Reconstruction of Normal Fault Blocks in the Ann-Mason and Blue Hill Areas, Yerington District, Lyon County, Western Nevada

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ABSTRACT

The Yerington porphyry copper-skarn-iron oxide-copper-gold district is a classic area of continental extension, having been extended more than 150% by multiple generations of Cenozoic east-dipping normal faults that penetrated a minimum of 8 km depth into the crust, initiated at high angles, and rotated to shallower dips until being cut by younger sets of faults. This study examines the Cenozoic normal faults in the vicinity of the Ann-Mason and Blue Hill areas through detailed mapping of two major faults, logging intervals of drill core containing the fault damage zones, and constructing fault surface maps, i.e., geologic maps of the proximal footwall and hanging wall of faults superimposed on structural contour maps of the fault planes. Six normal faults, representing four geometric sets or temporal generations of faults numbered from oldest to youngest are described and analyzed, with particular emphasis on the oldest two generations. Fault surface maps constrain the slip vectors of the faults and their variability along strike. Faults of the latest three generations strike northerly and dip easterly. Faults of the second generation, which are of middle Miocene age, include the Blue Hill (~2.8 km slip with increasing displacement to the north) and Singatse (3.7 km slip) faults. These second-generation faults have damage zones that persist ~15 m on either side of the fault and have hanging-wall splays that merge into the main fault surface. The first generation faults are represented by the 1A fault, which is one of a series of sub-parallel, generally small-offset faults that presently strike southeast and dip steeply to the southwest. Analysis of drill hole data indicates that the 1A fault, which might have the most amount of slip of any fault in the set, has ~230 m of apparent sinistral separation. The incremental untilting of the three later generations of faults restores the 1A fault to a steeply south-dipping fault with normal, dip-slip displacement. The 1A fault appears to connect with a fault that is exposed at the surface west of the area of drill hole constraints and cuts the Weed Heights member of the Mickey Pass Tuff (27 Ma) and is cut by the middle Miocene Singatse fault, bracketing its timing.

The structural contour maps reveal new insights into the subsurface geometry of several faults. The Blue Hill fault presently dips ~22° southeast along the northwestern side of a large mullion in the fault plane. A stepwise reconstruction indicates that all faults had initial dips of ≥ 60°, with the Singatse initiating at 73°. The significance of the first generation of faults at Yerington, though poorly understood, may have counterparts in eastern Nevada, where sets of easterly striking normal faults also formed prior to periods of extreme extension. The restorations demonstrate that mineralization in the Ann-Mason and Blue Hill areas originated in the same dike swarm, and thus are genetically related, and that another dike swarm to the south passing near the Casting Copper-Ludwig septum could have porphyry mineralization to the northwest at depth on one or both sides of the Blue Hill fault.

Key Words: Structural reconstruction, Yerington district, Basin and Range province, porphyry copper

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INTRODUCTION

Multiple sets of rotated normal faults (also called “domino-style” or rotational planar normal faults), for which the Yerington district is well known, are a manifestation of high-magnitude extension in the Basin and Range province (Wernicke and Burchfiel, 1982; Davison, 1989). Rotated normal faults are essential in not only preserving near-surface crustal architecture over geologic time, but also in exposing deep subsurface features without requiring large topographic relief (Seedorff, 1991a; Dilles and Einaudi, 1992; Seedorff et al., 2008). Debate on the mechanics and kinematics of crustal extension can be furthered through three-dimensional structural reconstructions of mineral deposits with their abundance of subsurface data from drill holes and careful field observations from mapping of natural and man-made exposures (Proffett, 1977; Proffett and Dilles, 1984; Davison, 1989; Stockli et al., 2002; Surpless, 2012). Beyond that, structural reconstructions suggest where fault-offset blocks of mineralized systems may exist, thus yielding possible exploration targets (Ransome, 1903; Lowell, 1968; Wilkins and Heidrick, 1995; Nickerson et al., 2010).

The Yerington district is a hybrid/superimposed system with porphyry copper, skarn, and iron oxide-copper-gold (IOCG) mineralization (Einaudi, 1977; Harris and Einaudi, 1982; Dilles, 1987; Barton and Johnson, 2000; Dilles et al., 2000b) that has been structurally dismembered and rotated 60 to 90° by late Cenozoic faults, as indicated by highly tilted Oligocene ash-flow tuffs, which extended the district by more than 150% (Geissman et al., 1982a; Proffett and Dilles, 1984). Reconstructions based on previous mapping and geophysical work show that the district underwent pre-Oligocene deformation that tilted it ≥20° westward prior to Miocene and younger faulting that produced even larger degrees of tilting (Geissman et al., 1982b; Proffett and Dilles, 1984), resulting in a total of about 90° of westward tilting. Recent work continues to add to the understanding of the structural geology of the area, particularly east and south of the main district (e.g., Surpless, 2010, 2012; Schottenfeld, 2012).

In part because of the extraordinary three-dimensional exposure, the greater Yerington district continues to be a natural laboratory for investigating hydrothermal processes and the genesis of porphyry copper deposits (e.g., Dilles et al., 2015) and for understanding the origin of IOCG deposits in porphyry copper districts (Runyon, 2013; Runyon et al., this volume). In the last decade, the Yerington district has undergone a revival of exploration and development activities, by Entrée Gold at Ann-Mason and Blue Hill, by Quaterra at McArthur and the Yerington mine, and by Nevada Copper at Pumpkin Hollow. The associated drill holes from exploration offer additional controls for structural geologic studies.

The purpose of this study is to further the understanding of the kinematic evolution of normal faults in the greater Ann-Mason and Blue Hill areas within the Yerington district, building on previous published geologic information and taking advantage of dense drill hole data in and around the Ann-Mason porphyry copper deposit. Entrée Gold has added over 35 km of exploration drilling since 2010 in the study area. As described below, the Cenozoic faults of the district can be grouped into four geometric sets or temporal generations, numbered from oldest to youngest. The geology of the district offers numerous geologic markers that can be utilized in fault restorations, including a Tertiary erosion surface above which Oligocene volcanic rocks were deposited, dike swarms and other discrete phases of a Jurassic batholith, and faults of older generations that must connect following each step of a structural restoration. Fault surface maps, i.e., geologic maps of the immediate footwall and hanging wall of each fault overlain on structure contour maps of the fault planes, are employed as a method to provide detailed, three-dimensional control on the geometry of faults and to assess and portray changes in the magnitude and direction of slip along each fault. The results are based on detailed mapping of the traces of two major faults, logging intervals of drill core to describe and to constrain the limits of the fault damage zones, and constructing fault surface maps of selected faults. We find that the faults in Yerington are neither perfectly planar nor strongly listric in geometry, but instead curvilinear. Analysis indicates that the 4th and 3rd generations of faults have somewhat greater magnitudes of slip than previously reported. A fault of the 3rd generation, with a geometry that is not tightly constrained, may have a different slip direction than previously inferred. A representative fault is characterized from a largely undescribed fault set, striking at high angles to the other fault sets. We show through a structural reconstruction that the restored position of offset pieces of the Ann-Mason and Blue Hill ore bodies belong to the same dike swarm and indicate where the present locations of offset, buried portions are possibly located.

LOCATION AND HISTORY

Location

The Yerington district is located in west-central Nevada, near the western margin of the Basin and Range province and within the Walker Lane dextral shear zone (Proffett, 1977; Hardeman and Oldow, 1991; Surpless, 2012). The district encompasses the Buckskin, Singatse, and Wassuk Ranges and Smith and Mason Valleys (Figures 1, 2). It is a composite porphyry copper-IOCG district consisting of the Yerington, Ann-Mason, Blue Hill, MacArthur, Bear, and Pumpkin Hollow deposits as well as many smaller historic workings (Knopf, 1918; Carten, 1986; Dilles, 1987; Dilles et al., 2000a). The study area is due west of the town of Yerington and spans the breadth of the Singatse Range and northern Smith Valley. Triassic through recent sedimentary, intrusive, and extrusive rocks record a series of discrete events across the Buckskin, Singatse, and Wassuk Ranges that provide multiple stratigraphic and structural markers to aid in structural reconstruction.
District exploration and mining history

