Text and references accompanying Nevada Bureau of Mines and Geology Open File 12–2

Preliminary Geologic Map of the Sahwave and Nightingale Ranges, Churchill, Pershing, and Washoe Counties, Nevada

by

Nicholas Van Buer

Department of Geological Sciences, Stanford University, Stanford, CA

INTRODUCTION

The part of the Mesozoic Cordilleran Batholith that crosses the NW Basin and Range is in many places obscured by Cenozoic cover, but relatively continuous outcrop of ranitic rocks occurs in the area of the Sahwave and Nightingale Ranges, about an hour northeast of Reno (fig. 1). Much of the previous mapping in this region was at reconnaissance scale (often 1:250,000) or focused on specific areas of mineralization or Cenozoic and Quaternary history. To elucidate the structural and petrologic history of this part of the magmatic arc in greater detail, the Sahwave and Nightingale Ranges, covering parts of twelve 7.5´ quadrangles, were mapped at 1:24,000 scale (reduced to 1:62,500 scale for publication), with an emphasis on portraying and defining basement structures and the younger features which affect them. As a result of this mapping, this region was discovered to expose the only Late Cretaceous, large, zoned intrusive suite (similar to coeval intrusions in the eastern Sierra Nevada such as the Tuolumne Intrusive Suite) yet documented in the NW Basin and Range, providing evidence that the granitic rocks of NW Nevada are effectively the northernmost part of the Sierra Nevada Batholith (Van Buer and Miller, 2010). This text provides context for the map and summarizes the geologic history of the region, but the detailed petrology, geochemistry, and geochronology of the Cretaceous intrusive rocks are treated more thoroughly by Van Buer and Miller (2010), and additional information on the Tertiary history of the area can be found in Whitehill (2009).

GEOGRAPHY OF THE STUDY AREA

The mapped area covers the entire Sahwave and Nightingale mountain ranges, an area of over 1200 km^2 (fig. 2). Most of the map area lies within Pershing County, but the southernmost and westernmost parts of the map area are in Churhill and Washoe counties, respectively. This area is about an hour northeast of Reno, and is accessible from the towns of Nixon, Gerlach/Empire, and Lovelock (fig. 1). No part of the map area is more than half a day's walk from

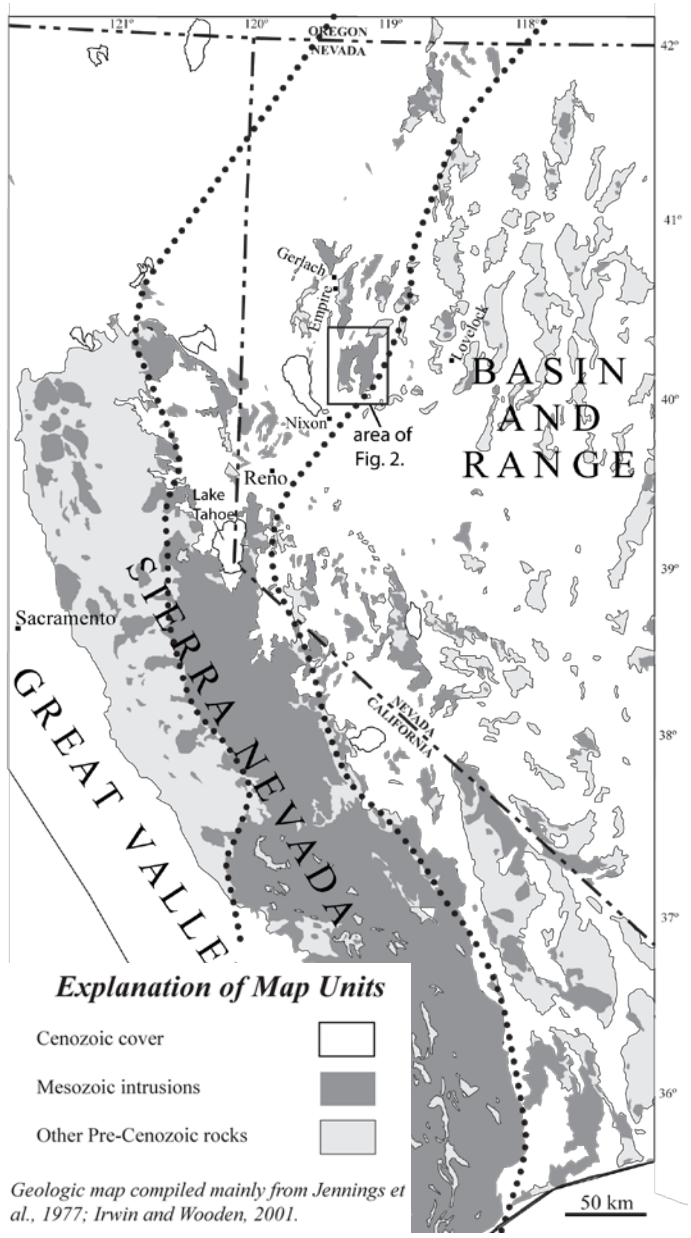

Figure 1. Mesozoic intrusions of the Sierra Nevada Batholith (bounded by dotted lines) continue northwards into the Basin and Range, where they are partially obscured by Cenozoic cover. The study area has some of the most continuous outcrops available.

a decent dirt road. The Sahwave and Nightingale Ranges are about 50 km long and trend north-south (fig. 2). Each range has a maximum relief of about 1 km, with elevations in the map area ranging from 1149 m at the lowest part of the Winnemucca basin to 2278 m at Juniper Mountain in the northern Sahwave Range (Figs. 2, 3). The land between the ranges, known as Sage Hen Valley, lies 400–500 m higher than the basins to the east or west, and the topography of each range is generally steeper on the side facing away from this upland valley (fig. 2). To the east and west, Granite Springs Valley and Winnemucca Valley are much broader than Sage Hen Valley and contain playas (fig. 2), although Winnemucca Valley held a more substantial lake as recently as 1945 (Zones, 1961).

