Structural reconstruction and age of an extensionally faulted porphyry molybdenum system at Spruce Mountain, Elko County, Nevada

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ABSTRACT

This study integrates a cross-sectional restoration of normal faults and porphyry-related hydrothermal alteration zones with six new U-Pb zircon dates to constrain the ages of mineralization and large-magnitude Cenozoic extension at Spruce Mountain, northeastern Nevada (USA). Paleozoic sedimentary rocks and sparse rhyolitic intrusive rocks host a porphyry molybdenum deposit dated as ca. 38 Ma that contains associated skarn, carbonate replacements, fissure veins, and jasperoid. At least six crosscutting sets of normal faults with variable dip directions (east, west, and north) and angles (<15° to >60°) are identified at Spruce Mountain, reflecting overprinting phases of extension. Based on the restored cross section, normal faulting at Spruce Mountain resulted in ~6.9 km (120%) of total extension and ~35° of net eastward tilting. The first four fault sets, late Eocene (ca. 38 Ma) or older, collectively accommodate most of the total extension (~5.4 km). Later faults probably were active in the Miocene and Quaternary. All restored faults had initial dips of 45° or greater, and the restored preextensional structure of Spruce Mountain consists of west-vergent folds and gentle westward dips of Paleozoic rocks. Spruce Mountain is classified as a rhyolitic porphyry Mo or Climax-type deposit, with extensive skarn. Eocene rhyolite porphyry dikes associated with porphyry Mo mineralization locally intrude the migmatic core complex and a few kilometers from the southwestern tip of the adjacent Pequop Mountains (Fig. 1). The Spruce Mountain mining district covers the summit and northern flank of Spruce Mountain and extends northward onto Spruce Mountain Ridge. The district contains porphyry molybdenum and associated skarn, carbonate replacements, fissure veins, and jasperoid and has been explored for Carlin-type gold mineralization (LaPointe et al., 1991; Field et al., 2011; Smith et al., 2013). When applied to structurally dismembered mineralized systems, cross-sectional structural reconstructions can be used to predict where fault-offset fragments of the system are located and to delineate potential exploration targets (e.g., Lowell, 1968; Seedorff, 1991b; Dilles and Proffett, 1995). In addition, structural restorations can lead to a better understanding of the preextensional geology of a region and provide insights into mechanisms of crustal extension, particularly when they are integrated with absolute age constraints (e.g., Proffett, 1977; Gans and Miller, 1983; Dilles and Gans, 1995; Surplus, 2012).

This study focuses on the Spruce Mountain district of northeastern Nevada, a topographically rugged area with >1 km of local relief and complex structure produced by faults with opposing senses of displacement (Hope, 1972). Spruce Mountain is ~30 km east of the Ruby Mountains–East Humboldt Range metamorphic core complex and a few kilometers from the southwestern tip of the adjacent Pequop Mountains (Fig. 1). The Spruce Mountain mining district covers the northern flank of Spruce Mountain and extends northward onto Spruce Mountain Ridge. The district contains porphyry molybdenum and associated skarn, carbonate replacements, fissure veins, and jasperoid and has been explored for Carlin-type gold mineralization (LaPointe et al., 1991; Wolverson, 2010; E.M. Struhsacker, 2014, personal commun.). The Spruce Mountain district is ~40 km south-southwest of the Pequop mining district, where Carlin-type gold deposits were discovered recently (Bedell et al., 2010; Felder et al., 2011; Smith et al., 2013).

This region has undergone significant amounts of both Mesozoic crustal shortening and subsequent Cenozoic extension (e.g., Cambi and Chamberlain, 1997), but there is ongoing debate over the total amount of extension in eastern Nevada and the relative importance of late Eocene versus middle Miocene extension (e.g., Seedorff, 1991a; Miller et al., 1999; Sullivan and Snoke, 2007; Henry, 2008). When applied to structurally dismembered mineralized systems, cross-sectional structural reconstructions can be used to predict where fault-offset fragments of the system are located and to delineate potential exploration targets (e.g., Lowell, 1968; Seedorff, 1991b; Dilles and Proffett, 1995).

INTRODUCTION

Cenozoic extension has played an important role in the formation, preservation, and exposure of ore deposits in the Basin and Range province (western United States and Mexico; Dreier, 1984; Spencer and Welty, 1988; Seedorff, 1991a). However, postmineralization extension can also complicate the exploration and development of mineralized systems by dismembering and tilting ore deposits, thus distorting their original structural configurations (e.g., Proffett, 1977; Wilkins and Heidrick, 1995; Rahl et al., 2002; Begbie et al., 2007; Stavast et al., 2008). When applied to structurally dismembered mineralized systems, cross-sectional structural reconstructions can be used to predict where fault-offset fragments of the system are located and to delineate potential exploration targets (e.g., Lowell, 1968; Seedorff, 1991b; Dilles and Proffett, 1995). In addition, structural restorations can lead to a better understanding of the preextensional geology of a region and provide insights into mechanisms of crustal extension, particularly when they are integrated with absolute age constraints (e.g., Proffett, 1977; Gans and Miller, 1983; Dilles and Gans, 1995; Surplus, 2012).

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igneous dikes that provide constraints on (1) the age of extension and porphyry molybdenum mineralization, and (2) the original geometry of mineralized zones prior to subsequent extensional deformation. We conclude that at least 6 individual sets of crosscutting normal faults accommodated ~6.9 km (120%) of extension at Spruce Mountain, and that the first 4 fault sets, which collectively accommodate 5.4 km of extension, were active at or before ca. 38 Ma. Although the oldest normal faults currently dip at <15°, based on the structural reconstruction, all faults had initial dips of ~45° or greater. We also discuss implications of this cross-sectional reconstruction for the timing and style of extension in the northeastern Great Basin and its importance to mineralization processes and mineral exploration at Spruce Mountain.

**GEOLOGIC SETTING**

Spruce Mountain is part of a belt of Precambrian to Mesozoic continental margin strata and Mesozoic to Cenozoic igneous rocks situated to the east of contractional allochths emplaced during the mid-Paleozoic to mid-Mesozoic (Figs. 1 and 2). It is significant that this belt of rocks is also within a zone of metamorphic core complexes that characterizes the eastern fringe of the hinterland of the Mesozoic Sevier fold and thrust belt (Fig. 1; Dickinson, 2011; Cashman et al., 2011). Cordilleran metamorphic core complexes, which are exposures of formerly deeply buried mid-crustal and lower crustal metamorphic-plutonic rocks, are the iconic landforms of extended crust (Crittenden...
et al., 1980; Sullivan and Snoke, 2007). Spruce Mountain is located in the middle of three core complexes, Ruby Mountains–East Humboldt Range, Albion–Raft River–Grouse Creek, and Snake Range (Fig. 1).

In proximity of Spruce Mountain, crustal thickening events, perhaps Late Jurassic to Late Cretaceous in age, are recorded by thrust faults and regional metamorphic rocks exposed in the Ruby Mountains–East Humboldt Range to the northwest, in the Wood Hills to the north, and in the Pequop Mountains to the northeast (Thorman, 1970; Howard, 1980; Sneke and Miller, 1988; Hudec, 1992; Camilleri and Chamberlain, 1997). Thermobarometry and thermochronology data from the East Humboldt Range and the Wood Hills suggest that a decompression event may have occurred there as early as the Late Cretaceous, which may reflect the onset of crustal extension in northeastern Nevada (Hodges et al., 1992; McGrew and Sneek, 1994; McGrew et al., 2000; Druschke et al., 2009; Hallett and Spear, 2014). However, work has also underscored the importance of middle Miocene extension in the region (e.g., Miller et al., 1999; Colgan and Henry, 2009).

Spruce Mountain exposes Ordovician to Permian miogeoclinal sedimentary rocks (Fig. 2) in numerous fault-bounded blocks (Fig. 3A). Lower Paleozoic rocks exposed at the deepest structural levels may have reached greenschist facies metamorphic grade (Camilleri and Chamberlain, 1997). Throughout most of the district, the Paleozoic rocks dip to the east at moderate to steep angles, but in some fault blocks in the northern part of the district, Paleozoic rocks dip consistently westward (Fig. 3A), similar to the nearest exposures of Paleozoic rocks 10 km west of the district (Hope, 1972).

No Mesozoic sedimentary rocks crop out at Spruce Mountain, but ~1.0–1.2 km of lower Triassic marine shale and limestone are exposed ~10 km east of Spruce Mountain within the core of the Pequop syncline (Fraser et al., 1986; Swenson, 1991). Cenozoic volcanic and sedimentary rocks unconformably overlie Paleozoic rocks at Spruce Mountain. A southeast-dipping Cenozoic dacite tuff crops out near Cole Creek on the eastern side of the district and overlies Permian and upper Pennsylvanian rocks (Fig. 3A). Sedimentary rocks that crop out in the southwestern corner of the district (Fig. 3A) dip gently to moderately to the east-northeast (Harlow, 1956; Hope, 1972) and have been assigned to the Miocene Humboldt Formation (Harlow, 1956; Coats, 1987).

Although intrusive rocks constitute only a small fraction of the surface exposures at Spruce Mountain, a variety of intrusive rocks have been observed in the district (Fig. 3A; Table 1). Prior to this study, there were no radiometric ages on intrusive rocks from Spruce Mountain. However, in nearby ranges, most igneous rocks range from Jurassic through late Eocene in age (e.g., Wright and Snoke, 1993; Henry, 2008; Bedell et al., 2010).