Mining in the Yerington district began as late as 1865 with the Ludwig, Mason Valley, and Bluestone mines in the Singatse Range producing copper sulfates (Jackson et al., 2012). These, and many of the small, underground, historic workings (dominantly skarn and carbonate replacement) in the district such as the McConnell, Homestake, Western Nevada, Nevada-Empire, Douglas Hill, Casting Copper, Malachite, Blue Jay, and Montana Yerington mines were connected by the Nevada Copper Belt Railroad built in the early 1900s to the Thompson smelter near Wabuska, approximately 15 km north of Yerington, which operated between 1912 and 1928 (Tingley, 1990; Jackson et al., 2012; Spiller et al., 2012). Anaconda began exploration in the Yerington district in 1941, initially focusing on the area around the Nevada-Empire mine located above the center of the pres-
ent-day Yerington pit. Spurred by U.S. government subsidies to encourage domestic copper production, Anaconda began mining in 1951 (Bryan, 2012). Anaconda’s Yerington porphyry copper mine was active from 1951–1979, and its geologists discovered several more deposits (Ann-Mason, Blue Hill, MacArthur, and Bear), making important contributions to the geologic literature (e.g., Proffett, 1972, 1977; Proffett and Proffett, 1976; Einaudi, 1977; Brimhall et al., 2006). Other notable mineralized occurrences in the district include the Pumpkin Hollow deposit, initially discovered by U.S. Steel in 1960, and the Lagomarsino deposit, a faulted piece of the Bear system discovered by Phelps Dodge (Tingley, 1990; Doebrich et al., 1996). Following the loss of their Chilean and Mexican properties in the mid-1970s, Anaconda was purchased by the Atlantic Richfield Company (ARCO), which shut down operations in 1979 and sold the former Anaconda-held properties in the Yerington district by 1981. Since 1984, the history and control of the district has been fragmented and is briefly summarized in Table 1, but the most active current operators are Nevada Copper, Entrée Gold, and Quaterra.

**GEOLOGIC FRAMEWORK**

**Tectonomagmatic and metallogenic setting**

The Yerington district and associated mineralization is...
dominated by the Yerington batholith, which formed from 169.4–168.5 Ma (Dilles and Wright, 1988). The Yerington batholith is a product of Jurassic magmatism in the western United States that is divided by Barton et al. (2011) into two episodes of mineralization: an early period (~210–190 Ma) of weak, sparse porphyry Cu, Zn-Pb-Ag, and IOCG mineralization and a mid-Jurassic (170–155 Ma) period containing all IOCG systems.

The dextral transtensional Walker Lane initiated in the mid-late Cenozoic as a response to the changed plate boundary configuration as early as ~24 Ma as evidenced in the Gillis and Gabbs Valley Ranges, and movement is bracketed between 23.1 and 22.2 Ma at the present day western boundary in the Wassuk Range (Hardyman and Oldow, 1991; Dilles and Gans, 1995; Surpless, 2012). Starting in the mid-Miocene, intermediate-silicic volcanism, large-magnitude extension, and basaltic magmatism characterized the western Great Basin from the Toquima Range in central Nevada to Death Valley, with much of the intermediate-silicic volcanic rocks deposited in west-draining paleo-river valleys prior to the development of a drainage divide within the Sierra Nevada (Figure 1 of Henry and Faulds, 2010). Fault systems of rotated normal fault sets have been documented with ≥100% extension at the Hall, Robinson, and Royston districts, in addition to Yerington (Shaver and McWilliams, 1987; Seedorff, 1991b; Seedorff et al., 1996). Throughout the Basin and Range province, two broad structural patterns have been observed: a “Basin and Range” pattern (i.e., high-angle normal fault-bounded horsts and grabens) with minimal extension and rotation, and a pattern of low-angle normal faults and/or rotated normal faults associated with high-magnitude extension and rotation (Proffett, 1977; Stewart, 1998; Eckberg et al., 2005).

### Mesozoic geology and structure

A succession of mid-Triassic (or older) volcanic and sedi-

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**Table 1. RECENT MINING AND EXPLORATION HISTORY OF THE YERINGTON DISTRICT.**

<table>
<thead>
<tr>
<th>Mining Company</th>
<th>Years of Activity</th>
<th>Major Properties</th>
<th>Activity &amp; Claims of Major Discovery</th>
<th>Key References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrée Gold (US), Inc.</td>
<td>2010-Present</td>
<td>Ann-Mason, Blue Hill, Roulette</td>
<td>Continued drilling, mapping, and geophysical surveying; Preliminary Economic Assessment completed in 2012</td>
<td>Jackson et al., 2012</td>
</tr>
<tr>
<td>Nevada Copper</td>
<td>2005-Present</td>
<td>Pumpkin Hollow</td>
<td>Feasibility study completed in 2012; continued drilling, mapping, and geophysical surveying</td>
<td>Spiller et al., 2012</td>
</tr>
<tr>
<td>Singatse Peak Services, LLC [Quaterra Resources, Inc.]</td>
<td>2011-Present</td>
<td>Yerington Mine, MacArthur</td>
<td>Completed a Preliminary Economic Assessment on the MacArthur deposit; confirmation drilling on the Yerington mine and Bear deposits</td>
<td>Bryan, 2012; Henderson et al., 2012</td>
</tr>
<tr>
<td>PacMag Metals Limited</td>
<td>2005–2010</td>
<td>Ann-Mason, Blue Hill, claims around Minnesota</td>
<td>Drilling (RC and DD) of the Ann-Mason and Blue Hill deposits (6,973 m and 3,438 m, respectively); drilled a magnetic anomaly around the Minnesota mine, encountering pyrite-dominated, copper-poor mineralization.</td>
<td>Jackson et al., 2012</td>
</tr>
<tr>
<td>Lincoln Gold Corporation</td>
<td>2004–2005</td>
<td>Blue Hill</td>
<td>Gold exploration program (soil geochemistry and RC drilling) at Lincoln Flat property; company declined to earn in due to results of exploration program</td>
<td>Jackson et al., 2012</td>
</tr>
<tr>
<td>Giralia Resources NL</td>
<td>2003</td>
<td>Ann-Mason</td>
<td>No exploration work conducted</td>
<td>Jackson et al., 2012</td>
</tr>
<tr>
<td>Phelps Dodge Corporation</td>
<td>1995</td>
<td>Blue Hill</td>
<td>Blue Hill deposit drilling</td>
<td>Jackson et al., 2012</td>
</tr>
<tr>
<td>Cyprus Metals Exploration Corporation</td>
<td>1989–1998</td>
<td>Pumpkin Hollow</td>
<td>Drilling primarily expanded the Pumpkin Hollow’s North and South deposits</td>
<td>Spiller et al., 2012</td>
</tr>
</tbody>
</table>

_N.B., Subsidiary company’s “parent/controlling” companies are noted in brackets if heavily intertwined._
mentary rocks associated with a Triassic continental margin volcanic arc were faulted and folded synchronous with Jurassic plutonism (Proffett and Dilles, 2008). The Middle Jurassic is characterized by high-K, calc-alkaline silicic to intermediate magmatism between 170–165 Ma (Dilles and Wright, 1988; Barton, 1996). Two suites of volcanic rocks, the Artesia Lake and the Fulstone Spring Volcanics, are deduced through contrasting sulfide content to be the respective syn-emplacement and post-emplacement vented products of the 169.4–168.5 Ma Yerington batholith (Lipske and Dilles, 2000; Proffett and Dilles, 2008). Major normal faults bound a large Mesozoic graben that contains the Yerington batholith and that may have formed during rapid magma withdrawal (Dilles and Proffett, 1991). Other faults that have been identified within the Ludwig septum were active at the time of emplacement and were utilized for fluid flow and dike emplacement.

