Sahwave Batholith, NW Nevada: Cretaceous arc flare-up in a basinal terrane

Nicholas J. Van Buer and Elizabeth L. Miller

DEPARTMENT OF GEOLOGICAL AND ENVIRONMENTAL SCIENCES, STANFORD UNIVERSITY, 450 SERRA MALL, BLDG. 320, STANFORD, CALIFORNIA 94305-2115, USA

INTRODUCTION

The Mesozoic Sierra Nevada Batholith preserves an extensive record of continental-margin arc magmatism that serves as a classic, worldwide model, especially for high-intrusive-flux magmatism. Previously, however, only reconnaissance-level studies (e.g., Smith et al., 1971; Barton et al., 1988; Van Buer et al., 2009) have explored the possibility that this batholith might extend past the Sierra Nevada mountains into the NW Basin and Range Province (Fig. 1), where Mesozoic relationships are obscured by Cenozoic volcanism and basin development related to extensional faulting. Consequently, many published figures depicting the Sierra Nevada Batholith are truncated against the edge of the Basin and Range or the Nevada border (e.g., Tikoff and de Saint Blanquat, 1997; DeGraaff-Surpless et al., 2002; Lackey et al., 2005), and the Sierra Nevada Batholith is often considered to be restricted to the mountains it was named for. However, boundaries as recent as the Neo- gene limit of Basin and Range extension (dotted line, Fig. 1), which defines the eastern scarp of the Sierra Nevada, would seem to rather arbitrarily delimit the much older Mesozoic Sierra Nevada Batholith. Although Mesozoic outcrops in the Basin and Range are less continuous and more deeply weathered than those in the genetically scoured Sierra Nevada, the Sahwave and Nightingale Ranges, about an hour NE of Reno, Nevada, form a broad, uplifted horst block of Mesozoic basement that is well suited for investigating the relationship between plutonic rocks in the NW Basin and Range and in the Sierra Nevada (Figs. 1 and 2). Detailed mapping in the Sahwave and Nightingale Ranges, combined with reconnaissance of the surrounding areas, was used to identify distinct intrusive units for further quantitative study. Most of the intrusive units in this area were identified as belonging to a single, very large, roughly concentrically zoned intrusive suite, emplaced at ca. 90 Ma, referred to here as the Sahwave intrusive suite (Fig. 2). Zoned intrusive suites of approximately the same age in the Sierra Nevada, such as the Tuolumne intrusive suite, have received detailed geochronological, mineralogical, geochemical, and structural study due to vigorous and ongoing debate about their petrogenesis and emplacement (e.g., Bateman, 1992; Coleman et al., 2004; Žák and Paterson, 2005; Hirt, 2007; Gray et al., 2008), and therefore provide an excellent data set for comparison with the Sahwave intrusive suite. As the first report of its kind in this region, this paper attempts to set forth several types of basic data, from map data and rock descriptions to modal mineralogy, U-Pb geochronology, and major- and trace-element, and isotope geochemistry. Comparison of data between these intrusive suites allows us to evaluate whether the Sierra Nevada Batholith should be considered to extend into the NW Basin and Range (Fig. 1). Furthermore, differences between these regions of high intrusive flux may have important implications for arc flare-up models.

REGIONAL GEOLOGIC SETTING

Subduction-related arc magmatism in the Cordillera began in the Triassic and continued episodically into the Late Cretaceous (and into the Paleocene north of the Snake River Plain and in southern Arizona; Fig. 1). The resulting batholithic belt has been variably disrupted by Cenozoic extension and translation and now forms several distinct segments, including the Idaho Batholith, the Sierra Nevada Batholith, and the Peninsular Ranges Batholith (Fig. 1). The final episode of magmatism in California and Nevada spanned ca. 120–85 Ma, and was particularly voluminous during the latter half of this period (e.g., Barton et al., 1988; Ducea, 2001). In most of the U.S. Cordillera, the Cretaceous batholith exhibits a regular younging pattern from west to east that is generally mirrored by geochemical trends from more mafic to more felsic (e.g., Evernden and Kistler, 1970; Hyndman, 1983; Silver et al., 1979).
One of the most distinctive features of the Sierra Nevada Batholith is the series of large, compositionally zoned intrusions of the Cathedral Range intrusive suite, emplaced along the eastern edge of the main Sierra Nevada Batholith at the very end of Cretaceous arc magmatism between ca. 94 and 83 Ma (Evernden and Kistler, 1970; Kistler et al., 1986; Tikoff and Teyssier, 1992). Representing a high level of magmatic flux (e.g., Ducea, 2001), these intrusions generally exceed 1000 km² in area, and are characterized by central megacrystic K-feldspar granites or granodiorites surrounded by more mafic equigranular granodiorites (e.g., Bateman, 1992; John and Robinson, 1982; Titus et al., 2005; Hirt, 2007; Saleeby et al., 2008). Similar large, zoned intrusions are also present in the Peninsular Ranges Batholith (Fig. 1), although these are somewhat older (primarily ca. 99–92 Ma) and have tonalite and trondhjemite as well as granodiorite compositions (e.g., Gastil, 1983; Walawender et al., 1990).

The Cretaceous Sierra Nevada and Peninsular Ranges Batholiths, which contain these large intrusions along their east sides, straddle the boundary between North American continental crust and oceanic terranes to the west, as approximated by the initial ⁸⁷Sr/⁸⁶Sr = 0.706 line (Fig. 1; e.g., Gastil, 1975; Saleeby, 1981; Kistler, 1990); in contrast, the locus of Cretaceous magmatism between the Sierra Nevada and western Idaho (Fig. 1) does not appear to be adjacent to regular continental crust. Wall rocks to the Cretaceous intrusions in this area include a basinal terrane of early Mesozoic deep-marine strata and the early Mesozoic arc terranes bounding it to the north-west and southwest (Fig. 2; e.g., Speed, 1978; Quinn et al., 1997; Wyld, 2000). These rocks have regionally been metamorphosed to sub-greenschist to lower greenschist grade but often reach amphibolite grade proximal to Mesozoic intrusions (e.g., Willden, 1964; Bonham, 1969; Johnson, 1977; Barton et al., 1988). The basinal strata, which belong to the monotonous Late Triassic (Norian) to earliest Jurassic Auld Lang Syne Group, are essentially submarine fan deposits, metamorphosed into slate/phyllite with subordinate quartzite lenses and rare calc-silicate/marble layers (Burke and Silberling, 1973; Speed, 1978). Correlative, but thinner, strata overlie the shelfal, earlier Triassic Star Peak Group east of the main locus of Cretaceous magmatism (Silberling and Wallace, 1969), but farther west, the basal strata exceed 6 km, and no base is exposed (Compton, 1960; Burke and Silberling, 1973; Speed, 1978). Jurassic shortening associated with the Luning-Fencemaker thrust belt (LFTB) is developed in Mesozoic basin sequences (Oldow, 1984). Distribution of Mesozoic intrusions is modified from King and Beikman (1974).

The metamorphic and plutonic rocks of the northern Sierra Nevada and the northwest Basin and Range are unconformably overlain by Eocene, Oligocene, and Miocene volcanic and sedimentary rocks (Fig. 2). This widespread unconformity represents a profound change from erosion in the latest Cretaceous and early Tertiary to active deposition of volcanic and sedimentary strata in the Eocene to Miocene and is an important datum for reconstructing geologic relationships prior to Miocene extension and related tilting (Van Buer et al., 2009). Uplift and erosion of the Tertiary strata have resulted in exposure of the unconformity and underlying Mesozoic basement in the tilted footwalls of most major Basin and Range normal faults, leaving a discontinuous Mesozoic outcrop pattern (Figs. 1 and 2).
Although the Cretaceous Cordilleran magmatic arc has been traced across NW Nevada (Fig. 1) based on reported pluton ages between 105 and 85 Ma (e.g., Smith et al., 1971; Barton et al., 1988; Wooden et al., 1999), reconnaissance studies and compilations have not adequately addressed the character of the intrusions across this intervening region. Previous mapping in northwestern Nevada includes thorough coverage only at 1:250,000 scale, which does not differentiate between separate plutonic units (Willden, 1964; Bonham, 1969; Willden and Speed, 1974; Johnson, 1977). More detailed work has been completed on Jurassic and Triassic intrusions in western Nevada (e.g., John et al., 1994), and on intrusions in the gold-producing region of north-central and northeast Nevada (Fig. 1; reviewed in du Bray, 2007). For Cretaceous plutons in NW Nevada, some structural and geochronological work has been completed (e.g., Wyld and Wright, 2001; Ciavarella and Wyld, 2008; Colgan et al., 2010), but no detailed petrologic or geochemical data have been published that are adequate to address the magma genesis of these intrusions and their relationship to contemporaneous intrusions in the Sierra Nevada.

