University of Nevada, Reno

Mid- to Late-Paleozoic Deformation on Buck Mountain, Nevada

A thesis submitted in partial fulfillment of the
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by
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Abstract

New detailed structural mapping of the strata capping Buck Mountain in White Pine Co., Nevada, has documented two distinct episodes of folding. The structures and angular unconformities at Buck Mountain are consistent with late-Paleozoic deformation and regional unconformities documented previously elsewhere in northern and central Nevada.

Folds in the Morrowan-Atokan Ely Limestone are erosionally truncated and depositionally overlain by the mid-Desmoinesian Hogan Formation. The lacuna developed at this stratigraphic level is temporally consistent with a regional unconformity ("C5" of Snyder et al., 2000). This unconformity is an upper boundary on regional west-vergent folding. In addition, two disconformities are found on Buck Peak. Both disconformities correlate with known regional unconformities, one Desmoinesian-Missourian ("C6") and the other Missourian to Sakmarian (mid-Wolfcampian) ("P1").

F1 folds are pre-Desmoinesian in age and are the oldest structures discussed. These folds range from close west-vergent to open, upright, and symmetric folds. The range of fold geometries is driven by localization of strain during shortening. F1 folds are erosionally truncated and refolded around a younger northwest fold axis. When F1 folds are restored, their original plunge is ~10° to the northeast.

The map-scale syncline fold at Buck Mountain is a syncline developed in the Ely Limestone, Hogan Formation, and both Lower and Upper Strathearn formations and is therefore part of a second fold set (F2). It is a gentle to open, symmetric, upright, cylindrical fold plunging ~15° to the northwest (323°) with a wavelength of about 1 km and unknown amplitude. The age of this fold is poorly constrained at Buck Mountain (post-Sakmarian to Oligocene), but it appears to correlate with Mesozoic folds in adjacent ranges.

No evidence was found for low-angle faulting on Buck Mountain. Previous work identified a single attenuation fault at the base of the mountain (Nutt, 2000). In addition, reconnaissance work described intense folding at the top of the range, suggesting the presence of a different low-angle fault there. However, this study found that the folds are not localized around structurally defined surfaces. Rather, they occur at all structural levels. Thick massive carbonate layers form gentle long wavelength folds and local minor faults with 2-3 meters of offset. Thinner-bedded carbonate layers form open folds with shorter wavelengths. The contrast in fold style and apparent intensity is interpreted as a competency response to shortening between thick- and thin-bedded carbonate layers.

The presence of mid-Pennsylvanian folds at Buck Mountain is important because it: 1) correlates with other sub-C5 folds and faults in eastern Nevada and extends the known geographic extent of these structures, 2) helps constrain the orientation of the regional Pennsylvanian deformation, and 3) documents a regional eastward decrease in intensity of mid-Pennsylvanian folds and faults.

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Introduction

Traditional Model and Evidence for Revision

The traditional view of the Paleozoic and early Mesozoic tectonic evolution of western Laurentia is punctuated by two orogenic events. These two events are the Devonian-Mississippian Antler orogeny and the Permian-Triassic Sonoma orogeny (Roberts et al., 1958; Silberling and Roberts, 1962). The Antler orogeny is generally associated with the eastward emplacement of the Roberts Mountains allochthon. The Sonoma orogeny is associated with eastward emplacement of the Golconda allochthon. In the traditional model the intervening time is thought of as a time of quiescence. However, structures and/or unconformities observed by several different studies (e.g., Dott, 1955; Ketner, 1977; Snyder et al., 2000; Trexler et al., 2003; 2004; Sweet, 2003; McHugh, 2003; Villa, 2007; Linde, 2010; Siebenaler, 2010) are not temporally attributable to either the Antler orogeny or the Sonoma orogeny. These studies document repeated basin inception, folding, and erosional truncation at many different locations during late Paleozoic time. Several studies have pointed out that the traditional model is flawed and needs to be revised to explain these observations.

Structures have been documented in eastern and central Nevada that cannot be attributed to either the Antler or Sonoma orogeny (e.g., Dott, 1955; Erickson and Marsh, 1974; Ketner, 1977; Theodore et al., 2003; Trexler et al., 2003; 2004). Locally, several structures previously interpreted as thrust faults have been reinterpreted as unconformities (Trexler et al. 2004). This reinterpretation is supported by robust biostratigraphy. The field relations show truncated folds and faults depositionally overlain by significantly younger strata. Basin inception, folding, and erosional truncation are repeated several times in central and eastern Nevada throughout Pennsylvanian and Permian time (e.g., Dott, 1955; Ketner, 1977; Trexler et al., 2003; 2004). Mounting data suggest multiple mid- to late-Paleozoic tectonic events (Trexler et al., 2003; 2004; Sweet, 2003; McHugh, 2003; Villa, 2007; Cashman et al. 2008; Linde, 2010; Sibebenaler, 2010; Cashman et al., in press). Newer data show that the folds, faults, and unconformities are regionally significant events in northern and central Nevada.

Criteria for selecting Buck Mountain for study

Buck Mountain was selected for structural analysis for four reasons:

1. Pennsylvanian and Permian rocks are present and well expressed
2. Detailed biostratigraphy has already been done
3. Kinematics of structures had not been determined
4. Location is southeast of similar studies

1) Pennsylvanian and Permian rocks are necessary to constrain the age of late Paleozoic deformation. On Buck Mountain the youngest rocks present are Early Permian in age and therefore folding and faulting younger than Early Permian is difficult to constrain. 2) Detailed biostratigraphy has been done on Buck Mountain (Payne and Schiappa, 2000). Accurate age determinations for the Pennsylvanian and Permian rocks constrain the timing of folding and faulting. The age of the stratigraphy also allows for regional correlation of structures and unconformities. 3) Folds appeared to be intense and localized high in the Ely Formation (Jim Trexler and Walt Snyder Pers. Com.; 2008). The

kinematics of the structures were unknown. The location however, was noted as a potential study area to further document mid- to late-Paleozoic structures. 4) Buck Mountain is farther south and east than previous studies, allowing us to extend the known geographic distribution of regional extent late Paleozoic deformation.

Purpose of this study

The seven objectives for this study are:

1. Construct a geo-referenced geologic map, with cross-sections
2. Determine the nature of any unconformities
3. Determine the depth of incision of unconformities
4. Describe the kinematics of folds and faults
5. Constrain age(s) of folds and faults
6. Provide additional age constraint on regionally significant folds and faults
7. Revise the known geographic extent of late Paleozoic structures

1) A geologic base map is necessary for post-mapping structural analysis. A geo-referenced geologic base map will also aid future studies done on Buck Mountain. 2) The age of Pennsylvanian and Permian unconformities at Buck Mountain was previously established; however the contact relationships were not documented. The nature and geometry of the unconformable contacts is of significance in a regional context. 3) The depth of erosion along the unconformable contacts is of interest when correlating unconformities in a regional context. The erosive nature of an unconformity is such that significant erosive events remove earlier unconformities. 4) Several locations in central and eastern Nevada document unique, unconformably trimmed folds and faults. 5)

Precise timing of several distinctive folding and faulting events as well as regional unconformities is integral to regional correlation. 6) This study is a portion of a larger investigation of mid- to late-Paleozoic deformation in central and eastern Nevada. Therefore, correlation of the folding and faulting can constrain shortening direction and the intensity of structural development on a regional scale. 7) The regional extent of different structures is important in determining the tectonic significance of each deformational event.

Brief Outline of Thesis

This thesis starts with a brief review of background material relevant to this study. Next is a short discussion of the methods used to document the structural and stratigraphic relationships. A brief discussion of the stratigraphy present on Buck Mountain highlights the age, rock type, and contact relationships of the upper Paleozoic units. The structure discussion starts with the geometry and location of structures found on Buck Mountain. It finishes with the number of structures developed, their kinematics, and the relative age of structures documented on Buck Mountain. A brief geological history of Buck Mountain follows the structural data. Next is a section discussing regional correlation , and implications of the results. The conclusions section is a short list of the findings of this study and ideas for future work.

Background

This section provides background information in three main contexts: 1) regional geologic setting, 2) structures surrounding Buck Mountain, and 3) previous structural descriptions of Buck Mountain. This is not a comprehensive examination of the Paleozoic and younger sedimentation and deformation in eastern Nevada. It is meant as a summary of specific sedimentological and structural events relevant to Buck Mountain.

Buck Mountain is located in eastern Nevada approximately 80 km northwest of Ely, Nevada (Figure 1). The study area is on the eastern edge of the Central Nevada Thrust Belt, east of the Roberts Mountain and Golconda allochthons, and south of the Ruby Mountains Metamorphic Core Complex (Figure 2). Buck Mountain is composed of rocks deposited in the Morrowan-Atokan Ely, mid-Desmoinesian Hogan, and Missourian-Sakmarian Strathearn basins (Dott, 1955; Rich, 1977; Stevens, 1977; Payne and Schappa, 2000; Sweet 2003).

Brief Structural History of Eastern Nevada

This section is an abbreviated chronologic summary of the structural evolution of eastern Nevada. It focuses on several events relevant to either Buck Mountain or to the study of mid- to late-Paleozoic deformation in central and eastern Nevada.

Antler Orogeny

The Antler orogeny is expressed as the emplacement of the Roberts Mountains allochthon eastward along the Roberts Mountains thrust (Roberts, 1951)(Figure 2). The orogeny is Devono-Mississippian in age, dated by the sediment deposited in the Antler Foreland Basin. The Roberts Mountains thrust places rocks of the western facies of the Laurentian Paleozoic Miogeocline over rocks of the eastern facies, with displacement of as much as 140-200 km (Roberts, 1951; Nilsen and Stewart, 1980; Speed and Sleep, 1982; DeCelles, 2004; Dickinson, 2006). The Roberts Mountains thrust can be traced south-southwesterly from ~115.5° to ~118° W longitude (Oldow, 1984) (Figure 2). The Antler orogeny formed a long-lived topographic highland. The Antler highland shed clastic material both west into the Havallah Basin and east into the Antler Foreland Basin (Stevens, 1977; Jansma and Speed, 1995). Rocks at Buck Mountain are entirely younger than the Antler orogeny. Deformation related to the Roberts Mountain allochthon ends west of Buck Mountain and was not evident in the study area.

Antler Overlap Sequence

The Antler Overlap Sequence is a suite of sedimentary rocks unconformably overlying folded and faulted rocks of the Roberts Mountain Allochthon and the Antler Foreland Basin (Saller and Dickinson, 1982). It is important because it brackets the duration of the Antler orogeny. The rocks deposited in the Antler Overlap Sequence are Pennsylvanian and Permian in age. Internally the primary formations of the overlap assemblage are folded, faulted, and bounded by unconformities. The unconformities are consistent with named regional Paleozoic unconformities and structures (Snyder, 2000;

Villa, 2007; Cashman et al. in press). The broad term “Antler Overlap Sequence” only obscures the internal stratigraphy and structural complexity and unconformities. For more explanation see Unconformities and Deformation sections below.

Sonoma Orogeny

The Sonoma orogeny is expressed as the emplacement of the Golconda allochthon eastward along the Golconda thrust (Figure 2). The Sonoma orogen is Permo-Triassic in age (Vetz, 2010). It is similar to the Antler orogeny in that it tectonically places western basinal sediment of the Havallah and Schoonover sequences over the Antler Overlap Sequence (Stevens, 1977; Miller et al., 1984; Dickinson, 2000) (Figure 2). As much as 70 km of displacement is observed on the Golconda thrust in central Nevada (Garbrielse et al., 1983). The Golconda thrust can be traced south-southwest from ~115°-~119° W longitude and roughly parallels the Roberts Mountains thrust (Oldow, 1984) (Figure 2). The Golconda allochthon comprises Devonian basalt and chert, Mississippian volcaniclastic and fine grained siliciclastic rocks, and Pennsylvanian-Permian limestone (Miller et al., 1984). The Havallah Basin is interpreted to be an older basin east of an island-arc, with the arc and Antler highlands as sediment sources (Miller et al., 1984). Deformation related to the Golconda allochthon is only know west of Buck Mountain and is therefore not anticipated in the study area.

Central Nevada Thrust Belt

The Central Nevada Thrust Belt is ~400 km long zone of dominantly north-striking, east-directed north-south striking structures. It can be traced east to west from longitude 115°W-116°W and from north to south between latitudes 37.30˚ N and 39.30˚ N (Taylor et al., 1993; DeCelles, 2004) (Figure 2). The Central Nevada Thrust Belt is temporally constrained between the Permian and mid- Cretaceous based on the age of faulted and unfaulted strata in eastern Nevada (DeCelles, 2004). The structural style of the Central Nevada Thrust Belt as steep (35°-55°) thrust ramps differs from that of the Antler orogen and the Sonoma orogeny (Taylor et al., 1993). It is linked north to south through the Pancake Range (Gilbert and Taylor, 2001) at the same longitude as Buck Mountain. Deformation of the Central Nevada Thrust belt is expected at Buck Mountain. Taylor et al. (2000) interpret the Central Nevada Thrust Belt to represent the early foreland structural development of the Sevier orogen.

