Research Article

Reconstructing the Physical and Chemical Development of a Pluton-Porphyry Complex in a Tectonically Reorganized Arc Crustal Section, Tioga Pass, Sierra Nevada

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In ancient or partially eroded arc sections, a protracted history of tectonism and deformation makes interpretation of local volcanic-plutonic relationships challenging. The fragmentary preservation of volcanic rocks relative to the extensive plutonic record in upper-crustal arc sections also suggests that a broader-scale approach that includes volcanic-hypabyssal-plutonic “fields” is useful. In this context, studies of hypabyssal intrusions emplaced at the intersection of volcanic and plutonic fields provide additional physical and chemical constraints on shallow-level magmatic processes. New mapping, U-Pb zircon geochronology, and geochemistry at Tioga Pass, in the central Sierra Nevada arc section, document the physical and chemical evolution of the Tioga Pass hypabyssal complex, a ca. 100 Ma system that includes an intrusive dacite-rhyolite porphyry unit and comagmatic Tioga Lake quartz monzodiorite. We interpret these units as a Cretaceous subvolcanic magma feeder system intruding a package of tectonically displaced Triassic and Jurassic volcanic and sedimentary rocks, rather than the previous interpretation of a Triassic caldera. The Tioga Pass magmatic system is a well-exposed example of a hypabyssal complex with meso- to micro-scale structures that are consistent with rapid cooling and emplacement between 0–6 km depth and compositions suggestive of extensive fractionation of largely mantle-derived magma. The Tioga Pass porphyry unit is one of many hypabyssal intrusions scattered along a ~50-kilometer-wide belt of the east-central Sierra Nevada that are spatially associated with coeval volcanic and plutonic rocks due to tectonic downward transfer of arc crust. They provide a valuable perspective of shallow magmatic processes that may be used to test upper-crustal plutonic-volcanic links in tectonically reorganized arc sections.

1. Introduction

Studying the volcanic-plutonic connection in ancient and partially eroded arc sections presents some unique challenges, particularly from a temporal and geochemical perspective. Exposed sections, often biased towards deeper plutonic levels, may provide a somewhat time-averaged (yet longer-lived) record of arc activity, while volcanic units are susceptible to the effects of hydrothermal alteration and metamorphism (e.g., [1, 2]). Syn- to post-arc deformation and tectonism overprints the magmatic record and can reorganize and displace local and regional stratigraphy, masking true field relationships.

However, tectonic shuffling is also one of the primary reasons to study these crustal sections. Tectonism often results in the exposure of multiple crustal levels, providing information on the physical and spatial relationships of both plutons and contemporaneous volcanic rocks and can additionally reveal the physical structure (e.g., shape and size) of the subvolcanic magma plumbing system. Restoring local- to regional-scale structures allows for inclusion and evaluation of magmatic-tectonic relationships through mapped spatial and temporal associations of structures and magmatic rocks. Together, these factors suggest that ancient arc crustal sections provide a different perspective to understanding plutonic-volcanic relationships compared to modern systems.
In upper-crustal arc sections, hypabyssal intrusive complexes are important features as they are exposed in both volcanic- and plutonic-dominated arc domains (e.g., [3, 4]). They represent a physical connection between these environments, which is key to reconciling existing plutonic-volcanic observations and models (e.g., [5–8]). As hypabyssal complexes are emplaced at shallow levels, they have the potential to provide a snapshot of magmatic processes that relate to both plutons and volcanic rocks, such as crystal accumulation, melt extraction, and eruption (e.g., [9]).

In the Sierra Nevada arc section, several studies have drawn attention to the Mesozoic volcanic-plutonic connection, either by regional-scale comparisons between mid- to upper-crustal plutons and volcanic stratigraphic sections (e.g., [10–16]) or by the study of local volcanic features, such as calderas (e.g., [17–19]). More information on shallow levels of the plumbing system, accessed through the hypabyssal record, improves our understanding of the physical development and evolution of upper-crustal magma plumbing systems and has the potential to link observations made across wide spatial scales, from a single intrusion to a regional-scale magmatic "field."

At Tioga Pass, in the eastern-central Sierra Nevada, we reinterpret a proposed Triassic caldera [19] as a Late Cretaceous hypabyssal complex. We present new field mapping, U-Pb zircon ages, and whole-rock element and isotopic geochemical data from Tioga Pass to characterize magmatic and tectonic histories from Triassic to Late Cretaceous time. We demonstrate that both the Tioga Lake quartz monzonite and intrusive dacite-rhyolite porphyry are ca. 100 Ma and represent comagmatic parts of a punched laccolith-shaped body (steep-sided and flat-topped, with vertical walls discordant to host rock structure; [20]) that intruded blocks of faulted and tilted Triassic and Jurassic volcanic and sedimentary strata. The Tioga Pass system shares compositional and structural affinity with other Late Cretaceous intrusive and volcanic rocks in the east-central Sierra Nevada region and is one of several hypabyssal intrusions found across a ~50-kilometer-wide belt in the central Sierra Nevada arc section. These intrusions are key structural markers and may represent feeders to volcanic eruptions or stalled late melts from plutons.

2. Previous Work

2.1. Regional Background. The Mesozoic Sierra Nevada Batholith is an upper- to lower-crustal composite arc section, dominated by magnesium, calc-alkaline, metaluminous tonalite, hornblende-biotite granodiorite, and locally peraluminous granite. In the central Sierra Nevada, emplacement depths of Triassic-Cretaceous intrusive suites range from 6–10 km based on Al-in-hornblende barometry [21–23]. The 120–85 Ma Cretaceous flare-up resulted in the emplacement of voluminous upper-crustal intrusive complexes (e.g., [13, 24]). Cretaceous volcanic sections are locally exposed in several pendants of the Sierra Nevada Batholith, including the Ritter Range, Saddlebag Lake, and Piute pendants (Figure 1) [25–29], although most of the Cretaceous volcanic cover is interpreted to have been eroded. Calculated magma addition rates, using Cretaceous plutonic and volcanic rock areas, resulted in plutonic-volcanic ratios between 20:1 to 30:1 during flare-up magmatism [24].

2.2. Geology of the Saddlebag Lake Pendant. The Saddlebag Lake pendant exposes Paleozoic deep marine framework rocks and a sequence of Mesozoic arc volcanic and sedimentary packages [11, 28–31] (Figures 1 and 2). It is intruded by the Triassic Scheelite Intrusive Suite in the east and the Cretaceous (95–85 Ma) Tuolumne Intrusive Complex to the west [10, 13, 32]. Regional metamorphism pervasively altered rocks to greenschist facies [31, 33]; the prefix “meta.” is hereafter omitted from rock descriptions where the protolith is known. Unconformable contacts between westward-younging major stratigraphic packages were subsequently reactivated by strike-slip faulting [28, 30, 34]. Tioga Pass is located at the southeastern end of the Saddlebag Lake pendant (Figures 1 and 2), marking the transition of the Saddlebag Lake pendant into the northern Ritter Range pendant.

The distinctive lithologic units exposed west of Tioga Lake were previously mapped and studied by Kistler [35], Brook [31], and Schweickert and Lahren [19] (Figure 2). Interbedded sandstone and tuff units, discordant to regionally NW-striking volcanic units, could not be stratigraphically correlated to nearby Saddlebag Lake or northern Ritter Range pendants. Geologic interpretations from field relations varied widely, from hypabyssal pluton emplacement along a normal fault, a shallow volcanic vent structure, and a caldera structure [19, 31]. Schweickert and Lahren [19] interpreted a Triassic age for the proposed caldera collapse event, caldera fill sequence, and resurgent intrusions based on contact relationships between an intracaldera vent structure and the dated 222 Ma tuff of Saddlebag Lake (TRs; Figure 2).

The Dana sequence is a ~1 km thick layered package of volcanic and sedimentary units located southeast of Tioga Pass, in the vicinity of Mt. Dana, and has been linked to units at Tioga Lake (Figure 2; [19, 36, 37]). Russell [38] found basal shallow marine interbedded volcanic and sedimentary deposits, grading upwards into terrestrial ash-flow tuff, cross-bedded sandstone, and conglomerate. Intrusive units mapped at Tioga Pass, such as the quartz monzodiorite and dacite porphyry unit, were also found at Mt. Dana [35, 36]. Several intrusions and faults mask original contacts of the Dana sequence with surrounding units. Kistler [35] and Russell [38] assigned a lower Jurassic age to the Dana sequence, based on lithologic correlations to the Dunlop Formation (Nevada) and nearby Ritter Range pendant. Schweickert and Lahren [19] reinterpreted this section as part of the Triassic caldera-fill package.