**CRETACEOUS PLUTONIC ROCKS OF NORTHWEST NEVADA**

Although intrusive rocks can be found scattered throughout much of the western Basin and Range Province, they constitute a majority of the pre-Cenozoic outcrop in an area trending NNE from the Lake Tahoe area across NW Nevada (Fig. 2; Barton et al., 1988; Van Buer et al., 2009). Plutons in this area are not tightly stitched at the level of exposure, but rather are often separated by substantial areas of metamorphic outcrop, often more than 10 km across (Fig. 2). Intrusive rocks include quartz monzonite and rare diorite/quartz diorite, but are predominantly granodiorite (cf. Smith et al., 1971). Published geochronology indicates intrusion during the Jurassic (ca. 200–160 Ma) and the Cretaceous (ca. 115–85 Ma), with the greatest intrusion fraction between ca. 105 and 90 Ma (Rai, 1969; Evernden and Kistler, 1970; Smith et al., 1971; Morton et al., 1977; Marvin and Cole, 1978; Garside et al., 1992; John, 1992; Oldenburg, 1995; Wyld, 1996; Quinn et al., 1997; Wyld and Wright, 1997; Wooden et al., 1999; Wyld et al., 2001; Van Buer and Wooden, 2007), although many intrusions remain undated or poorly dated.

A particularly continuous area of Cretaceous plutonic outcrop occurs in the Sahwave and Nightingale Ranges, which together form a broadly synclinal horst, with major normal faults along the east side of the Sahwave Mountains and the west side of the Nightingale Range (Fig. 3). The bulk of both mountain ranges is granodiorite. This area of intrusive rock is separated from other plutons on the south and northeast by several kilometers of metamorphic wall rocks (Fig. 2), making the Sahwave and Nightingale Ranges a well-bounded target for detailed study. However, because granodiorite outcrops in the Seline Range, to the northwest, and the Trinity Range, to the east, are potentially contiguous, if not for intervening Cenozoic cover, these areas were also selected for reconnaissance study (Fig. 2). The nearest intrusive outcrops to the west, in the Lake Range, are visually dissimilar, and were not closely studied. In the Sahwave and Nightingale Ranges (Fig. 3), several reports and theses include local, more detailed mapping (Smith and Guild, 1942; East and Trengrove, 1950; Rai, 1969; Smith et al., 1971; Wood, 1993; Swenson et al., 1994; Wyld et al., 1995; Wyld, 1996; Quinn et al., 1997; Wyld and Wright, 1997; Wooden et al., 1999; Wyld et al., 2001; Van Buer and Wooden, 2007), although many intrusions remain undated or poorly dated.

1GSA Data Repository item 2010289, containing color copies of Figures 3, 4, and 15, is available online at www.geosociety.org/pubs/fl2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
NIGHTINGALE RANGES
NEW MAPPING IN THE SAHWAVE AND

The igneous rocks themselves. (Fig. 3), and contain very little data pertaining to sive contact, in the southern Nightingale Range the southwest margin of the Cretaceous intru-

Figure 3 (on this and previous page). Detailed map of the Sahwave and Nightingale Ranges (location shown with box in Fig. 2), showing distribution of Cretaceous plutonic bodies, older wall rocks, and Cenozoic cover. Based on mapping at 1:24,000 scale but shown here at 1:180,000 scale.

1969; Fanning, 1982; Stager and Tingley, 1988; Whitehill, 2009). Most of these papers relate to exploration of the tungsten-mining district along the southwest margin of the Cretaceous intrusive contact, in the southern Nightingale Range (Fig. 3), and contain very little data pertaining to the igneous rocks themselves.

NEW MAPPING IN THE SAHWAVE AND NIGHTINGALE RANGES

Mapping of the Sahwave and Nightingale Ranges was completed at 1:24,000 scale (reduced to 1:180,000 in Fig. 3). Each mountain range is generally more rugged on the side between its northern Paiute country rocks

The wall rocks of the Sahwave Batholith are mostly metamorphosed mudstone/shale with interbedded sandstone layers and lenses. A few discontinuous, 10–100-m-thick, coarsely crystalline marble layers are present south of the batholith, but calcareous layers are rare in the metamorphic rocks to the north (Fig. 3). These rocks have been identified as belonging to the Triassic to Early Jurassic Auld Lang Syne Group (Johnson, 1977). Away from the batholith, metamorphic grade is subgreenschist to lower greenschist, and original bedding is clearly seen. Fold axes and foliation in the adjacent Bluewing Mountains (Fig. 3) trend NE-SW, and exhibit top-to-the-SE vergence, consistent with Jurassic deformation in nearby parts of the Luning-Fencemaker thrust belt (Fig. 1; Oldow, 1984). Adjacent to the batholith, Triassic-Jurassic strata are metamorphosed to siliceous hornfels or biotite schists, and bedding is often tightly to isoclinally folded with a subvertical axial-planar foliation that is broadly parallel to the intrusive contact (Fig. 4A). A strong subvertical mineral lineation is also present within ~100 m of the intrusive contact, although it is often obscured by a subparallel intersection lineation. In the Bluewing Mountains, along the northern edge of the batholith, the zone of contact-parallel foliation is only a few hundred meters wide, whereas to the southwest, in the Nightingale mining district, foliation is subparallel to the contact over the entire exposed outcrop, up to 5 km away from the intrusion (Fig. 3). This NW-SE foliation is anomalous compared to NE-SW Jurassic structural trends, which tend to dominate in surrounding areas (e.g., Oldow, 1984).
Figure 4 (continued on following page).
Figure 4 (on this and previous page). (A) Looking down at tight folds in interbedded shales (dark) and calcareous siltstone layers (light), ~100 m from intrusive contact in southern Nightingale Range. Deformation is presumed to be Cretaceous since fold axes and lineations are aligned downward, paralleling the contact. Hammer for scale. (B) Thin section of Power Line intrusive complex under crossed polars. Note recrystallized biotite in center, strung out along a wavy foliation plane between feldspar and recrystallized quartz grains. For all thin section images, B—biotite, H—hornblende, K—potassium feldspar, M—magnetite, P—plagioclase, Q—quartz, S—sphene. (C) Hand sample of the Granodiorite of Juniper Pass. Dark grains are biotite and hornblende. Honey-colored grains are sphene, e.g., near the top left corner. (D) Thin section of Granodiorite of Juniper Pass under crossed polars. Note equigranular texture with biotite (upper right), and hornblende (lower left), in addition to microcline, plagioclase, and quartz. (E) Complex magmatic structures in the Granodiorite of Juniper Pass, ~2 km from outer margin. Note the wavy compositional layering, especially just below left of the hammer. The central, more leucocratic dike also displays complex interlayering with a more mafic phase just left of the hammer handle. Biotite within the lighter phases (black dots) is coarser than in the darker phases. (F) Outcrop of Granodiorite of Juniper Pass ~1 km from outer margin, showing elongated mafic enclaves and magmatic foliation (parallel to black line). Hammer head for scale at top of rock. (G) Thin section of Granodiorite of Bob Spring under crossed polars. Note the large, poikilitic K-feldspar, and the chloritized biotite (dark) at lower left. (H) Hand sample of Sahwave Granodiorite, showing large K-feldspar phenocrystal within a more equigranular matrix. (I) Thin section of Sahwave Granodiorite under crossed polars, showing conspicuous sphene wedges and small, ragged biotites. (J) Megacryst-rich pods in the Sahwave Granodiorite, outlined and labeled “m,” surrounded by relatively leucocratic material. Arrow points to hammer for scale. (K) Thin section of School Bus Granodiorite under crossed polars, showing large K-feldspar (center right), and myrmekitic contact between plagioclase and K-feldspar (upper left). (L) Vertical contact between School Bus Granodiorite (right half) and Power Line Complex (left half). Finger for scale. (M) Mingling and mixing relations between diorite and Granodiorite of Juniper Pass. Note interfinger-ing of darker and lighter units, as well as continuous gradations in color index. The dark splotches at lower right are lichen. Mechanical pencil for scale. (N) Aplite dike. Composite layering can be seen dipping steeply to the left (west). Hammer for scale at very top of rock.
With some exceptions, the generally quartzofeldspathic composition of the metasedimentary rocks is not conducive to the growth of diagnostic minerals besides white mica and occasional biotite. The Nightingale mining district contains a number of skarn deposits in the contact aureole of the batholith where calcareous layers have been metamorphosed, yielding grossular/andalumine, clinzoisite/epidote, and more rarely tremolite, diopside, and scheelite, in addition to the standard quartz, ± albite, and calcite. White mica pseudomorphs, apparently after both andalusite (square rods) and also cordierite (dark, mouse-dropping shapes), can be found in some of the more pelitic layers in the Bluewing Mountains near the northern margin of the batholith (Fig. 3). However, large (to over 5 cm) andalusite crystals remain intact in at least one area ~1 km from the northern contact, growing in random orientations that cut across the foliation.

**Early Intrusive Units**

The oldest intrusive unit, informally referred to as the Power Line intrusive complex (Kpl), occupies the northwestern Nightingale Range (Fig. 3), and is predominantly a medium-grained biotite hornblende granodiorite with 5–10 mm K-feldspar phenocrysts. However, this unit also includes many unmapped dikes and pods of darker granodiorite and diorite ranging from centimeters to hundreds of meters in dimension. Some of these are fine grained, weathering to a blue-grayish color, but all subunits share a similar, generally north-south–oriented, steeply dipping solid-state foliation (Fig. 3). This strong foliation distinguishes the Power Line complex from all other intrusive units, including the Sahwave intrusive suite, which intrudes the complex and crosses its foliation. Although many of the finer-grained mafic enclaves appear to demonstrate magma mingling, relationships among these subunits are somewhat obscured by poor outcrop and the solid-state foliation. In this section, the foliation is defined by biotite strung out along wavy foliation planes, and the sense of shear, if any, is unclear, because the rock bears no discernible lineation (Fig. 4B). Biotite and quartz appear to have been largely recrystallized (Fig. 4B), but feldspars remain intact, displaying distinct undulatory extinction, suggesting solid-state deformation at temperatures of ~400–450 °C or warmer, depending on strain rate. This unit also contains many large inclusions of metamorphic rock, mostly 5–200 m in length but including a 4-km-long potential roof pendant as well (Fig. 3). These are generally elongated in map view, and aligned subparallel to the foliation of the Power Line complex (Fig. 3).