### INTRUSIVE ROCKS AND U-Pb GEOCHRONOLOGY

The mapped distribution of intrusive rocks at Spruce Mountain is shown in Figure 3A. Six samples that represent many of the igneous rocks known at Spruce Mountain were selected for U-Pb zircon geochronology (Baril, 2013).
Figure 3 (on this and following page). Geologic maps of the Spruce Mountain area. (A) Map shows lithologic units, extensional faults color coded by relative ages, locations of samples for U-Pb dates with ages, and line of reconstructed cross section (see text). Map compiled and modified from Hope (1972), Fraser et al. (1986), and Swenson (1991), incorporating information from Harlow (1956), Coats (1987), and this study. Revisions in local areas based on footnotes in proof on map of Hope (1972), mapping by Saunders and Bresnahan (2010), and our field mapping and observations.
Figure 3 (continued). (B) Map showing simplified distribution of selected alteration-mineralization features and numbered locations of selected historical mines. Extensional faults color coded by relative ages, intrusive rocks, and the line of the reconstructed cross section are shown for reference. Sericitic alteration (not shown) occurs only locally in porphyry dikes. Map compiled from Hope (1972), LaPointe et al. (1991), American CuMo Mining Corporation (2014), and our observations.
and are described in Appendix 1. Igneous rocks with a fine-grained groundmass are assigned volcanic rock names (whether extrusive or shallow intrusive), whereas coarser grained porphyritic and equigranular rocks are given plutonic rock names. Hypabyssal rocks may have either a volcanic or plutonic name, depending on grain size. Sample locations are listed in Table 1 and plotted in Figure 3A. Table 1 also lists the stratigraphic hosts of each sample; this bears on the possible depth of emplacement of the intrusions, as well as the alteration-mineralization characteristics of each sample, which are relevant to evaluating the age of alteration mineralization. U-Pb dates were obtained from microanalysis of zircons by the laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) method at Boise State University (Idaho). Analytical methods and reporting procedures are described in Appendix 2, and results are summarized in Table 1.

Late Jurassic Dacite

A sample from a small dike of Late Jurassic porphyritic dacite that crops out on the North Peak of Spruce Mountain (SMlg47) is dated as 156 ± 2 Ma (Table 1). In addition, a sample from a small exposure of Late Jurassic flow-banded dacite (SMlg46), dated as 155 ± 4 Ma (Table 1), crops out ~1 km north of the Monarch mine (Figs. 3B).

Late Eocene Rhyolite

An east-west–trending dike or band of dikes of late Eocene rhyolite porphyry and quartz-rich breccias cuts across the northern side of Spruce Mountain, crossing the range at a pass near the Kille mine (Figs. 3A and 3B; Hill, 1916; Hope, 1972). Although poorly exposed, surface and dump samples indicate the presence of several varieties of rhyolite porphyry (72%–74% SiO₂) dikes, including altered porphyry dikes with ~25–30 vol% phenocrysts of quartz, K-feldspar, plagioclase, and minor biotite set in an aplite groundmass and less altered varieties with ~10–15 vol% phenocrysts and an aplite groundmass (E. Seedorff, personal data; Baril, 2013). A sample of coarse-grained rhyolite porphyry with ~30 vol% phenocrysts was collected near the Black Forest mine in the north-central part of the district (SMlg49). This sample is potassically altered and cut by quartz veins with minor molybdenite (Figs. 3A, 3B), and has a U-Pb zircon age of 39.1 ± 0.6 Ma (Table 1). Dates (⁴⁰Ar/³⁹Kr) on K-feldspar and biotite from the same sample, SMlg49, are similar to the U-Pb age, indicating rapid cooling in the late Eocene (C.D. Henry, 2013, written commun.). A sample of rhyolite porphyry with ~15 vol% phenocrysts (SMlg51) that was collected farther east of the Black Forest mine has a U-Pb zircon age of 37.5 ± 0.4 Ma (Table 1). Samples from the vicinity of the Standard mine on the western side of the district (Figs. 3A, 3B) yield U-Pb zircon ages of 37.7 ± 0.5 Ma on a flow-banded porphyritic rhyolite dike (SMlg44) and 37.3 ± 0.4 Ma on a rhyolite porphyry with ~30 vol% phenocrysts (Table 1).

Undated Intrusive Rocks

In addition to the intrusive rocks dated as part of this study, several other occurrences of undated igneous rocks have been reported at Spruce Mountain. A lamprophyre dike of unknown age was observed in the underground workings of the Black Forest mine (Fig. 3B) by Schrader (1931), and an undated stock of hornblende diorite intrudes Permian strata near the northern end of Spruce Mountain Ridge 19 km beyond the northern boundary shown in Figure 3. Small, altered dikes also crop out on Banner Hill (Fig. 3), some of which contain hydrothermal chlorite and epidote (Hill, 1916).

### Table 1. Summary of U-Pb Ages of Igneous Rocks in the Spruce Mountain District

| Sample   | UTM easting | UTM northing | Rock type (phenocryst content, vol%) | Local stratigraphic hosts of intrusion | Alteration, mineralization | Age (Ma) | 2σ (Ma) |
|----------|-------------|--------------|-------------------------------------|---------------------------------------|----------------------------|----------|---------|
| SMlg44   | 679937      | 4492126      | Porphyritic rhyolite (5)             | Pennsylvanian Ely Limestone           | Sericite and kaolinite after feldspars | 37.7     | 0.5     |
| SMlg45   | 680682      | 4490741      | Rhyolite porphyry (30)               | Pennsylvanian Ely Limestone           | Sericite and kaolinite after feldspars | 37.3     | 0.4     |
| SMlg46   | 683420      | 4493380      | Dacite (none)                        | Pennsylvania–Permian Riepe Spring Limestone | Sericite after plagioclase       | 155      | 4       |
| SMlg47   | 684690      | 4491810      | Porphyritic dacite (15)              | Mississippian Chainman Shale          | Propylitic alteration (chlorite, calcite, sericite, kaolinite) | 156      | 2       |
| SMlg49   | 685957      | 4492716      | Coarse-grained rhyolite porphyry (30) | Devonian Guilmette Formation and Pennsylvanian Ely Limestone | Quartz ± molybdenite veins, potassic alteration, minor chalcopyrite and pyrite | 39.1     | 0.6     |
| SMlg51   | 686910      | 4492715      | Rhyolite porphyry (15)               | Pennsylvanian Ely Limestone           | Potassic alteration and weak argilization; elsewhere can contain quartz veins | 37.5     | 0.4     |

*Universal Transverse Mercator North American Datum (NAD27) datum, UTM zone 11N.*
MINERAL DEPOSITS AND THE AGE OF PORPHYRY Mo MINERALIZATION

The Spruce Mountain district contains a porphyry molybdenum deposit associated with rhyolite porphyry intrusions and may also host Carlin-type gold mineralization. Our geochronologic data and mapping indicate that the porphyry molybdenum deposit formed in the late Eocene, ca. 38 Ma, whereas the age of Carlin-type mineralization in the district remains undetermined.

Skarn and carbonate replacement deposits were first discovered in the Spruce Mountain district in 1869, and there was at least small production from these ores for most years between 1869 and 1961 (Hill, 1916; Schrader, 1931; Smith, 1976; LaPointe et al., 1991). The district historically has been mined for lead and silver, with subordinate zinc, copper, and gold, from small underground mines, including the Ada H, Banner Hill, Black Forest, Keystone, Kille, Monarch, Paramount, and Standard (Fig. 3B). The principal hypogene ore minerals are argentiferous galena, tetrahedrite, sphalerite, chalcopyrite, pyrite, arsenopyrite, and minor bornite (Schrader, 1931). Scheelite occurs at the Atlantic prospect, which is a few hundred meters west of the Black Forest mine (Stager and Tingley, 1988). Supergene phases include cerussite, anglesite, malachite, and chrysocolla along with lesser amounts of wulfenite, calamine, and smithsonite. Oxidation extends to depths of 70 m or more, and most of the production was from supergene-enriched carbonate ores that contain higher silver contents than sulfide ores (LaPointe et al., 1991).

A map of alteration-mineralization products is shown in Figure 3B, which complements the companion geologic map (Fig. 3A). As shown on these maps, a belt of skarn, quartz-rich breccias, and local hornfels is discontinuously exposed at the surface along the east-west-trending band of silicic porphyry dikes, but hornfels is absent and skarn is mostly supplanted by jasperoid and carbonate replacement and fissure vein deposits in calcareous rocks at the eastern end of the band (Hope, 1972; LaPointe et al., 1991).

At the surface, the porphyry dikes are variably altered but have rare quartz-molybdenite veinlets with associated potassic alteration and locally exhibit quartz-sericite-pyrite alteration. In contrast, the skarns consist principally of garnet, pyroxene, actinolite, and fluorite (Granger et al., 1957; E. Seedorff, personal data; LaPointe et al., 1991; American CuMo Mining Corporation, 2014). Skarn is localized around the porphyry dikes. Copper and local tungsten are mostly restricted to skarn; zinc grades generally decrease toward porphyry dikes (Schrader, 1931). Lead and silver grades are highest in fissure fillings, commonly in marble or limestone (LaPointe et al., 1991). Both skarn and altered igneous rocks are enriched in tin, tungsten, and fluorine (E. Seedorff, personal data; Tingley, 1981a, 1981b).

From the 1950s through the early 1980s, the district was explored for porphyry mineralization, and at the end of this period a resource of ~80 Mt of low-grade molybdenum-copper mineralized rock (average grade not reported) was delineated in the southwestern part of the district by a joint venture of Freeport Exploration and AMAX (LaPointe et al., 1991). Complete results are not publicly available, although published cross sections showing selected results suggest that a well-mineralized area occurs near the Kille mine (American CuMo Mining Corporation, 2014) in the footwall of a steeply dipping normal fault (probably the West fault; Fig. 3B) and in the footwall of the gently dipping North Peak fault. In recent years, this part of the district has been controlled by Mosquito Gold Mines Limited, now known as American CuMo Mining Corporation; this company reports molybdenum intercepts (copper grades not reported) from 5 of the historic drill holes that are 105–366 m in length (American CuMo Mining Corporation, 2014). The average grades in each of the 5 intercepts range from 0.05% to 0.17% MoS₂ (~0.03%–0.1% Mo). A length-weighted average of these intercepts, which might be a rough estimate of the average grade of the resource, is 0.089% MoS₂ (~0.053% Mo). Molybdenum is preferentially localized in porphyry dikes, whereas copper is concentrated in adjacent skarns (American CuMo Mining Corporation, 2014) and appears to be best developed in Pennsylvanian Ely Limestone. Lead, zinc, and silver preferentially occur in carbonate replacement deposits and fissure veins in limestones and other calcareous and dolomitic rocks, especially of Pennsylvanian–early Permian age. Descriptions of underground exposures (e.g., Schrader, 1931) indicate that porphyry dikes at least locally intruded along normal faults, and a porphyry dike is mapped as intruding along the North Peak fault (Fig. 3A). Likewise, porphyry-related skarn mineralization at least locally occurs adjacent to dikes and along faults (Schrader, 1931), and brecciated quartz veins occur within the Prospect fault (Figs. 3A and 3B).