Ruby Mountains Metamorphic Core Complex

The Ruby Mountains Core Complex is a prominent Eocene to early Oligocene structural feature in Nevada (Figure 2). It is located ~100 miles north of Buck Mountain. Paleozoic and Mesozoic rocks there are displaced in a northwesterly direction along a low-angle detachment fault (MacCready et al., 1997; Howard, 2003) (Figure 2). Kinematic indicators including asymmetric sigmoidal feldspar augen, mica fish, S-C fabrics, and quartz c-axis preferred orientation record top-to-the-northwest displacement (MacCready et al., 1997). Kinematic indicators were measured along ~110 km of the metamorphic core complex from the southern end of the Ruby Mountains north to the northern end of the East Humboldt Range (MacCready et al., 1997). The Ruby Mountains show a transition from ductile deformation to brittle deformation along this transect, as a ~1-km-thick mylonite zone grades upward to brittle low-angle attenuation faults (MacCready et al., 1997). Structures related to this core complex have not been documented at Buck Mountain, but might occur there.

Normal Faulting in Nevada

Miocene and younger deformation in central Nevada is characterized by normal faulting. Structurally, the Basin and Range Province is characterized by high-angle, north-striking extensional faults. The aggregate Eocene-Recent extension is ~150 km (Wernike, 1992; Coogan and DeCelles, 1996). Miocene and younger extensional structures are expected at Buck Mountain and explain the elevation of the range today.

Unconformity Scheme

Several studies document post-Antler and pre-Sonoma unconformities in eastern Nevada (e.g. Dott, 1955; Ketner, 1977; Snyder et al., 2000; Trexler et al. 2003, Trexler et al. 2004, McHugh 2004, and Villa 2007). A naming scheme for the Upper Paleozoic unconformities in Nevada was devised (Snyder et al., 2000; Trexler et al. 2004; Cashman et al. 2008), modeled after the existing unconformity scheme for Mesozoic stratigraphy of the Colorado Plateau (Pipiringos and O’Sullivan, 1978; Peterson and Pipiringos, 1979). It uses the first letter of the time period (C for Carboniferous and P for Permian) and numbers in chronological order (Figure 3).

Unconformities can be traced from disconformities to angular unconformities across eastern Nevada. The angular nature of these unconformities is important in understanding the tectonic significance of these features and relates directly to their orogenic significance in the late Paleozoic (Trexler et al., 2003). Pennsylvanian and Permian unconformities are expected on Buck Mountain

Mid- to late-Paleozoic Unconformities

The following is a brief summary of important locations which show the nature of several unconformities in eastern and central Nevada. These sites all display structures and unconformities which formed between the Antler and Sonoma orogenies. However, the geographical extent and relative significance of each event and associated unconformity is not currently known. The tectonic forces driving the formation of these structures and unconformities are not well understood. This study at Buck Mountain was designed to enhance both kinematic and regional understanding of the late-Paleozoic geologic history.

Previous stratigraphic work on Buck Mountain document several unconformities (Payne and Schiappa, 2000). Reconnaissance work on Buck Mountain show folds in the Pennsylvanian Ely Limestone on but the folds have not been systematically measured or correlated (J.H. Trexler and W.S. Snyder, pers. comm. 2008). These unconformities and folds could correlate to similar features in other locations in eastern and central Nevada. Four well documented locates are described below.

Carlin Canyon

In Carlin Canyon four mid to late-Paleozoic unconformities and structures of at least two deformational events are documented (Trexler et al., 2003; Trexler et al. 2004) (Figure 4). At the oldest exposed unconformity in Carlin Canyon has Chesterian age rocks overlie Meramecian age rocks. This unconformity is angular and cuts down-section to the west. At the next higher unconformity Atokan age strata are overlain by Missourian age rocks. This unconformity trims west-vergent folds and west-directed thrust faults. The next stratigraphically higher unconformity places mid-Wolfcampian rocks over the Missourian rocks. This unconformity truncates open upright folds developed in Missourian age rocks. The stratigraphically highest unconformity present places late-Wolfcampian strata depositionally on mid-Wolfcampian rocks. This unconformity is not measurably angular but cuts down-section to the east. The four unconformities present in Carlin Canyon are interpreted as the C2, C6, P1, and P2 regional unconformities (Trexler et al., 2003; Trexler et al. 2004). The C5 unconformity (Atokan to mid-Desmoinesian) is not preserved at Carlin Canyon. Here the C6 unconformity is the upper boundary of west-vergent folds and has eroded away evidence for the C5 unconformity.

Edna Mountain

At Edna Mountain (Figure 4) three mid to late-Paleozoic unconformities and four deformational events are documented. At the oldest unconformity present has the undated, potentially Desmoinesian age, Highway Conglomerate overlies Atokan age rocks. This contact is significant because west-vergent folds are developed below the Highway Conglomerate and not above. At the next stratigraphically higher unconformity, has Missourian rocks are deposited over the Highway Conglomerate. This contact is a disconformity between the older Highway Conglomerate and the younger Antler Peak Limestone. At the stratigraphically highest Paleozoic unconformity, the mid-Kungurian (~mid-Leonardian) Edna Mountain Formation overlies on the Virgilian age Antler Peak Limestone. This unconformity truncates open upright folds developed in the Virgilian and older rocks. The ages of these three unconformities at Edna Mountain are consistent with the C5, C6, and P4 regional unconformities. The C5 unconformity may be preserved between the Highway Limestone and the undated Highway Conglomerate at Edna Mountain. West-vergent folding developed below the Highway Conglomerate is undoubtedly below the C6 unconformity and potentially below the C5 unconformity (Villa, 2007; Cashman et al., in press).

The Diamond Mountains

Two unconformities and three ages of structures deformational events have been documented in the Diamond Mountains (Larson and Riva, 1963; Sweet et al., 2002)

(Figure 4). Atokan age rocks are overlain by Missourian strata at the oldest unconformity (Linde, 2010). This unconformity truncates west–vergent folding (Cashman et al., 2008). The stratigraphically highest unconformity places Leonardian age rocks depositionally on Missourian age rocks. This unconformity is angular and trims gentle symmetric folds (Linde, 2010). The unconformities preserved here are consistent with the C6 and P4 regional unconformities. Additional reconnaissance work done here suggests west-vergent sub-C6 folding in the Morrowan to Atokan Ely Limestone (Cashman et al., 2008). Here, as at Carlin Canyon, the C5 unconformity either never existed or was removed by erosion along the C6 unconformity.

Pequop Mountains

Two unconformities and two deformational events are documented in the Pequop Mountains (Sweet et al., 2002) (Figure 4). At the oldest documented unconformity mid-Desmoinesian rocks overlie Atokan age rocks. This unconformity is angular and trims both east- and west-vergent folds. At the younger documented unconformity, rocks of late-Sakmarian (mid-Wolfcampian) age overlie on mid-Desmoinesian age rocks. This unconformity is not angular and is folded by Triassic age folds. The unconformities found in the Central Pequop Mountains are consistent with the C5 and P2 regional unconformities (Sweet, 2003).

Mid- to late-Paleozoic Deformation

Overview

The following is a brief summary of the best-documented structures in Pennsylvanian and Permian time in central and eastern Nevada. These structures are uniquely developed in specific age rocks. Importantly, these structures are truncated by unconformities of several different ages. These unconformities are important because they bracket the age of folding and faulting observed in the rock.

Upright and east-vergent folds

Upright and east-vergent folds are not specifically confined to one time or one tectonic event in eastern and central Nevada but occurs at several times. This makes correlation of structures based solely on this geometry problematic. East-directed thrusts and east-vergent folds are typical for the Anther orogeny, Sonoma orogeny, some mid- to late-Paleozoic shortening events, and the Central Nevada Thrust Belt. Without age constraint, open and east-vergent folds and east-directed faults cannot be differentiated from event to event. For this reason, unconformities and other cross-cutting relationships are invaluable to constrain the timing of regional folding and faulting.

West-vergent folding

Consistent west-vergent folds are regionally significant because they are the opposite polarity of typical folds developed in western North America. Northwest-vergent folds are present in Carlin Canyon (Trexler et al., 2004), the Central Pequop Mountains (Sweet, 2003), and the Diamond Mountains (Cashman et al., 2008). At Edna Mountain folds are west-southwest-vergent (Villa, 2007; Cashman et al. in press). Both folds and related faults are developed exclusively in Atokan and older strata. The upper age bracket may be as young as Missourian time. This style of folding is significant because it is unaccounted for in the current Paleozoic tectonic models. With a better age bracket and better constraint on the geographic area affected by this unique geometry of folding, a more precise tectonic model can be constructed.

Regional Setting

Buck Mountain is a north-trending fault-bounded ridge located 35 km northeast of Eureka, Nevada (Figure 2). Geographically it is an isolated ridge near the southern end of the Ruby Mountains. To the west are the Diamond Mountains which preserve a Mesozoic east-directed thrust fault and east-vergent folds (Brew, 1971) (Figure 5). To the north are the Ruby Mountains, known for large magnitude Eocene extension (McGrew and Snee; 1994) (Figure 5). To the east is Alligator Ridge, known for Mesozoic east-directed thrust faults and folds (Hichborn et al., 1996) (Figure 5). Mines at Alligator Ridge (Alligator Ridge mine) and the southern end of the Ruby Mountains (Bald Mountain mine) provide good exposures of high-angle faults that post-date regional thrusting (Rigby, 1960; Hichborn et al., 1996; Howald, 1996; Nutt, 2000; Nutt et al., 2003). The following section summarizes the structure of these mountain ranges from west to east, to provide regional context for the structures developed on Buck Mountain.

Diamond Mountains

Two fold sets and a thrust fault are preserved in the Diamond Mountains (Brew, 1971; Linde, 2010). Broad open folds are over-printed by later Mesozoic structures in the Diamond Mountains (Linde, 2010). The pre-Leonardian folds are gentle to open, symmetrical, and shallowly inclined with wavelengths of 0.5-1 km. They trend to the south-southeast (152°) (Linde, 2010). These folds are trimmed by an unconformity and are not found in Roadian and younger strata. The post-Leonardian folds are close to tight, asymmetric, east-vergent, and upright to overturned. Fold wavelengths are 0.5-1 km, and the folds trend north (352°) (Linde, 2010). The younger folds in the Diamond Mountains pre-date deposition of the Cretaceous Newark Canyon Formation. Therefore, the folds are dated as post-Permian and pre-Early Cretaceous (Brew, 1971). Also present in the Diamond Mountains is the southeast-directed Bold Bluff thrust, which is mapped for ~6 miles (~9.6 km) and juxtaposes different facies of the Mississippian Diamond Peak Formation. The fault surface strikes northeast and dips ~10° west (Brew, 1971). It is marked by minor thrusts, slickensides, folds, and locally by competent blocks surrounded by incompetent material (Brew, 1971). Age constraints are not documented; however, it is considered to be Mesozoic in age (Brew, 1971).

Ruby Mountains

The Ruby Mountains are located due north of Buck Mountain (Figure 5). There, a single large-scale detachment is preserved. The displacement direction along the detachment surface is generally top-to-the-northwest (MacCready et al., 1997). The age constraint on unroofing of the detachment is Eocene or older, based on ^{40}Ar/^{39}Ar dating of mica, hornblende, and potassium feldspar (McGrew and Snee; 1994).

Alligator Ridge mine

The Alligator Ridge mine is located 13 km northeast of Buck Mountain (Figure 5). The main fold developed at Alligator Ridge is an anticline with 5000 feet (~1500 m) of structural relief (Rigby, 1960). The Alligator Ridge anticline trends to the northeast and locally it has a steep to overturned east limb (Nutt, 2000, Nutt et al., 2003). Nutt (2000) interpreted this fold is as a Mesozoic structure, based on regional correlation with other folds of similar geometry.

A complex history of faulting is found at the Alligator Ridge mine. Faults striking northwest show both dextral and sinistral strike-slip movement during Mesozoic time (Howald, 1996). However, the most recent movement on these faults is dip-slip. Northwest-striking high-angle extensional faults have associated fault horses, ramps, and duplexes (Howald, 1996). The displacement on high-angle extensional faults is approximately 700 feet (~200 m) down-to-the-east-southeast (Howald, 1996). These faults were interpreted as reverse faults that have been reactivated as normal faults in the Tertiary. Howald (1996) interpreted the age of reverse faulting to be Cretaceous in age.

Bald Mountain mine

The Bald Mountain mine is located 30 km north of Buck Mountain (Figure 5). The main fold developed at the Bald Mountain mine is an open southwest-plunging asymmetric anticline (Hichborn et al., 1996). Dip on the west limb of the fold is 20-40° and on the east limb is 10˚-20° (Rigby, 1960). The anticline has 2400 meters of structural relief (Rigby, 1960). Hichborn et al. (1996) interpreted this fold as the southward plunging axis of the Ruby Mountain Metamorphic Core Complex. Nutt (2000) reinterpreted this fold as Mesozoic in age based on regional correlation with other folds of similar geometry.