The Yerington batholith is a composite pluton with three distinct, successive phases: the McLeod Hill quartz monzodiorite, the Bear quartz monzonite, and the Luhr Hill granite. Each phase is significantly volumetrically smaller than the prior one (75, 19, and 6 vol. % of the batholith, respectively), suggesting the continued evolution and differentiation of the batholith as it crystallized over time (Dilles, 1987). This is further supported by the increasing SiO2 content (60, 66, 68 wt. %, respectively) and estimated average depth of emplacement (<1, 1.5, 2.5–5 km, respectively), which suggests a tendency toward downward and inward crystallization of the composite pluton. Based on crosscutting and spatial relationships, the granite porphyry dikes associated with the formation of the Luhr Hill granite are demonstrably the source of mineralizing fluids for the porphyry deposits (Dilles, 1987; Dilles and Einaudi, 1992). The ore shells formed at depths of 3–6 km, and the highest Cu grades are found in the upper 2.5 km of each of the three major granite porphyry dike swarms (Dilles and Proffett, 1991). The mineralizing porphyry dikes have an aplitic groundmass, with 50% phenocrysts (orthoclase-quartz-plagioclase-hornblende-biotite). The porphyry dikes present

Cenozoic geology and structure

The Yerington district has been extended more than 150% by multiple successive sets or generations of east-dipping normal faults that penetrated a minimum of 8 km depth into the crust, initiated at high angles, and rotated to shallower dips until being cut by new fault sets (Proffett, 1977; Dilles and Gans, 1995). This is clearly established by the steep westward tilting of a precisely dated series of Oligocene ash-flow tuffs (27–23 Ma) that were confined to a paleovalley that flowed east to west through the Yerington district prior to the rise of the Sierra Nevada (Dilles and Gans, 1995; Henry and Faulds, 2010; Henry and John, 2013). These tuffs, originating 200 km east in the Toquima Range, were deposited onto the existing paleosurface prior to extension, and their contact with the Jurassic batholith (and local gravels) largely marks the mid-Tertiary erosional unconformity in the district (Proffett and Proffett, 1976; Garside et al., 2002). The deposition of volcanic rocks followed ~20° of westward tilting prior to the onset of Basin and Range faulting (Geissman et al., 1982b). This Oligocene erosion surface and the overlying volcanic rocks provide a key structural marker for the initiation of Basin and Range faulting in the Yerington district. The amount of tilting and extension that occurred during slip on faults of each generation is further constrained by the ages of intermediate to mafic volcanic rocks that mantle older faults and tilted strata and that are less rotated than older rocks (Proffett, 1977; Dilles and Gans, 1995).

Based on the work of Dilles and Gans (1995), faults of the oldest generation of east-dipping faults, including the Singatse and Blue Hill faults, were active between ~13.8–12.6 Ma, with ~35–40° of tilting, ~1–2 km spacing, and ≤4 km of offset on individual faults. Faults of the second generation, including the May Queen fault, were active from 11-8 Ma, with incremental tilting of 30–35° in the Wassuk Range and lesser amounts in the Singatse Range, were irregularly spaced, and had <1 km offset. Faults of the third generation, including the Sales and Montana-Yerington faults, have been active since ~4 Ma, were associated with ~10° of incremental tilting, were spaced at 1–4 km, and have ~2 km offset. Faults of all sets exhibit local trough shapes that may be part of larger mullions, whose axes trend roughly east-west, in which the concave side of the trough faces up and towards the east, as shown by the mapped traces of faults and structure contour maps constrained by drill hole piercements of faults.

Proffett (1977) demonstrated that high-magnitude extension is manifested mostly by closely spaced faults of the first generation that have large amounts of displacement and large degrees of tilting of hanging-wall rocks, whereas the two younger generations of faults are associated with wider spacing of faults and smaller degrees of tilting. The tilting associated with the normal faulting has essentially laid the district on its side (Proffett, 1977; Geissman et al., 1982a). This has generated and preserved a vertical cross section, with the Ann-Mason fault block alone displaying a 6-km range in paleodepth (Dilles and Einaudi, 1992; Dilles et al., 2000a). The genetic
relationships of the faults have not, however, been universally agreed to and have been a matter of some debate (Proffett, 1977, 2002; Brady et al., 2000, 2002), being part of a broader discussion about the nature of extensional faulting (e.g., Wernicke, 2009).

METHODS

Field work for this study was conducted in June and July 2013 as part of a thesis project sponsored by Entrée Gold (Richardson, 2014). Detailed, Anaconda-style, outcrop mapping (Einaudi, 1997; Brimhall et al., 2006) at a scale of 1:2,000 focused on outcrops along the traces of the Singatse and Blue Hill faults. Approximately 670 m of selected drill core were logged at a scale of 1:100, in which lithology, structure, proportions of various sulfides, mineralogy of veins and alteration envelopes, and average width and spacing of veins were recorded. This core constitutes intervals through the Blue Hill and Singatse faults, generally 30–100 m intervals of core from the hanging-wall through the footwall.

Geologic maps of the proximal footwall and hanging wall surfaces of the faults were constructed by using data from existing geologic maps, drill hole intercepts, and original mapping from field work. These maps are then superimposed on a structural contour map of the fault. Such fault surface maps, also known in the petroleum industry as fault cutoff maps (Tarepock and Bischke, 2003; Groshong, 2006, p. 229; Seedorff et al., this volume), can present traditional lithologic and structural data, but can also show overlays of other features such as hydrothermal alteration and metal grades (e.g., Keeler, 2010; Schottenfeld, 2012). Such maps permit a rigorous, three-dimensional reconstruction of the faults by restoring the hanging wall view over the footwall view, showing how the magnitude and direction of slip varies across the fault surface. The number of significant figures in slip measurements is kept to two (e.g., 2.6 km), reflecting the confidence in locating contacts and piercing points for structural reconstructions, and is better constrained than in many deposits due to the density of drill data and mapping of surface features. Unique determinations of the magnitude and direction of slip require piercing points on either side of the fault plane, which commonly are defined by the intersection of two other geologic contacts (e.g., intrusive contact, stratigraphic contact, erosion surface, or older fault plane).

In order to better understand the dismemberment of the Ann-Mason deposit, the structural history following offset on the Singatse fault has to be resolved before addressing where the offset portion(s) of the Ann-Mason porphyry copper system may be located. This involves the reconstruction of fault surface maps for the May Queen, Montana-Yerington, and Sales faults, which structurally offset the Singatse fault and create gaps in the Singatse fault surface (Figure 2). As these younger faults are dominantly under cover and were not the subject of the original field work, the data for these faults are derived from the map and cross sections of Proffett and Dilles (1984), which are based on years of mapping, drilling, and careful construction of detailed cross sections. Interpretations of the magnitude, slip direction, and initial structural attitudes of the faults in each of the fault sets are summarized in Table 2.

STRUCTURAL GEOLOGY

The following section first describes the character of the fault zones of the Singatse and Blue Hill faults, based on observations in drill core. Then each of the faults is described, grouped according to geometric characteristics (fault sets) and relative ages, from youngest to oldest.

Fault damage zones

The growth and progressive development of faults is commonly represented by what is recorded along the fault slip surface. The fault zone, however, extends beyond this “fault core” to include a surrounding volume of rock wherein deformation is more broadly distributed, known as the damage zone (McGrath and Davison, 1995; Caine et al., 1996; Kim et al., 2004). In the Yerington district, kinematic indicators along the slip surfaces are found locally, but commonly faults are deduced by the presence of clay gouge and comminuted rock, commonly juxtaposing Tertiary volcanic rocks against Jurassic intrusive rocks.

Selected intervals of drill holes that pierce the Singatse and Blue Hill faults, which currently dip at low-angles, were logged to characterize the subsurface expression of the fault wall-damage zones. The hanging walls of the faults (of which all but one

Table 2. FAULT CHARACTERISTICS.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Present Strike (Quadrant)</th>
<th>Present Strike Direction</th>
<th>Present Dip</th>
<th>Dip Magnitude (km)</th>
<th>Slip Direction (in modern plan view)</th>
<th>Direction of Increasing Displacement</th>
<th>Restored Strike (Quadrant)</th>
<th>Restored Dip Direction</th>
<th>Restored Dip Quadrant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Montana-Yerington</td>
<td>N15°W</td>
<td>075°</td>
<td>51°</td>
<td>1.1</td>
<td>E</td>
<td>N</td>
<td>N13°W</td>
<td>073°</td>
<td>60°</td>
</tr>
<tr>
<td>Sales</td>
<td>N10°W</td>
<td>080°</td>
<td>52°</td>
<td>1.6</td>
<td>E</td>
<td>S</td>
<td>N09°W</td>
<td>081°</td>
<td>62°</td>
</tr>
<tr>
<td>May Queen</td>
<td>N00°W</td>
<td>090°</td>
<td>35°</td>
<td>1.4</td>
<td>SE</td>
<td>N</td>
<td>N00°W</td>
<td>090°</td>
<td>60°</td>
</tr>
<tr>
<td>Singatse</td>
<td>N05°W</td>
<td>085°</td>
<td>13°</td>
<td>3.8</td>
<td>E/ENE</td>
<td>S(?)</td>
<td>N02°W</td>
<td>088°</td>
<td>73°</td>
</tr>
<tr>
<td>Blue Hill</td>
<td>N70°E</td>
<td>160°</td>
<td>22°</td>
<td>2.8</td>
<td>E/ESE</td>
<td>N</td>
<td>N22°E</td>
<td>112°</td>
<td>70°</td>
</tr>
<tr>
<td>1A</td>
<td>S61°E</td>
<td>199°</td>
<td>71°</td>
<td>0.2</td>
<td>ESE</td>
<td>—</td>
<td>N86°E</td>
<td>176°</td>
<td>56°</td>
</tr>
</tbody>
</table>
had Oligo-Miocene volcanic rocks) commonly have a brecci- 
ated zone that is 1–11 m thick \((n = 10, \text{ mean } = 8.2 \text{ m, mode } = 3 \text{ m})\), with local \(~3 \text{ m-thick brecciated zones occurring in the}

footwall of the faults (Figure 3a-b). Above the main hanging- 
wall breccia zone and locally in the footwall smaller brecci- 
ated zones are observed, commonly ranging from 2–10 cm. In 

drill hole EG-AM-11-025, the clasts become more rounded to- 
wards the fault contact, but in many drill holes the brecciated 
zone consists of more angular fragments, suggesting localized 
episodes of brecciation as the fault slipped. Clasts constitute 
\(~30–60\% \) of the breccia, ranging in size from 2 mm to 25 cm. 