There are several textural varieties of porphyritic rhyolite and rhyolite porphyry at Spruce Mountain. A phenocryst-rich (~30 vol%) rhyolite porphyry that is dated as 39.1 ± 0.6 Ma contains quartz veins and molybdenite (though the veins and molybdenum in the dated intrusion could be related to a younger intrusion). An intrusion with 15 vol% phenocrysts dated as 37.5 ± 0.4 Ma locally contains quartz veins, and intrusions as young as 37.3 ± 0.4 Ma with 30 vol% phenocrysts underwent strong hypogene sericite alteration. Analogies with porphyry molybdenum deposits elsewhere in the world (e.g., Wallace et al., 1968; Carten et al., 1988) suggest that Spruce Mountain may have several, possibly spatially separated, mineralizing intrusions.

Although some crosscutting relationships between faults and rhyolite intrusions are known (Table 2), other relationships remain to be determined. The spatial and genetic relationship between various rhyolite porphyry dikes and porphyry-related mineralization also is only weakly constrained (see Table 2). Therefore, it is not possible to determine whether porphyry-related mineralization was genetically related to intrusions as old as 39.1 ± 0.6 Ma, or to multiple intrusions of different ages. Consequently, we regard porphyry molybdenum mineralization at Spruce Mountain as having formed in the late Eocene, ca. 38 Ma.

In the northwestern part of the Spruce Mountain district, six holes drilled by Santa Fe Mining in the mid-1980s intersected significant gold-bearing intervals, and Renaissance Gold has explored the western side of the district for Carlin-type gold mineralization in the Pilot Shale and for gold skarn mineralization (Wolverson, 2010). The U-Pb dates place no constraints on the age of Carlin-type gold occurrences that are reported in the district.
TABLE 2. FAULTS AND FAULT SETS AT SPRUCE MOUNTAIN

| Fault set | Examples of named faults | Strike direction | Present-day dip of faults | Expected direction of concurrent tilting of fault blocks | Exposed crosscutting relationships with faults of older sets | Relationship to Cenozoic stratigraphic and intrusive units | Notes |
|-----------|--------------------------|------------------|--------------------------|----------------------------------------------------------|----------------------------------------------------------|----------------------------------------------------------|-------|
| 6 (youngest) | West fault | Northwest to northeast | Northwest and southwest, steep to moderate | Eastward | Faults cut and offset faults of sets 4 and 1; no spatial overlap with faults of set 5 | Some faults locally mantled by Quaternary alluvium, but faults on western range front active in Quaternary | Restricted to western part of area |
| 5 | Unnamed faults only | Northeast | Southeast, steep | Westward | Faults cut and offset faults of sets 4 and 2; no spatial overlap with faults of set 6 | Faults mantled by Quaternary alluvium | Restricted to southeastern-most part of area |
| 4 | Banner Hill, East, Mine Shaft faults | North | East, moderate to steep | Westward | Faults cut and offset faults of sets 3, 2, and 1 | Intruded by late Eocene (ca. 38 Ma) rhyolite porphyry dikes; Miocene sedimentary rocks mantle faults of set 4 and seem to have fanning upward dips from ~30° to 10° E | |
| 3 | Unnamed faults only | East-west | North, steep | Southward | Faults seemingly cut and offset faults of set 2 | Tertiary tuff mantles faults of set 2; dips ~35° SE | |
| 2 | Saddle, Coyote, and Prospect faults | South to southwest | West to northwest, moderate to steep | Eastward | Faults seemingly cut and offset faults of set 1 | N.A. (oldest set) | |
| 1 (oldest) | North Peak, South Peak, Spruce Spring faults | Variable; North Peak fault strikes northeast | Variable and shallow; North Peak fault dips 13°–17° northwestern | Variable; eastward for North Peak fault | Variable; eastward for North Peak fault | Intruded by late Eocene (ca. 38 Ma) rhyolite porphyry | Spruce Spring fault cuts and offsets South Peak fault |

Note: N.A.–not applicable.

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**PLAN-VIEW ANALYSIS OF FAULTING AT SPRUCE MOUNTAIN**

As part of a larger study (Pape, 2010), a map-based, plan-view analysis of extensional faulting at Spruce Mountain was done to help constrain the relative timing relationships among crosscutting normal faults and to determine the present-day geometries of low-angle faults in the district (Figs. 3 and 4). The surface geologic map of the Spruce Mountain quadrangle of Hope (1972) is the primary resource for this analysis, and additional data are incorporated from other sources, including our new field mapping and checks of key geologic relationships. The names of faults follow those of previous workers where possible; certain previously unnamed faults have been given names here for ease of reference.

**Crosscutting Fault Relationships**

Numerous crosscutting high- and low-angle normal faults have accommodated extensional strain at Spruce Mountain. These crosscutting faults are grouped into six sets of similar relative age and orientation, and are numbered 1 through 6, from oldest to youngest (Table 2; Fig. 3). In some cases, particularly in the southeastern part of the study area where numerous faults intersect, the crosscutting relationships among faults are uncertain. In these cases, faults have been assigned to a fault set, but the fault traces in Figure 3 are dashed and queried to reflect this uncertainty.

Faults from the two relatively youngest sets, fault sets 5 and 6 (Table 2), do not intersect each other within the study area, and thus their relative ages cannot be firmly established. Faults of set 6, which crop out on the western side of the study area, include the present-day range-bounding faults and the relatively large offset West fault. Faults in this set have northwest to northeast strikes and dip at high to moderate angles to the northwest and southwest. Northeast-striking, southeast-dipping, high-angle normal faults of small offset in the southeasternmost part of the study area are assigned to set 5. Faults of both of these sets cut faults grouped into the next oldest set, set 4 (Table 2). Fault set 4 consists of a group of generally north-striking, east-dipping, moderate- to high-angle normal faults that crop out throughout the study area. Fault set 2 consists of generally south- to southwest-striking, west- to northwest-dipping, high- to moderate-angle normal faults that crop out throughout the study area. Certain west-dipping faults grouped within fault set 2 may, in detail, cut each other. This is especially true in the southeastern part of the study area, where numerous faults intersect and crosscutting relationships are difficult to determine. Despite this complexity, these faults have similar orientations and display similar crosscutting relationships relative to faults from other fault sets; therefore, for simplicity, they have been grouped into fault set 2.

The oldest fault set includes all low-angle normal faults that are present within the study area. Where they crop out, these low-angle faults are always cut by high- to moderate-angle faults. However, like faults assigned to fault set...
2, individual low-angle faults within fault set 1 in some cases cut and offset other faults grouped in the same set. Collectively, these low-angle faults are the oldest extensional structures that crop out at Spruce Mountain (Table 2) and have, therefore, been included within the same fault set.

Although not strictly included as part of the structural analysis presented here, a final set of small-offset, high-angle faults crops out in the northeastern-most portion of Figure 3. These faults appear to have relatively planar geometries where they crop out at the surface (Fig. 4). Dips of faults calculated from these structure contour maps show that the Spruce Spring fault dips 15°–18° to the southwest, the South Peak fault dips south ~20°, and the North Peak fault dips northwest at 13°–17°. A subsidiary low-angle fault was originally mapped by Hope (1972) structurally above the North Peak fault on the North Peak of Spruce Mountain that juxtaposed the Ely Limestone with the Diamond Peak Formation and/or Chainman Shale (undivided). Field observations documented in Pape (2010), however, provide no evidence for this subsidiary fault. Instead, the contact between the Diamond Peak Formation and overlying Ely Limestone is interpreted to be a depositional contact.

The direction of slip on these low-angle faults has not been directly determined. Strata in the upper and lower plates of these faults dip fairly uniformly eastward, and stratigraphic section is always missing between the hanging walls and footwalls of the faults, which place younger strata on older strata. A westward, normal-sense, hanging-wall transport direction can explain these observations without requiring exceptionally large amounts of slip on these faults (Hope, 1972).

Mapped relationships among these faults (Fig. 3) indicate that the Spruce Spring fault is structurally above and truncates the South Peak fault (Hope, 1972). The relationship between the North Peak fault and the Spruce Spring and South Peak faults is less certain. The North Peak fault may be truncated by the northward projections of the Spruce Spring and South Peak faults (Hope, 1972); alternatively, the South Peak fault and North Peak fault may be the along-strike continuation of the same fault.

GEOLoGIC CROSS SECTION

Stratigraphic and Structural Constraints

As part of our structural analysis of the Spruce Mountain district, we constructed a northwest-southeast-trending cross section through the Spruce Mountain area showing our interpretation of the subsurface distribution of faults and stratigraphic units (Fig. 5A) as well as an overlay schematically showing zones of alteration (Fig. 5B). Thicknesses of units are based primarily on to the axis of the syncline during Mesozoic folding. Given the probable compressional origin of these faults and the fact that they are not intersected by the restored cross section, they are not analyzed further here.
measurements reported by Hope (1972). Faults belonging to sets 6, 4, 2, and 1 project into the cross section (Fig. 5). Publicly available exploration drilling data in the Spruce Mountain district are sparsely distributed and limited to relatively shallow depths (typically <0.5 km). Therefore, it not possible to meaningfully show the distribution of igneous rocks on the cross section of Figure 5A.

Within the Spruce Mountain district, attitudes of bedding typically do not change substantially between the footwall and hanging-wall blocks across faults, suggesting that these faults are planar or curvilinear in the subsurface. There are few direct measurements of fault dips in the Spruce Mountain area because of poor exposure of fault surfaces in the district. Hope (1972) reported that the East fault and West fault dip ~45° to the east and west, respectively, near where these faults intersect the cross section (Fig. 5). In addition, the North Peak fault projects into the cross section with an apparent northwest dip of ~5° (Fig. 5). Otherwise, dips on faults are based on relationships between topography and the surface traces of faults.