In the very northwestern corner of the study area and throughout the southern Selenite Range (Figs. 2 and 3), there is a distinct granodiorite, here referred to as the Selenite Granodiorite (Kse) after the “Selenite Pluton” of Smith et al. (1971). This unit has a conspicuous, generally north-south magmatic foliation defined by the alignment of euhedral plagioclase and hornblende phenocrysts in rock with a hypidiomorphic igneous texture. Polysynthetic twinning in the plagioclase is frequently visible to the unaided eye. This unit is tentatively not included in the Sahwave intrusive suite, which intrudes it along a sharp contact (Fig. 3) and only rarely contains euhedral plagioclase.

**SAHWAVE INTRUSIVE SUITE**

The metamorphic rocks, the Power Line complex, and the Selenite Granodiorite are intruded by members of the Sahwave intrusive suite, which consists of three concentric, partially intergradational intrusive units centered on the Sahwave Range and a distinct lobe-forming unit that stretches across the central Nightingale Range (Fig. 3). Rocks of similar appearance also occur in the western Trinity Range, separated from the Sahwave Range by Cenozoic fill in Granite Springs Valley, suggesting that the Sahwave intrusive suite may underlie much of this broad area as well (Fig. 2). The outermost and oldest intrusive unit is a medium- to coarse-grained equigranular biotite hornblende granodiorite referred to as the Sahwave Granodiorite of Juniper Pass (Ksb; Fig. 3). This unit is discernible by its conspicuous 4–8 mm biotite crystals. Additionally, large hornblende phenocrysts are common around the periphery of this intrusion, giving the rock a characteristic “Dalmatian” appearance (Figs. 4C and 4D). Hornblende and plagioclase are both present throughout the Sahwave intrusive suite, but only in the Granodiorite of Juniper Pass does the hornblende form crystals notably larger than the 1–3 mm euhedral sphene. In detail, the mineral proportions and color index of this unit vary quite a bit; in places, it can be classified as a tonalite or a quartz diorite. Gradiational compositional variation can sometimes be seen across large outcrops; more rarely, internal contacts can be discerned where slightly lighter and darker phases occur together. In a few places, straight or wavy compositional layers, 1 cm to 1 m thick, are bounded by sharp contacts (Fig. 4E). Many of these internal structures are subtle, and only readily seen in fresh outcrop, so it is possible that they are fairly pervasive. Mafic enclaves are found throughout the unit, but are only common within 1–2 km of the exterior contact. Enclaves are typically 5–30 cm in length and flattened by a ratio of 2:1–5:1 or more (Fig. 4F). Mafic schlieren are common in the same region. The Granodiorite of Juniper Pass has a discernable magmatic foliation that is defined by the alignment of mafic minerals and sometimes subhedral plagioclase, which is generally similar to the alignments of mafic schlieren and mafic enclaves as well (Fig. 4F). Magmatic foliation tends to be strongest near the outer contact, which it often parallels (Fig. 3).

The Granodiorite of Juniper Pass grades inward to the more felsic and uniform Granodiorite of Bob Spring (Kbs), a medium-grained biotite granodiorite or granite, characterized by seriate K-feldspar phenocrysts up to ~2 cm. Although relative age relations with the Granodiorite of Juniper Pass are difficult to determine from the gradational intrusive contact, in map pattern, the Granodiorite of Bob Spring appears to cut out the center of the Juniper Pass (Fig. 3) and is presumed to be younger. In the field, this gradational contact is arbitrarily mapped where large K-feldspar phenocrysts become more conspicuous than large biotite crystals. Biotite in the Granodiorite of Bob Spring is more homogeneously distributed, and generally no larger than 1 mm. The K-feldspar phenocrysts are poikilitic, mostly surrounding plagioclase and biotite (Fig. 4G), and are occasionally sieved textured and difficult to see. In general, Kbs is finer grained toward its center, and K-feldspar phenocrysts are less common. The Granodiorite of Bob Spring bears euhedral quartz grains that are generally only ~1 mm in size but reach 3–5 mm in the southern part. Mafic minerals are often badly chloritized, and feldspars show signs of sericitization. Foliation in this unit is usually absent or at least too weakly defined to measure.

The Sahwave Granodiorite (Ks), a K-feldspar megacrystic biotite granodiorite (Figs. 4H and 4I), intrudes the central part of the Granodiorite of Bob Spring along a generally shallowly dipping contact that is sharp on the north side but gradational along its south side (Fig. 3). K-feldspar megacrysts are 2–4 cm across, somewhat poikilitic, and more abundant (usually 1%–5% by volume) than in the Granodiorite of Bob Spring. The abundance of K-feldspar megacrysts can vary greatly from place to place, and at outcrop scale, it is not uncommon to see distinct stringers and pods enriched in K-feldspar megacrysts, rarely up to as much as ~20% (Fig. 4I). The Sahwave Granodiorite forms relatively bold outcrops compared to adjacent parts of the Granodiorite of Bob Spring, but the rock is uniformly crumbly and often spheroidally weathered.

The Nightingale Range contains a distinct lobate unit referred to as the School Bus Granodiorite (Ksb; Fig. 3). This unit is a relatively leucocratic granodiorite, distinguished by scattered 1–2 cm K-feldspar phenocrysts and 3–6 mm
Intrusive Contacts

The intrusive contacts are generally not exposed well enough, or, when gradational, defined well enough to measure their attitudes directly, and furthermore they are generally too irregular where exposed on the outcrop scale to make meaningful map-scale measurements directly. Contact attitudes, such as those shown on the cross section in Figure 3, have been estimated from map patterns using three-point constraints in areas where the contact appears to be approximately planar. Where contact orientation is evident, it tends to be steeply dipping and sub-parallel to magmatic foliation, but there are a couple of notable exceptions. These are the contacts along the two largest metamorphic blocks or pendants at the southern end of the Sahwave Range, and the shallow contact where the Granodiorite of Juniper Pass underlies the Power Line complex in the northwestern Nightingale Range (Fig. 3). It is not clear, however, if these cases represent the true roof of the intrusion. In the northwestern Nightingale Range, the low-angle portion of the contact terminates westward as the top contact of a horizontal dike of the Granodiorite of Juniper Pass intruded into the Power Line complex (Fig. 3), suggesting that the contact in this area may simply surround a flap of wall rock that was in the process of being stopped off. External contacts of the Sahwave intrusive suite frequently dike into the metamorphic rocks and apparently surround stopped blocks (Fig. 3), suggesting that stopping is at least a locally important process. In other areas, external contacts are sometimes quite planar, demonstrating smooth parallel foliation in the adjacent, sub-vertically lineated wall rocks (Fig. 3), suggesting that the wall rocks were flattened in pure shear and flowed ductilely downward to accommodate the laterally expanding pluton.

CHRONOLOGY OF EMPLACEMENT

Although relative ages for the plutons can be determined from contact relations, the only published K/Ar hornblende (and biotite) ages are 91 ± 6 (88 ± 4) Ma and 95 ± 6 (92 ± 4) Ma for the Granodiorite of Juniper Pass and the Selenite Granodiorite, respectively (Smith et al., 1971). These error bars are about as large as the total span of ages. To more precisely define the timing and duration of magmatism in the study area, samples from each of the six main intrusive units were selected for age determination. An additional sample of granodiorite from the Trinity Range, resembling the School Bus Granodiorite, was dated to investigate whether the Sahwave intrusive suite might continue this far to the east (Fig. 2).

U-Pb SHRIMP Methods

Zircons from these seven samples (Table 1) were analyzed by secondary-ion mass spectrometry using the Stanford-U.S. Geological Survey sensitive high-resolution ion microprobe–reverse geometry (SHRIMP-RG) to yield U-Pb age determinations. Zircons were separated from each sample using standard procedures. Sample zircons and chips of R33 standard zircons were mounted in epoxy, ground halfway through the grains with fine sandpaper, and polished with diamond compound. All grains were imaged both in reflected light with an optical microscope and in cathodoluminescence (CL) using a JEOL 6500 scanning electron microscope to reveal zonation as well as cracks, inclusions, and other potential problem areas. U, Th, and Pb isotopes, along with Zr, Hf, La, Ce, Nd, Sm, Eu, Gd, Dy, Er, and Yb were analyzed with the Stanford-USGS SHRIMP-RG using an oxygen ion beam between 4 and 6 nA and a spot size of 20–30 μm. Isotope ratios were normalized using zircon age standard R33 (419 Ma; Black et al., 2004) and concentration standard CZ3. Age data were reduced using SQUID and ISOPLOT software (Ludwig, 2001, 2003) to yield 207Pb-corrected 206Pb/238U weighted-average ages (Table 1; Fig. 5). Complete data tables can be found in Appendix Table A1.