3. Methods

We remapped the Tioga Pass area at 1:10,000 scales, compiled map data from the literature [19, 35, 36, 38] and collected U-Pb zircon laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) data to temporally constrain regional stratigraphy. We dated tuff units at the base and the top of volcanic packages, defined by regional unconformities or faults, to bracket the range of possible ages.
Figure 1: Simplified geologic map of the east-central Sierra Nevada, modified from the Geologic Map of Yosemite National Park by Huber et al. [102], illustrating the extent of Cretaceous plutonic (pink), hypabyssal porphyry (orange), and volcanic (green) fields. Dashed rings include areas of the Minarets and Merced Peak calderas as reported by Fiske and Tobisch [17] and Lowe [18]. Numbers indicate names of known Cretaceous hypabyssal intrusions: 1-Tioga Pass Porphyry—see Figure 2 for detailed map; 2-Shellenbarger Lake Porphyry; 3-Post Peak Porphyry; 4-Star Lakes Porphyry; 5-Red Peak Porphyry; 6-Ireland Lake Porphyry; 7-Johnson Peak Porphyry; 8-Beartrap Lake Porphyry. Locations of metavolcanic and metasedimentary pendants are labeled, and the extent of Triassic-Jurassic volcanic rocks within each pendant is shown in the cross-hatched pattern. The boundaries of the Piute Meadow, Saddlebag Lake, and northern Ritter Range pendants are shown with a dotted line. At the southern end of the map, the blank region marks the southern extent of the map study area. In other cases, blank regions of the map indicate regions of Paleozoic metasediments or Quaternary cover. The grey colored pluton in the vicinity of the Piute Meadow pendant is an unknown age. Inset map shows the Sierra Nevada Batholith and location of the study area (box).
Figure 2: Geologic map of the Tioga Pass area, based on new 1:10,000 scale mapping and compilation of maps by Russell [38], Greene [36], and McColl [103]. Unit colors indicate rock type (see legend) and units are labeled by estimated age (Pz, TR, J, K) and rock type. In some cases, units are labeled by age and unit name if given: TRsl: rhyolite tuff of Saddlebag Lake; TRbm: rhyolite tuff of Black Mountain. Blank regions denote the areas of Quaternary cover, for example, alluvium, talus, or glacial moraine features. Transects A-A', B-B', and C-C' refer to cross-sections through the Saddlebag Lake pendant and northern contact of intrusive rocks, through the southern extent of the Saddlebag Lake pendant and intrusive rocks, and through the Dana sequence, respectively (see Figures 3(a)–3(c)). Cross-section of transect D-D' is shown in Figure 6. Sense of slip on major faults is labeled where constrained. Stereographic projections: great circles of the mean bedding of the Tioga Lake section (grey line; \(N = 8\) measurements; strike/dip = 323/81), Saddlebag Lake pendant (black line; \(N = 75\) and 163/86), Dana sequence section (dotted line; \(N = 26\) measurements; 317/79), and porphyry intrusion magmatic layers (dashed line; \(N = 17\) and 141/71); (right): Great circles of the mean foliation within the Tioga Lake section (\(N = 12\); 323/81), in the surrounding Saddlebag Lake pendant strata (\(N = 75\); 160/85) and the porphyry/quartz monzodiorite magmatic foliation (\(N = 26\); 147/83). [1] in legend refers to the location of the published age of the rhyolite tuff of Saddlebag Lake by Schweickert and Lahren [19]. For U-Pb zircon sample information, refer to Table 1. Samples TP-7 and TP-14 not shown, located ~500 m north of area shown in Figure 2.
3.1. U-Pb Zircon Geochronology. LA-ICP-MS U-Pb zircon analyses were performed at the University of Arizona LaserChron Center using conventional lab procedures (e.g., [40–42]). Full analytical methods and data tables are included in Supplementary Materials (available here). Sri Lanka, FC-1, and R33 zircon grains were used as primary age standards [41]. For igneous samples, 20–30 zircons were analyzed where possible, and a weighted mean age calculated, reported at the 2σ level. We included in our weighted mean calculation only concordant zircons with U/Th < 10 as defined by Gehrels et al. [42] for igneous zircons. This excluded a small number of zircons (n = 17 grains) from the total sample set of igneous samples (n = 199 grains). For detrital zircon ages from sedimentary units approximately 100 zircons were analyzed, where possible. The location of the youngest zircon peak, made of at least 3 zircons with overlapping uncertainty, is interpreted as the maximum depositional age of the sample [43]. For published LA-ICP-MS ages where sample data are available (e.g., [28]), we reinterpreted age estimates using the above protocol in order to improve consistency across samples.

3.2. Whole-Rock Geochemistry. Sixteen samples were collected for whole-rock elemental geochemistry to characterize the porphyry (n = 10) and the quartz monzodiorite unit (n = 6). Fourteen samples were analyzed by X-ray fluorescence (XRF) at Pomona College using lab procedures outlined in Lackey et al. [44]. Five samples were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) for major oxides and/or trace elements at Activation Laboratories, Ancaster, under the “4LithoResearch” package. Three samples were analyzed for trace elements by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at Texas Tech University. Two samples were selected for whole-rock isotopic analysis performed at the University of Arizona, following methods in Otamendi et al. [45]. The standard error for isotope samples is between 0.0007%–0.0008% for 87Sr/86Sr and 0.0009–0.0018% for 143Nd/144Nd, and between 0.003–0.008% for Pb isotopes. Detailed analytical methods are included in Supplementary Materials.

4. Results

4.1. Stratigraphy of the Study Area. The wide-ranging geologic interpretations at Tioga Pass highlight the importance of combining a detailed stratigraphic and field-based record with modern geochronology to resolve outstanding uncertainty. Stratigraphic, field, and geochronologic relationships are described below for the intrusive complex and the surrounding host rocks. We use these to establish which units are spatially and/or temporally associated, restore tectonic effects, and examine the contact relationships between units. We use previously defined regional terms, such as the Triassic “Koip sequence” and Triassic-Jurassic “Dana sequence,” to describe and group temporally and spatially related strata [13, 35].

The upper Paleozoic deep marine section forms the eastern boundary of the Tioga Pass complex, where fine-grained sandstones are interbedded with chert and phyllite (Pzs; Figures 2 and 3(a)–3(c)). A detrital zircon maximum depositional age of 435 Ma was attained from a fine-grained sandstone sample northwest of Tioga Lake (sample TP-8; Table 1, Figures 2, 4, and 5). The lithology and age of overlying Triassic Koip sequence metavolcanic rocks in the Saddlebag Lake pendant have been described by Brook [31], Barth et al. [10], Paterson and Memeti [28], and Cao et al. [34]. At Tioga Pass, the rhyolite tuff of Black Mountain (TRbm; Figures 2, 3(a), and 4) defines the base of the Koip sequence and yielded an age of 229.6 ± 1.8 Ma (sample TP-14, Figure 5). This age estimate is overlapping with a U-Pb zircon sensitive high-resolution ion microprobe (SHRIMP) age from Barth et al. [10] of 232 ± 2 Ma. The overlying Cooney Lake conglomerate (TRcl; Figures 2, 3(a) and 3(b), and 4) contains meter-wide pebbly layers interbedded with coarse sandstone. Detrital zircon ages for Cooney Lake conglomerate samples form a narrow unimodal distribution with minimum peaks at 219–220 Ma (samples KA-9, TP-7, TP-1, Figure 5). The overlying 224 ± 1 Ma rhyolite tuff of Saddlebag Lake (TRsl; Figures 2, 3(a) and 3(b), and 4) [10] separates the Cooney Lake conglomerate from a package of crystal-rich flows of andesite-dacite composition (TRan; Figures 2, 3(a), and 4). The uppermost section of the Koip sequence (TRuv; Figures 2, 3(a) and 3(b), and 4) includes layers of clastic rhyolite-dacite tuff, crystal-rich andesite flows, and volcanic breccia, thinly interbedded with volcaniclastic conglomerate and sandstone. One sample of a rhyolite breccia east of the Maul Lake fault yielded an age of 220.0 ± 2.2 Ma and constrains the top of the preserved section of Koip sequence metavolcanic rock units at Tioga Pass (Figures 4 and 5; sample KA-6).

The ten-meter-wide, brittle Maul Lake fault (NW corner of Figure 2) juxtaposes Koip sequence units (TRuv) with the ca. 95 Ma Kuna Crest granodiorite (Kkc; Figures 2, 3(a), and 4; [32]). Jurassic metasedimentary rocks and Cretaceous volcanic rocks form part of the stratigraphy further north in the Saddlebag Lake pendant (e.g., Sawmill Canyon, [28]; Virginia Canyon, [34]) (Figures 1 and 4), and south in the Ritter Range pendant [46]; however, they are not exposed at Tioga Pass. They were likely entirely removed during intrusion of the Tuolumne Intrusive Complex (Figure 4) [28, 47].