It is uncertain how the Spruce Spring and South Peak faults may project into the cross section (Figs. 3 and 4). Hope (1972) interpreted both of these faults as steepening northward and truncating the North Peak fault south of the cross section. Alternatively, the South Peak fault could represent the along-strike continuation of the North Peak fault if the projection of this fault is bowed over the peak of Spruce Mountain. It is also possible that the Spruce Spring fault may project into the cross section at high structural and stratigraphic levels. However, given the uncertainties in its three-dimensional geometry, the Spruce Spring fault was not projected into the section of Figure 5.
Present-Day Distribution of Structures

The cross section shown in Figure 5 represents the interpretation of the present-day structure of the Spruce Mountain area that best fits available data. A critical aspect of the subsurface structure is the geometry of the low-angle North Peak fault, which is cut and downdropped on either side of the peak of Spruce Mountain by the East and West faults (Fig. 5). In Figure 5, the North Peak fault is inferred to maintain a shallow west-dipping orientation in the subsurface and to root westward in the apparent hanging-wall transport direction. The eastern continuation of the North Peak fault is interpreted to project above the present-day land surface in the eastern part of the cross section, where it is cut by the small-offset Coyote fault, and to project above the southern Pequop Range east of Spruce Mountain (Figs. 3 and 5).

This interpretation differs substantially from the previous structural interpretation along the same line of section by Hope (1972), who depicted the North Peak fault as abruptly changing orientations from a subhorizontal dip on the peak of Spruce Mountain to dipping ~40° E in the eastern portion of the cross section after being downdropped by the East fault. Hope’s (1972) structural interpretation results in the North Peak fault projecting beneath the southern Pequop Range, where no surface exposures of major extensional faults are present (Fraser et al., 1986; Swenson, 1991), and, therefore, requires the entire southern Pequop Range to be underlain by the North Peak fault.

STRUCTURAL RECONSTRUCTION

Methodology

A stepwise cross-sectional restoration of extensional faulting illustrates the Cenozoic structural evolution of the Spruce Mountain area (Fig. 6). The primary geologic markers employed for restoring fault offsets are Ordovician through Permian sedimentary rocks that are assumed to maintain relatively...
Figure 6. Stepwise structural reconstruction of the central Spruce Mountain area, based on cross section of Figure 5. (A) Present-day structure and pin lines along cross section, with faults and key stratigraphic horizons projected above the topographic profile. Horizons projected above present-day topography are shown with 50% transparency. (B–E) Sequential restoration of crosscutting normal faults of sets 6, 4, 2, and 1 (faults of sets 3 and 5 not present in cross section). The dashed gray horizontal line shown in each restoration panel represents the minimum relative paleosurface elevation allowable at each restoration step (ignoring local topography). The magnitude of fault block rotation applied to each panel relative to immediately preceding panel is as follows: (B) 22°WNW (C) 33°ESE (D) 20°WNW (E) 27°WNW.
constant gross thicknesses within the study area. No attempt was made in the reconstructed cross section to differentiate stratigraphic units older than the Pogonip Group, which is the oldest marker employed in the reconstruction, and igneous units are omitted for reasons cited herein.

Roughly simultaneous movement on subparallel faults is expected from geometrical considerations (e.g., Davison, 1989), and certain active fault systems in the Basin and Range province behave in that manner. For example, major steeply east dipping faults at Rainbow Mountain, Dixie Valley, and Fairview Peak, western Nevada, exhibited coordinated movement during a series of earthquakes in 1954 that accommodated westward tilting of the intervening basins and ranges. In addition, concurrent movement was observed on the west-dipping, antithetic Westgate and Gold King faults immediately east of that fault system (e.g., Slennon and Bell, 1987; Hodgkinson et al., 1996; Caskey et al., 1996). Detailed studies of areas with multiple sets of Cenozoic domino-style faults are also consistent with coordinated movement on major subparallel normal faults and synthetic splays (e.g., Proffett, 1977; Gans and Miller, 1983).

For Spruce Mountain, we utilize a stepwise approach to restoration, restoring movement on all faults of a given set concurrently, beginning with the youngest set (set 6), then working backward in time, set by set (Fig. 6). The movement on any given fault is assumed to become locked when the stress required to produce continued slip along them is greater than required to initiate a new set of high-angle faults. Once a fault is cut and offset by a fault of a younger set, the older fault also is buttressed against any renewed movement. Given the nature of the geologic complexity coupled with limited three-dimensional exposure at Spruce Mountain, however, it is not possible to preclude the possibility that some faults with opposing dips that are members of adjacent fault sets might have been active concurrently. The offsets on faults in the cross section (Fig. 5A), which belong to sets 6, 4, 2, and 1, are restored in a stepwise fashion from youngest to oldest (Fig. 6). The cross section is restored as a series of rigid fault blocks, ignoring internal deformation (e.g., folding) within individual fault blocks. These assumptions can lead to space problems where fault blocks are differentially tilted. However, these space problems are small relative to the uncertainties of subsurface fault dips and are assumed to be accommodated by slight curvature of faults and/or internal deformation within major fault blocks.

Evidence for Tilting

Several lines of evidence suggest that extensional faulting was accompanied by fault block tilting, ultimately resulting in a net eastward tilting of fault blocks in the Spruce Mountain area. (1) Outcrops of (Miocene?) sedimentary rocks within the southern portion of the study area display generally eastward dips between 15° and 30°. (2) The trace of the basal contact of the undated (likely either Eocene or Miocene) Cenozoic dacite tuff relative to topography (Fig. 3) suggests that this tuff dips gently to moderately eastward in the central Spruce Mountain district. Moreover, although no strike and dip measurements directly constrain the bedding orientation of this tuff in the immediate study area, a single dip measurement of 35°SE was obtained on a small outcrop of the tuff ~3 km beyond the northern edge of the area in Figure 3 (Hope, 1972), and is consistent with the observation that the tuff unit as a whole appears to have been tilted eastward. (3) Paleozoic strata within the Spruce Mountain area dominantly dip eastward, which is consistent with eastward extensional tilting if these strata were horizontal or gently dipping prior to Cenozoic extension. This is a reasonable assumption if the preextensional structure in the Spruce Mountain area was characterized by broad open folding of a style similar to the adjacent Pequop syncline immediately to the east. (4) East-dipping Paleozoic strata in the footwalls and hanging walls of the normal faults that currently dip at low angles generally display moderate to high (>40°) cutoff angles with these faults where they are exposed at the surface, suggesting that these faults initiated at high to moderate angles. (5) The inferred westward hanging-wall transport directions of the currently low-angle faults is consistent with eastward fault block tilting if these faults initiated as higher angle, west-dipping normal faults.

Given this evidence, rotation consistent with the sense of slip of each restored fault set is applied to the stepwise cross-sectional restoration (Fig. 6). Although the magnitude of tilting associated with each fault set is uncertain, there are some loose constraints on the overall history of tilting (Table 2). The undated southeastward-dipping Cenozoic tuff mantles faults of sets 1 and 2, implying that most or all of the southeast-directed tilting of this unit occurred from movement on faults of younger sets. In addition, the sedimentary rocks in the southeastern part of the map area, probably belonging to the middle Miocene Humboldt Formation, lap across faults of set 4 and appear to have fanning-upward dips from 30° to 15°E (Table 2). This suggests that fault blocks in the southern part of the district have undergone a net eastward tilting of as much as 30° since the mid-Miocene. Given the relative age constraints, and considering that both the Cenozoic dacite tuff and sedimentary rocks display similar eastward dips in the central Spruce Mountain district, it is likely that most of the eastward tilting of these rocks occurred in association with slip on west-dipping faults grouped with fault set 6 (Figs. 3 and 6). Because cutoff-angle relationships suggest that the currently low-angle faults in the Spruce Mountain area most likely initiated at high to moderate angles, the final reconstructed panel (Fig. 6E) is shown tilted 36° west relative to the present-day cross section. This restores the North Peak fault, which currently dips northeast at 13°−17° (Fig. 4), to an initial northwestward dip of −45°−50° (Fig. 6E). Although the Spruce Mountain area contains faults of varying polarity over time (Table 2), the net eastward tilting of ~35° suggests that movement on faults of the three sets of down-to-the-west faults, of the first, second, and sixth generations of normal faults, dominated the overall tilting history.

Further constraint on the approximate history of fault block tilting associated with each fault set comes from the probable amount of differential burial and/or exhumation of the Paleozoic marker strata at each time step in the
Restored Preextensional Structure of the Spruce Mountain Area

The magnitude of extension restored in the cross section, which is the difference in final and initial distances between reference lines of 12.6 and 5.7 km, respectively, is ~6.9 km, which is equivalent to 120% extension (Fig. 6). Although the total amount of extension across the section is large, it was distributed among numerous faults. The largest amount of slip on any one fault in the restored section, the Banner Hill fault, is 1.9 km; however, the North Peak fault, West fault, Mine Shaft fault, and Saddle fault all have offsets >1 km. Some low-angle faults mapped in the area, such as the Spruce Spring fault, were not projected into the reconstructed cross section; if, alternatively, they are present in the section, then this would increase the estimate of extension across the Spruce Mountain area, such that the estimates of the amount of extension based on Figure 6 may be closer to a minimum value.

Note that reconstruction of Figure 6 implies that some beds rotated through horizontal as a result of tilting associated with multiple generations of normal faults; for example, Paleozoic rocks on the eastern side of the map area that currently dip 20°–30°SE (Figs. 3 and 6A) would have dipped ~10°–15° northwest prior to faulting (Fig. 6E). As a result, the attitudes of these Paleozoic rocks in the restored section imply west-vergent folding and gentle westward dips (~15°). The overall westward dip of beds in the restored section is interpreted to reflect that the Spruce Mountain district was involved in large-scale, open folding of a character similar to the Pequop syncline immediately east of Spruce Mountain. Spruce Mountain may have been on the western limb of an anticline that connected to the Pequop syncline prior to being dismembered by extensional faulting and may have connected to another upright syncline further west. The kilometer-scale, west-vergent anticline shown in the restored cross section (Fig. 6E) is consistent with the scale and character of west-vergent folding and thrust faulting that occurred in the southern Pequop Mountains during development of the Pequop syncline (Swenson, 1991) and with the notion that the Spruce Mountain area was similarly deformed during the same contractional deformational event.