The Bald Mountain mine has two dominant high-angle normal fault orientations. The first fault set strikes 300˚ and displaces section down-to-the-north. The second set is N-NE striking and displaces section down-to-the-southeast. Also present in the Bald Mountain mine are locally developed low-angle west-dipping thrust faults which deform rocks no more than 10 meters from the fault surface. The damage zones associated with these faults are 1-5 meters thick (Hichborn et al., 1996).

Discussion of Permian lithofacies nomenclature

The Pennsylvanian and Permian strata on Buck Mountain have been ascribed to several different units in the last 50 years. The formations mapped southeast of Buck Mountain are the Permian Rib Hill Sandstone and the Arcturas Formation, both are Lower Permian in age (Nutt, 2000). The rocks capping Buck Mountain have been called the Tomera Formation (Dott, 1955; Rigby, 1960; Merrill, 1960; Campbell, 1980; and Tomastik, 1980). More recently a detailed biostratigraphic study has redefined the strata as the mid-Desmoinesian (Late Pennsylvanian) Hogan Formation and the Missourian (Early Permian) Lower Strathearn Formation, and The Sakmarian (Early Permian) Upper Strathearn Formation (Payne and Schiappa, 2000). The unit names used by this study are the Hogan Formation, Upper and Lower Strathearn formations, on the basis of detailed biostratigraphic control (Payne and Schiappa, 2000).

Structural Descriptions of Buck Mountain

Overview

This section is a condensation of structural descriptions of Buck Mountain prior to this study. Discussed are folds, faults, and interpretations made from 1960-2000 (Rigby, 1960; Merrill, 1960; Tomastik, 1980; Campbell, 1980; Nutt, 2000; Payne and Schiappa, 2000; J.H. Trexler and W.S. Snyder pers. comm. 2008).

Mapping on Buck Mountain has been refined and updated several times in the past 50 years. Initial mapping in 1960 identified a large, open, generally north-trending syncline in the Molean and Tomera formations. This fold was defined along the crest of the range and named the Buck Mountain syncline (Rigby, 1960; Merrill, 1960). Later mapping identified large-offset, north striking, down-to-the-east and down-to-the-west normal faults. Several smaller east striking, down-to-the-north and down-to-the-south normal faults cross the range (Campbell, 1980; Tomastik, 1980). Additional mapping documented a low-angle east-directed attenuation fault in the Pennsylvanian Ely Limestone at the base of Buck Mountain (Nutt, 2000). A detailed biostratigraphic analysis used fusulinids and conodonts to bracket the ages of strata present on Buck Mountain (Payne and Schiappa, 2000). This study significantly revised the age of rocks mapped on Buck Mountain.

Intense deformation apparently localized at the top of the Ely Limestone was observed by a team measuring stratigraphic section in the Ely Limestone (Jim Trexler and Walt Snyder, pers. comm. 2008). The kinematics of this deformation remained unknown. The relation of this deformation to one or more low-angle fault surfaces was not clear, nor was the relation of all previously mapped structures related to the refined precise biostratigraphically constrained rock ages. A goal of this study is to determine whether there is more folding at the top of the mountain than structurally lower on the mountain. If so, is the fault at the top of the Ely Limestone related to an east-directed thrust as in the Diamond Mountains or, a low-angle detachment as in the Ruby Mountains, or a low-angle attenuation fault as at Alligator Ridge, or something else? The overall goal is to determine the timing, kinematics, and distribution of folds and faults present on Buck Mountain.

Methods

Overview

This section describes the methodology used to compile a field map on a Panasonic Toughbook®. Discussed are the benefits and challenges of mapping in this way. Also included in Appendix A is a troubleshooting discussion related to the logistical and general challenges posed by field mapping on a computer. Other than the Toughbook®, standard mapping and structural techniques were used to refine and interpret the geology of Buck Mountain.

Toughbook® Mapping

All mapping was done in the field using a Panasonic Toughbook®. Mapping on a Toughbook has four advantages over traditional paper mapping. 1) I was able to plot precise azimuth strike orientations at precise UTM grid locations in real time. 2) I was also able to map at any scale to fit ever-changing needs. 3) I had all previous mapping saved in a geodatabase as georeferenced images in ArcGIS 9.3.1. 4) I was also able to plot stereograms in the field using Rich Allmedinger's StereoWin program.

Computer-based mapping presents four challenges: 1) The computer-based GPS unit would occasionally stall while mapping. 2) Occasionally the computer battery would fail in the field. 3) The computer would crash while mapping. 4) When mapping in full sunlight the computer screen is unusable. My solutions to these challenges are presented in Appendix A.

My new mapping used updated ages and unit names documented on Buck Mountain (Payne and Schiappa, 2000). The Ely-Diamond Peak contact is a compilation of mapping done by Campbell (1980), Tomastik (1980), and Nutt (2000). The aerial extent of mapping from the current study is ~40 km^2 total. Approximately 29 km^2 of mapping was compiled by walking contacts south and southeast of Moore Peak. The remaining 11 km^2 of mapping was completed with air photos. The most detailed mapping for this study was focused south and southeast of Moore Peak. Air photo mapping extends north of Moore Peak ~7.5 km (Plate 1).

Paleozoic Stratigraphy

Overview

The focus of this thesis is late Paleozoic geologic history of rocks at Buck Mountain; part of that record is the depositional history of the late Paleozoic rocks. Consistent recognizable stratigraphy is integral to structural mapping (Figure 6). The purpose of this thesis is not a detailed stratigraphic study. The stratigraphic descriptions here are limited to brief recognition criteria of the Diamond Peak Formation, Ely Limestone, Hogan Formation, Lower Strathearn Formation, and Upper Strathearn Formation.

Sedimentary rocks exposed at Buck Mountain range in age from Mississippian to Permian (Figure 6). The Ely Limestone conformably overlies the Mississippian Diamond Peak Formation and the Mississippian Chainman Shale. The strata overlying the Pennsylvanian Ely Limestone at Buck Mountain are the Pennsylvanian Hogan Formation, the Permian Lower Strathearn Formation, and Permian Upper Strathearn Formation. Permian rocks younger than the Upper Strathearn Formation are not preserved on Buck Mountain (Figure 6). Two Tertiary volcanic units are present in the area and are briefly mentioned in this section. These volcanic units are only included in this study to constrain the age of faulting.

Mid to late-Paleozoic unconformities are widespread in eastern Nevada and are commonly associated with angular discordance and distinct lithofacies changes. These unconformities are significant because they truncate folds and faults. Bracketing the age of the structures is done by dating the youngest rocks present below and the oldest rocks above the unconformity. Several unconformities have been identified and correlated across eastern Nevada (e.g., Trexler et al., 2003; 2004). Nomenclature and correlation of these unconformities are discussed in the background section of this thesis under the sub-heading “Unconformity Scheme”.

Mississippian Strata

Mississippian Diamond Peak Formation

The following description for the Diamond Peak Formation is compiled from the observations of several previous workers (e.g., Nolan et al., 1956; Campbell, 1980; and Tomastik, 1980). The Diamond Peak Formation is the oldest unit exposed in the map area (Figure 6).

The basal contact of the Mississippian Diamond Peak Formation is unconformable (Sweet, 2003) exposed south of the map area (Tomastik, 1980) with minor outcrop to the east (Nutt 2000). At the unconformity, Chesterian age rocks overlie Meramecian age rocks (Figure 6).

At its type section the Diamond Peak is mostly shale, sandstone, and conglomerate with a siliceous matrix (Nolan et. al, 1956). The Diamond Peak is late Mississippian in age based on brachiopods collected from several areas in the vicinity of Eureka, Nevada (Figure 2) (Nolan et al., 1956). The Diamond Peak Formation on Buck Mountain is 199 meters (Campbell, 1980) to 274 meters (Tomastik, 1980) thick. It is comprised of red to brown medium-sand size chert-lithic sandstone (Humphrey, 1960). Locally it has conglomeratic lenses containing chert clasts up to 2.5 cm diameter that vary in color from dominantly green, to red, white, and black (Humphrey, 1960).

Pennsylvanian Strata

Pennsylvanian Ely Limestone (Morrowan-Atokan*)*

Regionally, the Diamond Peak-Ely contact is a 100 foot (~30 meter) thick gradational contact (Nolan et al., 1956; Humphrey, 1960). The base of the Ely Formation is defined as the last noncalcareous sandstone unit before the first limestone unit (Humphrey, 1960). The contact zone typically comprises interbedded limestone and siliceous litharanite (J.H. Trexler, written communication) (Figure 6).

On Buck Mountain the Ely Limestone is distinguished by thick intervals of mudstone and wackestone, and thinner intervals of packstone and grainstone. Thick cliff-forming layers give the Ely Limestone its characteristic pattern in oblique air photos taken of Buck Mountain (Figure 7). The benches are continuous for several kilometers along the flanks of the mountain. Outcrop is abundant and useful for structural measurements, but locally bedding can be hard to find in thick intervals.

The Ely Limestone consists of mudstone to grainstone representing a shallow shelf carbonate system (Figure 8). The Ely Limestone is medium to dark grey on fresh surfaces and weathers from a tan-grey to a medium-grey. The allochems present in the wackestone, packstone, and grainstone are dominantly brachiopod shells, crinoid stem fragments, and small horn corals throughout the unit. Toward the top of the Ely Limestone on Buck Mountain, large gastropod shells can be found. The Ely Limestone also has abundant chert lenses and nodules (Figure 8). Regionally this formation represents a shallow productive carbonate platform (Nolan et al., 1956; Rich, 1977: Perry, 1994). The cyclothemic carbonates at Buck Mountain are typical for the Ely-Bird Springs Basin and interpreted as shallowing-upward small scale cyclothemic carbonate intervals (Perez-Huerta, 2004). The cyclicity of the Pennsylvanian carbonates in eastern Nevada is a far-field effect of sea-level change driven by multiple glacial maxima in the southern hemisphere during the late Paleozoic (Mii et al., 1999; Gibling and Rygel, 2008; Greb et al., 2008; Sturmer et al., 2009).

The Ely Limestone is Morrowan in age (Figure 6) based on brachiopods and bryozoans collected from several areas ~30-40 km southwest in the vicinity of Eureka, Nevada (Figure 2) (Nolan et. al, 1956). Additional collections of brachiopods ~50 km southeast near Eberhardt, Nevada support this age (Humphrey, 1960).

The estimated thickness of the Ely Limestone from this study is approximately 750 meters. Other reported thicknesses of the Ely Limestone on Buck Mountain range from approximately 307 meters (Campbell, 1980) to 515 meters (Tomastik, 1980) thick. However, structural complexity and erosion by the C5 unconformity make accurate thickness measurements problematic on Buck Mountain.

Pennsylvanian Hogan Formation (mid-Desmoinesian)

The Ely-Hogan interface at Buck Mountain is a distinct undulatory contact. It has a maximum local relief of ~5 meters. The Ely-Hogan contact is distinguished by a significant break in slope immediately above large cliffs of folded Ely Limestone (Figure 7). Folds observed in the Ely Limestone are truncated and depositionally overlain by the Hogan Formation (see structure section for details). The northern portions of the map area have distinct knobs of Ely Limestone poking through the Hogan Formation on a modern surface (Figure 9) which are interpreted to be a remnant erosional surface, corroborated by limestone rip-up clasts in carbonate matrix at the base of the Hogan Formation (Figure 10). This is interpreted to be a basal conglomerate.

The Hogan Formation is easily identifiable as a tan-to red-weathering sandy siltstone with minor beds of poorly exposed limestone (Figure 6). Outcrop of the Hogan Formation is sparse, and unreliable for structural measurements (Figure 11). The base of the Hogan Formation contains intraclasts of a limestone in a carbonate matrix. This basal interval is approximately 0.5 m-1m thick. The siliciclastic rocks present are sandstone and siltstone. The siltstone is flaggy-weathering, tan, sandy siltstone. The sand grains are rounded to sub-rounded, well-sorted, and fine-grained, with quartz and chert grains in a calcareous cement. Locally, the Hogan Formation contains dark grey to black thinly-bedded petroliferous carbonate mudstone and wackestone in beds less than half a meter thick (Figure 6).

The Hogan Formation is mid-Desmoinesian in age, constrained by conodont and ammonoid biostratigraphy (Payne and Schiappa, 2000) (Figure 6). Both suites of fossils were collected directly from Buck Mountain.

The Hogan Formation is not genetically related to the older Ely Formation. These strata are also dissimilar to the Strathearn Formation, also present on Buck Mountain. Payne and Schappa (2000) interpret the Hogan Formation as a rapidly subsiding basin independent of both the Ely Basin and Strathearn Basin.