TABLE 1. SHRIMP U-Pb GEOCHRONOLOGY SAMPLE DATA

<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample no.</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Age (±2σ, Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sahwave Granodiorite</td>
<td>JC03-SV3</td>
<td>40°07′56″</td>
<td>119°04′05″</td>
<td>88.5 ± 2.0</td>
</tr>
<tr>
<td>School Bus Granodiorite</td>
<td>NVB-207</td>
<td>40°07′37″</td>
<td>119°16′06″</td>
<td>91.2 ± 1.2</td>
</tr>
<tr>
<td>Granodiorite of Bob Spring</td>
<td>SH-21</td>
<td>40°12′29″</td>
<td>119°06′02″</td>
<td>92.8 ± 1.7</td>
</tr>
<tr>
<td>Granodiorite of Juniper Pass</td>
<td>NVB-206</td>
<td>40°18′47″</td>
<td>119°01′04″</td>
<td>92.7 ± 1.4</td>
</tr>
<tr>
<td>Granodiorite in Trinity Range</td>
<td>NVB-286</td>
<td>40°10′13″</td>
<td>118°46′20″</td>
<td>90.3 ± 0.6</td>
</tr>
<tr>
<td>Selenite Granodiorite</td>
<td>NVB-212</td>
<td>40°25′58″</td>
<td>119°16′09″</td>
<td>96.3 ± 0.8</td>
</tr>
<tr>
<td>Power Line intrusive complex</td>
<td>NVB-208</td>
<td>40°08′38″</td>
<td>119°13′20″</td>
<td>104.9 ± 0.9</td>
</tr>
</tbody>
</table>

Note: Reported ages are 207Pb-corrected 206Pb/238U weighted-average ages. SHRIMP—sensitive high-resolution ion microprobe.
Figure 5. Sensitive high-resolution ion microprobe U-Pb results. At left, selected spot ages used for weighted-mean ages are shown by solid bars. Rejected spot ages are shown by empty bars. Weighted averages are shown by gray lines. Diagrams on right are inverse concordia plots, showing accepted spot analyses with solid symbols and rejected spot analyses with empty symbols. Ages along concordia (gray line with tick marks) are shown on the corresponding tick marks at bottom. All errors are 2σ.
U-Pb SHRIMP Results

Zircons generally show crisp magmatic oscillatory zoning under CL and do not contain distinct cores (Fig. 6). Only one grain, from NVB-286, appeared to have a distinct core and rim, but both parts gave exactly the same age. Individual grain analyses showed a moderately large amount of scatter, although most analyses spread out along or just above concordia (Fig. 5). Select analyses were dismissed (open symbols) because of discordance, high common Pb, and Pb loss in high-U zircons (Fig. 5; Table A1, see Appendix). It is difficult to tell whether the spread in ages is caused by disturbed U-Pb systematics or actually represents prolonged periods of crystallization in a large active magma chamber episodically fed by new batches of magma. Older and younger zircons from individual samples are not visually different or distinguishable in CL images (example shown in Fig. 6). Some of the significantly older ages can be ascribed to scavenging from slightly older plutonic rocks, such as the distinct population at 109.7 ± 0.8 Ma in NVB-208 (Fig. 5). However, these rocks lack clear evidence of older inherited zircons (only one grain out of 77 analyzed was more than ~8 m.y. older than the enclosing host rock, at a modest 139 Ma). The lack of significant inheritance suggests that these magmas may have originated at zircon-undersaturated conditions.

SHRIMP U-Pb results (Table 1; Fig. 5) give ages for individual units in agreement with the relative ages inferred from intrusive relations. The Granodiorite of Juniper Pass and the Granodiorite of Bob Spring give indistinguishable ages, but the latter is presumed to be younger from crosscutting map relations. These ages are also equivalent within error to published K/Ar hornblende and biotite ages (Smith et al., 1971). Ages from the Sahwave intrusive suite span from ca. 93 to 88.5 Ma, demonstrating that this batholith is contemporaneous with the large intrusions of the ca. 95–83 Ma Cathedral Range intrusive epoch defined in the Sierra Nevada Batholith (Evernden and Kistler, 1970; Kistler, 1999). The sample of granodiorite from the western Trinity Range (NVB-286) is also shown to have crystallized in this time range, at 90.3 ± 0.6 Ma, supporting the idea that it is part of the Sahwave intrusive suite and that these rocks may underlie much of the intervening Granite Springs Valley as well (Fig. 2). Whereas ages associated with the Sahwave intrusive suite are clustered relatively tightly, spanning about 4 m.y., the Selenite Granodiorite and the Power Line complex are significantly older, at 96.3 ± 0.8 and 104.9 ± 0.8 Ma, respectively, justifying their classification as distinct units.

CONTINUITY OF THE CRETACEOUS CORDILLERAN BATHOLITH

Our initial study of batholithic rocks in the area around the Sahwave and Nightingale Ranges in the NW Basin and Range strongly supports the suggestion of Smith et al. (1971) and Barton et al. (1988) that the Cretaceous Cordilleran batholith is continuous across NW Nevada (Figs. 1 and 2). Although obscured by Cenozoic cover, especially under the unbroken volcanic plateau covering NE California, SE Oregon, and part of NW Nevada, Cretaceous batholithic rocks form a majority of Mesozoic outcrops along a NNE-trending belt of the northwestern Basin and Range (Fig. 2; Barton et al., 1988; Van Buer et al., 2009). The extent of this intrusive belt to the north and west is unclear due to complete Cenozoic volcanic cover, but relatively low upper-crustal seismic velocities compatible with granitoid rocks persist almost to the NW corner of Nevada (Fig. 2; Lerch et al., 2007). Granodiorite units in the Sahwave and Nightingale area are similar to many described units in the Sierra Nevada Batholith, including units that, for example, contain conspicuous sphele, euhedral biotite and hornblende, or K-feldspar megacrysts. Large, concentrically zoned intrusions are also common in the Sierra Nevada (e.g., Bateman, 1992). U-Pb SHRIMP dating in the Sahwave and Nightingale area confirms earlier geochronologic estimation of Late Cretaceous ages simultaneous with major intrusion in the Sierra Nevada. Ages spanning from ca. 110 Ma (represented by inherited zircons in the Power Line complex) to ca. 88.5 Ma indicate a long-lived history of repeated intrusion in this part of the batholith, consistent with prolonged histories of magmatism in similarly sized areas of the Sierra Nevada Batholith (e.g., Bateman, 1992; Irwin and Wooden, 2001; Saleebey et al., 2008). These lines of evidence all support the idea that Cretaceous intrusive rocks in the study area formed in a broadly similar arc environment as those in the Sierra Nevada, and represent a continuation of the Cretaceous Cordilleran arc across the NW Basin and Range (Fig. 1).

Whether or not the Cretaceous intrusions in NW Nevada should actually be considered to be part of the Sierra Nevada Batholith is largely a semantic issue. However, if the boundaries of this Mesozoic batholith are to be set based on Mesozoic features, we note that the mostly Late Cretaceous intrusions of our study area lie due east of Early Cretaceous intrusions near Susanville, in the northernmost Sierra Nevada, which are generally considered to be part of the Sierra Nevada Batholith (Fig. 2; Oldenburg, 1995). Before Tertiary extension and translation across the Walker Lane (which is considered to be <30 km at this latitude; Faulds et al., 2005), these two areas would have been even closer (Van Buer et al., 2009), representing the east and west edges of the eastward-younging batholith (Figs. 1 and 2). Therefore, we tentatively suggest that the Cretaceous intrusions of NW Nevada be referred to as part of the Sierra Nevada Batholith. To better clarify the relationship between intrusions of NW Nevada and the Sierra Nevada, however, we analyzed the magma genesis of the Sahwave intrusive suite using detailed mineralogical and geochemical data, which we compared to similar data from the most well-studied intrusion of the same age in the Sierra Nevada, the Tuolumne intrusive suite.

MINERALOGY AND GEOCHEMISTRY OF THE SAHWAVE INTRUSIVE SUITE

Because the main, concentric part of the Sahwave intrusive suite appears to be younging inward, with mafic units grading into more felsic units, the rocks along a radial transect
effectively record the magmatic evolution of the system over its 4 m.y. intrusive history. For this reason, the Sahwave intrusive suite was sampled from center to margin along a transect extending north from the central Sahwave Granodiorite to the outer edge of the batholith and along a second, smaller transect through the School Bus lobe in the Nightingale Range (rows of black dots, Fig. 3). Each transect contains samples spaced approximately 1 km apart (Table 2), chosen from the most pristine outcrops available. Along these transects, the mineralogy records changes in the crystallizing assemblage and determines rock classification under the International Union of Geological Sciences (IUGS) scheme (Streckeisen, 1976). Major- and trace-element chemistry responds in detail to element partitioning and mixing during melting, crystal-liquid fractionation, assimilation, and other petrogenetic processes (e.g., Hildreth and Moorbath, 1988). Sr and Nd isotope systems treat with penetrating epoxy if needed, and ground flat. The slabs were etched with concentrated hydrofluoric acid and stained for concentrated hydrofluoric acid and stained for elemental analysis by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (Tables 2 and 3). Additionally, six aplite samples from the southern Sahwave Range were analyzed by XRF only at the University of California, Santa Cruz.