Regional studies of Mesozoic deformation and metamorphism in the Pequop Mountains–Wood Hills–East Humboldt Range region to the north of the Spruce Mountain area and in the Ruby Mountains to the west have demonstrated that significant crustal thickening must have occurred in northeastern Nevada during the Mesozoic (e.g., Thorman, 1970; Snoke and Miller, 1988; Camilleri and Chamberlain, 1997). Metamorphic mineral assemblages and sheared fabrics locally present in impure limestones of the Pogonip Group on the southern side of Spruce Mountain have been interpreted to indicate that these rocks reached lower greenschist facies metamorphic conditions during the Mesozoic and that significant structural thickening occurred in the Spruce Mountain area during the Mesozoic (Camilleri and Chamberlain, 1997). However, no thrust faults have been mapped locally in the Spruce Mountain district, and the reconstructed cross section (Fig. 6) suggests that significant structural duplication of stratigraphic section between Ordovician and lower Pennsylvanian rocks, that is, the reconstructed section (Fig. 6E) is consistent with the scale and character of west-vergent folding and thrust faulting that occurred in the southern Pequop Mountains during development of the Pequop syncline. Thus, any significant structural thickening and overthrusting at Spruce Mountain during the Mesozoic was likely limited either to deeper or, possibly, shallower structural and stratigraphic levels than are currently exposed at the surface.

Constraints on Age of Extensional Faulting at Spruce Mountain

Several observations constrain the timing of faulting at Spruce Mountain. First, all normal faults in the Spruce Mountain district deform Paleozoic rocks and dismember older Mesozoic contractional structures and, given regional considerations regarding the onset of extension in the Great Basin (e.g., Wernicke et al., 1987; Seedorff, 1991a; Dickinson, 2006), are most likely all Cenozoic structures, although ages as old as Late Cretaceous are possible. Eocene rhythmic phyllite dikes (ca. 38 Ma; Table 1) crop out throughout the central portion of the Spruce Mountain district (Fig. 3). These dikes cut or intrude the North Peak fault (a member of fault set 1) and locally intrude the Mine Shaft fault (a member of fault set 4) (Fig. 3; D. Pace, 2013, personal commun.). Thus, both of these faults, and by analogy other faults of these sets, were active during or prior to the late Eocene. Sedimentary rocks that crop out in the southern part of the study area, which probably correlate with the middle Miocene Humboldt Formation (Harlow, 1956; Coats, 1987), dip eastward and appear to dis-
play fanning-eastward dips, indicating that at least some extensional faulting within the Spruce Mountain district occurred during the middle to late Miocene. Based on relative age constraints, some of the faults that are grouped in sets 5 and 6 were probably active in the middle to late Miocene. The ages of faults that were active during the Quaternary have been determined mostly on the basis of photogeologic evidence (e.g., Dohrenwend et al., 1991, 1996). As shown by dePolo (2008), several normal faults mapped on the eastern sides of Spruce Mountain Ridge and Spruce Mountain ruptured in the Quaternary (i.e., in the past 1.8 m.y.), and the latest slip on normal faults mapped along the western sides of Spruce Mountain Ridge and Spruce Mountain probably is even more recent (latest Quaternary, i.e., <130 k.y.). Notably, several faults grouped in fault set 6 appear to have been active during the Quaternary, including the relatively large offset West fault. Given the current absolute and relative age constraints at Spruce Mountain, it is not possible to determine rigorously which faults grouped in sets 5 and 6 initiated during the probable middle to late Miocene extensional event and which faults initiated later. It is possible (and even likely) that some faults included in these relatively youngest fault sets initiated during the middle to late Miocene and subsequently were active more recently, whereas other faults also grouped in these sets may have initiated much later.

Restoration of Magmatic-Hydrothermal Features at Spruce Mountain

The reconstruction in Figure 6 and crosscutting relationships can be utilized to infer the original geometry of mineralized zones at Spruce Mountain. Because porphyry dikes intrude faults of sets 1 and 4, and quartz veins appear to have formed along the Prospect fault of set 2, it appears that at least some, if not all, of the hydrothermal alteration features formed after movement on faults of sets 1, 2, and 3, and perhaps during movement on faults of set 4. Thus, the hydrothermal system might have been subjected to extension and associated tilting related to movement on faults of sets 5 and 6 and possibly some portion of the movement on faults of set 4. Consequently, the alteration zones were probably formed after the time represented in the restoration by Figure 6C, but before that in Figure 6B. Figure 7 shows the restored distribution of interpreted hydrothermal features (Figs. 3B and 5B) prior to movement on faults of sets 4 through 6.

Given the large geologic uncertainties, the distribution of features is plausibly consistent with a relatively upright hydrothermal system that developed as faults of set 4 began to move. Based on this reconstruction, the original two-dimensional geometry of mineralized zones was ~6 km long by ~3 km deep elliptical pattern with carbonate replacement deposits surrounding skarn. In addition, given our assumptions regarding the timing of mineralization relative to extensional faulting, the stepwise reconstruction of Figure 6 indicates that the hydrothermal system underwent ~10° of westward net tilting and ~2.7 km of extension associated with postmineralization deformation by fault sets 4 through 6.

DISCUSSION

Comparison and Classification of Mineral Deposits at Spruce Mountain

The presence of rhyolite and granite porphyry dikes, quartz-molybdenite veins, and the geochemical enrichment in Sn-W-F suggest that the mineral deposits at Spruce Mountain, except for the Carlin-type prospect, are various manifestations of a porphyry molybdenum deposit. The limited subsurface information available suggests that the proximal part of the system contains quartz-molybdenite veins and is relatively copper free, in contrast to porphyry molybdenum deposits of the quartz monzonitic-granitic porphyry Mo-Cu sub-class such as the Hall (Nevada Moly) and Buckingham deposits in Nevada (Seedorff et al., 2005). The best copper grades at Spruce Mountain seem to be somewhat more distal, located in skarns that are developed fairly close to contacts with rhyolite and granite porphyry.

The best analogues for Spruce Mountain are the Mount Hope deposit in Eureka County 145 km to the southwest (Westra and Riedell, 1996) and several molybdenum prospects in White Pine County to the south (Seedorff, 1991a). Spruce Mountain and Mount Hope are assigned to the rhyolitic porphyry Mo category (of Seedorff et al., 2005), which includes end-member deposits such as Climax and Henderson (Colorado), but also deposits that have less evolved igneous compositions (e.g., lower SiO2, Rb, and Nb and higher Sr and Zr contents) and metals with higher overall Cu:Mo ratios, such as Mount Hope. The latter deposits were referred to as transitional deposits by Westra and Keith (1981, Table 2 therein) and Carter et al. (1993, Table II therein). In the classification of Ludington and Plumlee (2009), the Spruce Mountain deposit would be regarded as a Climax-type deposit.

Spruce Mountain may be the best example of a rhyolitic porphyry Mo or Climax-type porphyry molybdenum deposit with extensively developed skarn. The overall copper content of Spruce Mountain and certain prospects in White Pine County such as the Ellison district (Johnson, 1983) may be somewhat higher than other rhyolitic porphyry molybdenum deposits where carbonate rocks are largely to entirely absent, such as Climax, Henderson, Mount Hope, and Pine Grove (Utah). Carbonate wall rocks probably promoted efficient precipitation of copper in skarn at Spruce Mountain and the occurrences in White Pine County compared to other rhyolitic porphyry Mo deposits.

Significance of Ages of Igneous Rocks and Ore Deposits at Spruce Mountain

With some notable exceptions, including a large body of work in the Ruby Mountains–East Humboldt metamorphic core complex (e.g., Hodges et al., 1992; Wright and Snoke, 1993; Brooks et al., 1995; Henry, 2008; Bedell et al., 2010), there are few radiometric ages in this part of northeastern Nevada, where exposures of igneous rocks generally are sparse. U-Pb ages reported here for igneous rocks at Spruce Mountain are Late Jurassic and late Eocene.
The Jurassic rocks at Spruce Mountain occur as small dikes that are dated as 155–156 Ma. Large Jurassic intrusions occur in the Dolly Varden Mountains, Delcer Buttes, Ruby Mountains, and Snake Range (Miller et al., 1988; Miller and Hoisch, 1995; Barton et al., 2011), and small dikes of Jurassic age are widespread but sparsely present in other parts of northeastern Nevada, such as in the Pequop Mountains (Bedell et al., 2010; Camilleri, 2010; Wyld and Wright, 2015). At some localities such as Spruce Mountain, the Jurassic rocks are barren, whereas they are at least variably mineralized at the present levels of exposure at other sites, such as the Delcer district (LaPointe et al., 1991) and the Victoria skarn breccia pipe in the Dolly Varden district (Atkinson et al., 1982; Zamudio and Atkinson, 1995).

Dated rhyolite porphyries at Spruce Mountain range in age from ca. 39 to ca. 37 Ma (Table 1) and have ages similar to those of granite and rhyolite porphyry bodies in nearby parts of eastern Nevada (Stewart and Carlson, 1976;

Figure 7. Interpretive preliminary reconstructed cross section of selected alteration-mineralization features at Spruce Mountain, showing how present-day distribution of features from Figure 5B might be distributed prior to movement of faults of set 4 in geologic reconstruction of Figure 6.
For example, we restore ~35° of net eastward tilting between the present day variables, the net tilting magnitude uncertainty is the most easily quantified impact on extension estimates at each step of the restoration. Of these two extension estimates at each step of the cross-section restoration.

This simplifying assumption of pure dip-slip motion along the line of the restored cross section effectively increases the number of potentially valid retrodeformable cross sections. Thus, in structurally complex areas like Spruce Mountain, this exercise becomes more challenging. In part this is because, in a complexly faulted area like Spruce Mountain, the crosscutting fault relationships themselves provide considerable constraint on the range of structurally viable fault dips and geometries in the subsurface, and individual fault geometries frequently cannot be varied independently and still result in viable retrodeformable cross sections. Therefore, in structurally complex areas like Spruce Mountain, accurate quantification of the impact of fault dip uncertainty on extension estimates would necessitate the construction of multiple alternative cross-section reconstructions.

