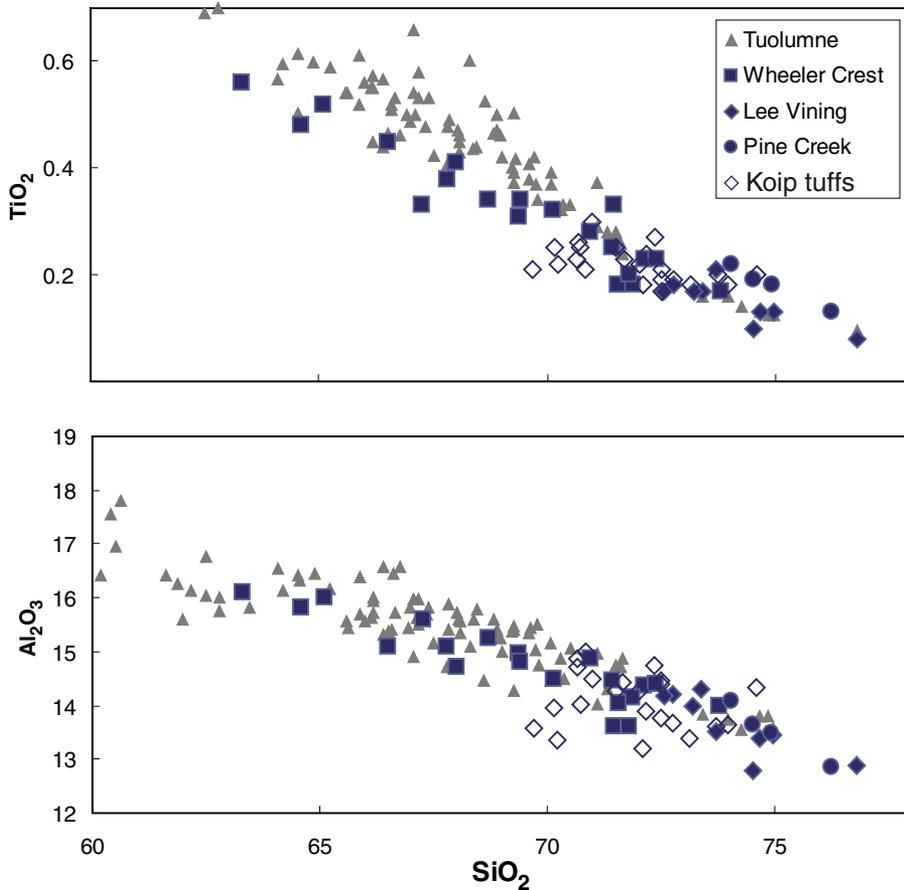
Figure 12. Geochemistry of high charge major elements in whole rocks of the Scheelite Intrusive Suite (additional analyses from Bateman et al., 1984) and tuffs from the Koip sequence in the Saddlebag Lake pendant. Compositions of adjacent Late Cretaceous Tuolumne Intrusive Suite shown for comparison (Bateman and Chappell, 1979; Gray et al., 2008).
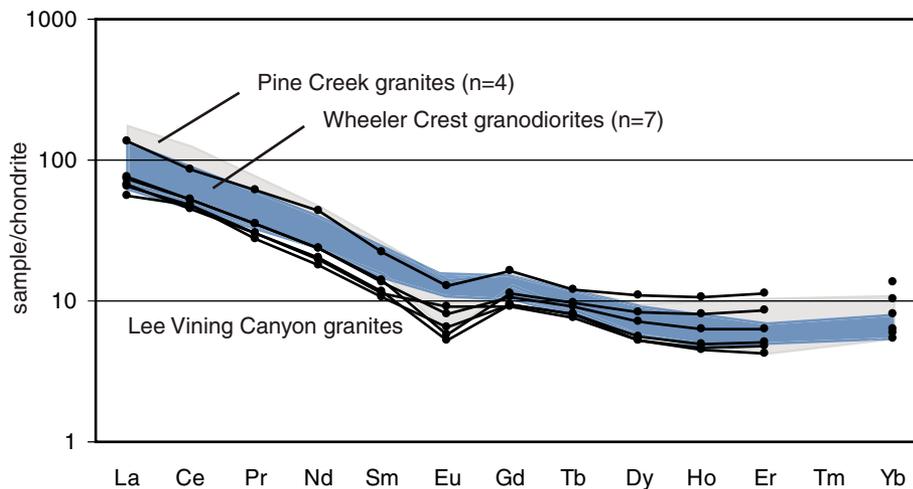
Figure 13. Rare earth element abundances in whole rocks of the Scheelite Intrusive Suite, normalized to chondrite (Boynton, 1984). Note the overall similarity in element abundances, and the deeper negative Eu anomalies in the granites as compared to the granodiorites.