The Hogan Formation is regionally trimmed above by the C6 unconformity and unconformably overlies the Ely Limestone (C5 unconformity). Therefore the preserved thickness is variable, ranging from less than 10 meters to more than 30 meters thick (Figure 6). The total original thickness is unknown.

Permian Strata

Permian Strathearn Formation (Missourian-Sakmarian)

The Strathearn Formation as originally defined by Dott (1955) is split into two different units based on precise mapping and biostratigraphic dating (Trexler et al., 2004). The Strathearn Formation contains an intraformational unconformity (P1 unconformity). The P1 unconformity separates the upper and lower members of the formation elsewhere (Figure 6) (Payne and Schappa, 2000). The older Lower and younger Upper Strathearn formations have similar lithofacies but were deposited at significantly different times (Figure 6). Therefore, the Strathearn Formation needs to be separated to differentiate the two distinct times of deposition. The Lower Strathearn Formation is Missourian in age and the Upper Strathearn Formation is Sakmarian (mid-Wolfcampian) in age (Payne and Schiappa, 2000) (Figure 6).

Lower Strathearn Formation (Missourian)

The Hogan-Lower Strathearn contact is covered and unexposed. There is no discernable angularity between bedding in the Hogan and Lower Strathearn formations. The Lower Strathearn Formation is easily identifiable by ~1-2 meter thick limestone ledges above the gentle hillslope of the Hogan Formation (Figure 7).

The Lower Strathearn Formation is composed of interbedded siliciclastic rocks and carbonate rocks (Figure 6). Outcrops are common and ideal for structural measurements. The Lower Strathearn Formation is identified by carbonate beds interbedded with small siltstone and sandstone lenses, and thin chert-pebble conglomerate beds (Figure 12). It is dominated by ~1-2 meter thick carbonate intervals. The rock types include both carbonate and siliciclastic rocks. The siliciclastic rocks are laminated, very fine (0.105 µm) quartz sandstone to siltstone in beds approximately 0.3 m in thickness. On a fresh surface the siliciclastic beds are tan to drab green and weather to a tan color. The coarser-grained siliciclastic rocks are matrix-supported chert-pebble conglomerates, containing sub-rounded red, white, brown, and green chert clasts ranging in size from coarse sand to pebble size (0.5mm-1 cm). Locally some portions of the chert-pebble conglomerate contain fossil shells. The limestone portions of the Strathearn

Formation vary non-cyclically from calcareous mudstones to packstones. The dominant allochems found in the wackestones and packstones are crinoid stem fragments, fossil shell hash, bryozoans, horn corals, and colonial corals.

The Lower Strathearn Formation is Missourian in age constrained by fusulinids and ammonites collected on Buck Mountain (Payne and Schiappa, 2000). Regionally, the Lower Strathearn Formation is bounded by the C6 and P1 unconformities (Figure 6).

Upper Strathearn Formation (Sakmarian [mid-Wolfcampian])

The Lower Strathearn-Upper Strathearn contact is poorly exposed. There is no discernable angularity between bedding in the Lower and Upper Strathearn formations. The contact does appear locally on “Hinge Hill” (Plate 1). Here the Upper Strathearn Formation is a clast-supported, sub-angular, chert-pebble conglomerate containing cobble- to pebble-sized clasts of a limestone. It is interpreted to be a basal conglomerate of the Upper Strathearn Formation.

The Upper Strathearn Formation is composed of interbedded siliciclastic and carbonate rocks. The rock type is similar to the Lower Strathearn Formation. Outcrops are common and ideal for structural measurements. The defining characteristics of the Upper Strathearn Formation are intervals of coarse-grained siliciclastic rocks. The coarse-grained siliciclastic rocks are clast-supported chert pebble conglomerates, containing sub-angular to sub-rounded red, white, brown, and green chert clasts ranging in size from coarse-sand to pebble size (0.5mm-1 cm). Locally some portions of the chert-pebble-conglomerate contain cobbles of limestone up to ~10 cm in diameter. Internally the limestone-cobbles found in the Upper Strathearn Formation are matrix-supported chert-pebble conglomerates. These cobbles are derived from the Lower Strathearn Formation.

The Upper Strathearn Formation is Sakmarian (mid-Wolfcampian) in age (Figure 6). This date is constrained by fusulinids and ammonites collected on Buck Mountain (Payne and Schiappa, 2000).

The undifferentiated Strathearn Formation unconformably overlies the Ely Limestone at its type section near Elko, Nevada (Dott, 1955). Regionally, the undifferentiated Strathearn Formation is interpreted to represent a shallow, rapidly subsiding basin independent of the Hogan Basin (Sweet, 2003).

The Upper and Lower Strathearn formations have a variable and incomplete combined thickness of between 5 and 125 meters because, like the Hogan Formation, they are also unconformity-bounded (Figure 6). Regionally undifferentiated Strathearn Formation is bounded at the top by the P2 unconformity. However, there are no Permian rocks younger than Sakmarian (mid-Wolfcampian) age on Buck Mountain; therefore, it is unknown whether the unconformity that truncates the Upper Strathearn Formation here is P2 age or younger (Figure 6).

Tertiary Volcanic rocks (Miocene-Oligocene)

The Ely Limestone, Hogan Formation, and both Strathearn formations are unconformably overlain by Oligocene tuffaceous rock and undifferentiated Miocene-Oligocene volcanic rocks. The tuffaceous rocks consist of a white biotite lithic tuff composed of pumice fragments and medium-grained quartz, feldspar and biotite phenocrysts, locally altered (Nutt, 2000). The undifferentiated volcanic rocks are intermediate composition volcanic flows and tuffs which in some places overlie the biotite tuff. The total volcanic section is ~60-180 meters thick (Nutt, 2000). The volcanic rocks are exposed northeast of Buck Mountain and are not relevant to mid- to late-Paleozoic tectonics but do bracket the age of some folds and faults on Buck Mountain.

Structure

Overview

Buck Mountain has two non-coaxial fold sets, ranging in age from late Pennsylvanian (F1) to post-Sakmarian (Mesozoic?) folds (F2). F1 folds are uniquely developed in the Pennsylvanian Ely Limestone and are refolded by F2 folds. Both F1 and F2 folds are cut by two sets of post-Eocene high-angle normal faults.

This section is a thorough description of the macroscopic and mesoscopic structure of the study area. Standard chronologic nomenclature is used for describing the fold relationships F1, and F2, where F1 is the oldest. In order to understand older structures, the younger folding and faulting must be removed. This section contains original data unless stated to the contrary. A discussion of regional correlation will follow this section.

Pennsylvanian Folding (F1)

Geometry

Folds found exclusively in the Morrowan-Atokan Ely Formation (F1) are the oldest observed in the study area. F1 folds show a transition in deformational intensity and are refolded around younger F2 folds. F1 folds are doubly-plunging to the northeast and southwest (Figure 13).

F1 folds on Buck Mountain have two different geometries. The more intense folds are close, west-verging (Figure 14). This geometry changes coaxially to an open, symmetric, and gently plunging fold set (Figure 15). Both fold styles plunging gently ~12° to the southwest (202°). When subsequent F2 folds are removed, the dominant axis orientation is gently plunging to the northeast (Figure 16). F1 folds have a wavelength of ~100 meters and amplitude of approximately ~20-30 meters (Figure 15).

The orientation of F1 folds changes east of the Central Highlands fault (Plate 1). Here, F1 folds are close, asymmetric, cylindrical, and have a sub-horizontal axis plunging ~6° to the southeast (168°) (Figure 17). The wavelength and amplitude cannot be reliably measured. This fold set is consistent with the scale and intensity of F1 folds found west of the Central Highlands fault.

Viewing F1 folds

F1 folds are best exposed on the east side of Buck Mountain at "Train Ridge" and the next ridge south "Syncline Ridge" (Plate 1). The best location to view open F1 folds is looking at the north face of "Train Ridge" (Figure 15). The obvious well-exposed fold train is upright and does not display a sense of vergence. The fold train is significant because it unequivocally shows the amplitude, wavelength, and style of deformation in the area. From this same location a west-vergent F1 fold is seen one ridge south at "Syncline Ridge". At this location, a west-vergent fold is locally developed (Figure 15).

Relative age and evidence

The F1 folds are found exclusively in the pre-Atokan rocks on Buck Mountain. This fold set does not extend into the overlying mid-Desmoinesian Hogan Formation (Figure 18). Therefore, F1 folds have to post-date deposition of the Morrowan-Atokan Ely Limestone and pre-date deposition of the mid-Desmoinesian Hogan Formation. The axes of the F1 folds are folded around a common northwest axis (F2) (Figure 13) and therefore predate F2 folding.

Interpretation of west-vergent folds

West-vergent folds are widespread on Buck Mountain. These folds are documented on both the east and west side of the Buck Mountain syncline. The geometry is close, asymmetric, and gently plunging both to the northeast and the southwest. The orientation of west-vergent folds is coaxial with open upright folds also documented on the east and west side of the Buck Mountain syncline. The following section is a discussion of potential interpretations for west-vergent folds on Buck Mountain.

Several interpretations for west-vergent folds are can be made for F1 folds. They include: 1) the folds are parasitic to the Buck Mountain syncline, 2) the folds are large-scale soft-sediment deformation, and 3) the folds are older tectonic folds independent of the Buck Mountain syncline.

Parasitic Folds on the Buck Mountain Syncline

For the F1 west-vergent folds to be parasitic folds on the Buck Mountain syncline three features would be expected: 1) the folds would need to change their sense of vergence depending on which limb of the Buck Mountain syncline they were on. 2) The folds would have to fold all units that the Buck Mountain syncline folds. 3) All folds on Buck Mountain would need to have the same axis orientation.

First, the west-vergent folds have a consistent geometry from east to west across the Buck Mountain syncline fold axis. Secondly, the west-vergent folds do not involve any strata younger than mid-Desmoinesian in age. These folds are erosionally truncated by the mid-Desmoinesian Hogan Formation (C5 unconformity). Finally, the axis orientation of the west-vergent folds is perpendicular to the fold axis orientation of the Buck Mountain syncline. Therefore, they cannot be parasitic to the younger broad-scale folding of the Buck Mountain syncline.

Soft-sediment Deformation of the Ely Limestone

For the F1 west-vergent folds to be large-scale convolute bedding some or all of the following features would be expected: 1) large-scale vertical pipes to dewater the sediment, 2) discrete zones of dewatered and deformed sediment directly overlain by undisturbed beds of the same unit, and 3) down-slope failure would leave denuded zones and rootless folds (Nichols, 1999).

First, no large scale vertical pipe features are present on Buck Mountain. Second, large apparently flat layers overlie folded rocks on Buck Mountain. However, these are long wavelength folds which are locally faulted with offsets of 2-3 meters and result from a competency contrast between thin and thick intervals. Third, no denuded zones are found and all folds are rooted and continue into the underlying rock and to stop at the Ely-Hogan contact. Therefore, these folds cannot be convolute bedding.

Tectonic Folds Independent of the Buck Mountain Syncline

For the F1 west-vergent folds to be tectonic folds independent of the Buck Mountain syncline some or all of the following features would be expected: 1) development of pressure solution fabrics (e.g. styolites and veins); 2) consistent folding throughout a single stratigraphic unit; 3) a consistent shortening orientation. 4) potentially a coaxial change in fold morphology.

The following observations support tectonic folding: 1) development of both styolites and veins in fold hinges, 2) folding permeating the whole Morrowan-Atokan section, 3) a consistent shortening orientation throughout the Ely Limestone, and 4) a coaxial change in fold morphology from close west-vergent folds to open upright folds.

Preferred interpretation

The preferred interpretation of west-vergent folds is that these are tectonic folds independent of the Buck Mountain syncline. This interpretation is favored because west-vergent folds are trimmed by the mid-Desmoinesian Hogan Formation, have stylolites developed in hinge-zones, permeate the Morrowan and Atokan section, are found on both sides of the Buck Mountain syncline, have a consistent shortening direction, are folded around a consistent northwest axis, and have a coaxial change in fold morphology.

Post Early-Permian Folding (F2)

Geometry

F2 folds are developed in all pre-Oligocene rocks on Buck Mountain. The dominant trend of F2 folds is to the northwest with a gentle plunge. This fold set refolds older structures and unconformities around a consistent northwest axis (Figure 13).

The Buck Mountain syncline, the dominant structure, is an F2 fold. This structure has been documented by several studies (Rigby, 1960; Merrill, 1960; Campbell, 1980; Tomastik, 1980). F2 folds are gentle to open, symmetric, and cylindrical folds plunging

~15° to the northwest (323°) (Figure 19). F2 folds have a wavelength of 1 km and have a minimum amplitude of ~300 meters. F2 folds dominantly do not display a sense of vergence. Symmetric dips on both east and west limbs are ~30˚ (Plate 1). Locally mesoscopic F2 folds are slightly east-vergent and could potentially be parasitic folds on the Buck Mountain syncline (e.g. "Horseshoe Hill").