The polyphase deformational history of northeastern Nevada further complicates the structural restoration of the Spruce Mountain district (Figs. 6 and 7). Specifically, the primary structural markers used for restoring fault offsets are Paleozoic passive margin strata, but these strata had an earlier history of contractional deformation during the Mesozoic and possibly in the Paleozoic (Snyder et al., 1991; Carpenter et al., 1993; Camilleri and Chamberlain, 1997; Howard, 2003; Trexler et al., 2003, 2004; Dickinson, 2006; Long, 2012, 2015; Rhys et al., 2015). At Spruce Mountain, Cenozoic extension has dissected and obscured the earlier contractional structures. Hence, there are uncertainties in both the nature of the extensional deformation, as well as the configuration of the preextensional structure. Consequently, an iterative approach is used in this study to produce a viable cross-sectional restoration, wherein the preextensional model is progressively modified to produce a restored extensional structural geometry that satisfies all of the available geologic constraints. This process results in a degree of internal circularity within the retrodeformable cross section because the extensional structure and the preextensional structural model are not mutually independent, i.e., uncertainties regarding the structure of both the extended and restored states of the cross sections effectively increase the number of potentially valid retrodeformable cross-sectional models.

Additional uncertainties are also introduced when attempting to reconstruct mineralized systems. Reconstruction of the geometry of magmatic-hydrothermal systems requires constraints on the ages of various generations of faults relative to the ages of intrusion and associated alteration mineralization, but the geometric constraints applicable to preextensional hydrothermal
systems, such as Yerington (Proffett, 1977; Richardson and Seedorff, 2015) or Teacup (Nickerson et al., 2010), are more straightforward than for synextensional hydrothermal systems such as Spruce Mountain. The observation that a given intrusive rock intrudes a fault requires that the intrusion postdate at least the initial movement on the fault; if the intrusion (e.g., a dike) is sheared or brecciated along the fault, then the same fault may have continued moving after the dike intruded the fault zone. Thus, the amount of postplacement deformation of the dike associated with movement on the fault may range from 0% to nearly 100% of the total deformation associated with movement on a given fault, and this may introduce considerable uncertainty regarding the amount of postplacement extension. Analogous reasoning applies to the relative ages and amounts of postmineral extension of hydrothermal systems that may be related to intrusions.

Despite these uncertainties, every step in a viable reconstruction must satisfy certain firm constraints: they cannot imply erosion of units that are still present in the bedrock today, nor can bedrock units exposed at the surface today be buried to depths during any stage in the structural evolution that are inconsistent with their present-day textures and thermochronologic characteristics. Moreover, the restoration must result in reasonable fault geometries and imply plausible fault kinematics. The reconstruction presented here meets these tests, although there are uncertainties in the assignments of the amount of extension to any generation of faults. The most robust reconstructions are possible from locales where there are abundant, widely distributed, pre-ore, syn-ore, and post-ore strata and intrusions that create compelling crosscutting relationships and that contain radiometrically datable units.

**Distribution, Polarity, Amount, and Style of Large-Magnitude Extension**

Cenozoic upper crustal extensional strain was generally directed east-west to northwest-southeast within northeastern Nevada and is distributed heterogeneously, with areas of high extensional strain separated by relatively low strain areas (Seedorff, 1991a; Colgan and Henry, 2009). This heterogeneous distribution of upper crustal extensional strain is a characteristic feature of extension in the Great Basin (e.g., Gans and Miller, 1983). Combined with a relatively uniform crustal thickness of 30–35 km across the eastern Great Basin (e.g., Allmendinger et al., 1987), this heterogeneity requires large-scale middle to lower crustal flow of rocks from domains that have undergone little upper crustal extension into regions of large upper crustal extension (e.g., Gans, 1987; Smith et al., 1991; MacCready et al., 1997).

Consistent with these regional observations, normal faulting and large extensional strain was directed east-west to northwest-southeast at Spruce Mountain and is more intense at Spruce Mountain than in the nearby southwestern Pequop Range, which is an essentially unextended structural block that preserves Mesozoic compressional structures (Swenson, 1991; Camilleri and Chamberlain, 1997). Our reconstruction of Spruce Mountain indicates that the 5.7 km distance between reference lines in the restored cross section (Fig. 6E) was extended by 6.9 km, resulting in a present-day length of ~12.6 km (Fig. 6A). This is equivalent to 120% extension between the fully restored and extensionally deformed states. Spruce Mountain, however, differs somewhat from other nearby highly extended areas in northeastern Nevada in that the large extensional strain in the central Spruce Mountain district is distributed among numerous, closely spaced, small to moderate offset (<2 km) faults in multiple, superimposed sets of faults. By contrast, extension in nearby southern Ruby Mountains appears to have been accommodated primarily by large offset (13–22 km) on a single west-dipping fault that produced eastward tilting (Colgan et al., 2010). Although Colgan et al. (2010) did not specify the amount of extension in the southern Ruby Mountains and vicinity, our choice of reference lines in their reconstruction (Colgan et al., 2010, fig. 11 therein) implies only ~45% extension, albeit over a present-day width of ~19.3 km. The relative amount of extension at Spruce Mountain is roughly three times that of the southern Ruby Mountains, although the absolute amount of extension at Spruce Mountain (~6.9 km) is somewhat smaller than that in southern Ruby Mountains (~8.6 km).

Notably, there is at least one fault within the southern part of the Spruce Mountain district, the Spruce Spring fault, which appears to have much larger offset than any other mapped faults in the district. This currently low-angle fault (which is grouped as part of fault set 1) places Permian on Ordovician rocks in the southern part of the Spruce Mountain district (Fig. 3). Assuming a previously unbroken stratigraphic thickness of ~4.5 km for the Ordovician to Permian sequence (Fig. 2), a ~50° initial westward dip for the Spruce Spring fault, and a gentle westward preextensional dip of 15° of the Paleozoic rocks at Spruce Mountain (Fig. 6), a minimum ~8 km of offset would be required on the Spruce Spring fault to place Permian on Ordovician strata. However, the Spruce Spring fault cuts off the South Peak fault, so the stratigraphic section was not unbroken; therefore, the 8 km estimate may considerably overestimate the amount of slip on the Spruce Spring fault.

The more distributed overall style of brittle extension at Spruce Mountain nonetheless contrasts with the style of extension observed in the southern Ruby Mountains. Precisely why extensional strains are in some cases distributed among numerous, closely spaced faults and elsewhere concentrated on a few large-offset faults is not well understood. Pervasive and distributed extensional faulting of bidirectional polarity can occur in transfer zones between major normal fault systems (e.g., Faulds and Varga, 1998). Geophysical models also suggest that the style of extension may be strongly affected by the thermal structure of the lithosphere and that normal faults that undergo large amounts of hydrothermal cooling during extension may have a tendency to accumulate greater amounts of offset (Lavier and Buck, 2002).

**Initial Dips of Normal Faults**

The angle of initiation of normal faults in continental extensional tectonics is a persistent controversy (e.g., Proffett, 1977; Wernicke, 1981; Gans et al., 1985; Roberts and Yielding, 1994; Wong and Gans, 2008), and structural reconstruction is an important method for constraining initial dips of faults. The
research of Spruce Mountain presented here as well as a published re-
construction of the southern Ruby Mountains (Colgan et al., 2010) indicate that 
the near-surface dips of major normal faults in this region generally initiated at 
moderate to high angles (i.e., >45° and commonly ~60°). These faults rotated to 
lower angles as they moved and, in many cases, subsequently were passively 
rotated to still lower angles (or higher angles) by movement and associated 
tilting by crosscutting younger faults. Although uncertainties remain in these 
reconstructions, the evidence nonetheless suggests that the normal faults in 
this region, including all of the faults in the Spruce Mountain area, initiated 
with moderate to steep dips at least through the seismogenic upper crust.

Structural Complexity and Changing Polarity of Faulting

Many extended regions contain more than one generation of normal faults, 
each of which constituted a normal fault system that was active for a finite 
period of time. For example, the Yerington district, western Nevada (Proffett, 
1977), the Royston district, west-central Nevada (Seedorff, 1991b), and the 
Hunter district, east-central Nevada (Gans, 1982) all are characterized by sev-
eral generations of faults with northward strikes and down-to-the-east off-
sets. As maps and cross sections of the Yerington district reveal, the resulting 
geology is complex (Proffett and Dilles, 1984; Richardson and Seedorff, 2015). 
The structure of such extended regions is nonetheless structurally relatively 
simple, in the sense that most of the faults with significant displacement have 
similar strikes and senses of displacement.

The geology of the Spruce Mountain area is also complex (Figs. 3 and 5), 
but in contrast to many areas within the Basin and Range province such as 
Yerington, the polarity of faulting changed over time: three sets of down-to-
the-west faults that produced large amounts of tilting, two sets of down-to-the-
east faults that produced small amounts of westward tilting, and one set of 
down-to-the-north faults with small amounts of southward tilting (Table 2). 
Periods of incremental eastward tilting were interspersed with periods of in-
cremental westward tilting, but time-integration of crustal extension resulted 
in ~35 ° of net eastward tilting of the district (Fig. 6).

Areas with superimposed sets of faults with variable strike directions or 
differing senses of displacement produce less net tilting of strata for compara-
ble amounts of extension (Axen, 1986). Few reconstructions (e.g., Shaver 
and McWilliams, 1987) have been previously attempted in regions that have faults 
of opposing polarities, such as Spruce Mountain, where the structural geomet-
ries are especially challenging to reconstruct.

