EXTENSION RELATED BRECCIAS: IMPLICATIONS FOR GROUNDWATER FLOW FROM PAHUTE MESA TO NEAR BEATTY, NEVADA

by

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Bachelor of Science, Slippery Rock University, 2006

Submitted to the Graduate Faculty of

The Department of Geology and Planetary Science in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2010

UNIVERSITY OF PITTSBURGH

SCHOOL OF ARTS AND SCIENCES

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It was defended on

April 13, 2010

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ABSTRACT

The Las Vegas Valley Shear Zone, a right lateral strike slip fault that trends >100 m at N60W, makes a right step east of Beatty, Nevada resulting in detachment faulting and rhyolitic volcanism characteristic of the South West Nevada Volcanic Field. In the Fluorspar Canyon region of the field area, the Fluorspar Canyon-Bullfrog Hills (FC-BH) detachment dips 40° N and separates Late-proterozoic and Paleozoic strata in the footwall from Tertiary Volcanics and sediments in the hanging wall. To the east, the detachment links with the moderately dipping Tate's Wash Fault. After removing the 40°N tilt, these two structures form a listric normal fault that cuts through the Paleozoic and into the crystalline basement. The hanging wall does not crop out in the field area and may be represented by the strata of the Grapevine Mountains of Death Valley. Extension along the FC-BH detachment migrates westward and occurs in previously recognized pulses.

Expansive breccias are a distinctive feature in the field area and are directly related to extension. This study examines mapped breccias to determine their origin and relationship to deep structures in the field area. Deposits related to deep structures may influence the flow of possibly contaminated groundwater from Pahute Mesa in the Nevada Test Site southwest into the Beatty region. Breccias are interpreted to be deposited as large slide masses or accumulated in extension-related low areas. Groundwater flows southwest possibly using the NE trending Thirsty Canyon Lineament as a pathway. Water ponds against the east side of the N-trending Hogback Fault as suggested by the presence of numerous springs. The breccias mapped in the study area are not directly fault related, do not cut the underlying detachment, and do not significantly influence groundwater flow. Flow continues southward into the Beatty, Nevada region via the Amargosa River.

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1.0 INTRODUCTION

1.1 HISOTRY OF THE NEVADA TEST SITE

The Nevada Test Site (NTS), located in south-central Nevada (figure 1.1), was the primary location of nuclear testing from 1951-1992. The site was chosen due to its sparse population and Federal control of most of the land (Laczniak et al. 1996). Nuclear testing began in 1951 with most detonations occurring at the surface. However, above ground explosions ceased due to concerns over atmospheric contamination (Laczniak et al., 1996).

The Limited Test Ban Treaty, established in 1961, required all nuclear tests to be performed underground to prevent atmospheric fallout. Throughout the history of the NTS, 828 underground detonations have been detonated (Department of Energy, 2008). Many tests took place at or below the water table, thereby introducing radionuclides into the groundwater system (Laczniak et al., 1996). Most underground tests (95%) were conducted at Yucca Flat, Rainier Mesa, and Pahute Mesa (figure 1.1). No explosive testing has been conducted at the NTS since September 1992 (Townsend and Grossman, 2001).