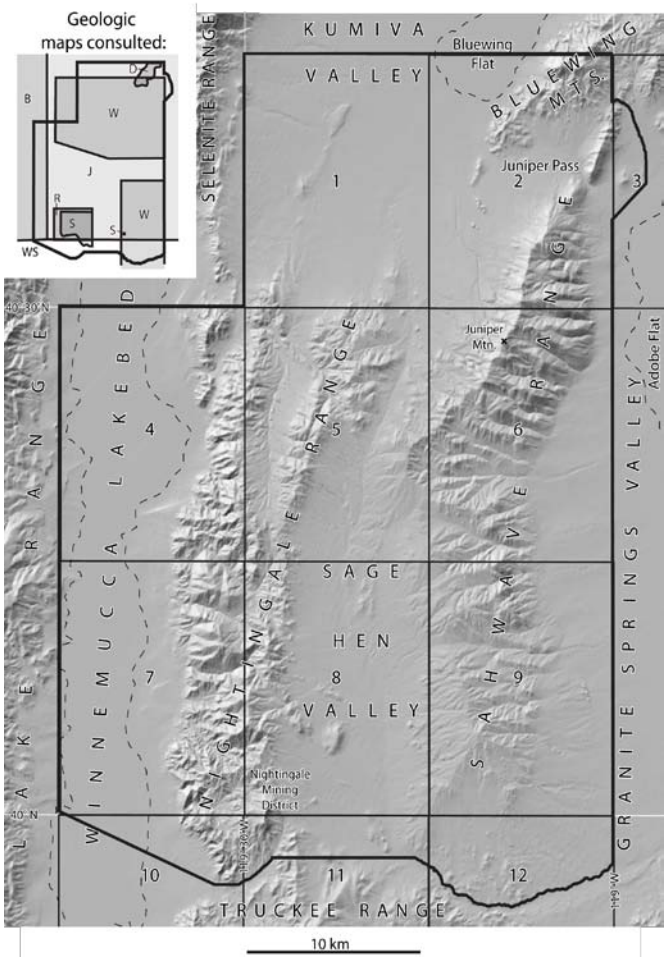

Figure 2. Simplified physical geography of the study area. The mapped 7.5′ quadrangles are 1 - Jayhawk Well, 2 - Juniper Pass, 3 - Bluewing Flat North, 4 - Tohakum Peak NE, 5 - Tunnel Spring, 6 - Bob Spring, 7- Tohakum Peak SE, 8 - Sage Hen Spring, 9 - Bluewing Spring, 10 - Russell Peak, 11 - Black Warrior Peak, and 12 - Telephone Well. Geologic maps consulted: B - Bonham, 1969; D - Dasher, unpublished mapping; J - Jennings, 1977; R - Rai, 1969; S – Stager and Tingley, 1988; W - Whitehill, 2009; WS - Willden and Speed, 1974.

The most rugged parts of the map area, in the western Nightingale Range and the northern Sahwave Range (fig. 2), bear relatively good rock exposure, although slopes are often obscured by colluvium or scree (fig. 3). Areas of lower relief, such as the southern Sahwave Range (fig. 2), however, are often blanketed by a thick layer of grus, and, aside from a few rocky tors, dikes comprise a majority of the competent outcrop. Vegetation is mainly sparse scrub, often dominated by sagebrush, and does little to obscure rock exposure (fig. 3). A few juniper and mountain mahogany grow at the higher altitudes, but the only real trees are four cottonwoods at the mouths of two canyons in the northeastern Sahwave Range.

Figure 3. View south towards Juniper Pass (center) through the northern Sahwave Range (high point Juniper Mountain) from the Bluewing Mountains, showing typical vegetation and outcrop patterns. Foreground outcrops are Triassic/Jurassic metasedimentary rocks, which are overlain unconformably by the Tertiary rhyolite flow which makes up the orange hills at left midground. Most of the Sahwave Range is Cretaceous granodiorite, which intrudes metasedimentary rock near the left edge of the photo, just above the highest orange hill. Adobe Flat, a playa, can be seen in the left background. Juniper Pass appears to be an antecedent stream gap.

PREVIOUS WORK

The area was first described by Clarence King's Fortieth Parallel Survey in 1867, but this was a brief reconnaissance only. They concluded that the Mesozoic metasedimentary rocks in this area were deposited unconformably over Archaean granitic basement (King, 1878). Tungsten was discovered in the Nightingale Mining District in 1917, leading to a number of local, economically-motivated studies (fig. 2; Hess and Larsen, 1922; Smith and Guild, 1942; East and Trengrove, 1950; Rai, 1969; Fanning, 1982; Stager and Tingley, 1988). Bonham (1969), Willden and Speed (1974), and Johnson (1977) mapped Washoe, Churchill, and Pershing counties, respectively, at 1:250,000 scale, providing the first solid regional geologic map of the area, but did not distinguish separate plutonic units (fig. 2). Other work in the region has

focused on Oligocene paleovalleys (Faulds et al., 2005), Quaternary lake deposits (e.g., Russell, 1885; Broecker and Orr, 1958; Zones, 1961; Benson and Thompson, 1987), wave-cut cave archaeology and geology (e.g., Orr, 1956; Sears and Roosma, 1961), and Holocene fault scarps (Wesnousky et al., 2005). The most recent mapping in the area was undertaken by Whitehill (2009), who investigated the Tertiary volcanic and sedimentary strata as well as the extensional faults that have uplifted and warped the Sahwave and Nightingale ranges (fig. 2). Other compilations containing geochemical data (but no geologic mapping) from basement rocks in the area include Zirkel (1876), Smith et al. (1971), Farmer and DePaolo (1983), and Wooden et al. (1999).

GEOLOGIC SETTING

The geologic history established in greater region surrounding the map area begins with Late Triassic (Norian) to earliest Jurassic deposition of deep marine sediments of the Auld Lang Syne Group ("basinal terrane" on fig. 4; e.g., Burke and Silberling, 1973; Johnson, 1977). Though generally unfossiliferous, these strata have been dated by the rare occurrence of ammonite fossils (Burke and Silberling, 1973). These basinal strata are mostly fine-grained siliciclastic units with scattered lenses of coarser material and rare carbonate, and are essentially submarine fan deposits (Burke and Silberling, 1973; Speed, 1978). They are regionally metamorphosed to subgreenschist or lower greenschist facies, forming slates and phyllites, and are colloquially known as "the mudpile" due to their general lack of easily recognizable stratigraphy (Willden, 1964; Bonham, 1969; Johnson, 1977). The base of the unit is not exposed near the study area, where stratigraphic thicknesses over 6 km have been measured in the Triassic to Jurassic deposits (Burke and Silberling, 1973; Speed, 1978). To the east, correlative strata are thinner, where they form the uppermost unit of a sequence of Triassic shelf deposits, which in turn overlie Permo-Triassic volcanic rocks and deformed Paleozoic deep marine strata of the Golconda and Roberts Mountains allochthons (fig. 4; e.g., Silberling and Wallace, 1969; Speed, 1978). Upper Paleozoic and lower Mesozoic volcanic rocks northwest of the basinal terrane, referred to as the Black Rock terrane, have a volcanic island arc affinity (e.g., Russel, 1984; Wyld, 1990). These regional relationships suggests that the Auld Lang Syne basin may have formed in a back-arc extensional environment (fig. 4; e.g., Quinn et al, 1997; Wyld, 2000).