Timing of Upper Crustal Extension

Extension across the Basin and Range province is time transgressive (e.g., 
Wernicke et al., 1987; Seedorff, 1991a; Dickinson, 2002). Within the Great Basin, 
extension initiated at least as early as the Eocene in the north-central Great 
Basin, and the most intense extensional deformation in the past 5–10 m.y. 
may have been in the southwestern Great Basin in the Death Valley–Beatty 
region. Sound field, geochronologic, and thermochronologic evidence has 
shown that there was an important middle Miocene extensional event at many 
sites around the Basin and Range (e.g., Miller et al., 1999; Stockli et al., 2002; 
Surpless et al., 2002; Colgan and Henry, 2009). However, not only has there 
been a spatial migration in the initiation of extension in a given area, but some 
areas are extended again following a hiatus in normal faulting (e.g., Seedorff, 
1991a; Seedorff and Richardson, 2014). Even in places such as the greater 
Yerington district where most of the extension is mid-Miocene or younger, 
extension was partitioned temporally between three intervals: a period of ex-
treme extension ca. 15–13 Ma and two less significant periods ca. 11–8 Ma and 
ca. 4 Ma to present (Dilles and Gans, 1995; Stockli et al., 2002; Surpless, 2012). 
At other locales, such as the Robinson district in east-central Nevada, many 
fault generations may have been active within only a few million years or less, 
without a significant hiatus (Gans et al., 2001).

Given the available age constraints, at least three periods of extension 
within the Spruce Mountain district can be recognized: an important phase of 
extension during or before the late Eocene, another period that likely occurred 
in the middle to late(? ) Miocene, and ongoing Quaternary extension. The earli-
est period of extension occurred after Mesozoic contraction and before and/or 
broadly concurrent with intrusion of rhyolite porphyry dikes in the district ca. 
38 Ma. This first period of extension coincides with movement on the first four 
normal fault sets in the Spruce Mountain district (Table 2) and may have been 
a single continuous event or may have been composed of multiple, discrete 
extensional episodes separated by periods of relative inactivity. Based on the 
structural reconstruction (Fig. 6), this early extensional period produced the 
largest amount of extension at Spruce Mountain (5.4 km). A later period, likely 
of middle to late Miocene age, produced the east-directed tilting of sedimen-
tary rocks in the southeastern part of the district when faults grouped in sets 
5 and 6 were active. The most recent period of extension occurred with the 
latest movement on faults grouped in set 6, which includes range-front fault 
scarsps mapped along the western sides of Spruce Mountain Ridge and Spruce 
Mountain that offset Quaternary deposits (dePolo, 2008).

In spite of the regional importance of middle Miocene extension in north-
eastern Nevada, other periods of extension cannot be overlooked. Extension at 
ca. 38 Ma or earlier appears to have resulted in considerably more extensional 
strain at Spruce Mountain than later episodes of extension. Late Eocene ex-
tension may have contributed more extensional strain than the mid-Miocene 
event in other parts of the Great Basin, including areas of east-central Nevada 
that are south of Spruce Mountain, such as the northern Egan Range and the 
Robinson district (Gans and Miller, 1983; Gans et al., 1989, 2001). Even in areas 
where the magnitude of middle Miocene extension overwhelms the impor-
tance of older extension, the earlier events nonetheless require geodynamic 
explanation. Moreover, late Eocene extension, regardless of magnitude, 
certainly played a role in localizing ore formation in many locales (e.g., late 
Eocene ores at Bingham, Utah, Redmond and Einaudi, 2010; at Cove-McCoy, 
Nevada, Johnston et al., 2008; at Battle Mountain, Nevada, Keeler and See-
dorff, 2007; and at many sites in White Pine County, Nevada, Seedorff, 1991a).
Implications of Crustal Extension and Structural Restorations for Mineral Exploration

Preexisting mineralized systems can be dismembered and tilted by normal faults (e.g., Proffett, 1977; Wilkins and Heidrick, 1995; Rahl et al., 2002; Begbie et al., 2007; Stavast et al., 2008), thereby aiding scientific understanding of the systems by creating greater exposures of their vertical and lateral extents (e.g., Dilles and Einaudi, 1992; Seedorff et al., 2005, 2008). Mineralized systems may also provide additional geologic markers for reconstructions, such as hydrothermal alteration or metal zoning patterns, which may aid structural reconstructions, especially where there are large areas with uniform rock types (Maher, 2008; Nickerson et al., 2010; Houston and Dilles, 2013; Seedorff et al., 2015). Mineralized systems or fault-bound fragments of them, especially those in the footwall blocks of large-displacement normal faults, may be uplifted and eroded during extension, yet in other cases, ore may be downdropped, buried, and preserved under postmineral rocks and may constitute an exploration target (Maher, 2008; Richardson and Seedorff, 2015). Numerical modeling indicates that crustal extension at the scale of an orogenic belt enhances the preservation of mineral deposits formed at relatively shallow levels of the crust, such as porphyry and epithermal systems; i.e., it postpones their erosion (Barton, 1996). Crustal extension also creates permeability and drives fluid circulation in the brittle upper crust (Ilichik and Barton, 1997), favoring the formation of certain types of deposits during periods of crustal extension, including epithermal silver-gold deposits, Carlin-type gold deposits, iron oxide–copper–gold deposits including detachment-style Fe-Au-(Cu) deposits, and certain classes of porphyry systems (Dreier, 1984; Spencer and Welty, 1986; Seedorff, 1991a; Tosdal and Richards, 2001; John, 2001; Barton et al., 2011; Coolbaugh et al., 2011). The geometric constraints on determining the amount of deformation of synextensional hydrothermal systems such as Spruce Mountain, however, are less straightforward than for preextensional deposits (see preceding).

Although the precise amount of deformation of the porphyry molybdenum system at Spruce Mountain system is not tightly constrained, it is clear that the Spruce Mountain system has been structurally dismembered, with deeper levels generally exposed on the western side and shallower levels on the eastern side of the district. Abrupt increases in grade with depth occur beneath some post-ore faults, and some of the highest molybdenum grades intersected to date are in the footwall of a steeply dipping post-ore normal fault. Thus, several of the generations of faults postdate ore formation, and the net tilting of the highly segmented hydrothermal system is ~10° west. It is highly unlikely, therefore, that the mineralizing plutons are entirely upright or fully intact. Early generations of normal faults are locally intruded by porphyry dikes and host tabular bodies of quartz-rich breccia. Mineralized skarn is spatially associated with the margins of porphyry dikes and occurs in certain premineral to synmineral normal faults.

The structural and magmatic setting of Spruce Mountain may be analogous to the Hunter district in White Pine County, where a rhyolitic center was emplaced at the onset of extension in that area during the late Eocene. Hydrothermal activity accompanied emplacement of porphyry dikes along normal faults, and faults continued to slip after crystallization of the dikes. In the Hunter district, most, if not all, normal fault–related tilting postdated intrusion of the dikes and extrusion of coeval volcanic rocks (Gans, 1982; Gans and Miller, 1983). Both the Hunter and Spruce Mountain districts are synextensional porphyry systems. Occurrences of Carlin-style mineralization at Spruce Mountain may belong to a genetically unrelated, earlier or later, system that partially overlaps the porphyry molybdenum system spatially. Spatial superposition of genetically unrelated systems is common in the Great Basin (e.g., Keeler and Seedorff, 2007) and is especially common for Carlin-type gold systems (e.g., Seedorff, 1991a; Seedorff and Barton, 2004; Hastings, 2008; Lubben et al., 2012; Hoge et al., 2015).

The early sets of faults at Spruce Mountain are prospective because they could have influenced the locations of porphyry intrusive centers, and they were conduits for hydrothermal fluid flow that produced skarn and carbonate replacement mineralization. In contrast, later generations of faults have dismembered the system and contributed to its post-ore tilting; hence, detailed structural restorations may be used to predict where mineralization is in a given block, where it is displaced by a post-ore fault, and thus where it might be discovered in nearby fault blocks. Results of future exploration activities will permit refinement or revision of this two-dimensional structural interpretation. With greater three-dimensional exposure (e.g., access to drilling results), an attempt at a three-dimensional structural restoration might be justified.

CONCLUSIONS

Complexly faulted Ordovician through Permian miogeoclinal sedimentary rocks, Cenozoic volcanic and sedimentary rocks, and sparse intrusive rocks are exposed at Spruce Mountain. Skarn, carbonate replacements, fissure veins, and jasperoid that were exploited by small underground mines in the district, principally for lead and silver, originally were the distal expressions of a porphyry molybdenum system at depth, although the system is now tilted and dismembered. The porphyry system, here dated by U-Pb zircon as late Eocene (ca. 38 Ma), is related to sparsely exposed rhyolite porphyry and granite porphyry intrusions. Spruce Mountain is a rhyolitic porphyry Mo or Climax-type porphyry molybdenum deposit with extensive associated skarn. The district also contains a Carlin-type gold prospect of unknown age.

Based on a plan-view analysis of geologic maps and a reconstructed cross section, at least six crosscutting sets of normal faults have been delineated with contrasting polarities of faulting. From oldest to youngest, these sets have senses of displacement of (1) down to the west, (2) down to the west, (3) down to the north, (4) down to the east, (5) down to the east, and (6) down to the west. The present-day fault network reflects the overprinting of multiple phases of extension, ranging in age from late Eocene or older to Quaternary, in which periods of incremental eastward tilting were interspersed with periods
of westward tilting. Based on age constraints from six new U-Pb age dates of igneous dikes within the district, some of which cut and intrude the oldest fault sets, the earliest phase of extension occurred at or before ca. 38 Ma. Early extension was accommodated by the oldest four fault sets, all of which are late Eocene or older in age, and resulted in the largest extensional strain in the district (5.4 km). Probable middle to late Miocene sedimentary rocks exposed in the southeastern part of the district were tilted during a later phase of normal faulting, which (along with minor additional extension during the Quaternary) resulted in ~1.5 km of additional extension in the central part of the district. Thus, we estimate that Cenozoic normal faulting accommodated a total of 6.9 km of extension (120%) across the central portion of the Spruce Mountain district. Although the oldest normal faults that crop out at Spruce Mountain currently dip <15°, based on the structural reconstruction, all faults in the reconstructed section had initial dips of ~45° or greater. The recognition of large-magnitude late Eocene or older extension at Spruce Mountain is important in that Paleogene extension in this region of northeastern Nevada has previously been regarded by many as relatively insignificant compared with later phases of extension during the middle Miocene. Our restorations and age dates at Spruce Mountain show that Eocene extension was at least locally significant in northeastern Nevada.