in agreement with Late Triassic zircon U-Pb ages (Fig. 15). However, this isochron is primarily controlled by a limited number of samples of granite with high Rb/Sr, and in detail initial Sr ratios appear to have been variable. At an assumed age of 220 Ma, initial Sr ratios for granodiorites range from 0.7058 to 0.7063, and granites are more variable and commonly less radiogenic, ranging from 0.7052 to 0.7064.

Initial ε_{Nd} (at 220 Ma) values range from −2.1 to −4.6. Granodiorites and mafic granites are more homogeneous and less radiogenic in calculated initial ε_{Nd}, ranging from −4.1 to −4.6, whereas granites range from −2.1 to −4.5.

Values of initial ε_{Nd} and ISr (initial $^{87}Sr/^{86}Sr$ at 220 Ma) are variable between rock units, and exhibit an overall trend toward lower ISr and higher ε_{Nd} (relatively less crustal) with increasing SiO_2 (Fig. 16). SIS granodiorites and mafic granites are tightly grouped and yield the most radiogenic Sr and least radiogenic Nd, despite having the most mafic compositions. SIS granites are isotopically more variable, ranging from compositions isotopically similar to granodiorites to more radiogenic Nd and less radiogenic Sr. Although Triassic granodiorites are isotopically quite similar to nearby Late Cretaceous intrusive suites, the trend toward more isotopically primitive granites is in contrast to the constant or more radiogenic whole-rock ISr trends observed in nearby Late Cretaceous intrusive suites (Coleman et al., 1992; Coleman and Glazner, 1997). ISr ranges from 0.7057 to 0.7062 with increasing silica in the nearby, well-studied Tuolumne Intrusive Suite (Fig. 16), and negatively covaries with ε_{Nd}. SIS samples generally have less radiogenic ISr overlapping more radiogenic parts of Tuolumne isotopic array, and are isotopically similar to the least radiogenic parts of the isotopic array from granodiorite of the John Muir Intrusive Suite.

The Rb/Sr and Sr isotope ratios of volcanic rocks are more variable than plutonic rocks, and suggest substantial variation in initial Sr isotopic ratios. There are 35 samples from the lower Koip sequence from Kistler (1993) and 10 samples of ash-flow tuffs from this study that yield a composite whole-rock Rb-Sr isochron age of 212 ± 11 Ma (initial $^{87}Sr/^{86}Sr$ = 0.7055 ± 4), not significantly different from the Sr whole-rock isochron for the SIS and broadly in agreement with Late Triassic zircon U-Pb ages of the ash-flow tuffs (Fig. 15). However, this isochron has greater scatter, and in detail initial Sr ratios appear to have been highly variable. At an assumed average age of 220 Ma, initial Sr ratios for most volcanic rocks range from 0.7050 to 0.7064, similar to the range observed in granitic rocks, while ~20% of the samples scatter toward calculated initial ratios as low as

0.7036. Bulk rock compositions are not known for most of the Kistler (1993) samples, but given the large range in alkali element abundances and Na/K in our samples of the ash-flow tuffs, we do not consider these lower values to be reliable indicators of magmatic compositions. We suggest that alteration (especially loss of Na and variable Ca enrichment) occurred during or soon after deposition of the volcanic rocks due to interaction with magmatic and/or meteoric waters. There is no evidence in these data for substantial marine water interaction; marine Sr is expected to have had $^{87}Sr/^{86}Sr = 0.7077 \pm 1$ at the time (Korte et al., 2003), higher than any measured ratio in Triassic volcanic or plutonic rocks in this study.

Isotopic ratios, in particular $^{143}Nd/^{144}Nd$, solidify the affinity of Triassic felsic volcanic rocks from the Saddlebag Lake pendant with units of the SIS. In contrast to highly variable Sr initial ratios, ε_{Nd} of tuffs shows very little variation, ranging from −1.3 to −2.3. These values largely overlap those of the granites with the least radiogenic Sr initial ratios (Fig. 16). We conclude that the tuffs are isotopically similar to high ε_{Nd} SIS granites, consistent with the inference from REE and high field strength element abundances.