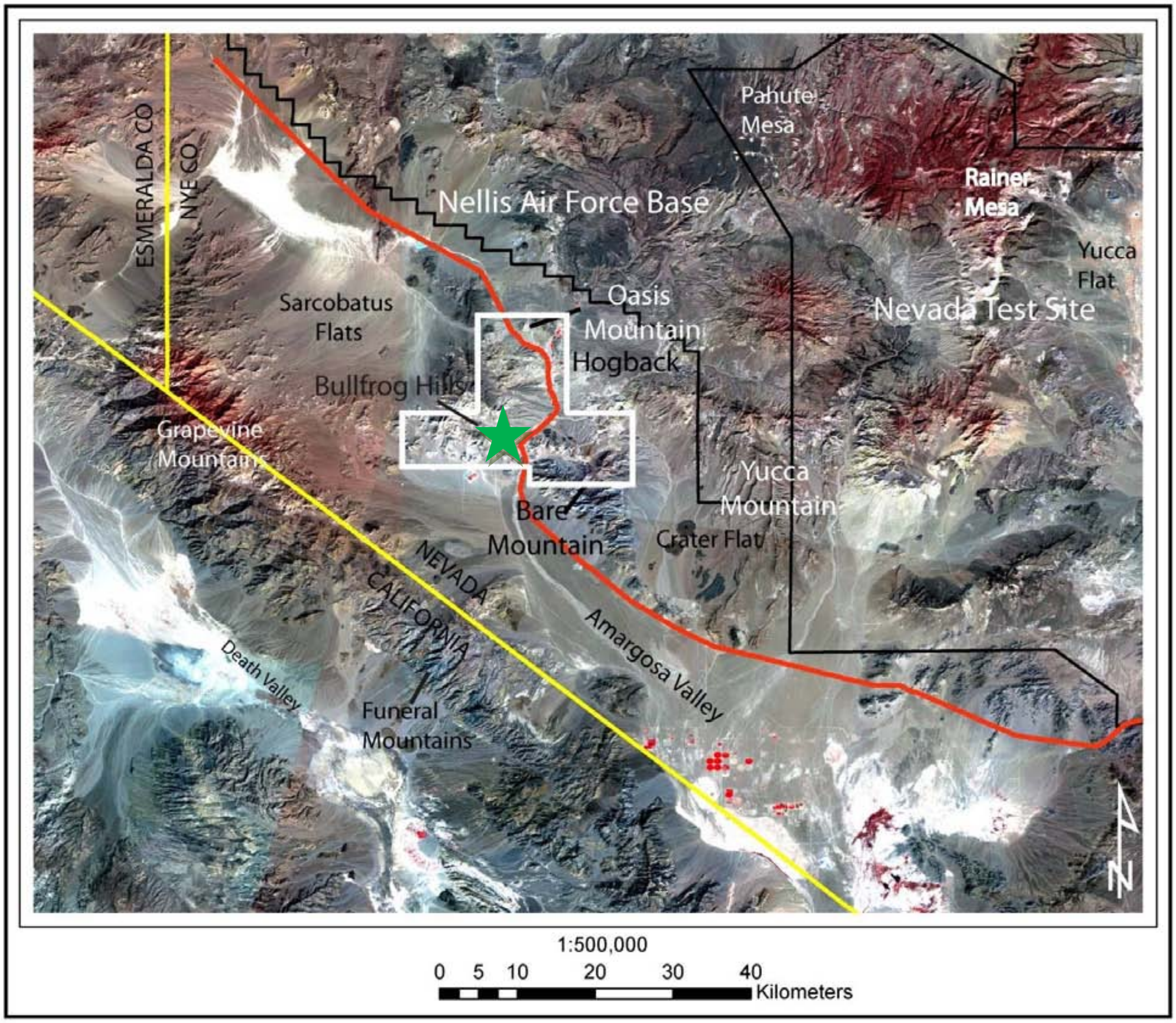


Figure 1.1 Location map of the field area and surrounding features. White lines boarder the field area. Bold red line is state Highway 95. Yellow lines represent the boarders between Nye County, NV, Esmeralda County, NV, and California. Black lines boarder the Nevada Test Site and Nellis Air Force Base (labeled appropriately). Green star marks the location of Beatty.

breccias that could provide pathways to accommodate faster than average water movement. This study examines surface structures and stratigraphy, especially of Tertiary units, in order to ascertain the distribution of aquifers and aquitards within the subsurface, and to assess faults and fault-related breccias that may serve as fast pathways for water movement.

Emphasis in this thesis is placed upon extensive bodies of breccia mapped in the area (Maldonado and Hausback, 1990; Minor et al, 1997; Connors et al, 1998; Fridrich et al, 2007) in order to determine which (if any) are related to deep, steep fault structures.

2.0 PHYSIOGRAPHY, STRUCTURE, AND STRATIGRAPHY OF THE FIELD AREA

2.1 GEOGRAPHIC AND PHYSIOGRAPHIC SETTING OF THE FLUORSPAR CANYON-BULLFROG HILLS REGION

2.1.1 Basin and Range Province

The study area is within the Basin and Range province in the southwest United States. This domain is characterized by alternating basins and mountain ranges attributed to extensional faulting. Ranges and basins are generally separated by listric normal faults. Footwall blocks are mountain ranges and the hanging walls underlie basins.

Westward extension began in the Miocene and locally continues. Overall, westward extension is recorded by the orientations of mountain ranges and basins (labeled in figure 1.1).