The clasts are subangular to subrounded (locally rounded), 
poorly sorted, and commonly heterolithic. The matrix composi- 

tion varies between brecciated zones but is dominantly a clay-

rich matrix surrounded by subangular to subrounded clasts with 
less abundant breccias where granular, fine-grained rock flour 

is the matrix. The breccias are termed chaotic breccias follow- 

ing the classification of Woodcock and Mort (2008). Less com-

monly, strongly comminuted, poorly indurated, clay-rich shear 

zones are present in half of the drill holes logged (Figure 3c). 

These zones range in thickness from 1–14 m \((n = 7, \text{ mean } = 6 \text{ m, mode } = 5.5 \text{ m})\). Fabrics developed in comminuted rock in 
the damage zone commonly are aligned parallel to the fault 
surface, which suggests an important component of motion in 
the damage zone parallel to the motion of the fault, although 
many small shears also are oriented at high angles to the fault 
surface. In the case of the Singatse fault, discrete bands of 
clay gouge are locally observed and range from 4–40 cm in 
thickness.

Fault set 4

Faults of set 4 are northerly striking, steep, easterly dipping 

faults that cut all other major faults in the district. Set 4 includes 
the Montana-Yerington and Sales faults.

Montana-Yerinton fault

The Montana-Yerington fault (Figure 4) is the range-

bounding fault along the eastern extent of the Singatse Range. 
The Montana-Yerington fault in map pattern takes the form of 
an embayment, representing a down-dip corrugation and the 
beginning of a salient or change in orientation on its southern 
end. It structurally offsets and creates gaps in the fault surfaces 
of older faults, including both the May Queen and Singatse. The 
structure contour map of the Montana-Yerington fault in pres-

ent-day orientation reveals that the fault strikes approximately 
N15°W and dips \(~51° E \) (Figure 4), similar to dips measured in 
outcrop (Proffett and Dilles, 1984) of 56 and 58° E. The fault 
is trough-shaped and planar-curvilinear in geometry. Geologic 
maps of the hanging wall and footwall show that the juxtapositi-
on of the lower \(~2 \text{ km of the floor or shoulder of the Yerington}
batholith against the uppermost \(~0.5 \text{ km of the Jurassic rocks}
and lower Tertiary volcanic rocks by the Singatse fault (Figure 
4a-b). On the westernmost portions of the geologic maps of the 

fault surface, the May Queen fault juxtaposes the Guild Mine 
member of the Mickey Pass Tuff in the hanging wall against 
the Weed Heights member of the Mickey Pass Tuff through the 
Bluestone Mine Tuff and Lincoln Flat Andesite in the footwall 
(Figure 4a-b).
Sales fault

The Sales fault is located ~1–2 km east of the Singatse Range in Mason Valley; along strike to the south it becomes the range-bounding fault in the Mickey Pass area, as the Sales fault bends in map pattern and changes from being salient to recessed in map pattern towards the south. In addition, the Sales fault splays southward into two closely spaced faults at the surface before rejoining and apparently being cut off by or merging with the range-bounding Montana-Yerington (possibly Bluestone Mine?) fault. It structurally offsets and, therefore, creates gaps in the fault surfaces of both the May Queen and Singatse faults. The structure contour map of the Sales fault reveals that the fault, in its present orientation, strikes ~N10°W and dips ~52° E (Figure 5), similar to a dip measured in outcrop (Proffett and Dilles, 1984) of 58° E. The Sales fault is planar-curvediplanar in geometry and gently bends to the south, with the dip direction changing from ENE to ESE. Geologic maps of the hanging wall and footwall show a large mass of the Luhr Hill granite that is in fault contact with a thin carapace of Bear quartz monzonite, due to the Singatse fault (Figure 5a-b). The Singatse fault is itself cut by the May Queen fault in the plane of the Sales fault and juxtaposes the above described rocks with a veneer of the uppermost rocks of the batholith across the Tertiary erosion surface through the volcanic rocks to the Blue-stone Mine Tuff. A small fault (Figure 5, black north-trending line) of uncertain affinity is shown in Proffett and Dilles (1984) and is shown as being internal to the volcanic rocks and tipping out along strike over a relatively short distance.

Fault set 3

The only significant fault in the study area that is a member of fault set 3 is the May Queen fault, although faults with a similar orientation occur elsewhere in the district (Proffett and Dilles, 1984; Schottenfeld, 2012) and to the southeast in the Wassuk Range (Surpless, 2010).

May Queen fault

The May Queen fault mapped by Proffett and Dilles (1984) is a moderately dipping fault within and to the east of the Singatse Range. The May Queen fault offsets the Singatse fault and creates gaps in its surface; in turn, the May Queen fault is dismembered by the Montana-Yerington and Sales faults into three smaller fault blocks (Figure 6). The rotation associated with movement on the Montana-Yerington and Sales faults results in variations in dips and strikes of the different fault-bounded fragments of the May Queen fault. The structurally lowest fragment is in the hanging wall of the Sales fault, where the May Queen fault dips ~10° ESE; the fault fragment located in the footwall of the Sales and the hanging wall of the Montana-Yerington fault dips ~38° NE; the fault fragment located in the footwall of the Montana-Yerington fault is dipping ~32°.
E (Figure 6a-b). All fragments are scoop- or shovel-shaped and face eastward (Figure 6a-b). Geologic maps of the hanging wall and footwall show that the trace of the Singatse fault in the plane of the May Queen juxtaposes Luhr Hill granite (Jpqm) against the uppermost portions of the Yerington batholith through the erosion surface and volcanic stratigraphy to the Bluestone Mine member and Lincoln Flat Andesite (Figure 6a-b). Another fault that may belong to this fault set (see discussion in “Significance of 3rd-generation faults”) was measured as striking N60°E and dipping 42° SE at the surface. The surface of the fault has slickenslides with a trend of S75°E and plunge ~32°.

Fault set 2

Faults of set 2 are closely spaced, northerly striking, gently easterly dipping faults that include the Singatse and underlying Blue Hill faults, as well as others shown on the map and cross sections of Proffett and Dilles (1984). The faults of set 2 are cut by faults of sets 4 and 3 and cut faults of set 1. The Singatse and Blue Hill faults are largely subparallel and thus are assigned to the same set; nonetheless, the Singatse fault cuts the downdip portion of the Blue Hill fault.

Singatse fault

The Singatse fault (Figure 7) is a gently dipping, concave-to-the-east fault that in map pattern wraps around much of the Singatse Range, with the northern and southern portions of the fault trace occurring near Mason Pass and Mickey Pass, respectively. To the east, the Singatse fault is structurally dismembered by the May Queen, Montana-Yerington, and Sales faults into a series of small, buried fault blocks. The geology of the southwestern portion of Singatse fault block is tightly constrained through abundant drill data (over 80 km of drilling at Ann-Mason in the last 55 years). The structure contour map of the Singatse fault reveals the overall strike of the fault is ~N05°W; it is curviplanar in geometry and dips ~13° E along the trough of the fault (Figure 7). Geologic maps of the footwall display the geology in the plane of the existing Singatse fault,
including the porphyry dike swarm (Jqmp) associated with the Ann-Mason deposit and the position of the 1A fault (described below under fault set 1). In addition, the geology was continued into up-dip, eroded portions of the fault surface by projecting the geology along cross section S-S’ up to the projected fault surface (Figure 8). Geologic maps of the hanging wall show a network of interacting hanging wall splays that repeat portions of the Oligocene volcanic succession in several places (Figure 7b). Several smaller faults create small gaps in the hanging wall and footwall of Singatse fault and have previously been interpreted by Proffett and Dilles (1984, section A-A’) to belong to the 3rd fault set, as they cut the Singatse and are truncated by the Montana-Yerington fault (Figure 7b). Stratigraphically below the volcanic rocks is the upper ≤1 km of Yerington batholith, which is offset by the Montana-Yerington fault. The Singatse fault is further dismembered by both the May Queen and Sales faults (Figure 7a-b). The hanging-wall portion of Ann-Mason dike swarm has been translated into these down-dropped fault blocks.