Three samples were analyzed for Sr and Nd isotopes at the Stanford-USGS Micro Analysis Center. The samples were prepared by grinding picked chips in a tungsten carbide mill, followed by a HF-HNO₃-HCl dissolution procedure in Teflon vials. Sr and Nd fractions were chemically separated using cation exchange columns in a clean laboratory before loading them into a multicollector Finnegan MAT 262 thermal ionization mass spectrometer on Ta (single) and Re (double) filaments, respectively. Measured ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd ratios were normalized to ⁶⁰Sr/⁶⁰Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219 to correct for mass-dependent fractionation. Initial isotope ratios were calculated using λ₁₂76Sr = 1.42 × 10⁻¹¹ (yr⁻¹) and λ₁₂79Nd = 6.54 × 10⁻¹² (yr⁻¹), and ¹⁴⁴Nd/¹⁴⁴Nd is reported as εNd relative to the chondritic uniform reservoir (CHUR) evolution model of Jacobsen and Wasserburg (1980).

**Mineralogical Results**

On a ternary quartz–alkali-feldspar–plagioclase diagram, samples from the Sahwave intrusive suite (circles) define a trend from the quartz diorite field to the granite field, with a majority of the samples falling in the granodiorite field (Fig. 7). These mineralogic trends are quite similar to those of the Tuolumne intrusive for elemental analysis by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (Tables 2 and 3). Additionally, six aplite samples from the southern Sahwave Range were analyzed by XRF only at the University of California, Santa Cruz.

Three samples were analyzed for Sr and Nd isotopes at the Stanford-USGS Micro Analysis Center. The samples were prepared by grinding picked chips in a tungsten carbide mill, followed by a HF-HNO₃-HCl dissolution procedure in Teflon vials. Sr and Nd fractions were chemically separated using cation exchange columns in a clean laboratory before loading them into a multicollector Finnegan MAT 262 thermal ionization mass spectrometer on Ta (single) and Re (double) filaments, respectively. Measured ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd ratios were normalized to ⁶⁰Sr/⁶⁰Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219 to correct for mass-dependent fractionation. Initial isotope ratios were calculated using λ₁₂76Sr = 1.42 × 10⁻¹¹ (yr⁻¹) and λ₁₂79Nd = 6.54 × 10⁻¹² (yr⁻¹), and ¹⁴⁴Nd/¹⁴⁴Nd is reported as εNd relative to the chondritic uniform reservoir (CHUR) evolution model of Jacobsen and Wasserburg (1980).

**Mineralogical Results**

On a ternary quartz–alkali-feldspar–plagioclase diagram, samples from the Sahwave intrusive suite (circles) define a trend from the quartz diorite field to the granite field, with a majority of the samples falling in the granodiorite field (Fig. 7). These mineralogic trends are quite similar to those of the Tuolumne intrusive for elemental analysis by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (Tables 2 and 3). Additionally, six aplite samples from the southern Sahwave Range were analyzed by XRF only at the University of California, Santa Cruz.

Three samples were analyzed for Sr and Nd isotopes at the Stanford-USGS Micro Analysis Center. The samples were prepared by grinding picked chips in a tungsten carbide mill, followed by a HF-HNO₃-HCl dissolution procedure in Teflon vials. Sr and Nd fractions were chemically separated using cation exchange columns in a clean laboratory before loading them into a multicollector Finnegan MAT 262 thermal ionization mass spectrometer on Ta (single) and Re (double) filaments, respectively. Measured ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd ratios were normalized to ⁶⁰Sr/⁶⁰Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219 to correct for mass-dependent fractionation. Initial isotope ratios were calculated using λ₁₂⁷⁶Sr = 1.42 × 10⁻¹¹ (yr⁻¹) and λ₁₂⁷⁹Nd = 6.54 × 10⁻¹² (yr⁻¹), and ¹⁴⁴Nd/¹⁴⁴Nd is reported as εNd relative to the chondritic uniform reservoir (CHUR) evolution model of Jacobsen and Wasserburg (1980).

**Mineralogical Results**

On a ternary quartz–alkali-feldspar–plagioclase diagram, samples from the Sahwave intrusive suite (circles) define a trend from the quartz diorite field to the granite field, with a majority of the samples falling in the granodiorite field (Fig. 7). These mineralogic trends are quite similar to those of the Tuolumne intrusive for elemental analysis by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (Tables 2 and 3). Additionally, six aplite samples from the southern Sahwave Range were analyzed by XRF only at the University of California, Santa Cruz.

Three samples were analyzed for Sr and Nd isotopes at the Stanford-USGS Micro Analysis Center. The samples were prepared by grinding picked chips in a tungsten carbide mill, followed by a HF-HNO₃-HCl dissolution procedure in Teflon vials. Sr and Nd fractions were chemically separated using cation exchange columns in a clean laboratory before loading them into a multicollector Finnegan MAT 262 thermal ionization mass spectrometer on Ta (single) and Re (double) filaments, respectively. Measured ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd ratios were normalized to ⁶⁰Sr/⁶⁰Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219 to correct for mass-dependent fractionation. Initial isotope ratios were calculated using λ₁₂⁷⁶Sr = 1.42 × 10⁻¹¹ (yr⁻¹) and λ₁₂⁷⁹Nd = 6.54 × 10⁻¹² (yr⁻¹), and ¹⁴⁴Nd/¹⁴⁴Nd is reported as εNd relative to the chondritic uniform reservoir (CHUR) evolution model of Jacobsen and Wasserburg (1980).

**Mineralogical Results**

On a ternary quartz–alkali-feldspar–plagioclase diagram, samples from the Sahwave intrusive suite (circles) define a trend from the quartz diorite field to the granite field, with a majority of the samples falling in the granodiorite field (Fig. 7). These mineralogic trends are quite similar to those of the Tuolumne intrusive for elemental analysis by X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (Tables 2 and 3). Additionally, six aplite samples from the southern Sahwave Range were analyzed by XRF only at the University of California, Santa Cruz.

Three samples were analyzed for Sr and Nd isotopes at the Stanford-USGS Micro Analysis Center. The samples were prepared by grinding picked chips in a tungsten carbide mill, followed by a HF-HNO₃-HCl dissolution procedure in Teflon vials. Sr and Nd fractions were chemically separated using cation exchange columns in a clean laboratory before loading them into a multicollector Finnegan MAT 262 thermal ionization mass spectrometer on Ta (single) and Re (double) filaments, respectively. Measured ⁸⁷Sr/⁸⁶Sr and ¹⁴⁴Nd/¹⁴⁴Nd ratios were normalized to ⁶⁰Sr/⁶⁰Sr = 0.1194 and ¹⁴⁴Nd/¹⁴⁴Nd = 0.7219 to correct for mass-dependent fractionation. Initial isotope ratios were calculated using λ₁₂⁷⁶Sr = 1.42 × 10⁻¹¹ (yr⁻¹) and λ₁₂⁷⁹Nd = 6.54 × 10⁻¹² (yr⁻¹), and ¹⁴⁴Nd/¹⁴⁴Nd is reported as εNd relative to the chondritic uniform reservoir (CHUR) evolution model of Jacobsen and Wasserburg (1980).
suite (small squares; Fig. 7). The Sahwave intrusive suite has on average a greater modal abundance of mafic minerals, mainly because mafic granodiorites compose a larger fraction of this intrusion than of the Tuolumne intrusive suite. In general, plagioclase and mafic minerals decrease in abundance toward the center of the intrusion, while quartz and K-feldspar increase, as expected from field relations (Fig. 8). However, these radial modal trends are far from monotonic (Fig. 8). For example, the modal percentage of alkali feldspar increases inward for the first 3 km from the contact, drops down to almost its starting value at ~6 km, and then increases to higher values in the Granodiorite of Bob Spring (Fig. 8).

The modal percentages of mafic minerals and plagioclase follow a roughly opposite pattern, except plagioclase actually increases inward from the margin to reach its maximum at ~6 km. Quartz abundance follows plagioclase's pattern in reverse. The greatest total variation occurs within the Granodiorite of Juniper Pass, which is perhaps not surprising given the color index variations and cryptic contacts seen in the field, but variation between individual samples seems to increase in the Granodiorite of Bob Spring (Fig. 8). Despite having a greater abundance of K-feldspar megacrysts, the Sahwave Granodiorite is modally quite similar to the Granodiorite of Bob Spring (Fig. 8). Despite having a greater abundance of K-feldspar megacrysts, the Sahwave Granodiorite is modally quite similar to the Granodiorite of Bob Spring (Fig. 8).

Geochemistry Results

Major-element chemistry (Table 2) confirms that the Sahwave intrusive suite represents a magnesian, metaluminous to weakly peraluminous, calc-alkaline series, with an alkali-lime index of 59.6. Major- and trace-element variation with respect to silica shows trends consistent with fractional crystallization and mixing (open symbols, Fig. 9). For example, as differentiation proceeds to higher % SiO2, the incompatible components Rb and K2O increase. Fractional crystallization of hornblende, sphene, and other mafic minerals can explain the decrease in FeO* and Y (not seen in aplite samples, which may have accumulated a Y-rich phase such as...
on 29 March 2019
by guest
Downloaded from https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/2/6/423/3038024/423.pdf

VAN BUER AND MILLER

Na2O from increasing and removes Sr (Fig. 9).