Yucca Mountain comprises fault blocks of tilted Tertiary volcanic rocks that trend northerly and stand above Crater Flat basin to the west and Jackass Flats on the east. The volcanic units were erupted from the Southwest Nevada Volcanic Field (SWNVF; figure 2.1) during the Miocene. As the proposed location of the waste repository, this area has been the subject of many geologic, hydrogeologic and geophysical studies (Blakely et al. 2000; Grauch et al., 1997; Hildenbrand et al., 1999; Mankinen et al., 1999; Mankinen et al., 2003; Schenkel et al., 1999; Sweetkind et al., 2001; Winograd and Thoradarson, 1975).

2.1.2 The Walker Lane Belt

The field area lies adjacent to the Walker Lane belt (WLB), a structural domain that extends from Northwest California to Las Vegas in southern Nevada (figure 2.2). The WLB is characterized by diversely trending mountain ranges that distinguish it from the general north-south trend of typical Basin and Range mountain ranges (references within Stewart [1988] and Faulds and Henry [2005]). Stewart (1988) divided the WLB into eight domains based on the dominant structural styles (figure 2.2a). The study area is located in the Goldfield Domain of the Walker Lane Belt, which is characterized by its lack of strike slip motion compared to other domains. Henry and Faulds (2005) do not include the Goldfield domain as part of the WLB due to the lack of strike slip faults (figure 2.2b).

The belt is purported to be part of the Pacific-North American transform margin and may accommodate about 20% of the dextral motion along western

North America (Faulds and Henry, 2005). Motion within Walker Lane is accommodated by north-west striking dextral strike-slip faults (Stewart, 1988).