**Blue Hill fault**

The constraints on the nature of the Blue Hill fault are based on surface mapping, including an exploration trench (Figure 9a, c-d), and from drilling intercepts at the Blue Hill prospect, the Roulette target, and one deep hole to the northwest of Ann-Mason just beyond the Singatse fault (Figures 2, 10). At the surface, the Blue Hill fault is expressed as one to several shears of clay gouge ~8–20 cm in thickness (Figure 9a-d). A discrete slip surface with slickenlines was not observed. The Blue Hill fault is projected further down dip beneath the Singatse fault, though it has not been intercepted by drill holes at those depths. A point derived from the intersection of the section S-S’ (Figure 8) of this study with section A-A’ of Proffett and Dilles (1984) is also used as an additional constraint on the position of the Blue Hill fault (Figures 8, 10). In the Blue Hill area, the Blue Hill fault dips ~22°SE and is planar-curvilinear in geometry. This portion of the fault appears to be the northwestern side of a trough, or bend, in the fault (Figure 10a-b). Structure contours are projected northeastward until they are truncated by the Singatse fault. The geologic maps of the hanging wall and footwall of the fault surface show plutonic rocks of the Yerington batholith (all phases except the Luhr Hill granite) in the eastern portions, with the Oligo-Miocene volcanic rocks overlying the Tertiary erosion surface in the western-central portions. In the hanging wall of the Blue Hill fault, drill holes intercepted the Guild Mine member of the Mickey Pass Tuff.
Figure 7. Singatse fault surface maps (dark blue fault trace in Figure 2). A. Footwall geology layer superimposed with structure contours. Lighter colored areas are projected geology up into the air. B. Hanging-wall geology layer superimposed with structure contours. Contour interval is 100 m, with dashed contours projected into the air. Fault gaps from small faults that have been qualitatively closed are shown. The trace of the Ann-Mason ore body from the footwall is shown as dismembered fragments in the hanging wall. Section lines from Proffett and Dilles (1984) are noted with the section name and PD84. UTM coordinates (Zone 11) are in 1000 m intervals. See Figure 4 for legend.
beyond the position based on projection of the surface geology (Figure 10b). Using the architecture of the Singatse fault (see above) as a template, two hanging-wall splays are interpreted to be present in the hanging wall of the Blue Hill fault to satisfy the subsurface data (Figure 10b).

**Fault set 1**

There are ~15 closely spaced faults of similar orientations that are intercepted in drill core under the structural cover of the Singatse fault. The 1A fault is examined because it is relatively well exposed by drilling and may be the fault with the most offset in this set, although the amount of offset is smaller than for faults of the sets described above.

**1A fault**

The 1A fault presently strikes N61°W and dips 71°SW (Figure 11). It is planar in geometry and is truncated up dip by the Singatse fault (dark blue). Drill piercements show that the 1A fault is truncated at an elevation of ~1600 m and has been drilled down dip to an elevation of ~600 m. Surface geologic maps of the fault (Figure 11a-b) mainly reveal a swarm of porphyry dikes (Jqmp) crosscutting the McLeod Hill quartz monzodiorite (Jgd). Nonetheless, two distinctive geologic markers are also present: (1) a mass of the Luhr Hill granite (Jpqm) occurs in the structurally deeper, southern portions of hanging wall and footwall of the 1A fault, and (2) a discontinuous, but clear, trend of a distinctive type of porphyry dikes (defined by Souviron, 1976, as Jqmp-a dikes) that can be traced from the southeastern portion to the center of the hanging wall and footwall maps (Fig 11a-b).

**INTERPRETATIONS: RECONSTRUCTIONS BASED ON FAULT SURFACE MAPS**

**Crosscutting relationships of faults: Fault generations**

The faults have been heretofore grouped by their descriptive characteristics, primarily their differences in strike and dip, into four geometric sets. The shared features between the faults of the same sets as well as the consistent crosscutting relationships between the various fault sets indicate that each set can be regarded as temporally distinct generation of faults. Thus, the faults of the 4th generation are the youngest, and faults of the 1st fault generation are the oldest. According to Andersonian fault mechanics, normal faults initiate at high angles (58–68°) in the uppermost crust and rotate to lower angles concurrent with slip (Anderson, 1951; Collettini and Sibson, 2001). The rotated, lower angle faults can become locked when the stress required to produce continued slip along them is greater than is required to initiate a new set of high angle faults (Sibson, 1977). These locked, dismembered fault plane fragments are then buttressed between the high-angle, newly active faults (Proffett, 1977; Chamberlin, 1983; Gans et al., 1985; Wernicke and Axen, 1988; Davis et al., 2004).
4th-generation faults

Montana-Yerington fault

Unique piercing points present in the hanging wall and footwall that are used to determine the slip magnitude are shown in Figure 4. Along the southern portion of the fault, east of Mickey Pass, there is ~0.4 km of slip measured in the plane of the fault from the cutoff of the contact between the Weed Heights and the Guild Mine members of the Mickey Pass Tuff by the May Queen fault (Figure 4). Along the northern portion of the Montana-Yerington fault, the cutoff of the contact of the Bluestone Mine Tuff and underlying Singatse Tuff by the May Queen fault has a ~1.0 km of slip (Figure 4). The slip direction up the plane of the fault changes south to north from N45°W to N75°W (Figure 4). The higher magnitude of slip in the northern portion of the fault is constrained in the arcuate portion or trough of the fault, whereas the less displaced southern portion of the fault occurs along a more planar section of the fault (Figure 4). Slip increases to the north, and consequently, suggests that the fault is tipping out to the south. If the observed average change in offset of ~0.6 km over ~3.5 km is representative along strike, then the fault tip would be located ~2.8 km south of Mickey Pass.

Sales fault

Restoring the hanging-wall map over the footwall map results in a reconstruction with several unique piercing points from which to measure the slip in the plane of the Sales fault (Figure 5). Along the southern portion of the fault, the cutoff of...
Figure 10. Blue Hill fault surface maps (light blue fault trace in Figure 2). A. Footwall geology layer superimposed with structure contours. Lighter colored areas are projected geology up into the air. B. Hanging-wall geology layer superimposed with structure contours. Contour interval is 100 m, with broad dashed contours projected into the air and narrow dashed contours projected at depth. The projected location of the offset portions of the dike swarms in the footwall are shown. Section lines from Proffett and Dilles (1984) are noted with the section name and PD84. UTM coordinates (Zone 11) are in 1000 m intervals.
Figure 11. 1A fault surface maps (purple fault trace in Figure 2). A. Footwall geology layer superimposed with structure contours. B. Hanging-wall geology layer superimposed with structure contours. Contour interval is 200 m. The dark blue line in the top right of each map is the line of intersection with the Singatse fault, representing where the 1A fault is truncated by the Singatse fault. C: Footwall alteration layer. D: Hanging-wall alteration layer. E: Footwall copper grade layer. F: Hanging-wall copper grade layer. UTM coordinates (Zone 11) are in 200 m intervals.
Figure 12. Lower-hemisphere, equal area stereographic projections of data from faults and volcanic compaction foliation in ash-flow tuffs are shown through the rotations of the various fault blocks. The dashed lines are the volcanic rocks (compaction foliations dips at 60° = green, 70° = green-yellow, 80° = brown, 90° = black), solid lines are Montana-Yerington (red) and Sales (orange), solid lines are May Queen (strawberry red = 32° dip of May Queen, magenta = 35° dip of May Queen, maroon = 38° dip of May Queen), the solid lines are the Blue Hill (light blue) and Singatse (dark blue), and the dash-dot line is the 1A fault (purple). A: The present day configuration of the fault and compaction foliation planes. B: Compaction foliation and fault plane configuration following the restoration of the 4th generation faults with 10° of tilting about a N-S horizontal axis. C: Compaction foliation and fault plane configuration following the restoration of the 3rd generation faults with 12° of tilting about a N-S horizontal axis. D: Compaction foliation and fault plane configuration following the restoration of the 3rd generation faults with 15° of tilting about a N-S horizontal axis. E: Compaction foliation and fault plane configuration following the restoration of the 3rd generation faults with 18° of tilting about a N-S horizontal axis. F: Compaction foliation and fault plane configuration following the restoration of the 2nd generation faults with 19°-25° of tilting (depending on the amount of tilt assigned to the 3rd generation faults) about a N-S horizontal axis to return the Singatse fault to 60°. G: Compaction foliation and fault plane configuration following the restoration of the 2nd generation faults with 32°-38° of tilting (depending on the amount of tilt assigned to the 3rd generation faults) about a N-S axis to return the shallowest dipping volcanic units to horizontal. Stereographic rotations were performed with the program OSXStereonets (Allmendinger et al., 2012).
the Tertiary erosion surface by the May Queen fault results in ~1.6 km of slip. Along the northern portion of the Sales fault, the restoration of the cutoff of the Singatse fault by the May Queen fault results in ~1.0 km of slip. The higher magnitude of slip along the southern portion of the fault occurs in a bend in the plane of the fault, possibly representing a salient in the fault (Figure 5). This geometry constrains the sense of motion, as the fault should move down the trough with minimal lateral motion across an adjacent ridge. The slip direction changes north to south from S30°W to S60°W. The magnitude of slip increases to the north, suggesting that the fault is tipping out to the north. Using the observed average increase of ~0.6 km over ~2.5 km, the fault tip is predicted to be located ~3.8 km further north along strike, due east of the MacArthur pit.