... Xenotime), and plagioclase crystallization keeps NaO from increasing and removes Sr (Fig. 9). Across a radial transect, major elements generally track the same patterns seen in the radial modal plot (Figs. 8 and 10). On average, major-element chemistry becomes more felsic toward the center of the intrusive complex (Fig. 10), but modal plot (Figs. 8 and 10). On average, major-element chemistry becomes more felsic toward the center of the intrusive complex (Fig. 10), but significantly varies from this general trend. Because these variations fall into a linear array when plotted with respect to silica, much of this local variation is attributed to mixing between different compositions. Evidence for such mixing is actually observed (Fig. 4M) between diorite intrusions and the Sahwave intrusive suite, radial major-element variations in the Sahwave intrusive suite tend to be somewhat more consistent with mixing between magmas of different composition. Rubidium and potassium are more felsic toward the margin and are less monotonic (Fig. 10). Trends are more similar between Sahwave and rich in Al2O3, CaO, FeO, MgO, and other elements enriching in the plagioclase (Eu compatible) as the residue containing garnet (heavy REE compatible) in xenotime), and plagioclase crystallization keeps NaO from increasing and removes Sr (Fig. 9).

... 

... GRANODIORITE OF JUNIPER PASS (Fig. 11), presumably due to greater fractionation of hornblende, in which these REEs are compatible (Arth and Barker, 1976). None of the units shows a consistent Eu anomaly. Similar REE patterns in the central Sierra Nevada Batholith have been interpreted to reflect differentiation from a deep-crustal residue containing garnet (heavy REE compatible) rather than plagioclase (Eu compatible) as the dominant aluminous phase (Ducea, 2001). This hypothesis is also supported by the relatively high Sr/Y ratio as compared to primitive mantle melts (Fig. 12), although arc rocks are generally enriched in fluid-mobile large ion lithophile elements as compared to relatively high field strength elements (Fig. 12). Zircon REE patterns (Fig. 11; only Granodiorite of Juniper Pass zircon data shown for simplicity) show small negative Eu anomalies, but this is probably due to the greater incompatibility of Eu in zircon.

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

... 

due to its $2^+$ charge, much as the positive Ce anomaly is associated with the $4^+$ charge taken by those ions. Figure 11 also shows the range of hypothetical liquid compositions that would be in equilibrium with Granodiorite of Juniper Pass zircon, using the partition coefficients for REEs in zircon from Sano et al. (2002). Ignoring La, the Granodiorite of Juniper Pass REE pattern is in equilibrium with Granodiorite of Juniper Pass hypothetic liquid compositions that would be in equilibrium with Granodiorite of Juniper Pass zircon, using the partition coeffi cients for REEs in equilibrium with Granodiorite of Juniper Pass hypothetic liquid minimum melt curve, which may suggest that aplite was extracted before water saturation was reached (cf. Nekvasil, 1988), but the other sample (collected 130 m below the Tertiary unconformity) falls just below the 1 kbar minimum (Fig. 14), consistent with an emplacement depth of 3–4 km. This depth estimate falls within the ~3–10 km range suggested by Van Buer et al. (2009) based on the lack of miarolitic cavities and caldera structures and the presence of andalusite in the contact aureole.

**A CATHEDRAL RANGE INTRUSIVE EVENT OUTSIDE THE SIERRA NEVADA**

The Sahwave intrusive suite is similar to the large intrusions of the Cathedral Range intrusive...
The emplacement mechanisms of these large, long-lived intrusions remain controversial. In light of detailed geochronology, geochemistry, and numerical modeling, a variety of subtle internal structures have been generally interpreted to suggest that these intrusive complexes were formed by repeated influx of magma batches into a system kept near its solidus (e.g., Coleman et al., 2004; Hirt, 2007; Saleeby et al., 2008). However, opinions differ greatly on the size, frequency, and emplacement mechanisms of these magmatic replenishment events, varying from frequent re-intrusion of small dikes (e.g., Glazner et al., 2004) to much larger batches of magma that remain above their solidi for extended periods of time (e.g., Žák and Paterson, 2005). We briefly evaluate evidence in the Sierra Nevada proper (Fig. 15) in terms of its ca. 92.5–88.5 Ma age range, >1000 km² size, modal and chemical zonation, and internal magmatic structures. It is different in that it has somewhat lower K/Na ratios, smaller abundance and lesser size of K-feldspar megacrysts, a larger proportion of mafic granodiorite, more primitive Sr and Nd isotopic ratios, a relatively equant rather than elongate shape, and its location to the north and east of the Sierra Nevada crest (Fig. 15). Additionally, the approximately 4 m.y. apparent duration of the Sahwave intrusive suite is shorter duration than that reported for many of the coeval intrusive suites along the Sierra Nevada crest, but it is similar to the durations represented by the most voluminous phases of those suites (Chen and Moore, 1982; Coleman et al., 2004; Saleeby et al., 2008). Many of these intrusive suites, e.g., the Tuolumne intrusive suite, had shorter reported durations of intrusion before extensive geochronology campaigns were carried out (e.g., Coleman et al., 2004), so it is possible that the Sahwave suite may also include minor phases that would extend its reported duration. Despite some differences, the similarities are compelling enough to consider the Sahwave intrusive suite a member of the Cathedral Range super suite. The continuation of this distinctive chain of intrusions into the NW Basin and Range further supports the idea of an originally continuous Sierra Nevada Batholith later disrupted by Cenozoic extension (Fig. 15). The wide separation between the Sahwave intrusive suite and the Sonora Pass intrusive suite shown in Figure 15 may suggest the existence of another intrusive suite (or suites) in the Reno area, where little-studied granitoids of similar age are exposed (91–86 Ma K/Ar biotite ages; Marvin and Cole, 1978; Garside et al., 1992).
The Sahwave intrusive suite generally has steep contacts and steep magmatic foliation (Fig. 3); thus, it is unlikely that it is a sill-like intrusion. Nevertheless, given its 40 km diameter at a relatively shallow depth of exposure, the intrusion must have been relatively flat-topped (Fig. 16). The downward extent of the batholith is not well defined by existing seismic or gravity data, but comparison to the oblique crustal arc sections exposed in southern California suggests that batholithic rocks may extend to the base of the crust, although large distinct intrusions in the upper crust may overlie a complex zone of smaller, vertically sheeted intrusions in the lower crust (Saleeby et al., 2003; Barth et al., 2008; Saleeby et al., 2008). Seismic data from farther north along the arc (Fig. 2; Lerch et al., 2007), however, indicate low velocities compatible with tonalitic/granitic rocks down to ~15 km, suggesting that the magmatic arc in NW Nevada is underlain by mafic residua and remnants of thin transitional crust, in contrast to the crust of the southern and central Sierra Nevada Batholith, which is relatively felsic (tonalitic) to its base (e.g., Saleeby, 1990; Fleitner et al., 2000). Even if the batholithic rocks studied here extend to only 15 km depth, as shown in Figure 16, the Sahwave intrusive suite still represents a volume of well over 10,000 km³, such that space accommodation and mechanisms of its emplacement are nontrivial problems.

Figure 9. Diagrams showing variation of FeO*, K₂O, Na₂O, Rb, Sr, and Y as functions of SiO₂ in Sahwave and Tuolumne intrusive suites (Tuolumne data from Gray et al., 2008).
mineralogy and chemistry it contains, it is entirely possible that this unit was emplaced over time as a series of smaller intrusive events. The cryptic internal structures and contacts within the Granodiorite of Juniper Pass are difficult to interpret, but the general smoothness of compositional variation within the sampled part of this unit suggests that individual batches of magma generally stayed hot long enough to partially mix with their successors. Other contacts within and around the Sahwave intrusive suite also vary greatly in style. Although often poorly exposed, contacts between units can be both sharp, such as where the School Bus Granodiorite intrudes the Granodiorite of Juniper Pass, or gradational over hundreds of meters, such as where the Granodiorite of Bob Spring intrudes the Granodiorite of Juniper Pass (Fig. 3). In certain places, contacts are observed to transition from sharp to gradational. This happens gradually along the contact of the Sahwave Granodiorite, but fairly abruptly where the Granodiorite of Bob Spring intrudes the Granodiorite of Juniper Pass east of the Power Line complex in the Nightingale Range (Fig. 3).

Sharp internal contacts likely reflect areas where new magma batches “eroded” their way into older magma that had partially cooled to the point where it behaved as a solid, perhaps even experiencing brittle fracture and stoping in places. Conversely, arcuate, gradational contacts likely formed where the previous batch of magma was either still partially molten, or at least close enough to its solidus to experience defrosting and partial to complete mixing along its contact. The apparent lack of internal contacts within the Granodiorite of Bob Spring, the School Bus Granodiorite, and the Sahwave Granodiorite (with the exception of a few contacts surrounding leucocratic segregations), combined with the general homogeneity of these units, suggests that each may represent a single phase of rapid magma input into a large, partially molten magma chamber. The concentric arrangement of these units further suggests that the central part of each unit was not fully mechanically and/or thermally stabilized before its successor intruded, and possibly flowed back downward after defrosting to accommodate the new magma. The concentric arrangement of successively more homogeneous (and generally more differentiated) units (Fig. 16) also suggests that the system was warming over time, allowing larger and longer-

Figure 10. Logarithmic plot showing major-element concentrations as a function of fractional distance along the radial transect from the outside to the center of the intrusion for the Sahwave and Tuolumne intrusive suites (Tuolumne data from Bateman and Chappell, 1979). Note that the Tuolumne data are from a shorter, east-west transect of about half the length of the Sahwave transect, but have been expanded as a fraction of radial distance.