4.2. Tioga Lake and Dana Sequence Sections

4.2.1. Tioga Lake Section. A coherent, NW-striking, and SW-to NE-dipping section of volcanic and volcaniclastic strata forms an approximately 800 x 400 m block exposed west of Tioga Lake (TRvs, TRan, and TRrh; Figure 2). This volcanic block is intruded on all exposed sides by a dacite-rhyolite porphyry unit and quartz monzodiorite unit (Kdp, Ktm; Figures 2, 3(b), and 4). Units include volcaniclastic sandstone,
pebbly monomict conglomerate, and andesite and rhyolite composition lava flows and tuff. The section has a total thickness of ~850 m. Meter-wide dacite porphyry dikes intrude these units at a high angle. A maximum depositional age of 217 Ma from a volcaniclastic sandstone in the intra-porphyry package (sample TCL 13-5; Figures 4 and 5) is similar to the youngest Koip sequence units in the Saddlebag Lake pendant.

4.2.2. Dana Sequence Section. The Dana sequence is a fault-bounded package of interbedded metavolcanic and metasedimentary units that is restricted to the area around Mt. Dana. It is surrounded by the Paleozoic chert-argillite unit. The package grades from mudstones and intermediate to felsic tuffs and flows (TRuv and TRtm; Figures 2 and 3(c)) into a ~200-meter-wide rhyolite tuff (TRrh; Figures 2 and 3(c)) and overlying volcaniclastic sandstone unit (TRvs; Figures 2 and 3(c)), consistent with the descriptions from previous studies [36, 38].

An andesite tuff from the exposed base of the Dana sequence yielded a weighted mean age of 212.8 ± 6.4 Ma; however, this sample yielded only 7 zircons, 6 of which were concordant (sample MD-8C; Figures 2, 4, and 5). A rhyolite flow ~200 m below the summit of Mt. Dana yielded an age of 195.1 ± 2.1 Ma (sample L101; Figures 2, 4, and 5). A fault-bounded rhyolite tuff yielded an age of 221.7 ± 2.5 Ma and could be a part of either the Koip or Dana sequence (sample MD-9; Figures 2, 3(c), 4, and 5).

4.3. Tioga Pass Intrusive Units

4.3.1. Quartz Monzodiorite. The Tioga Lake quartz monzodiorite (Ktm; Figure 2) crops out north, west, and east of Tioga Lake and has an elongate shape in map view (Figure 2). It was previously named the granodiorite of Tioga Lake ([13, 19], “unassigned granitic rocks” by [35]) and ranges in composition from quartz monzodiorite to granodiorite [48]. It is an equigranular biotite- (~5-10%) and hornblende-rich (~10%),

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**Figure 3:** Cross-sections from (a) the Saddlebag Lake pendant, (b) Tioga Lake, and (c) Dana sequence transects. See Figure 2 for locations and legend. Unit abbreviations are listed in Figure 2 legend and within the text. In cross-sections, vertical scale = horizontal scale. MLF = Maul Lake Fault, and GPF = Gaylor Peak Fault, marked on Figure 2.
Table 1: Summary of sample locations, U-Pb zircon ages, and rock units from Tioga pass.

| Sample  | UTM easting | UTM northing | Lithology                      | Map unit | Zircon type | Weighted mean age (Ma) | MSWD | Number of zircons used in calculation (number/total analyzed) | Age range of zircon (Ma) | Max age (d.z.) (Ma) |
|---------|-------------|--------------|--------------------------------|----------|-------------|------------------------|------|-------------------------------------------------|------------------------|-------------------|
| 3-3     | 0300700     | 4198040      | Granite                        | Kg       | Igneous     | 99.1 ± 1.4             | 4.9  | 18/19                                            | 91-110                 | N.A               |
| TP17    | 0301002     | 4199606      | Rhyolite portion of porphyry unit | Kdp      | Igneous     | 99.5 ± 1.6             | 0.18 | 29/29                                            | 95-107                 | N.A               |
| KA17    | 0301393     | 4198684      | Dacite portion of porphyry unit | Kdp      | Igneous     | 100.0 ± 1.3            | 0.29 | 26/26                                            | 95-113                 | N.A               |
| TIOGA   | 0301945     | 4200088      | Quartz monzodiorite            | Ktm      | Igneous     | 101.0 ± 1.5            | 0.76 | 26/26                                            | 95-109                 | N.A               |
| L101    | 0304940     | 4196433      | Rhyolite flow ibbd with sandstone unit | TRvs   | Igneous     | 195.1 ± 2.1            | 0.28 | 26/30                                            | 189-202                 | N.A               |
| MD-8C   | 0303483     | 4196495      | Andesite tuff at base of Dana sequence | TRuv | Igneous     | 212.8 ± 6.4            | 0.32 | 6/7                                              | 202-219                 | N.A               |
| TCL-13-5| 0301572     | 4198735      | Volcaniclastic sandstone       | TRvs     | Detrital    | N.A                   | N.A  | N.A                                             | 182 - >1000            | 217               |
| TP-7    | 0300642     | 4200824      | Conglomerate (sandstone interbeds) | TRcl    | Detrital    | N.A                   | N.A  | N.A                                             | 214 - >1000            | 219               |
| KA9     | 0300694     | 4199511      | Conglomerate (sandstone interbeds) | TRcl    | Detrital    | N.A                   | N.A  | N.A                                             | 202-232                | 220               |
| TP-1    | 0300964     | 4199692      | Conglomerate (sandstone interbeds) | TRcl    | Detrital    | N.A                   | N.A  | N.A                                             | 217 - >1000            | 220               |
| KA-6    | 0299695     | 4200931      | Rhyolite breccia               | TRuv    | Igneous     | 220.0 ± 2.2            | 6.8  | 19/25                                            | 204-227                 | N.A               |
| MD-9    | 0303750     | 4195932      | Rhyolite tuff                  | TRrh    | Igneous     | 221.7 ± 2.5            | 0.4  | 26/30                                            | 200-230                 | N.A               |
| TP-14   | 0300850     | 4199133      | Rhyolite tuff                  | TRbm    | Igneous     | 229.6 ± 1.8            | 1.5  | 29/30                                            | 210-257                 | N.A               |
| TP-8    | 0301024     | 4200296      | Metasiltstone/Phyllite         | Pzs     | Detrital    | N.A                   | N.A  | N.A                                             | 427 - >1000            | 435               |

Note: UTM projection is NAD1927, Zone 11S. Age data table and analytical methods can be found in the Supplementary File.
plagioclase dominated (60–70%) unit with quartz (15–30%);
grain size varies between 0.5 and 4 mm. The unit is
finer-grained and porphyritic towards the western intrusive con-
tact with the porphyry unit (Figures 2 and 6). The quartz
monzodiorite typically grades into the porphyry intrusion
close to the contact and contains abundant rounded to sub-
angular porphyritic enclaves throughout (Figure 7(a)).

A ~50-meter-wide mutually intrusive contact zone sepa-
rates the quartz monzodiorite unit from the adjacent por-
phyry; however, in some outcrops, the units have a sharp
intrusive boundary (Figures 6 and 7(b)). The quartz monzo-
diorite intrudes Paleozoic metasediments along a near-
vertical contact on northern and eastern exposures and con-
tains stoped blocks of metasediments and metavolcanic tuff
from 1 to 100-meter scale (Figures 3(a) and 3(b)). Close to
the contact with the Paleozoic quartzite, plutonic samples
contain clots of biotite.

**Petrography.** Plagioclase is the dominant mineral in the
hypidiomorphic quartz monzodiorite unit. Distinct, resorbed
cores, and well-defined oscillatory rim zoning are observed
throughout the pluton (Figure 7(c)). Plagioclase crystals have
euhedral to subhedral habit, show frequent plagioclase-
plagioclase contacts, and are almost always sutured with
other plagioclase crystals (Figures 7(c) and 7(d)). Euhedral
to subhedral hornblende crystals contain inclusions of mag-
netite. Biotite is interstitial, <0.5 mm in size, with minor
replacement by chlorite. Quartz occupies interstitial spaces
between feldspar crystal clusters and shows undulose extinc-
tion and recrystallization indicating low-temperature crystal
plastic deformation.

4.3.2. Porphyry Intrusion. The dacite-rhyolite porphyry
(Kdp; Figure 2) crops out as several large NW-striking elon-
gate intrusive bodies across the Tioga Pass area. The largest
continuous body is the exposed west of Tioga Lake. The por-
phyry has an aphanitic quartz-biotite groundmass and euhe-
dral plagioclase and alkali feldspar (~75–80%), biotite (~10–
15%), and hornblende (~5%) phenocrysts. The unit grades
from a low silica dacite to high silica rhyolite to the west.

The porphyry is internally structurally complex at the
micro- and meso-scale (Figure 6). Quartzite, pelitic schist,
rhyolite tuff, basaltic-andesite, and andesite lava flows make
up displaced blocks (up to tens of meters scale) that are incorporated into, and intruded by, the porphyry. Meter-scale rounded inclusions of the quartz monzodiorite unit are also observed within the porphyry intrusion (Figure 6).

The abundance of phenocrysts varies from <5% to 50%, while phenocryst size ranges from 1-4 mm. Crystal-rich (45-50%) dacite is observed near the contact with the Tioga Lake quartz monzodiorite, as well as in dispersed zones.