Viewing F2 folds

F2 folds are best seen at the top of "Hinge Hill" looking north (Plate 1). From this location the Buck Mountain syncline is readily apparent. The eastern limb climbs to the top of Buck Peak, while the western limb forms a resistant ridge that trends to the northwest. The core of the syncline is best developed on "Horseshoe Hill" (Plate 1) and seen looking north at the southern flank (Figure 20).

Relative age and evidence

F2 folds are developed in the Ely Limestone, Hogan Formation, and both Upper and Lower Strathearn formations, but not developed in the Oligocene volcanic rocks present in the area. Therefore, the F2 folds are post-Sakmarian to pre-Oligocene, but cannot be further temporally constrained.

Some studies claim F2 folds on Buck Mountain to be a Mesozoic structure (Rigby, 1960; Merrill, 1960; Taylor,1993; Nutt 2000). However, the style and geometry of folding is consistent with Early Permian folds ~15 km northwest in the Diamond Mountains (Linde, 2010). For a further discussion of defining ages to folds see the; "East-vergent and Upright Folds" section in the Background.

The preferred age interpretation of F2 folds on Buck Mountain is Mesozoic for the following reasons. 1) The older pre-Virgilian folds in the Diamond Mountains were transported by the younger Mesozoic Bold Bluff thrust fault. The implications are then that pre-Virgilian folds formed an unknown distance west of their current location. Therefore, correlation of the Buck Mountain syncline with pre-Virgilian folds in the Diamond Range is tenuous at best. 2) The Buck Mountain syncline in its present orientation has a similar trend and geometry to Mesozoic age folds at both the Bald Mountain mine and Alligator Ridge mine (e.g. Rigby, 1960; Nutt, 2000).

Post Eocene High-Angle Normal Faults

Buck Mountain has several well-developed high-angle normal faults. These structures displace Paleozoic through Tertiary rocks and cross-cut all older structures, making them the youngest structures present in the area. There are two dominant high-angle fault sets on Buck Mountain. The first is the west-striking Moore Peak fault and the second is the north-striking Central Highland fault (Campbell, 1980; and Tomastik 1980).

Moore Peak fault

The Moore Peak fault is a west striking north-side-down normal fault. It crosses the ridge crest one kilometer south of Moore Peak. The fault strikes ~260˚and dips 60˚ to the north; slip is approximately 274 meters north-side-down. The stratigraphic offset is Upper Strathearn Formation against the top of the Ely Limestone. The orientation and dip angle were determined from three-point problems. The displacement was estimated from a cross-section constructed perpendicular to the fault surface. A smaller antithetic fault north of the Moore Peak fault is south-side-down and has approximately 10-20 meters offset (Figure 21).

The best location to see the Moore Peak fault is from an unnamed hilltop north of “Broken Valley” (4395658 N, 618739 E, UTM NAD 83), looking due west at the “Northern Access Notch” (Plate 1). From here the Moore Peak fault and its antithetic fault are obvious and show visible displacement (Figure 21).

The Moore Peak fault cuts F2 folding and is cut by the Central Highland fault. It is not overlain by Tertiary volcanic rocks and therefore is not temporally well constrained. The Moore Peak fault has to be younger than the post-Early Permian folding and older than the post-Miocene Central Highlands fault.

Central Highland fault

The Central Highlands fault is a north striking, east-side-down normal fault located on the east side of Buck Mountain (Figure 22A) Brecciated zones related to this fault strike from ~030˚ to ~355˚ and dip from ~48˚ to ~75˚ to the east and southeast. The brecciated zones truncate bedding striking from ~160˚to ~190˚ and dipping between 30˚ and 55˚ west (Figure 22B). Throw on the Central Highland fault was determined from two cross-sections. The amount of displacement is between 365 and 396 meters. Calcite veins trending ~135˚ and dipping ~50˚ west are offset in a down-to-the-east orientation (Figure 22C).

The Central Highlands fault is poorly exposed on Buck Mountain. It is located along the eastern flank of Buck Mountain where an abrupt and dramatic break in slope marks the fault. However, the fault surface is not exposed and no scarp is visible.

The Central Highland fault is the youngest structure developed on Buck Mountain. It cuts the Moore Peak fault and also the Oligocene-Miocene volcanic rocks. The volcanic rocks present constrain the age of faulting to the time between the Oligocene and the Holocene. The Central Highland fault does not appear to be active. No scarps are present on the east side of Buck Mountain and a large amount of sediment covers the trace of the fault.

Low-Angle Faulting

I did not find evidence for low-angle faulting, either topographically high or low on Buck Mountain. Both F1 and F2 folds occur consistently throughout the Ely Formation. Folds are not localized above or below structurally defined surfaces. Long wavelength gentle folds are commonly developed in the thicker-bedded Ely Limestone. Locally folding becomes more intense and forms open folds and minor faults. Displacement along these minor faults is 2-3 meters (Figure 23). Shortening is accommodated in thinner beds with minor thrust faults and fault propagation folds (Figure 24).

Breccia previously interpreted to be associated with low-angle faults (Nutt, 2000) is localized near high-angle normal faults. Brecciated zones strike north-northeast (~030˚ to

~355˚) and dip from ~48˚ to ~75˚ to the east and southeast (Figure 22B). This orientation is consistent with high-angle down-to-the-southeast normal faults. I therefore interpret this brecciation to be related to the development of the Central Highlands fault.

Summary of Geologic History of the Buck Mountain area

Deposition of the Ely Limestone (Morrowan-Atokan)

Deposition of the Ely Limestone is Morrowan to Atokan in age. The age is based on brachiopods and bryozoans collected near Eureka, Nevada (Nolan et al., 1956; Humphrey, 1960). It is a cyclically varying carbonate. Cyclothemic carbonates of this age are found throughout eastern Nevada and western Utah (Rich, 1977; Sweet, 2003; Perez-Heurta, 2004). The cyclicity is interpreted to be driven by far-field glacio-eustasy in the southern hemisphere during the Paleozoic (Mii et al., 1999; Gibling and Rygel, 2008; Greb et al., 2008; Sturmer et al., 2009). The nature of the rock type suggests that the depositional environment was a shallow equatorial inland sea (Nolan et al., 1956; Rich, 1977; Perry, 1994).

D1- Folding of the Morrowan to Atokan Ely Limestone

The first deformational event (D1) is represented by the F1 fold set. The style of this fold set varies laterally. One fold end-member is close, asymmetric, west-vergent folds gently south-southeast (~200°) plunging ~10° (Figures 14). The second end-member is open, symmetric, and upright folds plunging gently to the south-southwest

(Figures 15). I interpret the two distinct geometries as a competency response to shortening. These folds are developed throughout the Ely Formation. This deformation is truncated by a mid-Desmoinesian unconformity. The Morrowan-Atokan rocks are depositionally overlain by mid-Desmoinesian rocks. This unconformity represents an unknown amount of pre-mid-Desmoinesian erosion in the Ely Formation.

Erosion of the Ely Limestone

C5 Erosion of the Morrowan-Atokan Ely Limestone on Buck Mountain is evidenced by four features. 1) Folds developed in the Ely Limestone are truncated at the preserved top of the Ely Limestone (Figure 18). 2) The surface at the top of the Ely Limestone is undulatory with a maximum relief of ~5 meters. Due to the undulatory nature of this surface, Ely Limestone is locally exposed through the Hogan Formation (Figure 9). 3) The rock type at this surface is a 1 meter thick carbonate layer with intra-clasts of limestone. This is interpreted as topography on a remnant erosional surface (Figure 10). 4) There is a significant lacuna developed between the Morrowan-Atokan Ely Limestone and the next higher unit, the mid-Desmoinesian Hogan Formation (Figure 6). This erosion surface is consistent with the C5 unconformity (Snyder et al. 2000) (Figure 3).

Deposition of the Hogan Formation (mid-Desmoinesian)

Deposition of the Hogan Formation is mid-Desmoinesian in age. The age is based on conodont and ammonoid samples collected on Buck Mountain (Payne and Schiappa, 2000). It is a finesand to siltstone, interbedded with thin layers of carbonate. The Hogan Formation is found locally in eastern Nevada and throughout western Utah (Rich, 1977). The nature of the rock suggests that the depositional environment was a deep basin (Rich, 1977; Sweet, 2003).

Erosion of the Hogan Formation

Erosion of the Hogan Formation is documented by two lines of evidence. 1) The Missourian Lower Strathearn Formation depositionally overlies the mid-Desmoinesian Hogan Formation (Payne and Schiappa, 2000) (Figure 6). This represents a significant lacuna between deposition of the Hogan Formation and the Lower Strathearn Formation. 2) There is an abrupt change in the lithofacies found above the fine-grain-sandstone and siltstone. The contact does not crop out and due to the weathering characteristics of the Hogan Formation. The lacuna represented by this contact is consistent with the C6 unconformity (Snyder et al. 2000) (Figure 3).

Deposition of the Lower Strathearn Formation (Missourian)

Deposition of the Lower Strathearn Formation is Missourian in age. The age is based on fusulinid and ammonoid birostratigraphy at Buck Mountain (Payne and Schiappa, 2000). The rock type varies from carbonates to coarse- and fine-grained siliciclastic rocks (Figure 12). The Lower Strathearn Formation is found in northeastern Nevada and western Utah (Dott, 1955; Stevens, 1977; Sweet, 2003).

Erosion of the Lower Strathearn Formation

Erosion of the Lower Strathearn Formation is shown by two kinds of data. 1) The Sakmarian (mid-Wolfcampian) Upper Strathearn Formation depositionally overlies the Missourian Lower Strathearn Formation (Payne and Schiappa, 2000) (Figure 6). This represents a significant lacuna between deposition of the Lower Strathearn Formation and the Upper Strathearn Formation. 2) The presence of a locally well-developed chert-pebble conglomerate which contains carbonate cobbles. The contact is poorly exposed and does not have an angular relationship between units. The lacuna represented here is consistent with the P1 unconformity (Snyder et al. 2000) (Figure 3).

Deposition of the Upper Strathearn Formation (Sakmarian)

Deposition of the Upper Strathearn Formation is Sakmarian (mid-Wolfcampian) in age, is based on fusulinid and ammonoid biostratigraphy at Buck Mountain (Payne and Schiappa, 2000). The rock type varies from carbonate to coarse- and fine-grained siliciclastic rocks. An important lithofacies found in the Upper Strathearn Formation is chert-pebble conglomerate locally containing carbonate cobbles. This lithofacies is interpreted as a basal conglomerate to the Upper Strathearn Formation. The Upper Strathearn Formation is found in northeastern Nevada and western Utah (Dott, 1955; Stevens, 1977).

D2- Folding of the Buck Mountain syncline (P-Mz)

The second deformational event (D2) is post-Sakmarian (mid-Wolfcampian) and pre-Oligocene. This age range is based on folded Early Permian and undeformaed mid-Tertiary rocks. D2 deformation is represented by F2 folds which are gentle, symmetric, upright, cylindrical folds plunging ~15° to the northwest (323°). These folds are consistent with both Mesozoic structures in the region (Taylor et al., 1993) and Permian folds in the Diamond Mountains (Linde, 2010). The absence of rocks younger than Early Permian at Buck Mountain makes distinguishing between these two folds ages impossible and correlation difficult. For a discussion of Permian and Mesozoic fold geometries see the “Background” section, sub-heading “East-vergent and Upright Folding”.

Deposition of Tertiary volcanic rocks (T)

The time of deposition of several different volcanic lithofacies is from the Oligocene to Miocene. The age is based on Ar^{40}/Ar^{39} dating of sanidine crystals in a reworked quartz-biotite tuff (Nutt, 1996; Nutt, 2000). The volcanic rocks represent the youngest depositional event on Buck Mountain and post-date the formation of the Buck Mountain syncline.

D3- High-angle normal faults

Two high-angle normal fault sets are present on Buck Mountain (D3). All rock units are truncated by the Central Highland fault (Figures 21 and 22). This constrains the age of the Central Highland fault to between the Oligocene and the Holocene. Displacements along D3 faults range from a few meters to many hundreds of meters.

Discussion

Overview

The late-Paleozoic unconformities and structures at Buck Mountain are significant for three reasons: 1) the type of unconformities present on Buck Mountain, 2) the age and orientation of folds and faults developed on Buck Mountain, 3) the significance of regional low-angle faulting on Buck Mountain. The following sections expand on these topics.