Figure 11. Chondrite-normalized rare-earth-element diagram comparing whole-rock analyses from the Granodiorite of Juniper Pass with zircons from the same unit and the modeled composition of the liquid that would have been in equilibrium with the zircons. Data from the rest of the Sahwave Intrusive Suite are grouped together for comparison.
lived magma chambers to be formed at both the level of exposure and perhaps at the deeper level of magma production. Warming over time in the southern Nightingale Range due to re-intrusion of the School Bus Granodiorite so close to the contact already heated once by the Granodiorite of Juniper Pass may also be responsible for the extensive shouldering-aside implied by the anomalous orientation of the wall rocks in this area (Fig. 3).

**Basinal Setting and Implications for Arc Flare-Up**

In light of the extensive similarities between the Sahwave intrusive suite and coeval magmatic systems to the south, it is interesting to note that the crustal environments of these intrusions are very different (Figs. 1 and 15). Whereas the other massive intrusions of the Cathedral Range intrusive epoch are interpreted to lie along the margin of North American continental crust, as marked by scattered roof pendants of the miogeocline and initial $^{87}$Sr/$^{86}$Sr > 0.706 (Fig. 1; e.g., Saleeby, 1981; Kistler, 1990), the Sahwave intrusive suite is positioned in a deep stack of basinal muds thought to overlie transitional or oceanic crust (Speed, 1978; Farmer and DePaolo, 1983; Elison et al., 1990). Because of its unique position relative to the other members of the Cathedral Range event, the Sahwave intrusive suite can be used to examine hypotheses about the potential causes for the massive magmatic flare-up represented by these intrusions. It has been suggested that this particular pulse of major magmatic activity may have been due to westward underthrusting of North American lower crust beneath the magmatic arc, which is hypothesized to have been near the western edge of a massive orogenic wedge (DeCelles and Coogan, 2006; DeCelles et al., 2009). The voluminous magmatism in the Sahwave and Nightingale Ranges at this time, however, demonstrates very primitive isotopic ratios of $^{87}$Sr/$^{86}$Sr ~ 0.7047 and $^{143}$Nd/$^{144}$Nd ~ 0.5125, which are not compatible with incorporation of a large crustal component. Similar or more primitive isotope ratios in the penecontemporaneous La Posta events of the Peninsular Ranges Batholith (Fig. 1; Walawender et al., 1990) corroborate this. Furthermore, modest reconstructed Cretaceous crustal thicknesses near the Sahwave Batholith (~38 km; e.g., Colgan et al., 2006) would suggest that the orogenic wedge did not continue this far west in northern Nevada.

Since the availability of continental lower crust does not appear to have been the main control on high magmatic flux in the arc at this time, it seems that a more regionally extensive and consistent triggering mechanism must be

---

**TABLE 4. Sr AND Nd ISOTOPIC DATA**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>$^{87}$Sr/$^{86}$Sr (±2σ)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Age (Ma)</th>
<th>$^{87}$Sr/$^{86}$Sr (±2σ)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Age (Ma)</th>
<th>$^{143}$Nd/$^{144}$Nd (±2σ)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH-1</td>
<td>0.70499 ± 2</td>
<td>53.6</td>
<td>808</td>
<td>92.6</td>
<td>0.70473 ± 2</td>
<td>5.95</td>
<td>17.65</td>
<td>-0.173 ± 6</td>
<td>4.45</td>
<td>21.54</td>
<td>-0.259 ± 8</td>
<td></td>
</tr>
<tr>
<td>SH-11</td>
<td>0.70528 ± 2</td>
<td>81.1</td>
<td>745</td>
<td>92.6</td>
<td>0.70486 ± 2</td>
<td>4.45</td>
<td>21.54</td>
<td>-0.259 ± 8</td>
<td>4.45</td>
<td>21.54</td>
<td>-0.259 ± 8</td>
<td></td>
</tr>
<tr>
<td>SH-29</td>
<td>0.70538 ± 2</td>
<td>104.2</td>
<td>662</td>
<td>88.5</td>
<td>0.70480 ± 2</td>
<td>2.64</td>
<td>13.63</td>
<td>-0.223 ± 9</td>
<td>2.64</td>
<td>13.63</td>
<td>-0.223 ± 9</td>
<td></td>
</tr>
<tr>
<td>S109-6*</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>88.5</td>
<td>0.70475†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td></td>
</tr>
<tr>
<td>S110-6*</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>88.5</td>
<td>0.70458†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td>n.r.†</td>
<td></td>
</tr>
</tbody>
</table>

*Corrections to the reported Sr values, based on the ages from this study and Rb/Sr ratios from co-located samples, are insignificant at the reported precision.

---

**Figure 13. Sr and Nd isotope systematics for Sahwave and Tuolumne intrusive suites (Tuolumne data from Gray et al., 2008). Also shown are data from nearby intrusive rocks within 150 km of the center of the Sahwave intrusive suite (data from Farmer and DePaolo, 1983).**

**Figure 14. Quartz-orthoclase-albite (Q-Or-Ab) ternary diagram comparing measured aplite compositions and minimum melt relations (lines) in a water-saturated system (Johannes and Holtz, 1996), at the pressures labeled in kilobars. Aplite samples were collected from dikes in the granodiorite of Juniper Pass.**
invoked. A widespread flare-up in the arc could have been related to the tectonic underplating of Franciscan subduction accretionary material (Saleeby et al., 2008), a change in subduction rate and/or obliquity, age, or composition of underthrust oceanic lithosphere, or the stress regime accompanying intrusion. Alternatively, subduction of thicker oceanic crust in the Late Cretaceous could potentially be called upon to both induce a magmatic flux event and subsequently terminate magmatism. Very shallow subduction of a large and thick oceanic plateau is hypothesized to have disrupted the Mojave-Salinia segment of the arc (Saleeby, 2003), but modestly thickened oceanic crust in adjacent segments might have led to moderately shallow subduction and the observed cessation of magmatism. Thicker oceanic crust might incorporate and react with a greater volume of seawater (especially if pillow basalts represent a disproportionate share of crustal thickening in oceanic plateaus; e.g., Gladczenko et al., 1997). Dragged downward by previously subducted, denser oceanic lithosphere, the leading edge of this thickened oceanic crust could have released its fluids into the mantle wedge, creating a massive, fluid-rich basaltic flux that might have remelted any stack of older basalt left underplated at the base of the arc crust by prior arc activity. Triggered by the same cause as the incipient flat-slab subduction, magmatic flux would increase until crowding from the increasingly buoyant oceanic lithosphere caused stagnation of the mantle wedge, halting magmatism.

CONCLUSIONS

New mapping, geochronology, petrology, and geochemistry in the Sahwave and Nightingale Ranges of western Nevada document the northward continuation of the Cretaceous Cordilleran arc across the NW Basin and Range and form the groundwork for more detailed future study. Intrusive activity in the Sahwave and Nightingale area continued from ca. 110 to 88.5 Ma, and included the emplacement of
APPENDIX TABLE A1. U-Pb SHRIMP ANALYTICAL DATA

<table>
<thead>
<tr>
<th>Spot number</th>
<th>Common ²⁰⁶Pb (ppm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>²³⁵Th/²³⁴U age (±1σ, Ma)</th>
<th>Total ²⁰⁶Pb/²⁰⁶Pb (±% err)</th>
<th>Total ²⁰⁷Pb/²⁰⁶Pb (±% err)</th>
</tr>
</thead>
</table>
| JC03-SV03: Sahwave Granodiorite

SV3-1 | 0.12 | 623 | 286 | 0.47 | 84.4 ± 1.3 | 75.4 ± 1.5 | 0.0486 ± 3.3 |
SV3-2 | 0.08 | 667 | 241 | 0.37 | 87.3 ± 1.3 | 73.3 ± 1.5 | 0.0484 ± 3.2 |
SV3-3 | 0.28 | 497 | 106 | 0.22 | 86.3 ± 1.4 | 74.0 ± 1.6 | 0.0499 ± 3.8 |
SV3-4 | 0.13 | 750 | 245 | 0.34 | 87.7 ± 1.3 | 72.9 ± 1.5 | 0.0488 ± 3.1 |
SV3-5 | 0.11 | 699 | 199 | 0.31 | 87.9 ± 1.3 | 72.8 ± 1.5 | 0.0486 ± 3.2 |
SV3-6 | 0.37 | 601 | 180 | 0.31 | 90.1 ± 1.4 | 70.8 ± 1.6 | 0.0508 ± 3.3 |
SV3-7 | 0.11 | 867 | 348 | 0.42 | 91.4 ± 1.3 | 70.0 ± 1.5 | 0.0487 ± 2.8 |
SV3-8 | -0.40 | 753 | 244 | 0.33 | 91.6 ± 1.4 | 70.1 ± 1.5 | 0.0447 ± 3.1 |
SV3-9 | 0.25 | 529 | 161 | 0.31 | 89.9 ± 1.4 | 71.0 ± 1.6 | 0.0498 ± 3.4 |