The exact history of deformation recorded in these basinal sediments varies somewhat from place to place, but generally includes the formation of NE-SW-striking penetrative slaty foliation in the argillaceous units during Jurassic deformation (e.g., Oldow, 1984; Thole and Prihar, 1998; Wyld et al., 2001). Folding associated with the primary foliation is generally SE-vergent, as are thrust faults within a regional zone of deformation known as the Luning-Fencemaker Thrust Belt (fig. 4; Oldow, 1984). West of the basinal terrane, Wyld and Wright (2001) document an early to mid-Cretaceous shear zone with major right-lateral strike slip (~400 km) and minor overprinting shortening (fig. 4). This shear zone is inferred to be part of a regional fault system active at this time, the Mojave-Snow Lake-Nevada-Idaho (MSNI) shear zone (Wyld and Wright, 2005), and projects just west of the study area (fig. 4; Wyld and Wright, 2001). Arc magmatism in the region was most

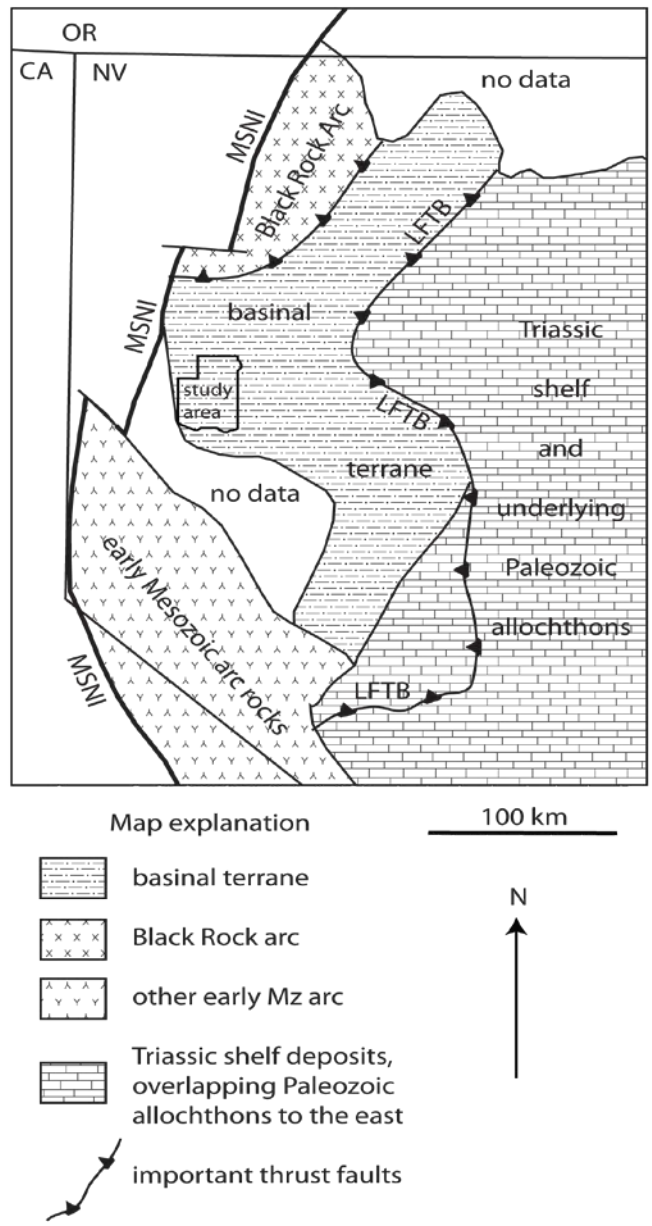

Figure 4. Map of terranes of the NW Basin and Range at the end of the Jurassic, before intrusion of the Cretaceous Sierra Nevada Batholith (modified from Martin et al., 2010). Only the frontal thrust of the Luning-Fencemaker Thrust Belt is shown (labeled LFTB on map); deformation associated with this belt extends throughout the basinal terrane (Oldow, 1984). MSNI = Mojave-Snow Lake-Nevada-Idaho Fault, active in the early to mid-Cretaceous (Wlyd and Wright, 2001, 2005). Terranes west of this fault not shown.

voluminous from ca. 110 to 85 Ma (fig. 1; e.g., Smith et al., 1971; Barton et al., 1988; Van Buer and Miller, 2010).

These mid- to late Cretaceous intrusions are associated with relatively narrow (up to kilometer scale) contact metamorphic aureoles, locally up to amphibolite hornfels, characterized by coeval deformation that overprints older fabrics (e.g., Compton, 1960; Ciavarella and Wyld, 2008). Cretaceous deformation in the region is otherwise relatively minor, although there is local evidence for extensional faulting in the early Cretaceous (e.g., Quinn et al., 1997; Wyld et al., 2001; Martin et al., 2010).