DISCUSSION

Age and Tectonic Setting

Granitic and volcanic rocks in the east-central Sierra Nevada record the earliest stages of magmatism in the eastern Sierra Nevada magmatic arc, allowing us to examine magma sources and connections between plutonic and volcanic processes in the initial stages of arc construction. Geochronologic and geochemical data provide a context for initiation of Cordilleran Mesozoic arc magmatism in this region, and for correlation to both the primarily volcanic arc to the north and east and the primarily plutonic arc to the south and east.

Ash-flow tuffs of the Koip sequence provide a firm basis for estimating the timing of subduction and the onset of early Mesozoic magmatism. Explosive silicic volcanism commenced earlier than any early Mesozoic plutonism recognized thus far in east-central California, and continued during granodioritic to granitic plutonism and assembly of the SIS. New zircon ages reported here confirm that the Koip sequence in the Saddlebag Lake pendant is entirely Late Triassic in age (Fig. 5), consistent with 203–214 Ma zircon ages for the equivalent Koip sequence section in the Ritter Range pendant to the south (Tobisch et al., 2000; S. Penniston-Dorland, 2010, personal commun.). Volcanism had begun by 232 Ma; a single zircon from the tuff of Black Mountain indicates that magmatism may have begun earlier, in Middle Triassic time. An Early to Middle Triassic onset for magmatism is also supported by 242–250 Ma detrital zircons in the Great Valley forearc (DeGraaff-Surpless et al., 2002; Surpless et al., 2006) and western Nevada retroarc (Manuszak et al., 2000), indicating that magmatism commenced regionally as early as earliest Triassic time. These igneous and detrital zircon ages from the central Sierra region, when considered with geochronologic evidence for the onset of Mesozoic plutonism to the south in the Mojave Desert and Transverse Ranges, provide a solid lower limit on the timing of truncation of the continental margin, and date inception of east-directed subduction to Early Triassic time (Miller et al., 1995; Barth et al., 1997; Barth and Wooden, 2006).

Granitic rocks in the east-central Sierra Nevada are the plutonic record beneath the Triassic Koip sequence volcanic arc. The SIS,
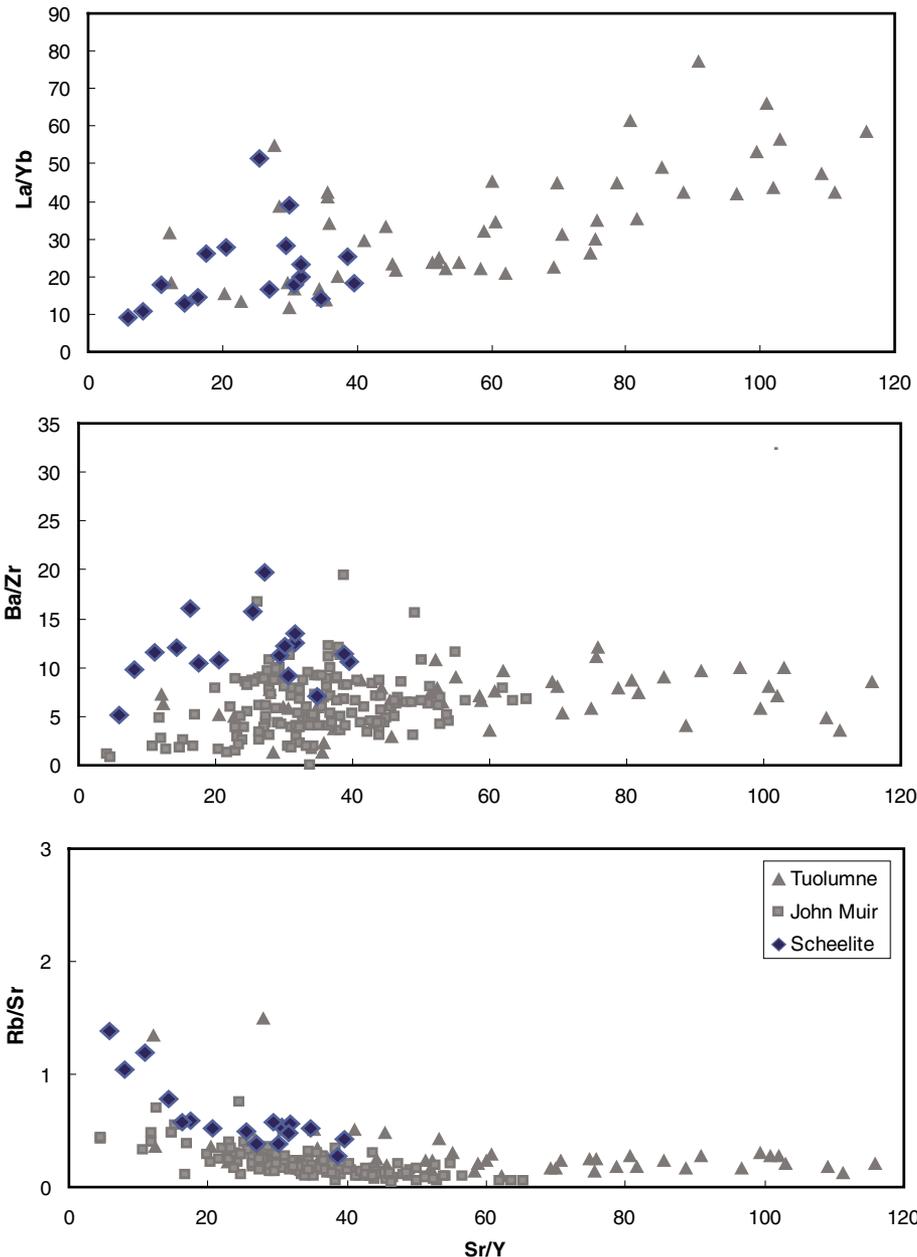
Figure 14. Trace element ratios in whole rocks of the Scheelite Intrusive Suite. Compositions of adjacent Late Cretaceous John Muir and Tuolumne Intrusive Suites are shown for comparison (Frost, 1987; Bateman and Chappell, 1979; Gray et al., 2008).