Within the central Spruce Mountain district, large extensional strains have been distributed among numerous normal faults. Stepwise, fault by fault restoration of the normal faults at Spruce Mountain yields a restored section that implies west-vergent folding and gentle westward dips of miogeoclinal strata. This geometry is interpreted to reflect that the Spruce Mountain area was on the western limb of an anticline that connected to the Pequop syncline to the east prior to being dismembered by extensional faulting. The structural reconstruction indicates that the entire extensional history of the district produced net eastward tilting of ~35°, which suggests that movement on faults of the three sets of down-to-the-west faults of the first, second, and sixth generations dominated the tilting history of the area.

The earliest four sets of normal faults at Spruce Mountain are pre-ore or syn-ore faults relative to hydrothermal alteration-mineralization related to the porphyry molybdenum system. Faults of these sets are prospective as they probably were conduits for hydrothermal fluid flow that produced skarn and carbonate replacement mineralization. However, the Spruce Mountain system has also been structurally dismembered by younger sets of normal faults. Net tilting of the hydrothermal system by postmineral faults is probably ~10° westward, and deeper levels of the system are generally exposed on the western side of the district. Cross-sectional restoration of the postmineralization extensional faulting and associated tilting suggests that the original deposit had a ~6 km long by ~3 km deep elliptical pattern in 2 dimensions, with carbonate replacement deposits surrounding skarn. Spruce Mountain joins Bingham, Utah, Cove-McCoy, Nevada, several deposits in the Battle Mountain district, Nevada, and many sites in White Pine County, Nevada, as mineral deposits where late Eocene extension, regardless of magnitude, played a role in localizing ore formation.

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Appendix 1. Descriptions of samples dated by U-Pb zircon method

SMIg44

SMIg44 is an Eocene porphyritic rhyolite dike ~1.1 km northwest of the Standard mine; it is 50 cm wide and strikes north-south. The texture is porphyritic with 5% phenocrysts and distinct flow banding along strike. The phenocryst assemblage includes 50% plagioclase 0.1–1 mm, 25% resorbed quartz 1–4 mm, 20% potassium feldspar 1–2 mm, and 5% biotite 0.1–0.5 mm. Sericite and kaolinite have partially to completely replaced the feldspars.

SMIg45

SMIg45 is an Eocene rhyolite porphyry intrusion ~0.6 km southeast of the Standard mine and 0.4 km west of the Ada H mine, and occurs as a circular body of float ~100 m wide. The rock is white to light gray with a porphyritic texture and shows pervasive alteration effects, including bleached and clay-altered feldspars and abundant iron oxides that may represent oxidized pyrite. Phenocrysts represent 30% of the rock and consist of 40% partially resorbed quartz 1–3 mm, 40% potassium feldspar 2–10 mm, and 20% plagioclase 1–2 mm. The matrix is a very fine grained mixture of quartz and feldspars. Sericite and kaolinite have completely replaced the feldspars.

SMIg46

SMIg46 is a Jurassic dacite ~1.5 km northwest of the Kille mine and is a light gray competent rock that forms large outcrops and exhibits distinct flow banding. The texture is fine-grained equigranular. The rock is composed of 70% plagioclase 1–2 mm and 30% quartz 0.5–2 mm; mafic minerals have been destroyed. Sericite alteration of plagioclase is pervasive. Calcite locally overprints sericite alteration.

SMIg47

SMIg47 is a Jurassic porphyritic dacite ~1.2 km south of the Kille mine that occurs in an elongate body of pale green rock 200 m long by 100 m wide. The texture is porphyritic with 15% phenocrysts in a fine-grained matrix. The phenocryst assemblage includes 60% plagioclase 0.5–2 mm, 20% quartz 0.5–2 mm, and 20% biotite 0.5–1 mm. The groundmass is composed of plagioclase, biotite, and quartz. This rock has been strongly propylitized, with complete alteration of plagioclase and biotite to chlorite and calcite. Plagioclase phenocrysts also display minor sericite and kaolinite alteration.
Figure A1. Concordia diagrams for U-Pb dates. See Appendix 2 for interpretations.
SMiG49

SMiG49 is an Eocene coarse-grained rhyolite porphyry ~0.5 km southeast of the Black Forest mine; it is light gray and contains 30% phenocrysts set in a fine-grained matrix of quartz and feldspar. Phenocrysts are 20% resorbed quartz 1–6 mm, 50% potassium feldspar 3–9 mm, 20% plagioclase 1–3 mm, and 10% biotite 0.5–1.5 mm. Very minor disseminated pyrite and chlorite are present. Quartz veins 1–20 mm wide are common, some of which contain fine-grained molybdenite. The rock has been potassicly altered with pervasive K-feldspar.

SMiG51

The second rhyolite porphyry unit occurs along a roughly linear trend across the entire study area that may be a large dike; the dated rock was collected on the south side of Banner Hill ~1.3 km east of the Black Forest mine. Exposures are commonly either masses of float or highly weathered rock exposed by prospect pits. The rock is bright white with a porphyritic texture. Parallel quartz veins 1–3 mm wide ~10 cm are present in outcrops on the western edge of the study area. Phenocrysts make up 15% of the rock and consist of 60% quartz 1–3 mm, 20% potassium feldspar 1–2 mm, and 20% plagioclase 1–2 mm. Alteration is typically weak argillicization, although one outcrop on the eastern edge of the study area contains potassium feldspar flooding, 1–2 mm fluorspar veins, and minor copper oxides.

APPENDIX 2. LASER ABLATION–INDUCTIVELY COUPLED PLASMA–MASS SPECTROMETRY U–Pb ZIRCON GEOCHRONOLOGIC METHODS

Sample Preparation

Zircon grains were separated from rocks using standard techniques and mounted in epoxy and polished until the centers of the grains were exposed. Cathodoluminescence (CL) images were obtained with a JEOL JSM-1300 scanning electron microscope and Gatan MiniCL. CL images guided the placement sites for microanalysis. U–Pb dates were obtained from spot analyses by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Isotope Geology Laboratory at Boise State University (Idaho).

Analytical Methods and Reporting Procedures

U–Pb isotope systematics and trace element compositions were analyzed by LA-ICP-MS using a ThermoElectron X-Series II quadrupole ICP-MS and New Wave Research UP-213 Nd:YAG UV (213 nm) laser ablation system. In-house analytical protocols, standard materials, and data reduction software were used for simultaneous acquisition and real-time calibration of U–Pb dates and a suite of high field strength elements (HFSE) and rare earth elements (REE) using the high sensitivity and unique properties of the interface (Xs cones), extraction lens, and quadrupole analyzer of the X-Series II. Zircons were ablated with a laser diameter of 25 µm using fluence and pulse rates of 5 J/cm² and 10 Hz, respectively, during a 30 s analysis (15 s gas blank, 45 s ablation) that excluded a pit ~25 µm deep. Ablated material was carried by a 1.2 L/min He gas stream to the nebulizer and the X-Series II. Zircons were ablated with a laser diameter of 25 µm.

U–Pb dates were obtained prior to each spot analysis and subtracted from the raw count rate for each analyze. 

For U–Pb dates, instrumental fractionation of the background-subtracted $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb ratios was corrected, and dates were calibrated with respect to interstratified measurements of the Plésiozic zircon standard (Sliamann et al., 2008). Signals at mass 204 were indistinguishable from zero following subtraction of mercury backgrounds measured during the gas blank (~1000 cps $^{204}$Hg), and thus dates are reported without common Pb correction. Radiogenic isotope ratio and age error propagation for each spot includes uncertainty contributions from counting statistics and background subtraction. For concentration calculations, background-subtracted count rates for each analyze were internally normalized to $^{29}$Si and calibrated with respect to NIST SRM-610 and SRM-612 glasses as the primary standards.

Errors on weighted mean $^{206}$Pb/$^{238}$U dates given in the following are presented at 2σ as follows: weighted mean date ± x/2, where x is the internal error and y is the error including the uncertainty on the standard calibration, propagated in quadrature. Weighted mean calculations were performed using Isoplot 3.0 (Ludwig, 2003). A standard calibration uncertainty of 1.0% (2σ) is used because that is the average of these experiments. In Table 1 errors on single dates do not include uncertainties on the standard calibration.

We experimented with other schemes to reject certain individual spot analyses. Although these routines in some cases resulted in slightly different dates, all dates were well within the uncertainties reported here.

Zircon standard AUSZ2 was measured as an unknown during the experiment as a quality control standard; 23 analyses of AUSZ2 yielded a weighted mean $^{206}$Pb/$^{238}$U date of 38 ± 0.5 Ma, in agreement with the chemical abrasion–thermal ionization mass spectrometry weighted mean date of 38.86 ± 0.01 Ma (2σ internal error; J. Crowley, 2012, personal commun.).

Results

Analytical results are summarized in Table 1; Figure A1 shows concordia diagrams for the six analyzed samples.

Sample SMiG44 has an interpreted age of crystallization of 37.7 ± 0.5 Ma and exhibits minor normal discordance, reflecting several spot analyses that exhibit lead loss. Sample SMiG45 has an interpreted age of crystallization of 37.3 ± 0.4 Ma and exhibits normal and reverse discordance, probably reflecting lead loss for some of the analyzed spots. Sample SMiG46 has an interpreted Jurassic age of crystallization of 155 ± 4 Ma and has several spot analyses that exhibit lead loss, but it also shows the greatest evidence of inheritance, likely with several different Precambrian age cores with ages of ca. 1.1 Ga and ca. 2.7 Ga. Sample SMiG47 has an interpreted Jurassic age of crystallization of 156 ± 2 Ma and exhibits minor discordance, reflecting several spot analyses that exhibit lead loss. Sample SMiG48 has an interpreted age of crystallization of 39.1 ± 0.6 Ma and exhibits normal and reverse discordance, reflecting lead loss for some of the analyzed spots. Sample SMiG51 has an interpreted age of crystallization of 37.5 ± 0.4 Ma and exhibits discordance that likely results from lead loss for some of the analyzed spots.

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Research Paper

Structural reconstruction, Spruce Mountain, Nevada

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