**Figure 5:** Normalized age probability plots illustrating sample age distribution for Paleozoic-Jurassic sedimentary samples and Triassic to Cretaceous volcanic samples. Ages determined by LA-ICP-MS U-Pb zircon geochronology. See Table 1 for sample locations, rock descriptions, and additional information. Note change in scale in center plot at 300 Ma.
throughout the porphyry unit (Figure 7(e)). Crystal-poor rhyodacite to high-silica rhyolite (<10% phenocrysts) forms the western part of the intrusion, with extensive mingling zones of intermediate composition magma and flow-banded rhyolite (Figures 6 and 7(f)). Grain-size generally decreases to the west. Massive and layered flow-banded zones of the porphyry unit are interpreted to be devitrified obsidian, from the outcrop and microscale observations of phenocryst and matrix grain size, composition, and local extent of the layering. Volcanic clasts are prominent in some layers of the unit (Figures 6 and 7(g)). Clasts of crystal-rich dacite are observed within the rhyolite portions of the porphyry (Figure 7(h)).

The porphyry has a discordant intrusive contact with Paleozoic metasediments and Lower Koip sequence units at Tioga Lake. In the east, the porphyry intrudes the Dana sequence and Paleozoic metasediments. Contacts are sharp and near-vertical (Figures 2 and 3(a) and 3(b)). The western contact of the porphyry with Saddlebag Lake pendant is offset <100 m by the Gaylor Peak fault. The contact between the porphyry and quartz monzodiorite is typically gradational, except where the porphyry cross-cuts the quartz monzodiorite unit as dikes or sheets.

**Petrography.** In thin section, the porphyry has a microcrystalline groundmass (Figures 7(i)–7(l)). Most groundmass appears devitrified to quartz, feldspar, mica, and oxides, although glass remains intact as inclusions or as amorphous aggregates 0.2–0.5 mm (Figure 7(l)). In flow-banded layers, the groundmass wraps around aligned phenocrysts forming a magmatic foliation (Figures 7(i) and 7(l)). Hornblende phenocrystals, observed in samples of intermediate composition, are euhedral-subhedral in shape and 1–3 mm in size. Some hornblende phenocrystals are replaced by biotite at their rims. Biotite phenocrystals are often euhedral and tabular mm-size grains, in some cases deformed (Figure 7(j)), while groundmass biotite is microcrystalline (up to 0.1 mm). Hornblende and biotite decrease in abundance from the contact zone towards the western exposed edge of the porphyry unit.

Plagioclase phenocrysts are ubiquitous in the porphyry unit (Figures 7(i)–7(k)). Plagioclase is the most abundant feldspar in the section of the porphyry unit closest to the contact, at approximately a 3:1 ratio of plagioclase to alkali feldspar. Westwards, the proportion of alkali feldspar phenocrysts increases to a 1:4 ratio of plagioclase to alkali feldspar (sample KA13; Figure 6). Alkali feldspar phenocrystals in sample KA13, a flow-banded rhyolite portion of the porphyry (Figures 6 and 7(i)) are ~1 mm in size and are coarser in the dark flow bands relative to the light bands. Feldspars have oscillatory zoning preserved throughout the unit, and there is a population of grains identified by truncated zones and contact melting points between two grains. Some phenocrysts are fractured and infilled with melt (Figure 7(l)). Plagioclase phenocrysts are often arranged in clusters (Figure 7(k)). Signs of local alteration by fluids include quartz-epidote veins and chlorite lenses in the groundmass (Figure 7(l)).
Figure 7: Field photos and photomicrographs of Tioga Pass samples. Letters correspond to locations in Figure 6. Photos a–d are from the quartz monzodiorite unit. (a) Rounded to angular porphyritic enclaves are common within the quartz monzodiorite unit (photo from Mt. Dana area, outside of Figure 6 transect); (b) Tioga Lake quartz monzodiorite unit at sharp contact with dacite porphyry dike; (c) Relict cores and zoning within a plagioclase crystal from the quartz monzodiorite, sample KA23; (d) Typical microstructure of the Tioga Lake quartz monzodiorite unit, with euhedral-subhedral plagioclase and interstitial quartz, sample KA23. Photos e–l are from the porphyry unit. (e) Crystal rich portion of the porphyry unit has 2-3 mm phenocrysts of feldspar set in an aphanitic grey groundmass; (f) Mingling zone at the western edge of the porphyry; (g) Clastic layers are found in the porphyry, with parallel orientation to flow bands; (h) porphyry clast within rhylitic portion of intrusive porphyry unit; (i) View of flow-banded rhyolite portion of the porphyry unit. The dashed line marks the contact between a dark and light flow band, sample KA13; (j) Typical microstructure of the porphyry, sample KA17; (k) Glomerocryst cluster in the porphyry unit, sample 254; (l) Flow-banded rhyolite in the porphyry unit, with fractured feldspar phenocryst. Fractures contain interstitial quartz and alkali feldspar. In the top right of the image, an example of a glassy inclusion ~0.2 mm in size. Smaller examples are found in the matrix, sample TP16-4b.
4.3.3. U-Pb Zircon Ages of Intrusive Units. The Tioga Lake quartz monzodiorite yielded a U-Pb zircon weighted mean age of 101.0 ± 1.5 Ma (sample TIOGA; Figure 8(a)), older than the 96 Ma U-Pb zircon age (n = 3 samples) reported by Schweickert and Lahren [19]. The porphyry unit was dated at the northern and southern extents of the unit and yielded ages of 100.0 ± 1.3 Ma and 99.5 ± 1.6 Ma (samples KA17 and TP17), indistinguishable in age within uncertainty from the Tioga Lake quartz monzodiorite (Figures 8(b) and 8(c)). Low MSWD values for these samples indicate the over-estimation of uncertainty [49] (Table 1). The 99.1 ± 1.4 Ma age estimate of an outcropping granite unit (sample 3-3; Kg on Figure 2) at the Kuna Crest granodiorite margin also overlaps in age with the quartz monzodiorite and dacitic porphyry unit. In this sample, the age of the youngest peak, at 98–99 Ma, is interpreted as the unit age, as the high MSWD value indicates that the current weighted-mean model does not suitably fit the data [49, 50] (Figure 8(d), Table 1). This age estimate for sample 3-3 is older than the 93.95 Ma isotope-dilution thermal ionization mass spectrometry (ID-TIMS) age estimates for the Kuna Crest margin ~10 km south of Tioga Pass [32]. In summary, the granite is contemporaneous with the dacite porphyry and quartz monzodiorite, but the petrogenetic relationship of the granite to these units remains uncertain.

4.4. Structural Features of the Study Area. Structural data from Mesozoic volcanic and sedimentary rocks and Cretaceous intrusive rocks are used to evaluate the timing and impacts of local tectonism in deforming and displacing units related to the intrusions and to provide information on the three-dimensional structure of the intrusive complex.

A bedding-parallel foliation and cleavage is well-exposed in Paleozoic and Mesozoic rocks, with an average foliation of strike/dip = 160/85 in the mapped area (Figure 2). Mineral stretching lineation (measured in biotite and quartz) plunges between 70–90°. The Triassic Tioga Lake block (Figures 2, 3(b), and 4) displays bedding rotated ~30° counterclockwise relative to the average orientation of Saddlebag Lake pendant units in the mapped area, with an average orientation of 133/83, also seen in foliation measurements (average orientation 323/81; Figure 2). Dana sequence units are eastward-dipping and gently to tightly folded, with an average orientation of 318/79 (Figure 2). Magmatic foliations (147/83) and well-defined flow bands (141/71) in the porphyry unit are oriented in a NW-SE direction (Figures 2 and 6). Along a SW-NE transect, layering of flow-bands, clastic layers, and mingling zones generally dip between 55–70°, shallower than the regional structural grain (Figures 2 and 6). The Sierra Crest Shear Zone is a ~300 km long dextral-transpressive shear zone in the eastern Sierra Nevada, recording ductile deformation from at least 95 Ma to 84 Ma based on pluton ages and biotite cooling ages, switching to brittle behavior between 84–80 Ma [28, 34, 51–53]. The porphyry intrusion locally has a solid-state foliation defined by deformed quartz grains and biotite phenocrysts that roughly parallels the earlier magmatic foliation. This solid-state foliation occurs at the western margin of the porphyry, where it intersects with the eastern margin of the Sierra Crest Shear Zone ("Cretaceous ductile shear zone" in Figure 2). The eastern margin of the Sierra Crest Shear Zone also deforms Triassic andesite flows and breccias in the Saddlebag Lake pendant. The western edge of the shear zone extends to the margin of the Kuna Crest granodiorite of the Tuolumne Intrusive Complex. Shear bands, boudinaged quartz veins, and σ-porphyroclasts are common structures within the sheared parts of the porphyry intrusion and generally indicate dextral shear.