Regional Extent and Significance of Pennsylvanian and Permian Unconformities

C5 unconformity

The C5 unconformity at Buck Mountain is regionally significant because it constrains the timing of late Paleozoic west-vergent deformation. Mid-Desmoinesian age strata overlie Atokan age strata along the C5 unconformity. Seven locations in eastern Nevada are known to have a lacuna consistent with this unconformity (Titus et al. 1995; Cole and Cashman, 2000; Sweet et al., 2002; Villa, 2007; Cashman et al. in press;) (Figure 25). At three of these locations the unconformity is angular: Buck Mountain, Edna Mountain, and the Central Pequop Mountains (this study; Cashman et al., in press; Villa, 2007; Sweet et al., 2002; respectively). The folds in the rocks below this surface are uniformly west-vergent. The C5 unconformity is disconformable south of Buck Mountain at Moorman Ranch (Sweet et al., 2002; Sturmer, Pers. Comm., 2010) and the Nevada Test Site (Titus et al. 1995; Cole and Cashman, 2000; Sweet, 2003) (Figure 25). Southeast of Buck Mountain the C5 unconformity is documented at Mokomoke Ridge and Nine Mile Canyon (Sweet et al., 2002; Sweet, 2003). However, the data are unpublished, and the type of unconformity at these two locations is unknown.

The depth of erosion of the C5 unconformity in northeastern Nevada is generally into Morrowan and Atokan strata (Figure 25). However, in southern Nevada it cuts down to Chesterian (Late Mississippian) strata at the Nevada Test Site (Titus, 1995; Cole and Cashman, 2000; and Sweet, 2003).

In general, the C5 unconformity changes from an angular unconformity in the north and northwest to a disconformity in the south and southeast. This northwest-southeast trend is roughly parallel to the shortening direction of the structures in Morrowan-Atokan strata traced from Edna Mountain to Carlin Canyon and Buck Mountain.

C6 unconformity

The C6 unconformity at Buck Mountain is regionally the most widely documented but this study shows it is not the upper constraint of west-vergent folding. The C6 unconformity depositionally places Missourian age strata depositionally on mid-Desmoinesian age strata. Ten locations in eastern Nevada are known to document a lacuna consistent with this unconformity (Figure 26) (Titus et al. 1995; Cole and Cashman, 2000; Payne and Schiappa, 2000; Sweet et al. 2002; Sweet, 2003; Theodore et al., 2003; Trexler et al., 2003; 2004; Villa, 2007; Cashman et al. 2008; Cashman et al.in press). It is an angular unconformity at Carlin Canyon and the Diamond Mountains (Trexler, 2003, 2004; Cashman, 2008 respectively). The C6 unconformity is a disconformity at Edna Mountain, the Nevada Test Site, and Buck Mountain (Cashman et al. in press; Titus, 1995; and this study respectively). The C6 unconformity is documented at Antler Peak, Beaver Peak, Grindstone Mountain, Nine Mile Canyon, and in the Osgood Mountains but its nature is unknown there (Sweet 2003).

The depth of erosion of the C6 unconformity in eastern Nevada is variable. The C6 unconformity cuts down to mid-Desmoinesian strata at three locations: Edna Mountain, the Nevada Test Site, and Buck Mountain (Cashman et al. in press; Titus,1995; and this study, respectively). At the C6 unconformity cuts down to Morrowan and Atokan age strata at six locations: Carlin Canyon, the Diamond Mountains, Antler Peak, Grindstone Mountain, Nine Mile Canyon, and the Osgood Mountains (Trexler, 2003, 2004; Theodore and Peter, 1998; Cashman, 2008, Sweet 2003 respectively). At the C6 unconformity at Beaver Peak, Missourian rocks are deposited on allocthonous Devonian age rocks (Theodore and Peter, 1998; Sweet, 2003).

The C6 unconformity is a significant erosional signal but is not the oldest age constraint on west-vergent folding. However, the depth of erosion of the C6 unconformity is often great enough to remove the C5 unconformity if it was originally present. At the seven locations where this occurs, the C6 unconformity provides the youngest temporal constraint on west-vergent folding. At the three locations where the C6 unconformity cuts into mid-Desmoinesian strata the C5 unconformity is the temporal constraint on west-vergent folds and west-directed faults.

P1 Unconformity

The P1 unconformity at Buck Mountain is regionally significant because it provides additional geographic constraint on the extent of this unconformity in northern

Nevada (Figure 27). Sakmarian (mid-Wolfcampian) strata overli strata of several ages along the P1 unconformity deposits. A lacuna consistent with this unconformity is known to occur at nine locations in eastern Nevada (Payne and Schiappa, 2000; Sweet, 2003; Theodore et al., 2003; Trexler et al., 2003; 2004) (Figure 27). It is an angular unconformity at Beaver Peak, Carlin Canyon, and Coal Mine Canyon (Theodore et al., 2003, Trexler, 2003, 2004, and Theodore and Peters, 1998; respectively). The folds and faults present below this surface are variable. At Beaver Peak an east-directed thrust is present (Theodore et al., 2003). In Carlin Canyon and Coal Mine Canyon bedding below this surface is slightly inclined (Trexler, 2003; 2004, and Theodore and Peters, 1998). The P1 unconformity is disconformable to the south at both Secret Canyon and Buck Mountain (Cashman et al. 2008; this study). The P1 unconformity is documented southeast at Moorman Ranch and Nine Mile Canyon, and to the west in the Sulfur Springs Range, and Osgood Mountains (Sweet et al., 2002) (Figure 27).

The depth of erosion of the P1 unconformity in eastern Nevada is not systematic (Figure 27). The P1 unconformity trims section down to Devonain strata in the Sulfur Springs Range (Sweet, 2003), and to Mississippian strata in Secret Canyon and Coal Mine Canyon (Cashman et al. 2008; and Sweet, 2003 respectively) (Figure 27). These three locations are parallel to the eastern extent of the Roberts Mountain thrust (Figure 27). The P1 unconformity generally intersects Pennsylvanian strata to the southeast at Moorman Ranch (Desmoinesian strata) (Sweet, 2003) and on Buck Mountain (Missourian strata) (Payne and Schiappa, 2000; this study; respectively). In the Osgood Mountains it cuts down to Virgilian strata (Sweet, 2003). While at Beaver Peak, Carlin Canyon and Nine Mile Canyon the P1 unconformity trims down to Asselian strata. The

P1 unconformity cuts to the oldest rocks near the easternmost exposure of the Roberts Mountain Thrust front (Figure 27). The P1 unconformity trims down to early Permian rocks to the north and west of Buck Mountain. To the southeast of Buck Mountain the P1 unconformity trims down to Pennsylvanian strata.

P2 Unconformity

The P2 unconformity is present but not exposed on Buck Mountain; it is regionally significant because it constrains the age of open folds and thrust faults at Carlin Canyon and Coal Mine Canyon (Figure 28). Artinskian (late-Wolfcampian to early Leonardian) age strata overlie strata of several ages along the P2 unconformity. A lacuna consistent with this unconformity has been documented at eight locations in eastern Nevada (Sweet et al., 2002; Theodore et al., 2003; Trexler et al., 2003; 2004; Cashman et al. 2008; Linde, 2010) (Figure 28). The folds present below this surface are gentle to open. In Carlin Canyon and Coal Mine Canyon bedding below this surface is slightly inclined (Trexler, 2003,2004; and Ashcroft 2011). The P2 unconformity is disconformable to the south and east of Buck Mountain at Secret Canyon, west of Buck Mountain in the Diamond Mountains and to the northeast in the Central Pequop Mountains (Cashman et al. 2008; Linde, 2010; Sweet, 2003, respectively). The P2 unconformity has been documented at Moorman Ranch, Mokomoke Ridge, and in the Sulfur Springs Range (Sweet et al. 2002).

The depth of incision of the P2 unconformity generally cuts down-section to the east in eastern Nevada (Figure 28). The P2 unconformity cuts down to Desmoinesian strata in Secret Canyon, the Diamond Mountains, and Mokomoke Ridge (Cashman et al. 2008; Sweet, 2003 respectively). West of Buck Mountain in the Sulfur Springs Range the P2 unconformity cuts down to Asselian strata (Sweet, 2003). At four locations the P2 unconformity cuts down to Sakmarian (mid-Wolfcampian) strata southeast of Buck Mountain at Moorman Ranch, and in Secret Canyon, and to the north-northwest in Carlin Canyon, and Coal Mine Canyon (Sweet, 2003; Cashman, 2008; Trexler, 2003; 2004; and Sweet et al., 2002; respectively).

Age and Orientation of Structures

Pre-mid-Desmoinesian west-vergent folds

Desmoinesian folds and faults are fundamentally important to refining the tectonic history. At three locations in Nevada, Desmoinesian folds and faults are unconformably overlain by mid-Desmoinesian age rocks (C5 unconformity) (Figure 25). In two other locations these folds and faults are overlain by Missourian age strata (C6 unconformity) (Figure 26). The intensity of these folds and faults decreases away from Edna Mountain, to Carlin Canyon, and Buck Mountain. Desmoinesian folds and faults on Buck Mountain (this study) and Carlin Canyon (Trexler et al., 2003; 2004) record a consistent northwest-southeast shortening direction. At Edna Mountain (Villa, 2007; Cashman et al. in press) they record a southwest shortening direction. Approximately 37 km southeast of Buck Mountain at Moorman Ranch a disconformity is recorded between Atokan and mid-Desmoinesian rocks (Figure 28) (Sturmer, Pers. Comm. 2010). Therefore, a consistent decrease in fold intensity is documented from Edna Mountain to Moorman Ranch.

West-vergent structures are discordant with the common east-vergent structural grain developed in western North America. These west-vergent structures are consistently developed in rocks as young as Atokan-Desmoinesian. The progressive decrease in intensity from northwest to southeast shows that west-vergent structures developed in Atokan-Desmoinesian time are not anomalous localized out-of-sequence thrusts or a single large-scale back-thrust. Rather, they are a diagnostic characteristic of the shortening environment in Atokan to Desmoinesian time. This shortening is regional in extent and is temporally distinct.

The consistent west-vergence of these structures is important in refining the traditional model tectonic history here. These structures record a tectonic regime which is fundamentally different to any other tectonic environment in western North America before or since the Pennsylvanian. Several different tectonic models are proposed by several workers. For a discussion of these models see the Implications for Late Paleozoic Tectonic Models section below.

Post-Sakmarian folding on Buck Mountain

The Buck Mountain syncline is Mesozoic(?) in age. The geometry is regionally consistent with the Bald Mountain and Alligator Ridge anticlines (Rigby, 1960; Merrill, 1960; Campbell, 1980; Tomastik, 1980). These folds are kilometer scale, gentle to open, symmetric to slightly asymmetric, east-vergent anticlines. No Mesozoic age rocks are preserved on Buck Mountain to bracket the age of folding. Both the Bald Mountain and Alligator Ridge anticlines are interpreted to be Mesozoic in age (Rigby, 1960; Merrill, 1960; Nutt, 2000). This interpretation is based on broad constraints: Paleozoic rocks are folded and Tertiary rocks are not (Nutt, 2000). Nutt (2000) attributes these folds to Sevier-age Cretaceous shortening in eastern Nevada.

The Buck Mountain syncline is loosely constrained temporally. The Buck Mountain syncline does not fold Miocene-Oligocene age volcanic rocks. The whole section is cut by two younger high-angle normal faults. Therefore, the Buck Mountain syncline is between Sakmarian (Early-Permian) and Oligocene in age. Regionally, Mesozoic folds and faults are loosely constrained in eastern Nevada as forming between mid-Permian and the Cretaceous (Taylor et al., 1993; 2000; DeCelles, 2004). The Cretaceous Newark Valley Formation overlaps some thrust faults and is cut by others (Taylor et al., 1993). Diachronous deformation is consistent with the structural evolution of the Sevier Orogeny (Carpenter et al., 1993; Taylor et al., 2000).

Low-angle Faults on Buck Mountain

Low-angle faults on Buck Mountain were not found, nor are features associated with them present. Three lines of evidence show low-angle faulting related to either shortening or extension is not present on Buck Mountain. 1) F1 and F2 folds are found at all structural levels throughout the mountain. The folds present are consistently developed with no observable discordance between bedding facies. 2) Previously mapped brecciation zones (Nutt, 2000) are present, but, are associated with high-angle normal faults and not with folds or low-angle faults (see High-angle fault section for further discussion). 3) Thick competent carbonate layers appear to be unfolded. However, detailed mapping show these layers respond to shortening by forming broad-scale gentle- to open-folds with locally developed minor-offset faulting (2-3 meters) (Figure 23). This apparent competency contrast is an explanation for the field observations of folds developed exclusively at the top of the Ely Limestone.

Implications for Late Paleozoic Tectonic Models

Four different tectonic models have been proposed for the tectonic setting of western North America in the late Paleozoic. These include: 1) collision of North America and South America-Africa along the southern edge of North America, 2) northeast-dipping subduction along the southwestern margin of North America, 3) a left-lateral transform system along the western margin of North America, and 4) southeast or northwest-dipping subduction along the northwestern margin of North America. The late Paleozoic structures at Buck Mountain formed in the mid-Pennsylvanian. Evidence for the timing and kinematics is briefly summarized in the following section. Each model is briefly compared to the evidence at Buck Mountain. These models are presented from east to west.