Significance of 4th-generation faults
These two faults, representing the youngest normal fault system in Yerington, both dip ~50°E, suggesting that they have undergone 10° of westward tilting since they first initiated if they initiated at a dip of 60° (Figure 12a-b). This interpretation is consistent with the gentle westward dips of surface exposures of basaltic andesite lava flows near the Western Nevada mine southwest of the town of Mason (Proffett and Dilles, 1984) and with similar dips on the top of bedrock on the floors of modern half-grabens, as shown on the cross sections of Proffett and Dilles (1984) that are constrained by drilling and geophysical constraints.

The Montana-Yerington and Sales faults exhibit opposing directions of increasing displacement, as is typical of adjacent faults forming segments of a modern normal fault system (Peacock and Sanderson, 1997). The map pattern (as seen on in the fault surface maps of the May Queen, Figure 6a-b), which shows increasing widths of fault gaps to the north and south and an unfaulted zone bridging the area between the two faults, suggests that this is a buried relay ramp underneath the alluvium of Mason Valley.

3rd-generation faults

May Queen fault
Geologic markers that constrain the magnitude and direction of slip in the southern portion of the fault surface are the contact of a porphyry dike (Jqmp) and the Border quartz monzonite (Jbqm) cut by the Singatse fault (Figure 6); they result in a restoration of ~1.3 km of slip. Markers used in the northern portion of the fault are the contact of the McLeod Hill quartz monzodiorite (Jgd) and the Border phase (Jbqm) against the Tertiary erosion surface, which result in a slip of ~1.4 km. Thus the increases in displacement to the north on the May Queen is ~0.1 km over 2.7 km, or 60 m per km. Following closure of the 4th generation fault gaps in the fault surface, the present-day slip directions, which range from N35°W to N45°W rotate 5° northward, thus to N30°W to N40°W and steepens the dip of the fault to ~42–48° (Figure 6). This is based on the assumption that the footwall of the Montana-Yerington has not undergone any vertical axis rotation.

Overlaying the slip paths on the structure contours of the fault show that they are moving at acute angles (~20°) to axes of trough in the fault. Assuming the fault initiated at 60° (Anderson, 1951), this might imply that the fault underwent ~12–18° of horizontal-axis tilting as a result of differential movement on the younger, crosscutting faults (Figure 12c-e).

Significance of 3rd-generation faults
This fault generation is not well exposed in the Singatse Range compared to the Wassuk Range and is described to offset the earlier 2nd generation faults “slightly” (Dilles and Gans, 1995, p. 482). The reconstruction based on the fault surface maps presented here shows that this generation has ~40% greater offset than previously depicted (<1 km of slip derived from D-D’ of Proffett and Dilles, 1984). This could be due to the fact the inferred slip direction is at ~45° to the lines of section used in previous reconstructions and was unable to account for this in- and out-of-section movement. If this one reconstruction were broadly valid, then it would require amending the statement by Proffett (1977, p. 255) that most, if not all, faults in Yerington have “no significant north-south component of displacement.” The May Queen fault can then be characterized as an oblique-slip normal fault with a right-lateral slip component, making it analogous with the oblique normal faults mapped in the Wassuk Range by Dilles (1993). Whether the slip direction of the May Queen is representative of the entire 3rd generation or is an outlier is unclear, and this uncertainty generates an alternate possibility. If a second fault of this generation were to have an opposing direction of increasing displacement, as is observed for the 4th-generation faults, then the net slip direction of the 3rd-generation fault system could have been east-west.

2nd-generation faults

Singatse fault
One important geologic marker for determining the slip on the Singatse fault is the Tertiary erosion surface cut by an earlier normal fault (southern circled location, Figure 7). Other piercing points are created by the position of the Ann-Mason porphyry dike swarm relative to other phases of the batholith (Figure 7). Several of the smaller faults in the hanging wall that create gaps have been qualitatively closed, as their lateral extents are entirely within the fault surface map. The broad trough-shaped geometry of the fault helps constrain the restoration, as slip oblique to fault grooves or corrugations is more difficult to accomplish, as it places a larger strain on wall rocks (Needham et al., 1996). Following the closure of the younger fault gaps, the restoration of the Singatse fault shows minimal rotation. The up-dip slip direction, measured near the erosion surface, is N85°W; ~3.6 km of slip is inferred along the northern portion of the fault block versus ~3.8 km of slip along the southern portion of the fault block.
Blue Hill fault

Several piercing points are available to measure the amount and direction of slip in the plane of the fault (Figure 10). To the south, the contact of the Bear quartz monzonite (Jqm) and McLeod Hill quartz monzodiorite (Jgd) in the Roulette area where drill holes cut the Tertiary erosion surface indicates 2.4 km of slip. To the north, the cutoff of the Bear quartz monzonite (Jqm) and Border quartz monzonite (Jbqm) contact by the Tertiary erosion surface (Figure 9a, c–d) indicates a slip here of 2.8 km. This demonstrates that slip on the Blue Hill fault is increasing to the north. The present-day slip directions change slightly (~2°) from south (N84°W) to north (N82°W), consistent with a slight change in slip magnitude moving along the strike of the fault.

Significance of 2nd-generation faults

This generation of faults, with slip magnitudes over twice that of the later generations of faults, was responsible for a large fraction of the total extension in the district. The tilting of the later two generations of faults equates to 22–28°; adding this amount to the down-trough dip of the Singatse fault steepens the fault to ~35–41° prior to the initiation of the 3rd generation faults. Additional tilting of ~19–25° would place the Singatse fault back at ~60° based on the assumption that the fault initiated at ~60° (Anderson, 1951; Dilles and Gans, 1995; Collettini and Sibson, 2001). This amounts to a minimum of 47° of westward tilting due to faulting in the Yerington district by returning all faults to ~60° (Figure 12f). A key structural marker in previous reconstructions in the Yerington district has been the dips of the volcanic units, with the assumption that they originally were deposited horizontally, although caution is warranted in areas such as this where tuffs were deposited in paleovalleys due to differential compaction (e.g., Henry and Faulds, 2010). The average dip of volcanic rocks in the district is 60° to 90° to the west. The fault restorations thus far would take volcanic rocks to horizontal in cross-sectional restorations, that the slip direction is parallel to the line of the Singatse fault along the side of a trough, giving it a lower apparent dip; as the down-trough direction of the Singatse fault is at an acute angle to the line of section, which is nearly due E-W at this location, the restoration would still return the volcanic rocks to horizontal in cross-sectional view along A-A’. This is the implicit assumption in cross-sectional restorations, that the slip direction is parallel to the section and entirely in the plane of the fault. In the case of Yerington, this is valid for the faults of the 2nd and 4th generations, less so for faults of the 3rd generation, and does not allow the faults of the 1st generation to be accounted for in the same two-dimensional reconstruction.