Magmatism was followed by late Cretaceous to early Tertiary erosion, and a widespread unconformity was developed across the region and overlain by Eocene to Miocene volcanic and sedimentary strata (e.g., Stewart, 1998; Henry, 2008; Van Buer et al., 2009). In the NW Basin and Range, east-west extension began in the mid-Miocene, ca. 15–12 Ma, and continues to the present day, manifested by the formation of tilted, roughly north-south trending ranges, usually bound by a normal fault on one side (sometimes both) and separated by deep Neogene basins (fig. 1; e.g. Stewart, 1998; Colgan et al., 2006; Lerch et al., 2008; Whitehill, 2009). Where extensional fault slip and associated tilting has been sufficiently great to rotate normal faults to shallow dips, a second (or even third) generation of steeper faults has developed (e.g., Proffett and Dilles, 1984; Surpless et al., 2002). Though externally drained in the early Tertiary (e.g., Henry, 2008; Cassel et al., 2009), faulting-induced basin and range formation, in conjunction with a the rain shadow effect of the Sierra Nevada, has led most of the Basin and Range Province (the "Great Basin") to become internally drained, with streams ending in playas, marshes, and occasionally, lakes. In the Pleistocene, the deeper basins of the NW Basin and Range were intermittently flooded by fresh water, including a regionally extensive lake system, Lake Lahontan. This lake filled to a maximum depth of ~280 m (shoreline elevation 1330 meters above sea level), last reached about 13,000 years ago (Benson and Thompson, 1987). This lake has left fine-grained lacustrine deposits, beach deposits, wave-cut terraces and caves, spits, perched deltas, and tufa deposits (which often cement the previous formations into durable beachrock) below its highstand elevation (e.g., Russell, 1885; Benson, 2004).

METHODS

Mapping in the field was carried out using U.S. Geological Survey 7.5´ quadrangle topographic maps (1:24,000 scale) as base maps, and was recompiled at 1:62,500 scale for publication. Aerial photography (U.S. Geological Survey. 1 m resolution orthophotoquads) or satellite imagery (National Agricultural Imagery Program 1 m resolution color orthorectified images), overlain with topographic map data, was consulted in the field while mapping, and again when digitizing in ArcMap. For example, dike locations plotted in the field were often adjusted up to about 25 m (0.4 mm on the map) upon digitization if their location in the digital image could be ascertained more precisely. (Note that image orthorectification is often only accurate to within ~6 m; Farm Service Agency, 2010.) Contacts and faults are generally plotted with solid lines only if their existence is fairly certain and their position is thought to be accurate within ~60 m; otherwise dashed lines are used (or dotted lines where faults are concealed). Some of the contacts between Quaternary units, such as between sand dunes and alluvium, or between alluvium and lake deposits, were mapped primarily from digital imagery, though field checked in areas near rock outcrop. Previous geologic mapping (fig. 2) was frequently consulted (especially Whitehill's 2009 work emphasizing the Tertiary history) but contacts were never copied directly, and my interpretation sometimes differs from that of previous authors. Some strikes and dips, however, were transferred from earlier maps, particularly in some parts of the Tertiary units (from Whitehill, 2009) and in parts of the Blue Wing Mountains (fig. 2; Sarah Dasher, unpublished mapping). My own structural measurements of obscure planar features, such as weak magmatic foliation, generally represent a field average of two or three measurements.

Because contact attitudes are rarely directly measurable in the area, attitudes shown in cross section are generally estimated from map patterns by structure contouring. Where no other information is available, normal faults are assumed to have formed at 60° dip and tilted the same amount as the titled Tertiary strata they cut.

LITHOLOGIC UNITS

Basement rock units in the Sahwave and Nightingale ranges include early Mesozoic metamorphic rocks and a number of Cretaceous plutonic rocks that intrude them. The plutonic rocks can be divided into two groups: rocks with an easily visible, roughly north-south, subvertical foliation (either magmatic or sub-solidus), and a set of younger, concentrically nested comagmatic intrusions with weak or contact-parallel magmatic foliation, referred to as the Sahwave Intrusive Suite. The Mesozoic rocks are beveled by an unconformity overlain by Oligocene and Miocene volcanic and sedimentary strata. Normal faulting, beginning in the Miocene, created the present structure of the Sahwave and Nightingale ranges and their flanking basins, which have been mantled in an array of Quaternary deposits. Map units will be discussed from oldest to youngest.

Triassic/Jurassic Metasedimentary Rocks

The oldest rocks in the map area, intruded by the Cretaceous Sahwave batholith, are mostly metamorphosed mudstone/shale with interbedded sandstone layers and lenses (JTRm). A few discontinuous, 10–100 m thick, coarsely crystalline marble layers are present south of the batholith, but calcareous horizons are rare in the metamorphic rocks to the north. These rocks have been identified as submarine fan sediments belonging to the Triassic to lower Jurassic Auld Lang Syne Group (Johnson,

1977). A very limited number (n = 6) of restored flute-cast measurements indicate paleocurrents roughly from the southeast, which is consistent with derivation from the continental shelf that lay in that direction (fig. 4). A particularly thick lens of quartzite, probably the remains of a submarine channel, holds up the peak of the Blue Wing Mountains (fig. 2).

Away from the Sahwave batholith, metamorphic grade is subgreenschist to lower greenschist facies, and original bedding can be clearly seen (though it is often folded). Adjacent to the batholith, Triassic/Jurassic strata are metamorphosed to siliceous hornfels or biotite schists, and bedding is often tightly to isoclinally folded or transposed with a sub-vertical axial-planar foliation that is broadly parallel to the intrusive contact. A strong sub-vertical mineral lineation is also present within ~100m of the intrusive contact, although it is often obscured by a subparallel intersection lineation. 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 (fig. 2) contains a number of skarn deposits in the contact aureole of the batholith where calcareous layers have been metamorphosed, yielding grossular/almandine, clinozoisite/epidote, and more rarely tremolite, wollastonite, diopside, and scheelite, in addition to the standard quartz, ±albite, and calcite. White mica pseudomorphs after andalusite (rod-shaped) and cordierite (mouse-turdlike), as well as cordierite-shaped voids, can be found in some of the more pelitic layers in the Bluewing Mountains (fig. 2) near the northern margin of the batholith. However, large (to 5 cm) andalusite crystals remain intact in at least one area about 1 km from the northern contact, growing in random orientations that cut across the foliation.