composed of the Wheeler Crest Granodiorite, the granite of Lee Vining Canyon, and Pine Creek Granite as defined here, is the oldest known and one of the largest intrusive suites in the Sierra Nevada region, and Pb/U zircon ages from each unit of the suite suggest assembly between 226 and 218 Ma. While these ages are somewhat older than previously reported bulk fraction zircon ages, they are consistent with correlation of the SIS with the middle and upper parts of the Koip sequence, as previously proposed (Bateman, 1992; Kistler, 1993; Schweickert and Lahren, 1999).

Our new 226 Ma age for the granite of Mount Olsen has important implications for the regional shortening history, and especially the history of east-vergent thrusting in the Saddlebag Lake pendant (Fig. 4), which previously had been interpreted to contain both Jurassic and Triassic thrusts. The western and eastern contacts of the granite of Mount Olsen appear to be Cenozoic normal faults. However, based on inclusions of wall rocks, Schweickert and Lahren (1987, 2006) interpreted the granite of

Mount Olsen to postdate and intrude the Lundy Canyon thrust, one of several major east-vergent thrusts that repeat most of the Triassic and older stratigraphic section in the pendant. Schweickert and Lahren (1987, 2006) relied on a multigrain zircon U/Pb age of 219 Ma for the pluton to conclude that the Lundy Canyon thrust was Triassic in age. Our new zircon data indicate that the pluton is identical in age (within analytical uncertainties) to the tuff of Saddlebag Lake (224 Ma), which is within a section imbricated by the Lundy Canyon thrust. These data may make Schweickert and Lahren's (1987, 2006) previous interpretation of the structural setting of the granite of Mount Olsen untenable, as map relations make clear that the thrust is younger than the tuff of Saddlebag Lake, i.e., younger than 224 Ma.

If the Mount Olsen pluton is the same age as, or older than, the tuff of Saddlebag Lake, resolution of this structural dilemma will require further work. Two possible scenarios are (1) the Mount Olsen pluton includes two distinctly different intrusive masses, one 226 Ma and a

younger one that had not previously been recognized; (2) the Mount Olsen pluton intrudes only the upper plate of the Lundy Canyon thrust and has been imbricated along with the Triassic section. One of us (Schweickert) currently favors the second hypothesis, which is permitted by existing map relations. Regardless of the correct explanation for the Mount Olsen pluton, our new data eliminate the possibility of a Triassic age for the Lundy Canyon thrust, and we consider it likely that it is Jurassic in age, like other higher thrusts in the pendant (Schweickert and Lahren, 2006). This age assignment suggests correlation of shortening in the Saddlebag Lake pendant with the early interval of the East Sierran thrust system (Dunne and Walker, 2004).