Collision of North America and South America-Africa

Mid-Pennsylvanian to Permian continent-continent collision along the southern margin of North America is shown by six lines of evidence (Kluth and Coney, 1981): 1) widespread unconformities, 2) northwest-trending folds, 3) northwest-striking thrust faults, 4) rapid basin subsidence, 5) rapid block uplift, and 6) coarse, clastic sedimentary influx which disrupts long-standing sedimentary trends (Kluth and Coney, 1981). The model proposed by Kluth and Coney (1981) is that a large peninsular projection of North America was pushed northwestward by the collision and suturing of South America and

Africa. The net result of this event was intracratonic big-block uplift and rapid basin subsidence. The timing of formation of these structures is roughly synchronous with the folding and unconformities on Buck Mountain. However, structures developed on Buck Mountain have a different geometry and intensity than those developed in the mid-continent farther east. The shortening direction predicted by Kluth and Coney (1981) is northwest to southeast. This shortening direction is consistent with that of Buck Mountain. However, the distance from this suture zone is large and the intensity of deformation in Nevada increases to the west. The westward intensity increase is inconsistent with Kluth and Coney's (1981) model.

Northeast-dipping Subduction Along the Southwestern Margin

Pennsylvanian to Permian northeast-dipping subduction under southwestern North America is suggested by three lines of evidence (Ye et al. 1996): 1) Desmoisnean-age volcaniclastic sediment and fusulinid-bearing carbonate rocks are found in the State of Chihuahua, Mexico. 2) The position of this arc is related to the northwest orientation of structures developed in the North American mid-continent. 3) Several asymmetric basins found in the mid-continent are consistent with this geometry of subduction (Ye at al. 1996). The model proposed by Ye at al. (1996) is a northeast-dipping subduction zone accreting a volcanic island arc to North America. The net result of this arc accretion is intracratonic big-block uplift and rapid basin subsidence in the mid-continent. However, structures developed on Buck Mountain have a different geometry, orientation, shortening direction, and intensity than those documented farther east in the mid-continent. The shortening direction presented by Ye et al. (1996) is northeast to southwest. This shortening direction is perpendicular to the mid-Pennsylvanian northwest to southeast shortening direction recorded in the structures on Buck Mountain.

Left-lateral Transform System Along the Western Margin

A Pennsylvanian to Permian sinistral transform fault system along the southwest continental margin is suggested by five lines of evidence (Stevens and Stone, 1988): 1) left-lateral displacement of Atokan through Wolfcampian age rocks to the Mexican state of Sonora, 2) a distinct southeasterly bend in the Morrowan to Wolfcampian facies which is perpendicular to the southwesterly trend of Late Mississippian and older facies, 3) northeast-striking thrust faults and northeast-trending folds, 4) erosional truncation of these structures by late-Guadalupian (Late-Permian) time and 5) Desmoinesian to late-Wolfcampian basin subsidence (Stevens and Stone, 1988). The model proposed by Stevens and Stone (1988) is a sinistral transform margin from California to Sonora, Mexico. The net result of this transform margin is large displacements of Paleozoic rocks southeastward to the Caborca-Hermosillo region of Northern Mexico. The orientation of structures developed by this margin are consistent with F1 folds found on Buck Mountain. The onset of left-lateral faulting is also consistent with the timing of pre-mid-Desmoinesian folds on Buck Mountain. The shortening direction presented by Stevens and Stone (1988) is northwest to southeast. This shortening direction is parallel to the northwest to southeast shortening direction present on Buck Mountain.

Down-to-the-Northwest Subduction Along the Northwestern Margin

Long-lived, Devonian to Permian, down-to-the-northwest subduction in the Northern Sierra Nevada and Klamath Mountains is suggested documented by two lines of evidence (Dickinson, 2000): 1) Volcanism migrating from northwest to southeast during the Devonian, and 2) prograding arc activity through an incrementally assembled subduction complex from early to middle Devonian time (Dickinson, 2000). The model proposed by Dickinson (2000) specifically mentions the polarity of the subduction center being poorly constrained. This model also proposes a temporary cessation of subduction in the Pennsylvanian to allow for the deposition of portions of the Havallah Sequence. A northeast to southwest subduction system would produce the same orientation of folds present on Buck Mountain; however, the fold vergence would depend on the polarity of the subduction system during the Pennsylvanian and Permian. The shortening direction presented by Dickinson (2000) is northwest to southeast. This shortening direction is parallel to the northwest to southeast shortening direction present on Buck Mountain. However, this model does not explain structures at Buck Mountain unless it is revised to include mid-Pennsylvanian shortening.

Summary

In summary, two models are consistent with the structural observations at Buck Mountain, while two models are inconsistent with them. Both a sinistral transform system and northwest dipping subduction could produce west-vergent folds with a northwest to southeast shortening direction as found on Buck Mountain. Therefore, these two models are preferred for mid to late Paleozoic deformation in eastern and central Nevada.

Conclusions

Importance of this work

This work is significant for four reasons.

- It provides a geo-referenced base map for future work for Buck Mountain.
- This project unequivocally constrains the timing of west-vergent folding in the Pennsylvanian between Atokan and mid-Desmoinesian time.
- Pre-mid-Desmoinesian folds at Buck Mountain are both close, west-vergent and open upright. This is important because it shows a significant decrease in Pennsylvanian deformational intensity in a northwest-southeast direction across central Nevada.
- Pre-mid-Desmoinesian structures occur at Buck Mountain this locality is farther southeast than previously described Pennsylvanian structures. This is significant because it revises the geographic extent of Pennsylvanian deformation in east-central Nevada.

Future Work

Three suggestions for future work are as follows.

- Detailed structure mapping of the Pennsylvanian and Permian rocks ~130 km northeast of Buck Mountain in Nine Mile Canyon: Nine Mile Canyon could potentially also have west-vergent folds developed under the C5 unconformity.
- A detailed structural analysis of the Ely Limestone in the Central Pequop Mountains to resolve the east- and west-vergent sub-C5 geometries: This could

help determine whether the east-vergent structures are related to a back-thrust or a younger folding event.

- A systematic sedimentological provenance study of the Desmoinesian strata in central and eastern Nevada and western Utah to determine potential sediment sources and to date the age of coarse-grained siliciclastic deposition that could be derived from a highland related to pre-mid-Desmoinesian deformation.

References

Brew, D.A., 1971, Mississippian stratigraphy of the Diamond Peak area, Eureka County, Nevada. U.S. Geological Survey Professional Paper 661, 84 p.

Campbell, M.D., 1980, Geology of the northern Buck Mountain area, White Pine County, Nevada. [M.S. Thesis]: University of Ohio, Athens. 71 p.

Carpenter, D.G., Carpenter, J.A., Dobbs, S.W., Stuart, C.K., 1993, Regional structural synthesis of Eureka fold-and thrust belt, east-central Nevada, *in* Structural and Stratigraphic Relationships of Devonian Reservoir Rocks, East Central Nevada: Nevada Petroleum Society 1993 Field Conference, Guidebook, p. 59-72.

Cashman, P.H., Cole, J.C., Trexler, J.H., Jr., 2000, Superposed fold-thrust events at the Nevada Test Site, *in* Lagerson, D.R., Peters, S.G., and Lahren, M.M, eds., Great Basin and Sierra Nevada: Boulder , Colorado, Geological Society of America Field Guide, p. 337-354

Cashman, P., Trexler, J., Snyder, W., Taylor, W., 2008, Late Paleozoic deformation in central and southern Nevada. *in* Duebendorfer, E.M.; Smith, E.I., eds., Field guide to plutons, volcanoes, faults, reefs, dinosaurs, and possible glaciation in selected areas of Arizona, California, and Nevada., Geologic Society of America Field Guide, v. 11, p.21-42.

Cashman, P.; Villa, D.; Taylor, W.J.; Davydov, V.I.; and Trexler, J.H., Jr., 2011, Late Paleozoic Contractional and extensional Deformation at Edna Mountain, Nevada: Geological Society of America Bulletin, (in press)

Coogan, J.C., and DeCelles, P.G., 1996, Extensional collapse along the Sevier Desert reflection, northern Sevier Desert basin, Western United States, Geology, vol. 24, no. 10, pp. 933 936.

Dott, R.H., 1955, Pennsylvanian stratigraphy of Elko and northern Diamond Ranges, northeastern Nevada. Bulletin of the American Association of Petroleum Geologists, v.39, n.11, p.2211-2305.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the cordilleran thrust belt and foreland basin system, western U.S.A. American Journal of Science, vol. 304, p. 105-168

Dickinson, W.R., 2000, Geodynamic interpretation of Paleozoic tectonic trends oriented oblique to the Mesozoic Klamath-Sierian continental margin: Geological Society of America Special Paper 347, p. 209-245

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin, Geosphere, v. 2, n. 7, p. 353 368.

Gibling, M.R., and Rygel, M.C., 2008, Late Paleozoic Cyclic Strata of Euramerica: Recognition of Gondwanan Glacial Signals During Periods of Thermal Subsidence in Fielding, C.R., Frank, T.D. and Isbell, J.L., eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper 442, p. 235-248

Gilbert, J.J., Taylor, W.J., 2001, Geometry of Mesozoic(?) contractional structures; implications for the tectonic development of the Central Nevada Thrust Belt, east-central Great Basin, Nevada, Geological Society of America Abstracts with Programs, v. 33, n.3, p. 65

Greb, S.F., Pashin, J.C., Martino, R.L., and Elbe, C.F., 2008, Appalachian Sedimentary Cycles During the Pennsylvanian: Changing influences of Sea Level , Climate, and Tectonics, in Fielding, C.R., Frank, T.D. and Isbell, J.L., eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper 442, p. 235-248

Hichborn, A.D., Arbonies, D.G., Peters, S.G., Conners, K.A., Noble, D.C., Larson, L.T., Beebe, J.S., and McKee, E.H., 1996, Geology and gold deposits of the Bald Mountain mining district, White Pine County, Nevada. *in* Jones, A.E., ed., Geological Society of Nevada, Guidebook, no. 23, p. 1-42.

Howald, W.C., 1996, A brief history and geologic overview of the Vantage Deposits, Alligator Ridge, Nevada, *in* Jones, A.E., ed., Geological Society of Nevada, Guidebook, no. 23, p. 97-104.

Humphrey, F.L., 1960, Geology of the White Pine Mining District, White Pine County, Nevada: Nevada Bureau of Mines and Geology Bulletin, v. 57, 119 p.

Jansma P.E., and Sleep, R.C., 1995, Kinematics of Underthrusting in the Paleozoic Antler Forland Basin, The Journal of Geology, v. 103, p. 559-575.

Larson, E.R., Riva, J.F., 1963, Perliminary geological map of the Diamond Springs quadrangle, Nevada. Nevada Bureau of Mines # 1963-013524, scale 1:62,500, 1 sheet, 20 p.

Linde, G., 2010, Permian tectonics in the Diamond Mountains, Eureka and White Pine counties, east-central Nevada. [M.S. Thesis]: University of Nevada, Reno.~120 p.

MacCready, T., Snoke, A.W., Wright, J.E., Howard, K.A., 1997, Mid-crustal flow during Tertiary extension in the Ruby Mountains core complex, Nevada; Geological Society of America Bulletin, v.109, n.12, p.1576-1594,

McGrew, A.J., Snee, L.W., 1994, 40AR/39AR thermocronologic constraints on the tectonthermal evolution of the northern East Humboldt Range metamorphic core complex, Nevada; Tectonophysics, v. 238, p. 425-450.

McHugh, J.C., 2003, Late Paleozoic contraction in the northern Hot Creek Range, Nye County, Nevada [M.S. Thesis]: University of Nevada, Reno, 107 p.

Merrill, J.D., 1960, Geology of the lower part of the Buck Mountain Quadrangle, Nevada. [M.S Thesis]: University of Southern California, Los Angeles, 93 p.

Mii, H., Grossman, E.L., and Yancey, T.E., 1999, Carboniferous Isotope Stratigraphies of North America: Implications for Carboniferous Paleogeograph, and Mississippian Glaciation: Geological Society of America Bulletin, V.111, p. 960-973

Miller, E.L., Holdsworth, B.K., Whiteford, W.B., 1984, Stratigraphy and structure of the Schoonover sequence, northeastern Nevada: Implications for the Paleozoic plate-margin tectonics, Geologic Society of America Bulletin, v. 95, p. 1063-1076

Nichols, G, 1999, Sedimentology and Stratigraphy: Massachusetts, Blackwell Science Ltd., 355 p.

Nilsen, T.H., and Stewart, J.H., 1980, The Antler orogeny--Mid-Paleozoic Tectonism in western North America: Geology, v.8, p. 298-302.

Nolan, T.B., Merriam, C.W., and Williams, J.S., 1956, The Stratigraphic Section in the Vicinity of Eureka, Nevada: Geological Survey Professional Paper 276, 77 p.