Early Intrusive Units

Power Line Intrusive Complex: The oldest intrusive unit, dated at 105 Ma (Van Buer and Miller, 2010; see chapter 3 for discussion of geochronology), is informally referred to as the Power Line intrusive complex (Kpl). Occupying the northwestern Nightingale Range (fig. 2), it is predominantly a medium-grained biotite hornblende granodiorite with 5–10 mm K-feldspar phenocrysts. 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, solid-state foliation that tends to be more pronounced towards the eastern side of the Nightingale Range. 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 thin section, the foliation is defined by biotite strung out along wavy foliation planes, and the sense of shear, if any, is unclear, as the rock bears no discernible lineation. Biotite and quartz appear to have been largely recrystallized, but feldspars remain intact, displaying distinct undulatory extinction, suggesting solid-state deformation at temperatures of ca. 400–450 °C or hotter, depending on strain rate (Passchier and Trouw, 2005). This unit also contains many large inclusions or apophyses of metamorphic rock, mostly 5–200 m in length but including a 4-km-long possible roof pendant. These are generally elongated in map view, and foliated steeply, concordant with the foliation of the Power Line complex.

Selenite Granodiorite: In the very northwestern corner of the study area and throughout the southern Selenite range (fig. 2) is a distinct granodiorite here referred to as the Selenite Granodiorite (Kse) after the “Selenite pluton” of Smith et al. (1971). This unit, dated at ca. 96 Ma (Van Buer and Miller, 2010), 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.

Sahwave Intrusive Suite

The metamorphic rocks, the Power Line complex, and the Selenite Granodiorite are intruded by the large (~1000 km2), zoned Sahwave Intrusive Suite, which comprises most of the basement outcrop in the map area. This intrusive suite consists of three concentric intrusive units and a distinct lobe-forming unit that stretches across the central Nightingale Range (fig. 2).

Granodiorite of Juniper Pass: The outermost and oldest intrusive unit is a medium- to coarse-grained equigranular biotite hornblende granodiorite referred to as the Granodiorite of Juniper Pass (Kjp) due to its excellent exposure at Juniper Pass in the northern Sahwave Range (fig. 2, 3). Dated at ca. 93 Ma (Van Buer and Miller, 2010), the Granodiorite of Juniper Pass is identified by its conspicuous 4–8 mm euhedral biotite crystals. Additionally, large hornblende phenocrysts are common around the periphery of this intrusion, giving the rock a characteristic “dalmatian” appearance. Hornblende and sphene are both present throughout the Sahwave batholith, 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 varies quite a bit; in places it can be classified as a tonalite or a quartz diorite. Gradational 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–1 m thick are bounded by sharp contacts. 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 contacts. Enclaves are typically 5–30 cm in length and flattened by a ratio of 2:1 to 5:1 or more. Mafic

schlieren are common in the same region. The Granodiorite of Juniper Pass has a discernible 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. Magmatic foliation tends to be strongest near the outer contact, which it often parallels.

Where contact orientation is evident, it tends to be steeply dipping and subparallel 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. It is not clear, however, whether these metamorphic pendants 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 across the foliation of the Power Line complex, suggesting that the contact in this area may simply surround a flap of wall rock that was in the process of being stoped.

Granodiorite of Bob Spring: The Granodiorite of Juniper Pass grades inward to the more felsic and uniform Granodiorite of Bob Spring (Kbs), dated at ca. 93 Ma (Van Buer and Miller, 2010), a medium-grained biotite granodiorite or granite characterized by seriate K-feldspar phenocrysts up to ~2 cm. 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, and are occasionally sieve textured and difficult to see. In general, Kbs is finer grained towards its center, and K-feldspar phenocrysts are less common. The Granodiorite of Bob Spring bears equant quartz grains that are generally only about 1 mm in size but reach 3–5 mm in the southern part. In the southern Sahwave Range this unit crops out in a few rocky tors, which in some cases appear to have gained their greater resistance to weathering by hydrothermal silicification. 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.

Sahwave Granodiorite: The Sahwave Granodiorite (Ks), a K-feldspar-megacrystic biotite granodiorite dated at ca. 89 Ma (Van Buer and Miller, 2010), 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. K-feldspar megacrysts are 2–4 cm across, moderately poikilitic, and more abundant (usually 1–5% by volume) than in the Bob Spring Granodiorite. 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%. These can vary from centimeters to meters in scale, do not have particularly sharp contacts, and are generally surrounded by rock that is more equigranular and leucocratic than average, suggesting that K-feldspar crystals may have been concentrated from the magma by flow segregation, or perhaps that leucocratic melt was filter-pressed out of fluid-softened areas of the magma. 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.

School Bus Granodiorite: The Nightingale Range contains a distinct lobate unit referred to as the School Bus Granodiorite (Ksb), after outcrops in a canyon containing two defunct school buses. This unit, dated at ca. 91 Ma (Van Buer and Miller, 2010), is a relatively leucocratic granodiorite, distinguished by scattered 1–2 cm K-feldspar phenocrysts and 3–6 mm biotite flakes. Unlike the main part of the Sahwave batholith, this lobe does not appear to be any more mafic around its outer edge, and is, in fact, remarkably homogeneous. Magmatic foliation is not generally distinguishable. The School Bus Granodiorite intrudes both the Power Line complex and the Granodiorite of Juniper Pass along sharp, vertical contacts that are fairly irregular at the map scale. Where it intrudes the Power Line complex, the units are often separated by metamorphic screens and blobs 20–200 m thick.

Minor Cretaceous Intrusives

The southern part of the Granodiorite of Juniper Pass contains a number of diorite bodies (Kd), varying from tens of meters to over a kilometer in scale. These fine- to medium-grained intrusions frequently contain ~5 mm euhedral plagioclase phenocrysts, and sometimes acicular hornblende crystals as well. These diorite bodies appear to be coeval with the Sahwave batholith, often showing magma mingling and mixing structures such as lobate and interfingering contacts, streaky fine-scale intermingling, and outcrop-scale continuous compositional variation indicative of wholesale mixing.