Faults in a NW striking brittle fault system are locally quartz-filled or associated with the mineralization of tourmaline and epidote. Dextral strike-slip motion is the dominant fault style based on offset markers between stratigraphic units and measured slickenlines. The Gaylor Peak fault, a Jurassic thrust fault [19, 29], is one example of a reactivated through-going brittle fault in the area. The mapped fault trace cross-cuts the ca. 100 Ma porphyry unit (Figure 2), suggesting that the fault was reactivated in the Late Cretaceous. Subhorizontal slickenlines are found along the fault trace, indicating strike-slip movement on the fault. Several smaller, near-vertical strike-slip brittle faults cross-cut the porphyry unit with minor offsets (<100 m). These faults represent the transition from ductile to brittle behavior of the shear zone [51].

4.5. Whole-Rock Geochemistry of Tioga Pass Intrusive Rocks. Major and trace element whole-rock geochemistry from Tioga Pass intrusive rocks (Figure 9) illustrates wide inter- and intra-unit compositional variation. Fields of Cretaceous plutonic, hypabyssal, and volcanic rock samples, between 105 and 95 Ma, from the central Sierra Nevada (data sources listed in Figure 9 and Supplementary Materials) are shown for comparison with the Tioga Pass units. All four groups show similar trends with overlap in composition. Plutonic rocks span the widest range in composition, while hypabyssal samples show a narrow range in composition.

4.5.1. Major Elements. Quartz monzodiorite samples contain between 55 and 64 wt.% SiO₂, whereas the silica content in the porphyry unit ranges between 63–73 wt.%. Al₂O₃, CaO, Fe₂O₃ (total Fe expressed as Fe₂O₃), TiO₂, MnO, P₂O₅, and MgO decrease in abundance with increasing SiO₂ contents in both units (Figure 9(a); Table 2). Samples of the porphyry unit are dominantly peraluminous with ASI between 1.02 and 1.15 (ASI = molar (Al₂O₃)/[(CaO-3.33*P₂O₅ + Na₂O + K₂O)]. One metaluminous porphyry sample (sample KA20) with ASI 0.86 crops out at the contact between the pluton and the porphyry. The quartz monzodiorite has an ASI between 0.90 and 1.06. The single peraluminous sample in this unit (KA26) is also from the contact zone. These samples from the contact have similar major element compositions and also share a compositional affinity with porphyry and quartz monzodiorite samples collected from the southwest and northwest slopes of Mt. Dana, respectively.

One sample of the quartz monzodiorite (sample KA23; 56 wt.% SiO₂) has high amounts of the major elements, e.g., 6.64 wt.% CaO, 9.42 wt.% Fe₂O₃, and 1.19 wt.% TiO₂, compared to the other samples. A porphyritic mafic magmatic enclave (sample TP16-1a) with mm-size feldspar phenocrysts...
Figure 8: LA-ICP-MS U-Pb zircon age distributions for Cretaceous intrusive units at Tioga Pass. From base of section to top: (a) sample TIOGA from the Tioga Lake quartz monzodiorite unit, (b) sample KA17 of the porphyry unit, (c) sample TP17 of the porphyry unit, and (d) sample 3-3 of the granite unit. Probability density function plot is shown in a red line. The zircon grain age in sample 3-3 represented by a filled circle was identified as an outlier in Isoplot [104]. Horizontal bars for individual grains represent 2σ uncertainty, circles represent grain ages. Vertical dashed lines indicate the calculated weighted mean age, and grey bars show the analytical uncertainty. In sample 3-3, the blue line represents the age of the youngest peak, which is slightly younger than the mean weighted age. See Table 1 for sample locations, descriptions, and additional information.
Figure 9: Elemental geochemistry data. See Table 2 for sample names and analytical data. (a) MgO (wt.%) vs. SiO$_2$ (wt.%); (b) K$_2$O (wt.%) vs. SiO$_2$ (wt.%); (c) Ba (ppm) vs. K$_2$O (wt.%); (d) Sr (ppm) vs. CaO (wt.%); (e) V (ppm) vs. TiO$_2$ (wt.%); (f) Sc (ppm) vs. CaO (wt.%); (g) Y (ppm) vs. SiO$_2$ (wt.%); (h) Rare earth element patterns normalized to chondrite [105]. Fields include Cretaceous volcanic, hypabyssal, and plutonic samples in the central Sierra Nevada. Data sources for fields: Peck and Van Kooten [96]; Lowe [18]; Ratajeski et al. [106]; Memeti [95]; Cao et al. [34]; Ardill et al. [107] and this study. Blue arrow points towards the top of the exposed section in the porphyry unit. This is not shown on c, as there is no clear trend from the base of the unit to the top.
Table 2: Major, trace element, and isotope compositions of Tioga Pass samples.

| Sample | Major oxides (wt.%) | Trace elements (ppm) |
|--------|---------------------|----------------------|
|        | SiO₂ | TiO₂ | Al₂O₃ | Fe₂O₃ | MnO | MgO | CaO | Na₂O | K₂O | P₂O₅ | Total | Method |
| TP16-1a | 61.79 | 0.85 | 17.70 | 5.14 | 0.10 | 2.35 | 4.96 | 3.73 | 2.80 | 0.27 | 99.70 | Method a |
| TP16-1b | 54.43 | 1.19 | 18.98 | 7.52 | 0.20 | 3.80 | 6.79 | 4.13 | 2.40 | 0.27 | 99.72 | Method a |
| TP16-3 | 60.40 | 0.87 | 17.67 | 6.51 | 0.12 | 2.57 | 6.64 | 3.79 | 1.76 | 0.25 | 99.71 | Method a |
| KA23 | 55.95 | 0.66 | 18.44 | 9.42 | 0.06 | 1.14 | 4.15 | 4.12 | 3.23 | 0.36 | 99.68 | Method a |
| KA26 | 63.08 | 0.61 | 17.00 | 4.74 | 0.09 | 0.96 | 3.89 | 3.99 | 3.37 | 0.20 | 99.68 | Method a |
| WP199 | 67.28 | 0.55 | 18.60 | 2.06 | 0.07 | 0.74 | 2.73 | 4.29 | 3.86 | 0.20 | 99.69 | Method a |
| TP16-4a | 69.54 | 0.50 | 17.37 | 2.64 | 0.05 | 0.70 | 2.34 | 4.16 | 4.20 | 0.50 | 99.78 | Method a |
| TP16-9 | 70.50 | 0.48 | 16.99 | 2.84 | 0.03 | 0.58 | 2.56 | 4.08 | 4.20 | 0.30 | 99.79 | Method a |
| WP166 | 66.15 | 0.38 | 16.35 | 2.36 | 0.03 | 0.55 | 2.50 | 3.79 | 3.71 | 0.18 | 99.74 | Method a |
| KA17 | 63.07 | 0.32 | 15.85 | 2.84 | 0.02 | 0.79 | 1.23 | 4.45 | 3.71 | 0.16 | 99.67 | Method a |
| KA13L | 71.42 | 0.55 | 15.10 | 2.78 | 0.06 | 0.32 | 1.35 | 2.56 | 3.71 | 0.27 | 99.52 | Method a |
| KA13D | 72.76 | 0.38 | 13.96 | 0.97 | 0.04 | 0.28 | 0.79 | 2.56 | 3.71 | 0.32 | 99.74 | Method a |
| KA20 | 63.07 | 0.70 | 16.82 | 4.44 | 0.09 | 0.79 | 1.35 | 4.45 | 3.71 | 0.32 | 99.75 | Method a |

Method a: a = analyzed in this study; b = analyzed in a previous study.
### Table 2: Continued.

| Sample | Tioga Quartz Monzodiorite | Tioga Porphyry Unit | Tioga Porphyry Unit |
|--------|---------------------------|---------------------|---------------------|
|        | Sample: TP16-1a TP16-1b TP16-3 KA23 KA26 | WP199 TP16-4a TP16-4b TP16-7 TP16-8 TP16-9 WP166 | KA17 KA13L KA13D KA20 |
| Easting | 0301669 0301669 0301445 0301761 0301578 | 0302927 0301385 0301385 0301267 0301106 | 0300981 0303306 0301393 0301088 0301088 |
| Northing | 4199853 4199853 4199784 4199365 4199447 | 4199746 4199746 4199755 4199747 4199528 | 4196242 4198684 4199100 4199100 |