Nutt, C.J., 1996, Cretaceous(?) to early Oligocene sedimentary and volcanic rocks at Alligator Ridge, Buck Mountain-Bald Mountain area, central Nevada, *in* Taylor, W.J., and Langrock, H., eds., Cenozoic structure and stratigraphy in central Nevada: 1996 Field Conference Volume, Nevada Petroleum Society Inc., Reno, p. 13-18

Nutt, C.J., 2000, Geologic Map of Alligator Ridge Area, Including the Buck Mountain East and Mooney Basin Summit Quadrangles and Parts of the Sunshine Well NE and Long Valley Slough Quadrangles, White Pine County, Nevada. United States Geological Survey Geologic Investigator Series I-2691, Scale 1:24,000, 1 sheet.

Nutt, C.J., and Good, S.C., 1998, Recognition and significance of Eocene deformation in the Alligator Ridge area, Central Nevada, Contributions to the gold metallogeny of northern Nevada, U.S. Geological Survey open-File Report 98-338, 10 p.

Nutt, C.J., and Hofstra, A.H., 2003, Alligator Ridge district, East-Central Nevada: Carlin-type gold mineralization at shallow depths. Economic Geology, v. 98, p. 1225-1241

Oldow, J.S., 1984, Spatial variability in the structure of the Roberts Mountains allochthon, western Nevada, Geologic Society of America Bulletin, v. 95, p. 174-185.

Payne J.D., Schiappa, T.A., 2000, Biostratigraphic characterization and tectonostratigraphic implications of a newly recognized Middle Pennsylvanian unit, Buck Mountain, White Pine County, Nevada, Geological Society of America Abstracts with Programs, v. 33, n.5, p.36.

Perez-Huerta, A., 2004, Brachiopods and paleoecological studies in the Pennsylvanian of the Great Basin. [Ph.D. Dissertation]: University of Oregon, Eugene. 419 p.

Peterson, F. and Pipiringos, G.N., 1979, Stratigraphic relations of the Navajo Sandstone to Middle Jurassic formations, southern Utah and northern Arizona: Geological Survey Professional Paper P 1035-B, p.43.

Perry, W.J., 1994, Stratigraphy and Structure of the Northern Pancake Range, Nye County, Nevada: a progress report: U.S. Geological Survey open-File Report 91-386, 28 p.

Pipiringos, G.N. and O'Sullivan R.B., 1978, Principal unconformities in the Triassic and Jurassic rocks, Western Interior United States; a preliminary survey: Geological Survey Professional Paper P 1035-A, p.29.

Rich, M., 1977, Pennsylvanian paleogeographic patterns in the western United States. *In* Paleozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium 1, Los Angeles, California, Society of Economic Paleontologists and Mineralogists, p. 87-111.

Rigby, J.K., 1960, Geology of the Buck Mountain-Bald Mountain area, southern Ruby Mountains, White Pine County, Nevada. *In* Geology of east central Nevada., None ed., Intermountain Association of Petroleum Geologists, 11th Annual Field Nonconference Guidebook, pp.173-180.

Roberts, R.J., 1951, Geology of the Antler Peak quadrangle, United States Geological Survey GQ 10, Scale 1:62,500.

Roberts, R.J.; Fergison, H.G.; Gilluly,J.; Holtz, P.E.; 1958, Paleozoic rocks of north-central, Nevada, American Association of Petroleum Geologists Bulletin: v. 42, n. 12, p 2813 2857.

Saller, A.H., Dickinson, W.R., 1982, Alluvial to Marine facies transitions in the Antler overlap sequence Pennsylvanian and Permian of north-central Nevada: Journal of Sedimentary Petrology, v. 52, p.925-940.

Silberling, N.J. and Roberts, R.J., 1962, Pre-tertiary stratigraphy and structure of northwestern Nevada, Geological Society of America Special Paper 72, p. 58.

Snyder, W.S., Trexler, J.H. Jr., Cashman, P.H., and Davydov, V.I., 2000, Tectonstratigraphic framework of the upper Paleozoic continental margin of Nevada and southeastern California: Reno, Geological Society of Nevada Program with Abstracts, p 76-77.

Snyder, W.S., Trexler, J.H. Jr., Davydov, V.I., Cashman, P., Schiappa,T.A. and Sweet, D., 2002, Upper Paleozoic tectonostratigraphic framework for the western margin of North America (extended abs.): AAPG Hedberg Research Conference: Late Paleozoic Tectonics and Hydrocarbon Systems of Western North America The Greater Ancestral Rocky Mountains, p. 58-61.

Speed , R.C., and Sleep, N.H., 1982, Antler orogeny and foreland Basin: A model, Geologic Society of America Bulletin, v. 93, p. 815-828.

Stevens, C.H., 1977, Permian depositional provinces and tectonics, Western United States. *In* Paleozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium 1, Los Angeles, California, Society of Economic Paleontologists and Mineralogists, p. 87-111.

Stone, P., and Stevens, C.H., 1988, Pennsylvanian and Early Permian paleogeography of east central California: Implications for the shape of the Ccontinental margin and the timing of continental truncation: Geology, v. 16, 330-333.

Sturmer D.M., Trerxler J.H., Poulson, S.R., Snyder, W.S., Davydov, V.I., Ritter, S.M., Groves, J.R., Cashman, P.H., Whitmore, R.J., Carbon isotope chemostratigraphy of the Lower Pennsylvanian cyclothems at Grindstone Mountain, Elko County, Nevada, Geological Society of America Abstracts with programs, v. 41, n.6, p.16

Sweet, D., and Snyder, W.s., 2002, Middle Pennsylvanian through Early Permian tectonically controlled basins: Evidence from the central Pequop Mountains, northeast Nevada: Late Paleozoic tectonics and hydrocarbon systems of western North America—The greater Ancestral Rocky Mountains: Tulsa, AAPG Hedberg Research Conference, p. 74-77

Sweet, D., 2003, The Late Paleozoic Tectonostratigraphy of the Central Pequop Mountains, Elko County, Nevada [M.S. Thesis]: Boise State University, Boise. 130 p.

Sweet, D., Snyder, W.S., Schiappa, T., Davydov, V.I., Trexler, J.H., Jr., 2004, Style and spatial distribution of the C5 unconformity (Desmoinesian) in eastern Nevada; implications for the destruction of the Ely Basin and the initiation of the Hogan Basin, Geological Society of America Abstracts with programs, v. 36, n.4, p.27

Taylor, W.J., Bartley, J.M., Fryxell, J.E., Schmitt, J.G., Vandervoort, D.S., 1993, Tectonic style and regional relations of the central Nevada thrust belt. *in* Lahren, M.M., Trexler, J.H., Spinosa, C., eds. Crustal evolution of the Great Basin and the Sierra Nevada: Cordilleran/Rocky Mountain Section, Geological Society of America Guidebook, Department of Geological Sciences, University of Nevada, Reno, 496 p.

Taylor,W.J., Bartley, J.M., Martin, M.W., Geissman, J.W., Walker, J.D., Armstrong, P.A., and Fryxell, J.E., 2000, Relations between hinterland and foreland shortening: Sevier orogeny, central North American Cordillera, Tectonics, v. 19, n. 6, p. 1124-1143.

Theodore, T.G., Moring, B.C., Harris, A.G., Armstrong, A.K., Finney, S.C.; 2003, Geologic Map of the Bever Peak Quadrangle, Elko and Eureka Counties, Nevada: Nevada Bureau of Mines and Geology, Report: 143, Scale 1:24,000, 1 sheet.

Theodore, T.G., and Peters, S.G., 1998, Links between crustal shortening during the late Paleozoic Humboldt Orogeny, northeast-striking faults and carlin-type Au deposits in Nevada: Geological Society of America Abstracts with Programs, v. 30, n.7, p.76

Tomastik, T.E., 1980, Geology of the southern part of Buck Mountain, White Pine county Nevada. [M.S. Thesis]: University of Ohio, Athens. p.240

Trexler, J.H., Jr., Cashman, P.H., Cole, J.C., Snyder, W.S., Tosdal, R.M., Davydov, V.I., 2003, Widespread effects of middle Mississippian deformation in the Great Basin of western North America: Geological Society of America Bulletin, v. 115, p. 1278-1288

Trexler, J.H., Jr., Cashman, P.H., Snyder, W.S., Davydov, V.I., 2004, Late Paleozoic tectonism in Nevada: timing, kinematics, and tectonic significance: Geological Society of America Bulletin, v. 116, p. 525-538

Vetz, N., 2010, Establishing the minimum age of the Sonoma orogeny using the Koipato Formation in west-central Nevada: Nevada Petroleum Society Monthly Newsletter, (March), Pg. 3.

Villa, D.E., 2007, Late Paleozoic deformation at Edna Mountain, Humboldt County, Nevada [M.S. Thesis]: University of Nevada, Reno. 122 p.

Wernicke, B.P., 1992, Cenozoic extensional tectonics of the Cordillera, U.S., In: Burchfiet, B., Lipman, P., and Zoback, M. (Eds.), The Geology of North America, vol. 63, The Cordilleran Orogen: Conterminous U.S.Geological society of America, Boulder, Colorado.

Ye, H., Royden, L., Burchfiel, B.C., and Schuepbach, M., 1996, Late Paleozoic deformation of the interior North America: American Association of Petroleum Geologists Bulletin, v. 80, p. 1397-1332.

Appendix A

Toughbook® mapping techniques and troubleshooting

Mapping for this study was entirely conducted using ArcGIS 9.3 on a Panasonic Toughbook® in the field. Due to the conditions on Buck Mountain basic issues became interesting challenges. Five main groups of issues are apparent: 1) GPS issues, 2) battery issues, 3) viewing the screen, 4) touch pad sensitivity, and 5) tablet mode. What follows are the specific challenges and tried and true solutions.

GPS Issues

The Globalsat® BU-353 GPS (external GPS) is an adequate companion to field mapping; however, three problems exist: 1) a 10-20 minute lag in operational ability at initial start up, 2) a random loss of signal, 3) occasional errors of more than eight meters. Solutions for these challenges follow. The 10-20 minute lag time is unavoidable. The simplest solution is to start the GPS in ArcGIS before hiking out to the outcrop. Spontaneous loss of signal is only solved by stopping the GPS in ArcGIS and opening the program GPSinfo. Here check to see if the GPS has swiched “COM ports”. Do this by clicking on the drop down tab and selecting either “COM 4” of “COM 5”. Next click the “Start GPS” button. The GPS is working when random numbers, letters, and symbols show up in the large box below. Note the “COM port” that is in use. Close this program and go back to ArcGIS, select the same “COM port” and start the GPS again. Three solutions exist for large amounts of location inaccuracy. First, is walking in a two meter by two meter square with the GPS exposed to the sky. Second, is carrying a small handheld GPS and waiting until the locations match within acceptable error. Third, is taking a bearing and relying on tried and true navigational skills. If the day is excessively overcast or there is minimal exposure to the sky large error will be unavoidable. Large error will also be unavoidable in the early spring due to an unfavorable satellite geometry in the northern hemisphere.

Battery Issues

Mapping with a Toughbook® in remote locations provides an obvious challenge in battery usage. Two solutions to keeping the battery charged are: 1) using a generator or 2) an AC adaptor and a car or truck battery. The AC adaptor greatly simplifies logistics of field work. However, it means the vehicle must be running to charge the battery. This poses two problems 1) overheating the vehicle and 2) potentially starting a grass or forest fire. If the vehicle is not running be cautious of the duration of charge time. Too much consistent draw on the vehicle battery will drain it. Using a generator increases the logistical complexity but alleviates one of the aforementioned risks; killing the vehicle battery. However, the manifold and exhaust of a generator are very hot. Therefore, the possibility of starting a grass or forest fire remains. Preserving the battery during the day means less charge time at night. Accept that the screen is not going to be visible most of the time, so turn down the Toughbook® monitor brightness to preserve battery life. Finally, always carry paper maps that can be drawn on. This mapping can be transferred to the computer later.

Viewing Issues

Two challenges exist around viewing the screen these include: 1) losing the cursor when digitizing and 2) too much external illumination. Two approaches to this problem are: 1) individual solutions to individual problems, and 2) using a rain jacket.

The following bullet-list is a concise list of individual solutions to individual problems. These are appropriate measures to take while moving and plotting point data on a Toughbook®.

1. Turn the touchpad sensitivity down as low as it will go. This is to avoid adding erroneous points to the geodatabase.
2. Turn off all National Agricultural Imaging Program (N.A.I.P.) imagery. National Agricultural Imaging Program images are great to map with. However, they are hard to see on a back lit computer screen in high-light environments.
3. Orient the computer so the screen is either entirely in the sun or entirely in the shade.
4. To find the cursor use the touch pad to slide the cursor entirely to the right and entirely down. It will come out of the lower right corner and away from buttons that could affect the program (e.g. the close “X” or “Start” buttons).

The single best solution for seeing the screen in general is draping a rain jacket over one’s head and the computer. The elimination of competing external light sources drastically improves the effectiveness of the computer monitor. This single solution alleviates all of the viewing issues. However, this solution presents its own problems, because, you cannot see what you are trying to map. That is unavoidable and requires enormous patience.