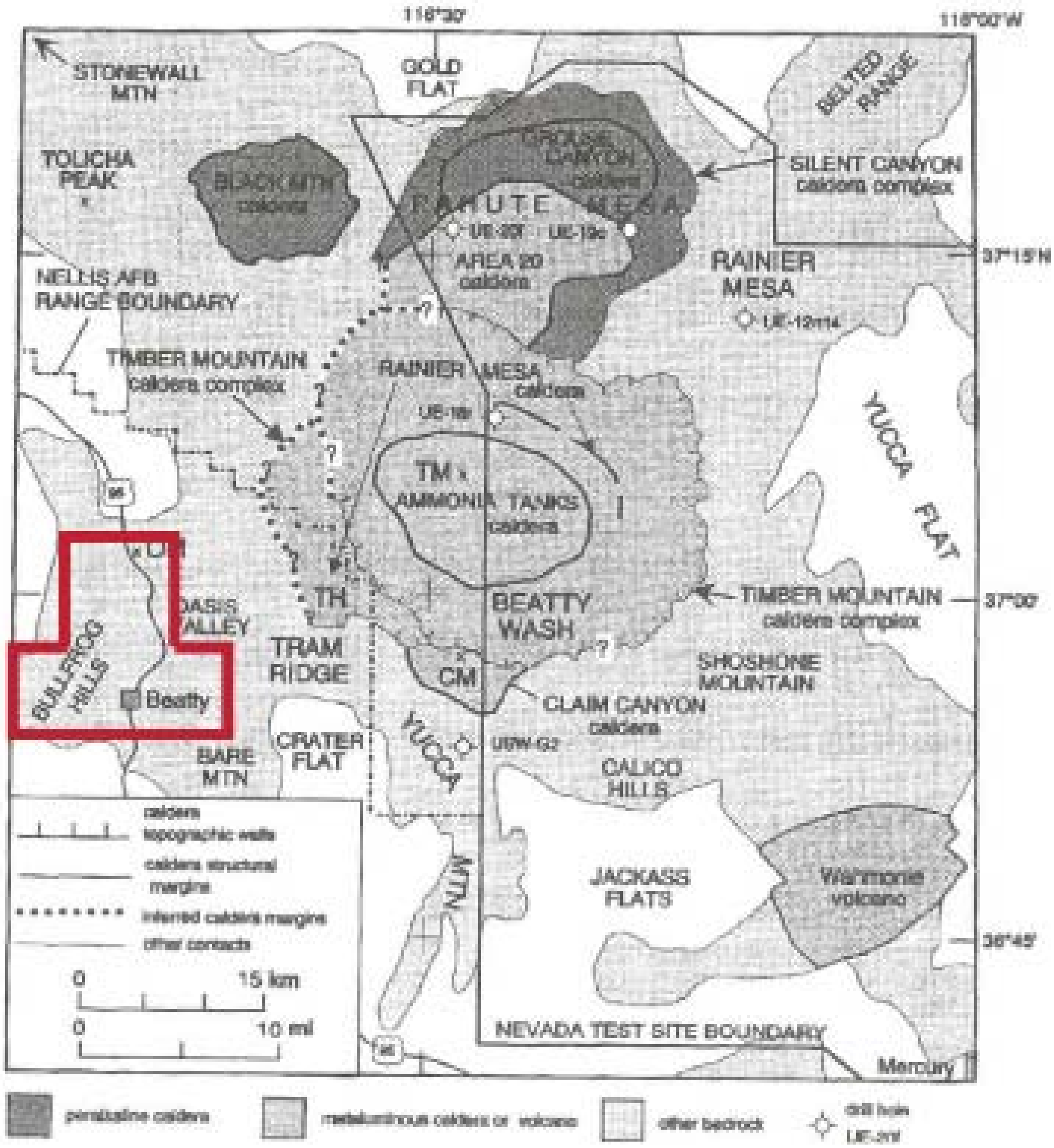


Figure 2.1 Map of the calderas in the SWNVF. CM is Claim Canyon Caldera, OM is Oasis Mountain, TM is The Timber Mountain, TH are the Transvaal Hills. Red lines boarder the field area. After Sawyer et al. (1994)