Precise ages for the SIS limit the significance of some hypothesized strike-slip faults in the east-central California. IBB3 is a hypothesized dextral fault that offset the eastern and western parts of the SIS and the Sr 0.706 isopleth (Fig. 1; Kistler, 1993). Schweickert and Lahren (2006) argued that lithostratigraphic and structural units in the Saddlebag Lake pendant are inconsistent with large offset across the northern trace of IBB3, projected to cut the Mount Olsen pluton. The southern exposed trace of IBB3 is cut by a 225 ± 16 Ma porphyritic felsic dike (Greene et al., 1997b) that is contemporaneous with and may have emanated from the older, 225 Ma part of the Wheeler Crest Granodiorite. Thus there is little remaining evidence for a Jurassic fault with tens of kilometers of dextral slip in the original postulated position of IBB3.

Dextral separation of ~65 km may also have occurred along the hypothetical Tinemaha fault (Fig. 1), without producing offset of the SIS (Stevens and Greene, 2000). The trace of this hypothetical fault is intruded by the Tungsten Hills Granite, which we suggest is Late Jurassic in age and not part of the Triassic SIS. Alternatively, Kylander-Clark et al. (2005) noted that a similar amount of Cretaceous and/or Cenozoic dextral slip across southern Owens Valley is required to explain offset of a distinctive Cretaceous dike swarm. Northward continuation of their Owens Valley fault could accommodate offset of the similar Devonian sections (of Stevens and Stone, 2005) at this much later time, also without offset of the SIS or the Tungsten Hills Granite, depending on its actual path through northern Owens Valley.

Late Triassic plutonic and volcanic rocks in east-central California are centrally located within the larger early Mesozoic Cordilleran arc in the western United States. Schweickert and Lahren (1993) proposed division of the early Mesozoic arc into northern and southern segments on the bases of known or inferred ages of magmatism and associated sedimentation. The
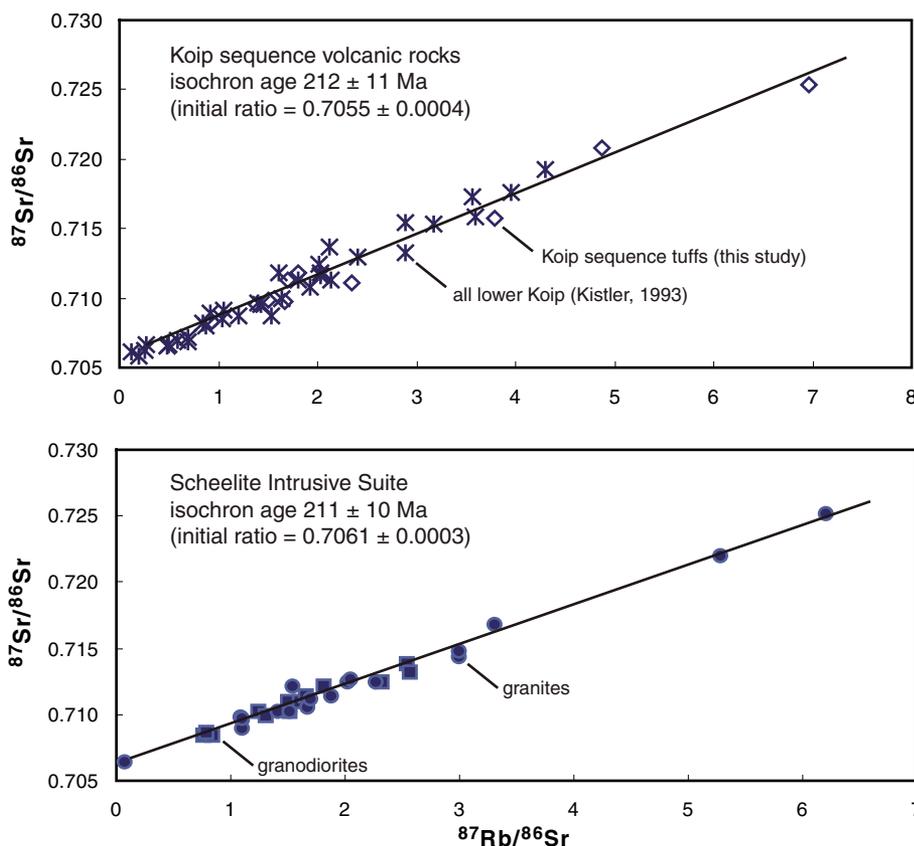
Figure 15. Strontium whole-rock isochrons from Triassic volcanic and plutonic rocks. Upper panel shows metavolcanic rocks in the lower Koip sequence from Kistler (1993, n = 35) and Koip sequence ash-flow tuffs from this study (n = 10). Lower panel shows samples of the Scheelite Intrusive Suite from this study (n = 14) and from Kistler (1993, n = 19).