Additionally, the Sahwave batholith and its country rocks are pervasively intruded by a series of leucocratic dikes and sills (Kap) that tend to be more resistant to weathering than the surrounding country rocks. Most of these dikes demonstrate wide variations in grain size between aplite and pegmatite textures, often showing evidence for repeated intrusion. The pegmatites are generally muscovite bearing, and may also contain tourmaline (schorl) and rarely garnet. The dikes range from 1 cm to 100 m in thickness and generally strike north-south, but in the Sahwave Range vary systematically between NNW trending in the south and NNE trending in the north. Dips are often moderately shallow, but only locally consistent in direction of dip. The most notable pegmatites, containing feldspar crystals up to 1 m in dimension, occur in the northeastern Sahwave Range, where they define a

domal structure. Variations in the orientation of these dikes are hypothesized to be due to perturbations in the principal stresses as a result of thermal contraction of the batholith. Another notable concentration of leucocratic dikes exists in the Nightingale Range, intruding the Power Line complex. These dikes crosscut the solid-state foliation of the Power Line complex and are occasionally composite, containing a phase with scattered large K-feldspar and biotite phenocrysts, suggesting that they may be genetically related to the School Bus Granodiorite, which could underlie this area beneath the current level of exposure. Pegmatite dikes cutting the metamorphic rocks along the margins of the batholiths are frequently folded and boudinaged in the foliation, which is subparallel to the country-rock contact. A few broader leucogranite intrusions (Klg), which are more uniform in grain size and contain minor biotite, are present near the southern margin of the batholith.

Tertiary Dikes

The Sahwave batholith is cut by a few generations of younger dikes, ranging from rhyolitic to basaltic in composition, which tend to be more resistant to erosion than the surrounding rock. Although these dikes have not been dated, they cut all aplite dikes. Their generally fine-grained nature suggests that they are substantially post-magmatic, and they are compositionally similar to volcanic rock units in the overlying Tertiary section. In order of intrusion, (as determined by cross-cutting relationships), the dike units are as follows: (1) Tb3 – dark, greenish-gray, aphanitic, aphyric basalt dikes. (2) Td2 – very fine-grained gray diabase dikes. (3) Tb2 – pyroxene ± olivine phyric basalt dikes (phenocrysts < 1 mm; often altered). (4) Tb – plagioclase phyric basalt dikes. The plagioclase phenocrysts are often of the size and appearance of rolled oats (~ 4 mm). (5) Tf – rhyolite dikes, generally flow-banded and a minimum of 10 m thick. Often they contain large quartz and biotite crystals that may be xenocrysts scavenged from the surrounding granodiorite. In areas with shallow inferred Tertiary paleodepth, rhyolite intrusions take the form of equant plugs 300–400 m across. (6) Td – coarser diabase dikes, containing plagioclase phenocrysts up to 3 mm, also some hornblende in the matrix. Though dark grey when fresh, these dikes weather to a distinctive spearmint-green hue. Unlike all the previous dikes, which generally trend WNW–ESE, these dikes trend NNE–SSW, paralleling the range-bounding normal faults. These dikes dip steeply towards the range-front fault, and have likely been back-tilted from an initially vertical orientation. They are the only dikes whose orientation may bear a kinematic relationship to east-west Basin and Range extension—the WNW–ESE orientation of the earlier dikes either reflects a pre-extensional stress orientation or the influence of the weak but approximately parallel magmatic fabric of the Cretaceous intrusive suite the dikes intrude.

Tertiary Strata

All metamorphic and plutonic rocks are unconformably overlain by Oligocene and Miocene volcanic and sedimentary rocks, which have been fairly throroughly described by Faulds et al. (2005) and Whitehill (2009). The following description includes my own observations as well. The volcanic units range from basalt flows to silicic ignimbrites, and the interbedded sediments (not thoroughly lithified) range from landslide deposits and fanglomerates to lacustrine clays (cf. Whitehill, 2009). Other than an occasional boulder lag or conglomerate, the basal Tertiary unconformity is frequently directly overlain by volcanic or volcaniclastic rocks. In the southern Nightingale Range (fig. 2), the basal volcanic rocks, which fill a paleochannel, are Oligocene ignimbrites dated at 31–25 Ma (sanidine $^{40}Ar/^{39}Ar$; Faulds et al., 2005), but elsewhere in the map area they are Miocene basalts dated at 18–14 Ma (whole-rock $^{40}Ar/^{39}Ar$; Whitehill, 2009), volcaniclastic units, and locally rhyolite flows. Just northwest of the map area, however, lacustrine deposits form the base of the section (Whitehill, 2009). The basal strata appear to predate normal faulting in the area, but younger volcanic rocks, dated at 14–12 Ma (whole-rock $^{40}Ar/^{39}Ar$; Whitehill, 2009), and volcaniclastic sediments may form thicker sequences at the base of nascent fault-bound extensional basins (Whitehill, 2009). In the southwestern Sahwave Range, primarily non-volcaniclastic sedimentary rock, including fanglomerate, sandstone, and shale (ca. 12–9 Ma) has been exposed by later faulting (Whitehill, 2009), and likely represents the sort of material which has continued to fill the adjacent Granite Springs and Winnemucca Cenozoic basins until the present day (fig. 2). This mapping distinguished only three Tertiary units: (Tv) primarily volcanic and volcaniclastic rock; (Ts) primarily non-volcaniclastic sedimentary strata, ranging from alluvial to lacustrine deposits, tilted, but often not fully lithified; and (Tc) a distinctive (though poorly exposed) boulder conglomerate in the east-central Nightingale Range that is presumed to be Tertiary because it contains metamorphic and volcanic clasts from units not present in the current watershed.

Quaternary Units

About half of the map area is covered by Quaternary deposits. Areas of basement rock covered with a thin veneer of alluvium, colluvium, or scree, were mapped according to the basement lithology if it could be reasonably inferred from soil composition or exposure in frequent gullies. Quaternary deposits were only mapped where they appeared to be more than about 2 m thick and 25 m wide. Older alluvial terraces are often preserved, but for the puposes of this study all alluvial fan and stream deposits were mapped as a single unit (Qa). Slumps, talus slopes, and other mass wasting deposits (Qls) are common in the steeper parts of the map area.

Winnemucca Valley and Kumiva Valley (fig. 2) both contain Pleistocene lake deposits (Ql). Extensive deposits related to ancient Lake Lahontan occur throughout Winnemucca Valley at elevations below about 1340 m (fig. 2), including coarse sand and gravel beach deposits, delta

deposits, and fine-grained lake deposits (mapped as a separate unit, Qp, where reworked in the modern playa). Alluvial deposits surficially terraced by wave action are nearly indistinguishable from thicker beach deposits, and are also mapped as Ql. Tufa is deposited extensively as a cementing agent, as a veneer on rock surfaces, and as hummocks or towers up to ~20 m high. Tufa-cemented clastic rocks are generally mapped as Ql, whereas freestanding tufa deposits are mapped as a separate unit, Qt. Lacustrine deposits at 1340 m (e.g., in Stonehouse Canyon) would appear to be about 10 m above the most recent 1330 m highstand level for Lake Lahontan (Benson and Thompson, 1987). This deviation is within the range reported throughout the Lahontan basin due to isostatic rebound and recent tectonic uplift; alternatively, these deposits could date from an earlier, higher highstand (e.g., Reheis et al., 2002).