NVB207: School Bus Granodiorite

NVB207-7 | -0.10 | 2081 | 457 | 0.23 | 89.0 ± 1.4 | 64.9 ± 1.4 | 0.0472 ± 1.6 |
NVB207-8 | 0.30 | 225 | 120 | 0.55 | 93.7 ± 1.8 | 68.3 ± 1.9 | 0.0503 ± 5.0 |
NVB207-9 | 0.05 | 1015 | 232 | 0.24 | 90.9 ± 1.4 | 70.6 ± 1.5 | 0.0482 ± 2.4 |
NVB207-10 | -0.01 | 1285 | 392 | 0.32 | 93.9 ± 1.4 | 68.3 ± 1.5 | 0.0476 ± 2.0 |
NVB207-11 | -0.41 | 357 | 94 | 0.27 | 92.4 ± 1.6 | 69.8 ± 1.7 | 0.0446 ± 4.1 |
NVB207-12 | -0.36 | 314 | 56 | 0.18 | 91.6 ± 1.4 | 70.3 ± 1.8 | 0.0450 ± 4.4 |
NVB207-13 | 0.50 | 232 | 55 | 0.25 | 88.6 ± 1.7 | 72.1 ± 1.9 | 0.0518 ± 4.8 |
NVB207-14 | -0.03 | 419 | 127 | 0.31 | 90.5 ± 1.5 | 70.9 ± 1.7 | 0.0476 ± 3.8 |

NVB206: Granodiorite of Juniper Pass

NVB206-1 | 0.66 | 152 | 76 | 0.52 | 94.8 ± 1.8 | 67.0 ± 1.9 | 0.0532 ± 6.0 |
NVB206-2 | 0.50 | 346 | 183 | 0.55 | 91.8 ± 1.3 | 69.4 ± 1.4 | 0.0518 ± 5.0 |
NVB206-3 | 0.07 | 224 | 66 | 0.31 | 94.2 ± 1.5 | 67.9 ± 1.6 | 0.0485 ± 4.8 |
NVB206-4 | 0.89 | 1420 | 187 | 0.14 | 43.9 ± 0.6 | 145.0 ± 1.3 | 0.0593 ± 4.9 |
NVB206-5 | 0.09 | 437 | 181 | 0.43 | 88.5 ± 1.2 | 72.2 ± 1.3 | 0.0485 ± 3.5 |
NVB206-6 | -0.44 | 230 | 112 | 0.51 | 90.9 ± 1.4 | 70.7 ± 1.5 | 0.0444 ± 4.9 |
NVB206-7 | -0.16 | 271 | 153 | 0.58 | 92.8 ± 1.4 | 69.1 ± 1.5 | 0.0444 ± 4.4 |
NVB206-8 | -0.02 | 475 | 186 | 0.41 | 91.7 ± 1.2 | 68.9 ± 1.3 | 0.0477 ± 3.5 |
NVB206-9 | 0.34 | 364 | 147 | 0.42 | 89.1 ± 1.3 | 71.6 ± 1.4 | 0.0505 ± 3.9 |

(continued)

ACKNOWLEDGMENTS

This research was partially sponsored by National Science Foundation (NSF) Tectonics grant 0809226, two Stanford McGee Grants, and a Geological Society of America (GSA) Student Research Grant. Van Buer was partially supported by a Burt and DeeDee McMurtry Fellowship. Special thanks are due to Joe Wooden for help acquiring and analyzing sensitive high-resolution ion microprobe (SHRIMP) data, to Bettina Wiegand for measuring Sr and Nd isotopes, and to other helpful folks at the Stanford-USGS Micro-Analysis Facility. We also thank Gail Mahood, Robinson Cecil, and Sandra Wyld for helpful reviews.

REFERENCES CITED

<table>
<thead>
<tr>
<th>Spot number</th>
<th>Common 206Pb (%)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>206Pb/238U age (±% err)</th>
<th>Total 207Pb/206Pb (±% err)</th>
<th>Total 206Pb/238U (±% err)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVB206-10</td>
<td>0.43</td>
<td>253</td>
<td>76</td>
<td>0.31 92.8 ± 1.5 68.8 ± 1.6</td>
<td>0.0513 ± 4.7</td>
<td></td>
</tr>
<tr>
<td>NVB206-11</td>
<td>0.65</td>
<td>1010</td>
<td>453</td>
<td>0.46 84.2 ± 1.0 75.5 ± 1.2</td>
<td>0.0528 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>NVB206-12</td>
<td>0.10</td>
<td>728</td>
<td>398</td>
<td>0.56 93.3 ± 1.1 68.6 ± 1.2</td>
<td>0.0486 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>NVB206-13</td>
<td>0.29</td>
<td>235</td>
<td>90</td>
<td>0.41 94.1 ± 1.5 68.7 ± 1.5</td>
<td>0.0502 ± 4.7</td>
<td></td>
</tr>
<tr>
<td>NVB206-14</td>
<td>0.23</td>
<td>666</td>
<td>177</td>
<td>0.27 104.0 ± 1.6 61.5 ± 1.5</td>
<td>0.0499 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>NVB206-13</td>
<td>0.06</td>
<td>690</td>
<td>169</td>
<td>0.25 103.9 ± 1.6 61.7 ± 1.5</td>
<td>0.0486 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>NVB206-10</td>
<td>2.63</td>
<td>961</td>
<td>254</td>
<td>0.27 100.3 ± 1.5 62.2 ± 1.5</td>
<td>0.0689 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>NVB206-9</td>
<td>0.08</td>
<td>1117</td>
<td>329</td>
<td>0.30 109.0 ± 1.6 58.8 ± 1.5</td>
<td>0.0488 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>NVB206-7</td>
<td>0.14</td>
<td>1218</td>
<td>311</td>
<td>0.26 105.2 ± 1.6 60.8 ± 1.5</td>
<td>0.0487 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>NVB206-4</td>
<td>4.26</td>
<td>531</td>
<td>118</td>
<td>0.23 96.3 ± 1.6 64.0 ± 1.6</td>
<td>0.0505 ± 2.7</td>
<td></td>
</tr>
<tr>
<td>NVB206-3</td>
<td>–0.05</td>
<td>908</td>
<td>857</td>
<td>0.98 93.0 ± 1.0 67.1 ± 1.0</td>
<td>0.0485 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>NVB206-1</td>
<td>0.69</td>
<td>547</td>
<td>196</td>
<td>0.37 90.5 ± 1.5 66.7 ± 1.5</td>
<td>0.0481 ± 1.9</td>
<td></td>
</tr>
<tr>
<td>NVB206-2</td>
<td>0.07</td>
<td>646</td>
<td>210</td>
<td>0.24 93.3 ± 1.1 68.5 ± 1.0</td>
<td>0.0486 ± 2.8</td>
<td></td>
</tr>
<tr>
<td>NVB206-11</td>
<td>0.03</td>
<td>2244</td>
<td>236</td>
<td>0.11 110.0 ± 1.6 58.3 ± 1.4</td>
<td>0.0479 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>NVB206-8</td>
<td>0.06</td>
<td>4127</td>
<td>1250</td>
<td>0.31 110.2 ± 1.6 58.2 ± 1.4</td>
<td>0.0477 ± 1.1</td>
<td></td>
</tr>
<tr>
<td>NVB206-5</td>
<td>0.05</td>
<td>908</td>
<td>857</td>
<td>0.98 105.8 ± 1.6 60.6 ± 1.5</td>
<td>0.0478 ± 2.3</td>
<td></td>
</tr>
<tr>
<td>NVB206-4</td>
<td>4.26</td>
<td>624</td>
<td>154</td>
<td>0.26 102.7 ± 1.6 59.8 ± 1.5</td>
<td>0.0819 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>NVB206-3</td>
<td>0.01</td>
<td>753</td>
<td>169</td>
<td>0.23 99.8 ± 1.5 64.1 ± 1.5</td>
<td>0.0504 ± 3.3</td>
<td></td>
</tr>
<tr>
<td>NVB206-2</td>
<td>–0.16</td>
<td>745</td>
<td>153</td>
<td>0.21 104.7 ± 1.7 61.4 ± 1.6</td>
<td>0.0489 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>NVB206-1</td>
<td>0.19</td>
<td>1218</td>
<td>311</td>
<td>0.26 105.2 ± 1.6 60.8 ± 1.5</td>
<td>0.0480 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>NVB206-08</td>
<td>0.11</td>
<td>766</td>
<td>179</td>
<td>0.24 105.9 ± 1.6 60.7 ± 1.5</td>
<td>0.0490 ± 2.5</td>
<td></td>
</tr>
<tr>
<td>NVB206-9</td>
<td>0.08</td>
<td>1117</td>
<td>329</td>
<td>0.30 109.0 ± 1.6 58.8 ± 1.5</td>
<td>0.0488 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>NVB206-12</td>
<td>2.63</td>
<td>961</td>
<td>254</td>
<td>0.27 100.3 ± 1.5 62.2 ± 1.5</td>
<td>0.0689 ± 1.8</td>
<td></td>
</tr>
<tr>
<td>NVB206-11</td>
<td>–0.10</td>
<td>4726</td>
<td>750</td>
<td>0.16 110.0 ± 1.6 58.3 ± 1.4</td>
<td>0.0474 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>NVB206-12</td>
<td>–0.05</td>
<td>555</td>
<td>121</td>
<td>0.23 106.6 ± 1.7 60.2 ± 1.6</td>
<td>0.0477 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>NVB206-13</td>
<td>0.06</td>
<td>690</td>
<td>169</td>
<td>0.25 103.9 ± 1.6 61.7 ± 1.5</td>
<td>0.0486 ± 2.6</td>
<td></td>
</tr>
<tr>
<td>NVB206-14</td>
<td>0.23</td>
<td>666</td>
<td>177</td>
<td>0.27 104.0 ± 1.6 61.5 ± 1.5</td>
<td>0.0499 ± 2.6</td>
<td></td>
</tr>
</tbody>
</table>

Note: SHRIMP—sensitive high-resolution ion microprobe.