northern segment, north and east of the Saddlebag Lake pendant, may be characterized as a largely shallow-marine Triassic arc formed on accreted basement rocks. This segment of the arc is typified by exposures in the Wassuk Range and Yerington District of western Nevada, where Middle and Late Triassic volcanic rocks and associated small plutons interfinger with or are overlain by Norian carbonate rocks (Fig. 5). The Triassic section in the Saddlebag Lake pendant correlates closely in time with these sections in the northern segment, but no Norian carbonates have been recognized. South and east of the Saddlebag Lake pendant, no well-dated Triassic volcanic rocks are known, but Early to Late Triassic plutonic rocks are widespread in the southeastern Sierra Nevada, Mojave Desert, and Transverse Ranges (Miller et al., 1995; Barth et al., 1997; Barth and Wooden, 2006). The ages of plutons in this southern arc segment correlate closely to the ages reported here for the SIS and Koip sequence ash-flow tuffs, but this segment may have been largely nonmarine, as plutons mostly intrude Paleoproterozoic cratonal basement. It seems likely that magmatism in both the northern and southern segments of the arc was ongoing by Middle Triassic time, and combining the plutonic, volcanic, and detrital zircon records suggests that magmatism probably commenced in both segments as early as earliest Triassic time (ca. 250 Ma; González-León et al., 2009; Dickinson and Gehrels, 2009; Riggs et al., 2009).

The other known Triassic volcanic section, south of our study area, is the problematic section in the Mineral King pendant in the southern Sierra Nevada. This pendant has some affinities to the northern arc segment in that it preserves fossiliferous Norian carbonates, although a tuff with a zircon age of 217 Ma is ~500 m higher in the stratigraphic section than these carbonate strata (Busby-Spera, 1984, 1986; Fig. 5). The position of this pendant relative to inferred intrabatholithic faults such as IBB2 and/or the Mojave–Snow Lake fault is not yet resolved (see reviews in Saleeby and Busby, 1993; Schweickert and Lahren, 1993). Further studies including precise geochronology are needed in lower Mesozoic volcanic rocks in central and southern Sierran pendants to resolve the tectonic position of rocks in the Mineral King pendant in relation to the rest of the Triassic arc.

Petrogenesis

Late Triassic plutonic and volcanic rocks in east-central California constitute a linked plutonic and volcanic rock suite. Whole-rock geochemical data indicate that the SIS is a calcic plutonic suite, but otherwise compositionally similar to adjacent metaluminous, high-K Late Cretaceous intrusive suites. Most major and trace elements show linear trends, but variations in initial isotopic data are inconsistent with an origin for this suite by simple fractionation (Figs. 16 and 17). Ash-flow tuffs in the Koip sequence are hydrothermally altered, but compositionally similar to contemporaneous felsic granodiorite and granite of the SIS in trivalent and quadravalent elements and Nd isotopes, confirming that assembly of the SIS occasioned eruption of large-volume dacitic to rhyolitic ignimbrites.