Although the Blue Hill and Singatse faults have been assigned to the same generation, the relationship between the Blue Hill and Singatse faults deserves further analysis. In terms of geometric relationships, the trace of the Blue Hill fault is truncated by the Singatse fault at the modern surface (Proffett and Dilles, 1984), the Blue Hill fault presently dips southeast (Figure 10), and the Singatse dips east (Figure 7). In terms of kinematics, there is also a difference in slip of ~1 km between the two faults. Two potential scenarios are proposed: A) that the Blue Hill fault entirely predates the Singatse fault, and B) that the two faults initiated more or less concurrently, and as the fault system evolved the Singatse grew and breached the Blue Hill fault, thus inactivating it. In scenario A, the Singatse fault, being younger, would have offset the Blue Hill fault through its life cycle, suggesting that the continuation of the Blue Hill fault in the hanging wall of the Singatse fault should be ~3.8 km east of the present truncation of the Blue Hill fault. In scenario B, both faults would have similar ~2.6 km slip magnitudes when the Singatse fault cut and inactivated the Blue Hill fault. This would then suggest that the continuation of the Blue Hill fault would be ~1.2 km east of the present truncation of the Blue Hill fault. To our knowledge, neither of these hypotheses has been tested in drilling or mapping.

The attitude of the exposed portion of the Blue Hill fault has hereto been ascribed to being located on the side of a scoop. The projected, in-the-air, continuation of the structure contours north of the Blue Hill fault trace must clear all current topography at minimum. The in-the-air fault surface at some point might change inflection along a bend such that it might intersect the modern surface again. To the north of the Blue Hill area the Martha Washington fault dips 15° NNE and could be the hypothesized continuation of the Blue Hill fault (Figure 2). The eroded portion of the fault projects over the Blue Hill deposit as a salient in the fault, and the modern, exposed fault segments would be embayments in the larger fault. This hypothesis is consistent with the approximate alignment of the Tertiary erosion surface on Proffett and Dilles (1984) from the hanging wall of the Blue Hill fault to the hanging wall of the Martha Washington fault.

1st-generation faults

1A fault

The geologic markers used for restoring the fault are the structurally deep contact between the Luhr Hill granite (Jpqm) and the McLeod Hill quartz monzodiorite (Jgd) and aligning the distinctively textured porphyry dikes (Jqmp-a). In its present orientation, the 1A fault has ~230 m of apparent left lateral slip in plan view (Figure 11). The slip runs nearly parallel to the modern strike of the fault, i.e., restoring the fault N70°W parallel to structure contours yields true, not apparent, slip (Figure 11). This amount of slip is additionally supported by
hanging wall and footwall maps of alteration types and copper grades (Figure 11c-f). As this fault is shown to be truncated the Singatse fault, then this fault must have been rotated passively by the later three generations of faults as they tilted ~60° westward. Stereographic rotations of the 1A fault through the tilt history of the younger faults restores the 1A fault to a strike of N86°E and a dip of ~56°S (Figure 12a-g). Coupling the offset direction with this rotation, the 1A fault was initially a down-to-the-south normal fault with a dip-slip displacement of 230 m.

Significance of 1st generation faults

This generation of faults has little attention in the literature to date. Faults of similar orientations have been known by previous workers in the district (Souviron, 1976; Figure 3 of Dilles and Einaudi, 1992) but have received little attention, presumably due to the relatively small offset and their orientation, which cannot be portrayed easily in east-west reconstructions. Faults of similar orientations that predate high-magnitude extension have been observed in east-central Nevada (Gans, 1990) and may represent possible analogs to the 1st-generation faults in Yerington. Other faults in the Yerington district are observed to record small amounts of strike-slip offset. These are hypothesized to be genetically related to the 1A fault set. Indeed, a possible surface continuation of the 1A fault is observed in the hanging wall of the Blue Hill fault (Figure 10b). This fault has a similar strike and separation. The lack of observed connection between the two faults is attributed to the strike of the fault being subparallel to the strike of the Jqmp dikes between the two areas and has hitherto been unrecognized. Further characterization of these faults and their offsets and faulting history would be a useful avenue of future work.

IMPLICATIONS FOR MINERAL DEPOSITS AND EXPLORATION

Each of the porphyry copper deposits in the Yerington district is related to a separate swarm of porphyry dikes, each centered on a cupola of the Luhr Hill granite (Proffett, 1979; Dilles and Proffett, 1995). Each set of Jurassic dikes was emplaced as a northwest-striking, subvertical swarm, with a central knot located over the top of the cupula (Dilles and Proffett, 1995). Porphyry copper mineralization with associated potassic alteration dominates in the central knot of the dike swarms, whereas IOCG mineralization and calcic (endoskarn) and other forms of alteration dominate the distal fins of the swarms (Dilles et al., 2000a).

Implications for dismemberment of Ann-Mason porphyry system

The Ann-Mason ore body is located within the Ann-Mason dike swarm (Figure 9 of Seedorff et al., this volume). The deposit is located underneath post-ore structural cover, beneath Tertiary volcanic rocks that occur in the hanging wall of the southwestern most portion of the Singatse fault. The ore body is truncated by the Singatse fault at the surface and by the Blue Hill fault at depth. Restoration of the Blue Hill fault places the Ann-Mason dike swarm over the dike swarm at Blue Hill (Figures 7, 10), thus suggesting that the Blue Hill area is the pre-tilt northwestern lateral continuation of the Ann-Mason porphyry system. The Ann-Mason ore body lies ~1.5–2 km below the Tertiary surface, whereas the Blue Hill ore body is ~1 km below the Tertiary surface in pre-tilt position, placing it at structurally higher levels in the Ann-Mason dike swarm. The portion of the Ann-Mason ore body that is truncated by the Singatse fault has been translated 4 km east, where it is further dismembered and down dropped by younger generations of faults. Thus, the pre-tilt southeastern lateral continuation of the Ann-Mason porphyry system is buried under the cover of Mason Valley, with a large fragment of it located near sea level beneath the Yerington pit (Figure 7b). Although the dike swarms associated with the Yerington mine and the Ann-Mason deposit each dip ~45°N, they are vertically separated and thus constitute two distinct dike swarms and associated hydrothermal systems in reconstructed view (Dilles and Proffett, 1995). The magnitude of slip on the 1A fault, though modest in comparison to other faults in the district, is significant in the context of block modeling of grades and mine planning.

Implications for dismemberment of Casting Copper dike swarm and Roulette target

The skarn deposits located in metasedimentary rocks south of Ann-Mason are related to an additional dike swarm that intruded the Lud wig septum. The dikes have been conduits for mineralizing fluids during their emplacement and cooling histories (Harris and Einaudi, 1982; Dilles and Proffett, 1995; Einaudi, 2000). The mineralizing fluids would have been sourced from a central knot of porphyry dikes presumed to occur at depth, from which the fluids would have risen and moved laterally until they encountered the carbonate rocks, forming the copper-bearing garnet-pyroxene skarn deposits at Casting Copper, Ludwig, Douglas Hill, and McConnell. One possible target, identified by Bronco Creek Exploration and optioned to Entrée Gold, is what is known as the Yerington West property (Eurasian Minerals, 2014) or Roulette target (Entrée Gold, 2010), which was initially drilled in 2010. Entrée Gold reported mineralized intercepts, but the potassic core apparently has yet to be drilled. Figure 8 shows where the Casting Copper dike swarm might project into the hanging wall and footwall surfaces of the Blue Hill fault, which might be used for further exploration of the Roulette target (Figure 2).

DISCUSSION

Fault surface maps: Three-dimensional reconstructions

Structural contour maps have been routinely generated
to define the three-dimensional extents of faults and bedding surfaces for a century or more, especially in the petroleum industry. Most structural reconstructions, however, have been based on carefully chosen lines of cross section (e.g., Dahlstrom, 1969) and thus are a two-dimensional technique. Fault surface maps, however, are a method employed to analyze data in three dimensions (Keefer, 2010; Schottenfeld, 2012; Seedorff et al., this volume). In the petroleum industry, fault surface maps are used and are known as fault cutoff maps or Allan diagrams (Allan, 1989; Tearpock and Bischke, 2003; Groshong, 2006, p. 229) but are not commonly used in the minerals industry.