In Kumiva Valley, the only significant lake deposit is a low, kilometer-long gravel bar about a kilometer south of Bluewing Flat (fig. 2), which lies about 10 m above the elevation of the playa surface. This gravel bar is inferred to mark the ~1352 m highstand level of Lake Kumiva (cf. Mifflin and Wheat, 1979). About 20 m higher absolute elevation than the highstand of Lake Lahontan (Benson and Thompson, 1987), this would have been a small isolated lake on the large island of a dozen or so ranges surrounded by Lake Lahontan (e.g., Russell, 1885).

Additionally, two active playas (Qp) were mapped. Bluewing Flat is very smooth, flat, and usually bone dry, but Winnemucca Lake received more substantial quantities of water in the recent past and consequently has a bit more topography—many areas might be better classified just as fine-grained lake deposits rather than an active playa surface. The water table seems to be very shallow, and the lowest parts of the playa can remain muddy (sometimes under a dry surface crust) quite late in the year (don't drive on this playa).

Eolian deposits (Qe) are among the youngest features in the area. This unit includes inactive, vegetation-stabilized dunes and sand sheets, mostly in Kumiva Valley, as well as active dunes, mostly in Winnemucca Valley. Field checking indicates that some of the eolian features inferred from satellite imagery, especially in Kumiva Valley, are in fact rather thin veneers of wind-blown sand. However, all such features have been retained for consistency, due to the practical difficulty of applying a robust minimum thickness limit. There are also plenty of dunes on the surface of Winnemucca playa, which were not mapped due to low visual contrast against the playa sediments in satellite imagery.

STRUCTURAL DEVELOPMENT

Jurassic to mid-Cretaceous Deformation

The earliest record of deformation in the map area is preserved in fabrics developed in the Upper Triassic to lowest Jurassic metasedimentary rocks (JŦm) in the Bluewing Mountains (fig. 2). Here, foliation and the axes of outcrop-scale, tight to isoclinal folds trend NE–SW and dip steeply. Additionally, at map scale, the primary foliation of the western Blue Wing Mountains is folded into an open, recumbent, overturned to the SE syncline with parasitic folds in its core. These features are consistent with the SE-vergent style of Jurassic deformation in nearby parts of the Luning-Fencemaker thrust belt (fig. 4; Oldow, 1984; Thole and Prihar, 1998).

In contrast, the 105 Ma Power Line intrusive complex and the many metamorphic pendants it contains are marked by a strong, roughly north-south, subvertical solid-state foliation. The 96 Ma Selenite Granodiorite shares a magmatic foliation of the same orientation. Without a clear lineation, these foliations remain kinematically ambiguous. However, this deformation could be related to the early- to mid-Cretaceous MSNI shear zone of Wyld and Wright (2001, 2005), which shares approximately the correct orientation, location, and timing.

Emplacement of the Sahwave Intrusive Suite

These early units are all truncated by the Sahwave Intrusive Suite. Although foliation in the Powerline intrusive complex is sometimes locally perturbed near the Sahwave Intrusive Suite contact, the most obvious deformation spatially associated with the Sahwave batholith appears in the adjacent metasedimentary rocks. These are locally foliated parallel to the steep intrusive contact with a strong subvertical lineation, suggesting that the wall rocks were flattened in pure shear and flowed ductilely downwards to accommodate the laterally expanding pluton. Boudinaged pegmatites of approximately the same age as the batholith (Van Buer and Miller, 2010) clearly demonstrate that ductile deformation was taking place in the contact aureole of the intrusion. In the Blue Wing Mountains (fig. 2), 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 (fig. 2), foliation is sub-parallel to the contact over the entire region of exposed metamorphic rock, up to 5 km away from the intrusion. This NW–SE foliation is anomalous compared to NE–SW Jurassic structural trends in surrounding areas (Oldow, 1984). Re-intrusion of the School Bus Granodiorite so close to the contact already heated once by the Granodiorite of Juniper Pass may be responsible for the more extensive ductile deformation (and mineralization) along the southwestern edge of the intrusion, whereas the active intrusive contact retreated significantly from the northern margin over time.

The steep contacts and magmatic foliation of the Sahwave Intrusive Suite suggest that it is not a sill-like intrusion. On the other hand, the presence of andalusite in its aureole limits its depth to less than ~ 10 km. Given its 40 km diameter at this depth, it must have been relatively flat-topped (constrained by the proximity of the surface). The downward extent of the batholiths 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 such as these may extend to the base of the crust, although large distinct intrusions in the upper crust may overlie a complex zone of smaller, sheeted intrusions in the lower crust (Saleeby, 2003; Barth et al., 2008; Saleeby et al., 2008). Conversely, seismic data from further north along the arc (Lerch et al., 2007) indicate low velocities compatible with tonalitic/granitic rocks down to only ~15 km, so the magmatic arc in NW Nevada may not encompass the entire crust, or may be more mafic at depth.

Even if the batholithic rocks studied here extend only to an additional 15 km depth, this intrusive suite still represents well over 10,000 km^3 of batholithic volume. Some fraction of this space may have been generated by ductile shouldering-aside and downward return-flow of the wall rocks, but this is frequently considered to be a relatively minor material transfer process in the upper crust (e.g., Paterson and Vernon, 1995). Major upper-crustal assimilation is ruled out isotopically (Van Buer and Miller, 2010). External contacts frequently dike into the metamorphic rocks and apparently surround stoped blocks, suggesting that stoping is at least a locally important process. If the kilometer-scale metamorphic outcrops in the southern part of the Granodiorite of Juniper Pass represent stoped blocks rather than roof pendants, this would indicate a greater role of stoping in the intrusive process. Gradual tectonic opening could make some additional accommodation space. For example, right-lateral motion across the North American subduction zone in the Late Cretaceous (e.g. Engebretson et al., 1985; Müller et al., 2008) could have produced significant localized extension if partitioned onto an intra-arc shear zone organized into right-stepping en-echelon segments (Tikoff and de Saint Blanquat, 1997; Tikoff and Teyssier, 1992). Such a shear zone has been identified in the Sierra Nevada (e.g., Busby-Spera and Saleeby, 1990; Greene and Schweikert, 1995), but not yet in the study area.