The outcrop pattern of the SIS is highly discontinuous, principally as a result of younger volcanic cover and foundering of the Long Valley caldera. The available outcrops are too fragmented to support broad petrologic conclusions regarding assembly of this large early intrusive suite of the Sierra Nevada batholith. Nevertheless, the petrographic and whole-rock geochemical data presented here indicate that the SIS shares a common heritage with younger, better exposed, and extensively studied components of the Late Cretaceous Sierra Nevada batholith such as the Tuolumne Intrusive Suite, and is likely to have formed by similar petrologic processes. Comparisons between these early and late Mesozoic intrusive suites are informative of changes in magma sources with time in this part of the Sierran arc.
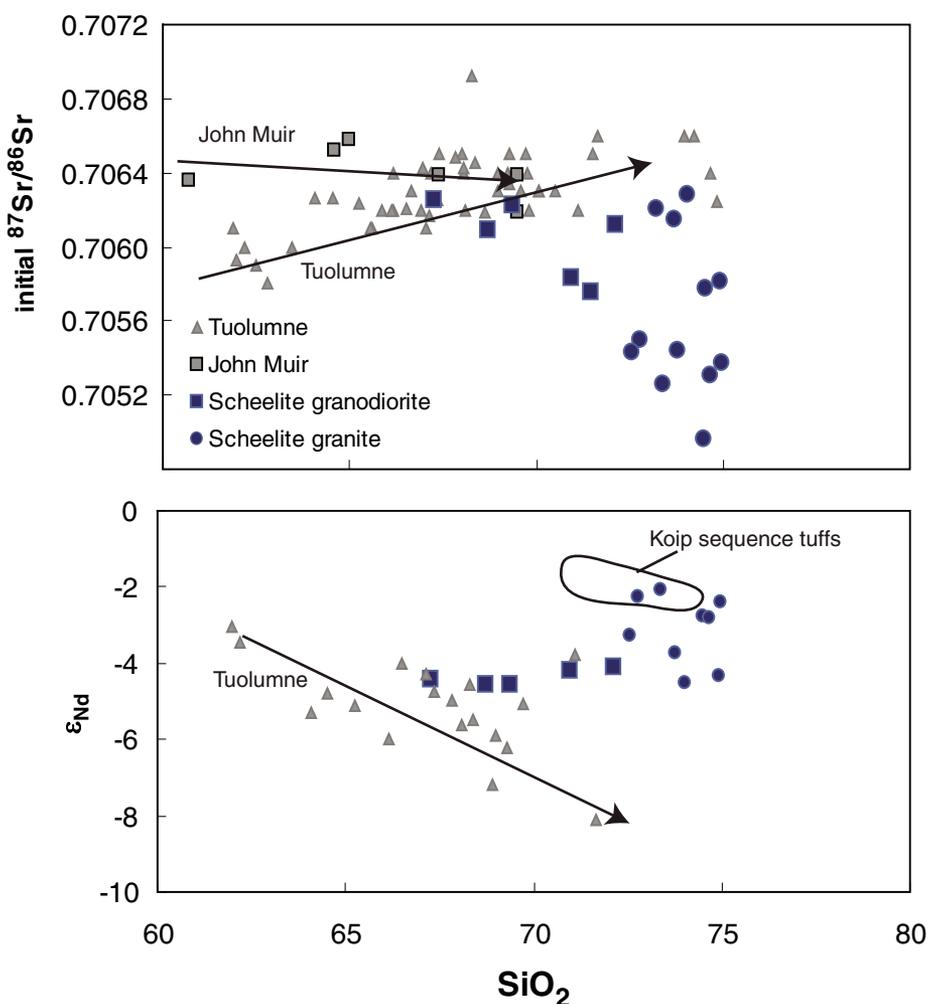
Figure 16. Whole-rock initial Sr and Nd isotope ratios (at 220 Ma) for samples of the Scheelite Intrusive Suite and Koip sequence ash-flow tuffs from the Saddlebag Lake pendant. Additional Sr isotope ratios for samples of Scheelite granites are from Kistler (1993, n = 3). Compositions of John Muir Intrusive Suite samples are from Coleman et al. (1992) and those of Tuolumne Intrusive Suite samples are from Kistler et al. (1986) and Gray et al. (2008). Arrows illustrate the isotopically homogeneous and heterogeneous trends in Cretaceous intrusive suites identified by Coleman and Glazner (1997).
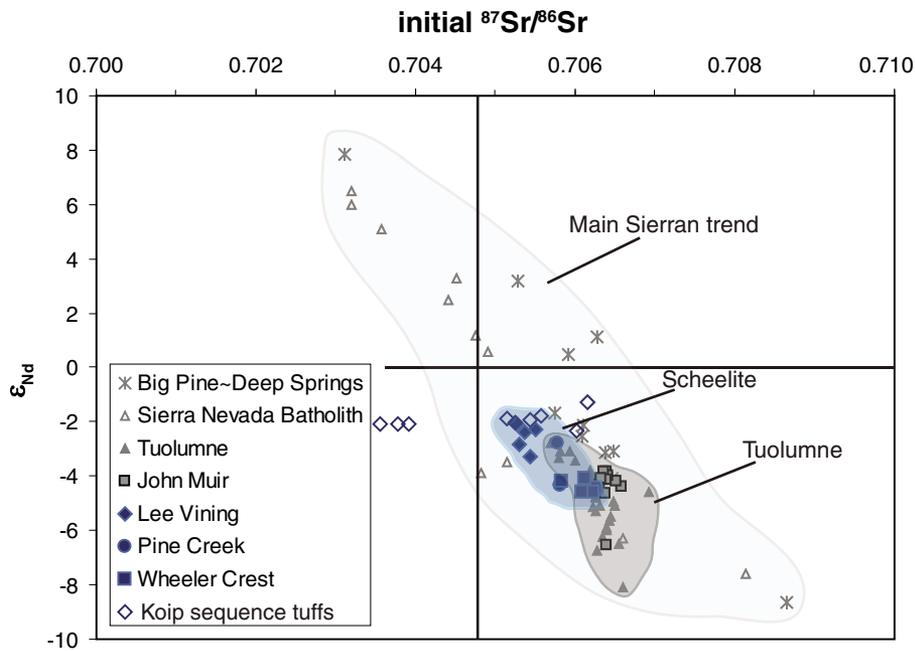
Figure 17. Whole-rock Nd-Sr isotope correlation diagram for Scheelite Intrusive Suite and Koip sequence ash-flow tuffs from the Saddlebag Lake pendant. Main Sierran trend is defined by regional granitic rock samples from the Sierra Nevada Batholith (DePaolo, 1981), and Cenozoic mafic lavas and mantle xenoliths from the Big Pine and Deep Springs volcanic fields (Beard and Glazner, 1995, 1998). Compositions of Late Cretaceous John Muir Intrusive Suite are from Coleman et al. (1992) and those of Late Cretaceous Tuolumne Intrusive Suite are from Kistler et al. (1986) and Gray et al. (2008). Note that some Koip ash-flow tuffs scatter off the main Sierran trend toward low initial Sr ratios as a result of hydrothermal alteration, but show no significant variation in initial ε_{Nd}.