| Element | TP16-1a | TP16-1b | TP16-3 | KA23 | KA26 | WP199 | TP16-4a | TP16-4b | TP16-7 | TP16-8 | TP16-9 | WP166 | KA17 | KA13L | KA13D | KA20 |
|---------|---------|---------|--------|------|------|--------|---------|---------|--------|--------|--------|-------|------|-------|-------|------|
| Eu      | -       | -       | 1.6    | 1.4  | 1.35 | -      | -       | -       | -      | -      | -      | 1.48  | 1.3  | 0.98  | 1.20  | 1.56 |
| Gd      | -       | -       | 5.0    | 3.6  | 4.17 | -      | -       | -       | -      | -      | -      | 4.02  | 3.4  | 4.61  | 5.02  | 6.27 |
| Tb      | -       | -       | 0.7    | 0.5  | 0.63 | -      | -       | -       | -      | -      | -      | 0.62  | 0.5  | 0.71  | 0.72  | 0.82 |
| Dy      | -       | -       | 4.2    | 3.0  | 3.65 | -      | -       | -       | -      | -      | -      | 3.57  | 3.1  | 4.62  | 4.60  | 5.27 |
| Ho      | -       | -       | 0.8    | 0.6  | 0.68 | -      | -       | -       | -      | -      | -      | 0.66  | 0.6  | -     | -     | -    |
| Er      | -       | -       | 2.2    | 1.7  | 1.88 | -      | -       | -       | -      | -      | -      | 1.89  | 1.8  | 2.81  | 2.61  | 2.95 |
| Tb      | -       | -       | 0.3    | 0.3  | 0.284 | -    | -       | -       | -      | -      | -      | 0.27  | 0.3  | -     | -     | -    |
| Lu      | -       | -       | 2.0    | 1.6  | 1.85 | -      | -       | -       | -      | -      | -      | 1.76  | 1.9  | 2.77  | 2.61  | 2.65 |
| Hf      | 5       | 2       | 4      | 3.6  | 4.2  | 5.6    | 4      | 6       | 6      | 5      | 5      | 4.7   | 6.1  | 9.1   | 6.1   | 6.0  |
| Pb      | 12      | 16      | 16     | B.D.L | 7    | 19     | 15      | 18      | 17     | 14     | 16     | 7     | 19   | 15    | 12    | 12   |
| Th      | 10      | 4       | 8      | 3.7  | 8.9  | 11.4   | 13      | 14      | 16     | 17     | 19     | 9.9   | 11.9 | 18.0  | 13.8  | 8.9  |
| U       | 1       | 5       | 4      | 1.3  | 3.3  | 1.3    | 6       | 6       | 5      | 4      | 4      | 3.6   | 3.2  | 5.4   | 4.6   | 2.7  |

**Method:**
- TP16-1a: Analyzed at the University of California, Berkeley.
- TP16-1b: Analyzed at the University of California, Davis.
- TP16-3: Analyzed at the University of Washington.
- KA23: Analyzed at the University of British Columbia.
- KA26: Analyzed at the University of Saskatchewan.
- WP199: Analyzed at the University of Alberta.
- TP16-4a: Analyzed at the University of British Columbia.
- TP16-4b: Analyzed at the University of Saskatchewan.
- TP16-7: Analyzed at the University of Alberta.
- TP16-8: Analyzed at the University of British Columbia.
- TP16-9: Analyzed at the University of Saskatchewan.
- WP166: Analyzed at the University of Alberta.
- KA17: Analyzed at the University of British Columbia.
- KA13L: Analyzed at the University of Saskatchewan.
- KA13D: Analyzed at the University of Alberta.
- KA20: Analyzed at the University of British Columbia.

**Isotope ratios:**
- $^{87}$Sr/$^{86}$Sr: 0.705015
- $^{187}$Os/$^{188}$Os: 0.135
- $^{206}$Pb/$^{204}$Pb: 18.9539
- $^{207}$Pb/$^{204}$Pb: 15.6539
- $^{208}$Pb/$^{204}$Pb: 38.6737

Note: UTM projection is NAD1927, Zone 11S.
has a similar SiO₂ content to KA23, but has higher MgO, Al₂O₃, and lower Fe₂O₃. Within the porphyry unit, there is a compositional trend in major elements linked to spatial location, as the porphyry becomes gradually more felsic towards the west (Figure 6; Figure 9 arrows); a pattern that is not observed in the quartz monzodiorite unit.

4.5.2. Alkali Enrichment. Samples in both units show a trend of increasing K₂O and decreasing Na₂O with increasing SiO₂ (Figure 9(b)). Barium and Rb also increase with increasing K₂O (Figure 9(c)). Sample KA13L contains anomalously high concentrations of K₂O and Ba (7.41 wt.% and 3208 ppm, respectively). In addition, elevated K/Na, K/Al, and Ba/Ti in sample KA13L suggests that this sample experienced pervasive alkali metasomatism [2].

4.5.3. Minor and Trace Elements. Strontium decreases with increasing SiO₂, and with decreasing CaO in the porphyry unit (Figure 9(d)), both decreasing towards the top of the mapped section (Figure 9 arrow). In the quartz monzodiorite, Sr varies from 500-600 ppm but does not vary with CaO. In both units V and Sc decrease with increasing SiO₂ and increase with increasing TiO₂ and CaO (Figures 9(e) and 9(f)). With increasing SiO₂, Y, Zr, and Rb in the porphyry unit increase, but Y decreases slightly in the quartz monzodiorite unit; Zr and Rb in the quartz monzodiorite increase (Figure 9(g)). Compositional overlap between units is evident in all the above elements between 62-65 wt.% SiO₂. Rare earth element (REE) patterns of the porphyry unit and the quartz monzodiorite display similar normalized La/Lu ratios of 7.3-11.1 and 8.5-15, respectively, although samples from the porphyry have a slight negative Eu anomaly that is absent in quartz monzodiorite samples (Figure 9(h)).

4.5.4. Isotopes. Initial strontium and neodymium isotope ratios (⁸⁷Sr/⁸⁶Sr and εNd) for the quartz monzodiorite sample (KA23) are 0.704997 and -0.29, respectively. In the porphyry sample (KA17), these ratios are 0.705494 and -1.33. εNd and ⁸⁷Sr/⁸⁶Sr values are within the mantle array [54] and are within the isotopic range of Cretaceous Sierra Nevada peridotite and pyroxenite xenoliths [55] (Figure 10(a)). Initial Pb isotopic ratios (20⁷Pb/²⁰⁶Pb, 20⁸Pb/²⁰⁴Pb, and 20⁶Pb/²⁰⁴Pb) in the quartz monzodiorite are 15.67433, 38.97684 and 19.15353, respectively. The porphyry unit has initial Pb ratios (20⁷Pb/²⁰⁴Pb, 20⁸Pb/²⁰⁴Pb, and 20⁶Pb/²⁰⁴Pb) of 15.65512, 38.67639, and 18.9539, respectively. Lead isotope ratios from the porphyry have a slight negative Eu anomaly that is absent in quartz monzodiorite samples (Figure 9(h)).

5. Discussion

The Tioga Pass area of the central Sierra Nevada contains a Cretaceous hypabyssal magmatic complex intruding into regionally extensive host-rock strata of the Saddlebag Lake and northern Ritter Range pendants, as well as the Tioga Lake and Dana sequence sections (Figure 11). Evidence for this new interpretation includes (1) ca. 100 Ma U-Pb zircon ages of the porphyry and quartz monzodiorite; (2) the grada-
tional contact between these two units and overlap in compositions indicating comagmatic emplacement; and (3) field and petrographic features characteristic of shallow (subvolcanic) emplacement. Field evidence combined with element and isotope compositions are permissive of a “magma feeder system” model (Figure 11) where fractionation was significant in producing the compositional zoning and peraluminous rhyolite from mantle-derived magmas. Specifically, amphibole (ASI ~0.5; Zen [58]) and clinopyroxene (ASI ~0; Zen [58]) fractionation can drive the resulting melt to peraluminous compositions (e.g., Zen [58], Nandedkar et al. [59], Clemens et al. [60]).

5.1. Tioga Pass Cretaceous Magmatic Complex. Weighted mean ages from the Tioga Lake quartz monzodiorite, granite, and porphyry unit are indistinguishable within uncertainty. As the contact between the granite and the other Cretaceous intrusions is concealed, interpretation of the relationship to the granite unit is hindered. However, field evidence from the quartz monzodiorite and the porphyry unit demonstrate that they are comagmatic across a contact that varies from gradational to sharp along strike. In addition, inclusions of the quartz monzodiorite are found within the porphyry and vice versa. The overlap in major and trace elements between units (at 62-65 wt.% SiO₂) near the contact zone, and the overlap in REE patterns, is consistent with a comagmatic relationship.

Observations consistent with a hypabyssal interpretation include the discordant intrusive contact of the porphyry unit and quartz monzodiorite with the surrounding host rocks, the porphyritic texture, the glassy inclusions and clasts, as well as the glomerocrysts and fractured crystals. The glass inclusions in particular are indicative of rapidly cooled magma. Devitrification is interpreted where the glassy inclusions are found together with the recrystallized matrix [61, 62]. Layers including clastic material suggest interaction with the surface, or near-surface, environment, either during magma ascent or possible eruption. Plagioclase and alkali feldspar phenocrysts are clustered, forming the distinctive glomeroporphyritic structure of the porphyry unit. In this case, the preferential contacts of like minerals are observed (e.g., plagioclase-plagioclase clusters are abundant), which is a common feature of hypabyssal rocks (e.g., [63]). Melt extraction from a crystal mush and/or the tectonic disruption of the mush could produce feldspar glomerocrysts in porphyries and volcanic rocks [6, 64–66]. Many of the phenocrysts are fractured, which could occur by a volcanic eruption, a decrease in pressure due to magma ascent, or the rapid “ungluing” of crystal groups [65, 67–69].