In the Yerington district, two-dimensional structural reconstructions have been a powerful exploration tool, resulting in the discovery of the Ann-Mason deposit (Proffett, 1977; Proffett and Dilles, 1984; Hunt, 2004). Faults of the second through fourth generations have similar northerly strikes, allowing for robust reconstructions along east-west cross sections (Figure 15, Proffett, 1977; Section A-A', Proffett and Dilles, 1984). Faults of the first fault generation such as the IA fault (Figure 11), however, strike at acute angles to the section and thus cannot be readily restored using the same cross section. In this study, the fault surface maps that incorporate the abundant new drill hole data around Ann-Mason were used to constrain the shapes of several faults in the Yerington district, to identify geologic markers and piercing points, and to perform stepwise reconstructions. Movement on the IA fault has been restored using lithologic markers, and the resulting offset also is consistent with the patterns of alteration and copper grades. Significant variations in the magnitude and direction of slip across fault surfaces are observed for several faults in the Yerington district. Reconstructions can be used to aid exploration of the dismembered hydrothermal systems along both the Ann-Mason and Casting Copper dike swarms.

The quality of the geologic inputs has a large impact on the utility and validity of structural reconstructions, whether designed for scientific or practical purposes. Techniques such as fault surface maps can be used in almost any situation, but the advantages are most apparent where three-dimensional constraints are abundant. Perhaps the greatest value in wider use of fault surface maps would be to better portray the locations and types of three-dimensional data available, which would permit readers and other users to have a better understanding of the nature of the constraints and thus to evaluate better the validity of a proposed reconstruction hypothesis. Readers and other users also might more easily develop and evaluate alternative hypotheses and more readily dispense with uninviable proposals.

Porphyry systems dismembered and tilted by normal fault systems

Throughout the southwestern United States, porphyry deposits are commonly structurally dismembered and tilted by normal faults (Wilkins and Heidrick, 1995; Seedorff et al., 2005; Maher, 2008). The surface geology around porphyry deposits then more nearly represents a series of cross-sectional views of the porphyry systems as the amount of tilting approaches 90°, exposing the vertical and lateral extents of these paleohydrothermal systems. Examples include: Ajo (Hagstrum et al., 1987), Globe-Miami (Maher, 2008), Hall (Shaver and McWilliams, 1987), Kelvin-Riverside-Tea Cup-Grayback (Nickerson et al., 2010), Robinson (Seedorff et al., 1996; Gans et al., 2001), and San Manuel-Kalamazoo (Lowell, 1968; Force et al., 1995), in addition to Yerington. Coupling these exposures with the abundance of drill data in the areas around these mined and prospective porphyry deposits has furthered our understanding of and appreciation for structural dismemberment by normal faults in the Yerington district is what led to the discovery of the Ann-Mason porphyry deposit (Hunt, 2004). The 0.15% Cu ore shell of the Ann-Mason deposit is truncated by the Singatse fault east of UTM 304,400E and between 4,317,300N and 4,318,000N (Jackson et al., 2012). The Singatse fault has translated the offset portion of the ore shell east, where it has been further dismembered by younger normal faults. A reconstruction presented here indicates that the continuation of the offset Ann-Mason ore body is currently located at depth (~1.5 km) beneath the Yerington pit. The Casting Copper dike swarm is related to skarn mineralization, and the core of the related porphyry system is as yet undiscovered. The increased control on the subsurface geometry of the Blue Hill fault provided better constraints on where the dike swarm is projected and its continuation across fault blocks, which could be used to guide drilling for ore in the footwall or hanging wall of the fault.

When exploring porphyry prospects, deposits, and systems, it should be the practice of every geologist to bear in mind the level in the system that they are examining. Moving across faults and seeing stark changes in alteration-mineralization zonation is indicative of large movements along the faults, which may yield exploration targets. Complexly deformed districts such as Yerington or Robinson could hide offset pieces of the system at depth and/or under structural cover or post-mineral cover.

Geometry and growth of normal faults

Normal faults are the time-integrated products of crustal extension, recording the variety of mechanisms and processes occurring during fault rupturing and slip. Individual exposures are commonly segments of large faults, which in turn are part of
larger fault systems, where several to many fault segments act in tandem to extend an area (Jackson and White, 1989; dePolo et al., 1991). Normal faults display a variety of geometries and morphologic characteristics. They are commonly not perfectly planar but instead may exhibit an overall concave upward curvature (Proffett, 1977; Jackson and McKenzie, 1983). Many faults have the same general strike along their traces, but with local variations as the fault plane curves and then returns to the overall strike direction again. This curvature in the fault plane can represent locations where a relay ramp was breached between two overlapping tips of discrete faults in the same system and took over to continue transferring strain between the faults as slip continued (Peacock and Sanderson, 1994; Childs et al., 1995; Walsh et al., 1999). Displacement has a complex relationship to geometry, commonly greatest near the center of the fault and decreasing to zero at the tips at either end (Peacock and Sanderson, 1997). The style of normal faulting observed may fall along a spectrum, from the “domino-style” end member where faults slip and rotate to lower angles where they may lock and are then cut by higher angle faults due to the stress differential required for continued slip (Proffett, 1977; Davison, 1989), to the metamorphic core complex end member where high-angle normal faults may be kinematically linked to movement on a gently dipping, basal master fault (Whitney et al., 2013; Platt et al., 2015). The question of just how the crust extends, its relationship to fault geometry, and the degree to which faults are kinematically linked remains a matter of debate and continued research (Jackson and McKenzie, 1983; Roberts and Yielding, 1994; Wernicke, 2009).

In the Yerington district, years of geologic mapping and drilling have provided abundant information regarding the local strikes and dips of normal faults at the surface and their geometry at depth. The faults are not perfectly planar nor are they listric—they are instead curviplanar. Along strike the faults exhibit embayments and salients in outcrop that produce troughs and ridges in the third dimension. The recesses and salients in the youngest, 4th-generation faults, if rotated to lower angles, would produce the troughs, or scoops, and ridges, or noses, that are observed in faults of older generations. The two faults of the 4th generation that were analyzed display opposing directions of increasing slip, suggesting that a buried relay ramp is present between them. The Singatse and Blue Hill faults contain hanging wall splays, with no footwall splays observed. This study also suggests that the Blue Hill and Martha Washington faults may represent adjacent embayments in a single fault that at the surface have become separated by truncation by the Singatse fault and subsequent erosion (Figure 2).

Although the increase in new drilling in the last decade, including in the greater Ann-Mason area, augments the known exposures of faults, the fault surface maps presented here underscore the uneven spatial distribution of constraints and the considerable uncertainties that remain in the geometry of faults in the district. These uncertainties contribute to the opportunity for new mineral discoveries in the Yerington district.

**FUTURE WORK**

Further work in the Yerington district could lead to a better understanding of the geometry and kinematic history of normal faulting. In particular, faults of the 3rd generation, including the May Queen fault, deserve further study to determine whether they indeed have a significant strike-slip component of offset. Fault surface maps of the rest of the 1st-generation faults, exemplified by the 1A fault, might lead to a better understanding of this generation of faults and its geodynamic significance, as well as better defining the geology of the Ann-Mason deposit. Additional drilling south of Blue Hill might further constrain the subsurface geometry of the Blue Hill fault and aid exploration for mineralization that seems to be associated with the Casting Copper dike swarm. Detailed mapping and exploration in the hanging wall of the Singatse fault could delineate the continuation of the Blue Hill fault north of Ann-Mason and define its relationship to the Martha Washington fault (Figure 2).

**CONCLUSIONS**

Faulted and tilted mineralized systems provide rare opportunities to describe the three-dimensional characteristics of faults. Additionally, the abundant recent drill-hole information and detailed mapping in the greater Ann-Mason area provide new constraints in the Yerington district. The data permit more robust three-dimensional structural reconstructions to quantify and to test theories and conventional wisdom about continental extension and the relationship of the structurally dismembered porphyry systems in the district. Fault surface maps are a tool to describe along-strike and down-dip variations and to portray the associated three-dimensional constraints on fault geometry. The normal faults in the Yerington district do not have strongly listric geometries, but rather are curviplanar. An analysis of the May Queen fault, a 3rd generation fault, suggests that it has a greater magnitude of slip than previously reported and may have a markedly different slip direction than faults of the 4th and 2nd generations. For the first time, a series of closely spaced, subparallel faults of an earlier (1st) generation are characterized. The 1A fault, which may be the fault in this generation that has the most offset, has 230 m of apparent dextral slip. Faults of this set presently strike southeast and dip steeply to the southwest but formed as steeply southwest dipping, dip-slip normal faults.

Restoration of movement on the Blue Hill fault places the Ann-Mason deposit over the Blue Hill deposit; both deposits are structurally offset pieces of mineralization related to the Ann-Mason dike swarm. The Casting Copper dike swarm could host porphyry-style mineralization at depth on one or both sides of the Blue Hill fault.

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