A necessary step in understanding the tempo and dynamics of a long-lived Cordilleran-style intermediate magmatic arc (e.g., Glazner, 1991; Ducea, 2001; De Celles et al., 2009) is to correctly identify and characterize its initial magmatic state prior to prolonged intraarc and retroarc mass redistribution. The incipient Cordilleran arc at this latitude appears to have been built in a continent-fringing tectonic position, similar to the Famatinian arc in the Cordillera of South America (Ducea et al., 2010; Otamendi et al., 2009). Incipient magmatism was apparently largely volcanic (based on the available petrologic record), but culminated in assembly of the SIS in an episode of comparatively high intermediate magma flux. These initial Sierran arc magmas transected a structurally complex upper crust constructed by accretion of older arc and backarc sediments onto the North American Paleozoic passive margin. While there is no evidence of direct involvement of North American cratonal crust in this magmatism, isotopic data indicate that comparatively enriched North American lithospheric mantle constituted the deeper framework of the arc. Geologic and isotopic data thus indicate the early presence of lithospheric mantle both behind and beneath the arc in a position to play an active role in intermediate, high-flux magmatism, a situation that persisted until Late Cretaceous time.

Zircon data indicate that SIS plutonism (and its associated volcanism) persisted for at least 6 m.y. (and perhaps 12 m.y.). As argued by Coleman et al. (2004) for the Tuolumne Intrusive Suite, this extended age range suggests that the petrologic diversity of the rock suite is unlikely to be adequately accounted for by models involving single-stage fractionation and/or magma mixing occurring in the shallow crust. Kistler et al. (1986) suggested that mixing of crustal partial melts with basaltic parental magma could explain variation among Tuolumne Intrusive Suite granodiorites. Gray et al. (2008) suggested a modified version of this model for a long-lived Tuolumne Intrusive Suite, where a prolonged thermal event in the lower crust driven by basalt intraplating and underplating could lead to the formation of progressively more silicic, mixed granodioritic to granitic magmas. The SIS largely overlaps the Tuolumne Intrusive Suite in major element compositions, and granodiorites in the two suites are isotopically identical, yet the SIS has lower Sr, Sr/Y, and similar to lower La/Yb. These data implicate mixing between mantle-derived parental SIS basalt magmas and a relatively feldspar rich (and perhaps shallower) crustal source compared to the Tuolumne Intrusive Suite. Furthermore, isotopic compositions of SIS granites suggest involvement of crustal source rocks similar to and less radiogenic in Sr and more radiogenic in Nd than the parental basaltic end member (Fig. 17). These observations further emphasize the likely crucial role of enriched lithospheric mantle as the source of parental mafic magma for granodioritic to granitic plutonic suites of the Sierra Nevada batholith, and for cogenetic silicic volcanic suites.

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