Given the vast size of the Sahwave Intrusive Suite and the variations in lithology between and among its members, it seems likely to have been emplaced as a series of many intrusive pulses over its approximately four-million-year history (Van Buer and Miller, 2010). However, smooth compositional variation and concentric arrangement within the gradationally zoned Sahwave Intrusive Suite suggests that individual batches of magma generally stayed hot long enough to partially mix with their successors. The Granodiorite of Bob Spring, the School Bus Granodiorite, and the Sahwave Granodiorite are particularly homogeneous, suggesting that each may represent a single phase of rapid magma input into a large, partially molten magma chamber. The concentric arrangement of successively more homogeneous (and generally more differentiated) units also suggests that the system was warming over time, allowing larger and longer-lived magma chambers to be formed at both the level of exposure and perhaps at the deeper level of magma production.

Mid-Miocene to Present Normal Faulting

Major normal faults bound the Nightingale and Sahwave ranges on the west and east sides, dipping west and east, respectively, such that the two ranges together form a horst block (cf. Whitehill, 2009). Still active today, the main faults exert strong control on topography, often truncating ridges and forming triangular facets, most spectacularly preserved in the southern Nightingale Range (fig. 2, just left of the “N” in “Nightingale Range”). These faults have backtilted the strata in both their hanging walls and their footwalls, warping the rocks between the two ranges into a broad syncline, with minor faults in the hinge area (cf. Whitehill, 2009). In the central and northern Nightingale Range, slip is actually partitioned between several, subparallel, smaller-offset faults, causing the range to bifurcate at its northern end (fig. 2) where the faults take a more northeasterly trend (cf. Whitehill, 2009). This system of faults continues to the northeast of the Nightingale Range across Kumiva Valley, where the faults are largely concealed, but raise a few subtle hills (fig. 2) and faint Quaternary scarps. The NE-striking, NW-dipping fault that uplifts the Bluewing Mountains (fig. 2) appears to be a continuation of this system as well. In cross section, cumulative slip across the range-bounding faults varies from about 5 km in the south to about 3 km further north.

Faulting in the Sahwave Range appears to be separated into two kinematically distinct segments by an E–W accommodation fault. South of this fault there appear to be two generations of N–S-trending faults. The first fault zone dips at a low angle (measured at ~33°; Whitehill, 2009), and is probably inactive at the surface today. It exhibits a fault-line scarp against a package of progressively tilted, ca. 12–9 Ma sediments in its hanging wall (Whitehill, 2009), but this may be simply related to the greater erosional resistance of granodiorite compared to partially lithified sediment. The second fault system breaks ground east of the first fault, offsetting Holocene alluvial terraces by as much as 3–4 m across an obvious fault scarp, and appears to dip more steeply (Whitehill, 2009; Wesnousky, 2005). To the south, this fault zone steps away from the range in a series of four left-stepping, en-echelon faults. These younger faults are responsible for exhuming the basin sediments exposed in the hanging wall of the older normal fault (Whitehill, 2009). These sediments are back-tilted ~30°, consistent with the older normal fault having originally formed at ~60° (Whitehill, 2009). Assuming a basin depth of ~2.5 km, as modeled from gravity data by Saltus and Jachens (1995), my cross sections show that the southern Sahwave normal faults have a cumulative slip of about 9 km, with about a quarter of the total slip taken place along the younger faults. Given that the southern Nightingale

Range has much more rugged topography than the Sahwave Range (fig. 2) despite an apparently much smaller total slip, I speculate that the titling and uplift of the Nightingale Range is, on average, younger than that of the southern Sahwave Range. The two sides of the intervening syncline, which exhibit somewhat different styles of faulting, may not have formed entirely at the same time.

North of the accommodation fault, the Sahwave Range bends NNE (fig. 2), and is bounded by normal faults on both sides. The eastern range-bounding fault exhibits a clear Holocene scarp (Wesnousky, 2005), but there is no evidence for an older, low-angle fault. The most abrupt topography in the range switches to the west side instead of the east side (fig. 2). Near its northern end, the range becomes narrower and lower, and is breached by what appears to be an antecedent stream gap, Juniper Pass (fig. 3). Gravity data also suggest that the northern part of Granite Springs Valley (fig. 2) is shallower (~1.5 km) than southern part (Saltus and Jachens, 1995). I infer from these lines of evidence that the northern Sahwave Range is neither as tilted, nor as deeply exhumed on the east side, as the southern Sahwave Range. The Tertiary section has been completely eroded from the northern Sahwave Range, but if it has been uplifted as much as the basin has sunk, fault slip on the east side would only be ~4–5 km, and maybe half as much on the west side (cross sections BB´, CC´). From my cross sections, I estimate the total extension across the Sahwave and Nightingale ranges north of the accommodation fault to be ~25–30%, and ~40–45% to the south of it.

SUMMARY

The geologic history of the Sahwave and Nightingale ranges can be summarized as follows:

1. Late Triassic to earliest Jurassic deposition of submarine fan sediments in a deep water basin.

2. Late Jurassic southeast-vergent folding, low-grade metamorphism, and foliation development related to the NE-SW-trending Luning-Fencemaker thrust belt.

3. Mid-Cretaceous intrusion of the Powerline intrusive complex and Selenite Granodiorite during north-south fabric development (MSNI shear zone???).

4. Emplacement of the Sahwave Intrusive Suite (~93–89 Ma); generation of the surrounding metamorphic and deformational aureole in the metasedimentary rocks.

5. Erosion and exposure of the batholith.

6. Deposition of Oligocene to Lower Miocene volcanic and sedimentary strata unconformably above Mesozoic basement. Intrusion of Tertiary dikes (?).

7. Mid-Miocene to present normal faulting and synclinal warping to generate the present Sahwave and Nightingale Ranges. Additional Miocene volcanism. Continuing erosion from the ranges and deposition in the basins.

8. Intermittent inundation of parts of Winnemucca and Kumiva valleys by Pleistocene lakes and generation of present surficial deposits.

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