The quartz monzodiorite transitions from an equigranular to porphyritic texture close to the contact with the porphyry unit, but the largest textural and structural variations are within the porphyry unit. The quartz monzodiorite and porphyry share similar mineralogy but differ in modal proportions of quartz, alkali feldspar, and biotite (more abundant in the western extent of the porphyry), and there is a decrease in hornblende and biotite phenocryst abundances westwards in the porphyry unit. The porphyry unit is stratified by rock type and structure, with layers uniformly dipping.
Figure 10: Whole-rock isotopes from Tioga Pass and select regional constraints. (a) Age-corrected $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\varepsilon$Nd with mantle reservoirs (DM, HIMU, BSE, EMI, and EMII), mid-ocean ridge basalt (MORB) and altered oceanic crust (AOC) labeled [54]. Cretaceous Sierra Nevada peridotite and pyroxenite xenoliths from Ducea and Saleby [55] are included for comparison. (b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs. $^{206}\text{Pb}/^{204}\text{Pb}$ showing the location of mantle reservoirs (DM, EMI, EMII, and HIMU) [54]. Western Cordilleran Pb isotope sources are drawn from Zartman [57]. Central Sierra Nevada fields drawn from Chen and Tilton [108], and pyroxenite xenolith field drawn from Ducea [56]. Data sources [1] Ardill et al. [107], [2] Lowe [18], [3] Memeti et al. [78], [4] Gray et al. [77].
Topographically, the porphyry grades from a crystal-rich dacite to a flow banded rhyolite at higher levels, and many of the major and trace elements are zoned from the base of the section to the top (Figures 9 and 11). This suggests that layers in the porphyry unit preserve their original orientation and have not been steeply tilted. Our tests of sample alteration (e.g., alkali enrichment) suggest that this is a primary chemical gradation. Further, the compositional zoning implies that either the porphyry is made up of multiple pulses or gradually fractionated from a dacite to a high-silica rhyolite (Figure 12).

Plagioclase appears to be an important mineral defining the intermediate-felsic composition of the intrusive units. It is likely controlling the decrease in Sr, and the high concentration of Sr and CaO in some quartz monzodiorite and porphyry samples suggests that these samples accumulated plagioclase. The quartz monzodiorite does not show the negative Eu anomaly of the porphyry unit nor a positive anomaly, but retains a subtle signature of feldspar accumulation at the upper-crustal levels. This interpretation is consistent with observations of the elevated plagioclase content, plagioclase-plagioclase contacts in the quartz monzodiorite, and plagioclase glomerocrysts of the porphyry unit. Zoning of K2O and Rb across the mapped section suggests an important role for K-feldspar fractionation, except in sample KA13L.

The porphyry is distinct from the quartz monzodiorite in that it has a peraluminous composition (with the exception of one sample at the contact zone reported above). In addition to the role of fluids and volatiles (e.g., [70]), one explanation is that the porphyry may contain a higher proportion of highly fractionated melt (preserved in the rock as glass or recrystallized glass matrix). The metaluminous quartz monzodiorite on the other hand is likely a cumulate that lost melt and accumulated feldspar. Another possibility is that the porphyry unit assimilated some of the surrounding host rocks (Triassic volcanic rocks or Paleozoic chert/argillite unit), supported by field observations of stpeed blocks (Figures 6 and 11). However, these blocks are found in both units, so assimilation of the blocks does not entirely explain the peraluminosity of the porphyry unit. Generating peraluminous rhyolite compositions in the porphyry unit from a mantle-derived magma (e.g., [71]; discussion below) suggest that fractionation played a significant role in generating the compositional variety observed in the porphyry unit.

A depleted mantle or oceanic crust (MORB) magma source (εNd > +7.5; [54]) does not fully explain the magmatic source of the Tioga Pass intrusions, which have negative εNd values, unless the depleted mantle source was progressively enriched and modified during earlier arc activity. In addition, the samples do not share isotopic affinity with enriched mantle reservoirs (EMI and EMII; Figure 10(a)). However, initial Sr, Nd, and Pb isotope ratios of the porphyry unit and quartz monzodiorite match Cretaceous lower crust and mantle lithosphere xenolith compositions [55], suggesting that the porphyry and quartz monzodiorite magmas are largely mantle-derived. Further, Lackey et al. [71] measured δ18O in zircon from the Tioga Lake quartz monzodiorite (5.98‰) and found values slightly elevated above the mantle range (5.3 ± 0.3‰; [72]). Initial Pb isotopes indicate that the magmas incorporated deep-marine sediments of the western Cordilleran passive margin ([57]; Figure 10(b)), which is compatible with field observations of the Paleozoic chert-argillite unit in contact with the Tioga Pass intrusions and detrital zircon studies.
that show that the age range from this type of unit is regionally extensive in the eastern-central Sierra Nevada (e.g., [30] and references therein). Although crustal contamination was limited, based on Rb-Sr, Sm-Nd, and O isotope systems, the marine sediments (and the underlying basement/lithospheric mantle) represent one likely assimilant.

Isotopes from Tioga Pass samples are relatively primitive compared to the isotopic compositions of intrusive suites from the central Sierra Nevada, which are on average $^{87}\text{Sr}/^{86}\text{Sr} > 0.706$ and $\varepsilon\text{Nd} < -1.7$ (e.g., [73–75]). This signal is not unique to Tioga Pass, and other Late Cretaceous intrusions with a similar isotopic composition, emplaced south of Tioga Pass, include the ca. 97 Ma quartz monzodiorite of Rush Creek, which is comparable to the Tioga Lake quartz monzodiorite in composition and size ([4, 76]; Figure 10(a)), and the hypabyssal ca. 100 Ma Shellenbarger Lake granite porphyry ([18]; Figures 10(a) and 10(b)). To the north of Tioga Pass, the 97 Ma Solidar Lake granodiorite [34] and a Cretaceous volcanic sample are isotopically similar to the Tioga dacite porphyry unit. The eastern margin of the Kuna Crest granodiorite and Kuna Crest lobe, emplaced at 95-94 Ma ([32], Memeti et al., in review), contain the most primitive compositions of the Tuolumne Intrusive Complex ([77]; Figures 4–12 in [78]; Memeti et al., in review) and represent much larger volumes of magma than the other examples. These intrusions and volcanic rocks are all located within an arc-parallel belt in the eastern-central Sierra Nevada that is also defined by $\delta^{18}\text{O}_{\text{zr}}$ approximating, or slightly higher than, mantle values between 5.5–6.5‰ [71]. Lackey et al. [71] interpreted this as a zone of minimal crustal contamination and extensive recycling of mantle lithosphere and upper-mantle (see also [79]). The similarity in isotope compositions suggests each of these intrusions had a similar mantle-derived magma source to the Tioga Pass system,
including a minor component of deep marine sediments (Figure 10). It further indicates that the whole-rock Sr, Nd, and Pb isotopes across this eastern belt capture the basement composition of the arc framework rocks (e.g., [80]).

5.2. Alternate Interpretation of the Tioga Pass Magmatic Complex. An alternate interpretation of the field and geochronologic data is that the porphyry represents the subvolcanic (intrusive) roots of a lava dome (e.g., [81]). The lack of vesicles within this unit suggests that the magma was already degassed or the microstructure was overprinted by Cretaceous regional tectonic shortening [34, 82–84]. Flowbanding structures are characteristic features of lava flows and domes, both in the upper parts of magma feeder conduits and at the surface [85, 86], a feature which is ubiquitous in the porphyry unit. Glomerocrysts have been recorded in extrusive lava flows and domes (e.g., [66]). The sharp, discordant intrusive contact between the intrusive units and older host rocks requires this to be a subvolcanic system but could have fed an extrusive structure such as a lava dome or stratovolcano (e.g., [4]).

5.3. Tectonic Implications. New geochronology from volcanic and sedimentary units at Tioga Pass expands our understanding of the regional early Mesozoic stratigraphy of the Saddlebag Lake and northern Ritter Range pendants. In combination with field relationships, this resolves differences between Triassic and Cretaceous tectonic histories and aids in refining the local structural history for this area. Triassic and Jurassic deposition is recorded in the Tioga Lake and Dana sequence sections, preserving the transition from Triassic emergent volcanism to shallow marine sedimentation. We suggest that correlative in situ units from the Saddlebag Lake and northern Ritter Range pendants are not observed because they were removed prior to, or during, emplacement of the 95–85 Ma Tuolomne Intrusive Complex, which truncates the ca. 220 Ma volcaniclastic unit at Tioga Pass. Some displacement of the Tioga Lake and Dana sequence sections may have been accommodated by the Gaylor Peak fault, as proposed by Greene [36] and Schweickert and Lahren [19]. If so, this must postdate Dana sequence formation (195 Ma) and precede the emplacement of the magmatic complex at 100 Ma, which intrudes these units. Subsequent strike-slip reactivation of this fault offsets the porphyry unit (Figure 11). Rotation of bedding and foliation in the Tioga Lake block could alternatively have occurred during the emplacement of the porphyry unit; rotated structures are also observed in <50 m stopped host-rock blocks within the porphyry unit.

Repeated episodes of deformation and tilting of strata occurred in the Triassic and Jurassic (e.g., [28, 34]); however, Cretaceous units of the Tioga Pass intrusive complex are less tilted and less strained than the older rocks in the same area. This may indicate that by 100 Ma (at the peak of the Cretaceous flare-up), tectonically driven steepening and shortening were waning. In intrusive rocks, the porphyry preserves evidence for ductile shear during Sierra Crest Shear Zone activity that occurred after porphyry emplacement at ca. 100 Ma, but prior to brittle faulting between 84–80 Ma (e.g., [51]).

The Kuna Crest granodiorite, Tioga Lake quartz monzodiorite, hypabyssal porphyry, and Cretaceous volcanic rocks are structurally juxtaposed at the present-day surface (Figures 1, 3(a)–3(c)). This tectonic association between plutons and volcanic rocks of similar age has been identified at other localities in the central Sierra Nevada (e.g., [14, 22]) and is attributed to downward transfer of host rock (e.g., [27, 47, 87, 88]). Using the minimum and maximum U-Pb zircon ages for each unit and Al-in hornblende barometry of the Kuna Crest granodiorite ([21]; Memeti et al., in review), the rate of downward transfer is estimated between 1.6–4 km/m.y., consistent with pendant-wide estimates from Cao et al. [47]. Whether downward transfer was episodic (over geologic timescales) or continuous remains to be tested.

5.4. Implications for Hypabyssal Intrusions in the Central Sierra Nevada and the Volcanic-Plutonic Connection. The Tioga Pass magmatic complex is one example of a shallowly emplaced, porphyritic magma feeder system in the central Sierra Nevada (Figure 11). Other Cretaceous hypabyssal intrusions scattered along a ~50-kilometer-wide belt of the central Sierra Nevada are recognized from a synthesis of published literature and our ongoing field studies using the field and textural criteria outlined in this study. Known hypabyssal intrusions are labeled in Figure 1 and are reported as far south as Kings Canyon National Park in the southern Sierra Nevada (not shown; [16, 89, 90]). Below we outline some of the general features of these intrusions in the context of our findings at Tioga Pass.

Hypabyssal intrusions across the central Sierra Nevada are typically small in areal extent (10 m–10 km in diameter) and have a range of 3D shapes, including punched laccoliths (flat-topped, steep-sided intrusions: [20], Figure 11), pipes, and porphyritic dikes [13, 17, 88]. They sometimes intrude through slightly older metavolcanic rocks; the ca. 100 Ma Shellenbarger Lake granite porphyry cuts across the Minaret caldera fill deposit and is interpreted as a hypabyssal resurgent dome to the Minaret caldera (Figure 1; [17, 86]).

Field observations of hypabyssal intrusions highlight the diversity of structures found at shallow levels and suggests that a range of magmatic conditions may be captured in these systems. In the central Sierra Nevada, hypabyssal intrusions are dominantly intermediate to felsic in composition, such as andesite, dacite, monzodiorite, granodiorite, and granite. Basaltic andesite compositions are locally found ([17]; S. Attia, pers. comm.). Textures are largely porphyritic, with phenocrysts of alkali feldspar, plagioclase, and biotite common [18, 91, 92]. Phenocrysts are set in a groundmass that ranges from medium-grained (akin to typical plutonic equigranular textures) to fine-grained or microcrystalline (volcanic aphanitic textures). In the latter case, the differentiating feature of a hypabyssal stock from a volcanic deposit is a discordant, intrusive contact with surrounding strata or older plutonic bodies [13, 90]. As exemplified at Tioga Pass, hypabyssal bodies often have complex macro- to microscale internal structures. In many instances they
contain miarolitic cavities and granophyric microstructures, which are compatible with volatile saturation and shallow emplacement at approximately 1 kbar [93, 94], although miarolitic cavities are also found in the Tuolumne Intrusive Complex (6–10 km; [78]).

Compositions of the hypabyssal intrusions can be used to reconstruct source characteristics, test crystal accumulation processes, and explore the possible genetic associations between plutons, hypabyssal intrusions, and volcanic rocks in the upper crust. Cretaceous plutons in the central Sierra Nevada are magnesian, calc-alkaline, metaluminous to peraluminous granodiorite, and granite in composition [13]. Porphyry and volcanic fields overlap considerably with plutonic compositions (Figure 9). However, the hypabyssal samples trend towards peraluminous and alkali-calcic compositions and are generally more compositionally restricted than plutons, between 62–76 wt.% SiO₂ (e.g., [18, 76, 95, 96]). Our findings at Tioga Pass extend the compositional range of known hypabyssal intrusions in the central Sierra Nevada (Figure 9), and in some cases, results are quite distinct from regional patterns (e.g., Yttrium; Figure 9). In addition to the Tioga Pass system, other Late Cretaceous plutons and hypabyssal intrusions emplaced along the eastern edge of the central Sierra Nevada have relatively primitive bulk isotopic compositions (Figure 10(a)) compared to average values for the arc section, illustrating a regional control on mantle and crustal components in the magma source that extends into the upper crust [71, 80].

Field relationships combined with chemical compositions of plutonic, hypabyssal, and volcanic rocks have been studied in other settings to characterize volcanic-plutonic systems and refine existing volcanic-plutonic models (Figure 12). For example, caldera structures that formed during the Cenozoic ignimbrite flare-up in western North America document a wide variety of structural and chemical volcanic-plutonic relationships, made possible due to the exposures of the magma plumbing from the surface to 9 km depths (e.g., [3, 6, 8, 97, 98]). Volcanic and shallow plutonic rocks within each system typically share a “compositional affinity” (e.g., Yttrium; Figure 9) and, in some cases, shallow plutons are interpreted as the residual magmas to erupted volcanic deposits (e.g., [9, 99]; Figure 12-magma feeder system model). Often, the exposed shallow plutons are resurgent into the erupted volcanic rocks, and thus did not directly feed volcanism (e.g., [3, 100, 101]; Figure 12-failed eruption model). In each example, shallow intrusions (0-6 km depth) provide windows into different levels of the magmatic system through time. The study of these intrusions is particularly important in areas where surface deposits and the uppermost crust are largely eroded, such as the Sierra Nevada.

6. Conclusions

(1) The Tioga Lake quartz monzodiorite and dacite-rhyolite porphyry are comagmatic intrusive units overlapping in age at ca. 100 Ma and are not related to a Triassic caldera system. Our favored interpretation is that the intrusions were emplaced at shallow crustal levels and represent part of the subvolcanic magmatic roots of once-extensive Cretaceous volcanic deposits, now partially preserved in host-rock pendants across the central Sierra Nevada. Thus, the only known Sierran caldera structures are the Cretaceous Minarets and Merced peak calderas.

(2) Whole-rock isotope from Tioga Pass, and nearby intrusions and volcanic rocks along the eastern belt of the central Sierra Nevada, are sensitive to the composition of regional arc framework rocks, including the underlying basement and mantle sources. Mantle-derived magmas along this eastern belt contain a minor crustal component consistent with the composition of the host Paleozoic deep marine sediments. The Tioga Lake and Dana sequence sections represent ~2 km of Triassic and Jurassic strata that is otherwise not preserved at Tioga Pass, due to surface or magmatic erosion. Cretaceous ductile and brittle activity reactivated earlier structures, and rapid downward flow of rocks juxtaposed volcanic, hypabyssal, and plutonic rocks.

(3) Subvolcanic porphyry intrusions in the Cretaceous central Sierra Nevada are widespread and are also documented in other parts of the arc section (e.g., [16, 90]). Combining this dataset with temporally and spatially associated volcanic and plutonic rocks provides a multilevel view of the uppermost parts of an arc crustal column, owing to either differential erosion and/or downward transfer processes that transported volcanic rocks erupted at the surface to 6–10 km depth before intrusion of broadly coeval plutons. In this regard, porphyry intrusions represent key structural markers in tectonic studies, where they are constrained by a crystallization age and emplacement depth (between approximately 0–6 km). We posit that these hypabyssal intrusions are also significant in that they may physically and chemically relate to volcanic deposits and/or the late melts drained from plutons.

Data Availability

Geochronology and geochemical datasets collected in this study are provided in Tables 1 and 2 in the manuscript, and in spreadsheets in the Supplementary File.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Claiborne, Joseph Colgan, Nancy Riggs, and Gerardo J Aguirre-Diaz improved the earlier versions of this manuscript. We thank Sarah Roeske for editorial handling.

**Supplementary Materials**

The supplementary data spreadsheet summarizes the data collected in this study. Table S1: U-Pb zircon data for igneous rocks. Table S2: U-Pb zircon data for metasedimentary rocks. Table S3: isotopic data. Table S4: data sources used to create the data clouds in Figure 9. Detailed analytical methods are included in the supplementary methods file. (Supplementary Materials)

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