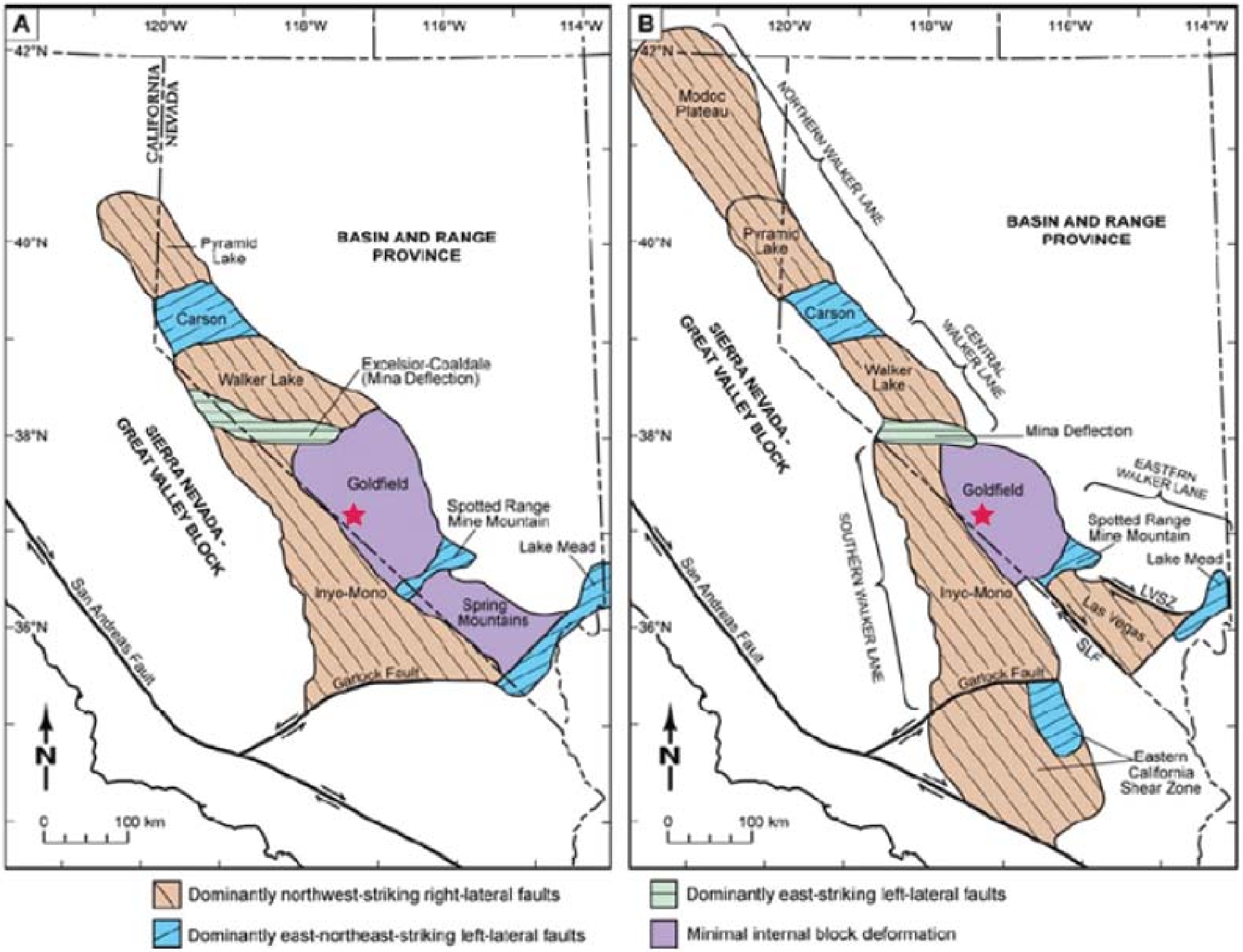


Figure 2.2 Location and boundaries of the different structural domains in the Walker Lane Belt. Box A shows the domains defined by Stewart (1988). Box B shows domains defined by Faulds and Henry (2005). Red star is the location of the field area. Modified from Faulds and Henry, (2005).

2.2 PRINCIPAL STRUCTURES

The field area and vicinity have been subject to several geologic investigations. Geologic mapping has been conducted multiple times in order to fully characterize the geologic setting and related groundwater flow system of the proposed waste repository, nearby to the east, at Yucca Mountain. In the Bare Mountain-Beatty-Bullfrog Hills area, geologic maps were prepared of Bare Mountain (Kleinhampl and Cornwall, 1961), Bare Mountain and the Fluorspar Hills (Monsen et al. 1992), the Bullfrog Hills (Ransom et al. 1910; Maldonado, 1990; Maldonado and Hausback, 1990; Minor et al. 1997; Connors et al. 1998), and Oasis Valley (Fridrich et al. 2007). Relevant regional studies were conducted by Snow and Wernicke (2000).

Geophysical studies also were conducted in the field area to ascertain the depth to pre-tertiary basement, subsurface structural geology, and distinguish caldera boundaries. Grauch et al. (1997) interpreted gravity data and recognized numerous subsurface features in Oasis Valley. Hildenbrand et al. (1999) use gravity inversion data to expand on Grauch et al. (1997) and construct a three-dimensional map of the pre-Tertiary basement. Mankinen et al. (1999) published a magnetic and gravity study of Pahute Mesa, incorporating their work with Grauch et al. (1997), in an effort to further constrain basin boundaries and other region features. Magnetotelluric data was interpreted by Schenkel et al. (1999) in an attempt to identify and describe geologic features that may influence groundwater flow from Pahute Mesa. Mankinen et al. (2003) reports the results of all the geophysical studies conducted in the Pahute Mesa and Oasis Valley region and discusses hydrologic implications.

2.2.1 Mesozoic Structures

Folding and thrusting in the Bare Mountain area and vicinity may have begun as early as Late Permian or Triassic. Thrusts, generally with east-directed transport, were important during the Mesozoic, especially as part of the Sevier orogeny (Armstrong, 1968; Fleck, 1970; Stewart, 1980; Stuckless and O'Leary 2007). Most prominent in the field area is the Meiklejohn Peak thrust that crops out on the northeastern side of Bare Mountain (Monsen et al. 1992). The Meiklejohn Peak Thrust is interpreted to be part of the long Belted Range thrust above which Ordovician carbonate units moved southwesterly onto Devonian carbonate at Bare Mountain. Thrusting accommodated by the Meiklejohn Peak thrust has a different transport direction than the regional direction during deformation in the Mesozoic. The Meiklejohn Peak may be a Tertiary transpressional structure active before the transportation of Bare Mountain to the west.

2.2.2 Tertiary Structures

Faults that accommodate extension include those with normal and strike-slip (dextral or sinistral) separation and shallowly dipping normal faults or detachments.

2.2.2.1 The Las Vegas Valley Shear Zone

The Las Vegas Valley Shear Zone (LVSZ) is dextral strike slip fault that extends more than 100 km from near Las Vegas, Nevada to south of the Spotted Range (figure 2.3) . Motion along the N60W-striking fault began roughly at 13 Ma and culminated at 6 Ma as shown by Faulds and Henry (2005). During this time frame, the LVSZ accommodated more than 60 km of dextral shear (Faulds and Henry, 2005). Movement along the LVSZ has been relatively minor since 6 Ma probably because its orientation is no longer convenient relative to Pacific-North American plate motions that shifted from N60W to N37W from 11 to 6 Ma (Faulds and Henry 2005).

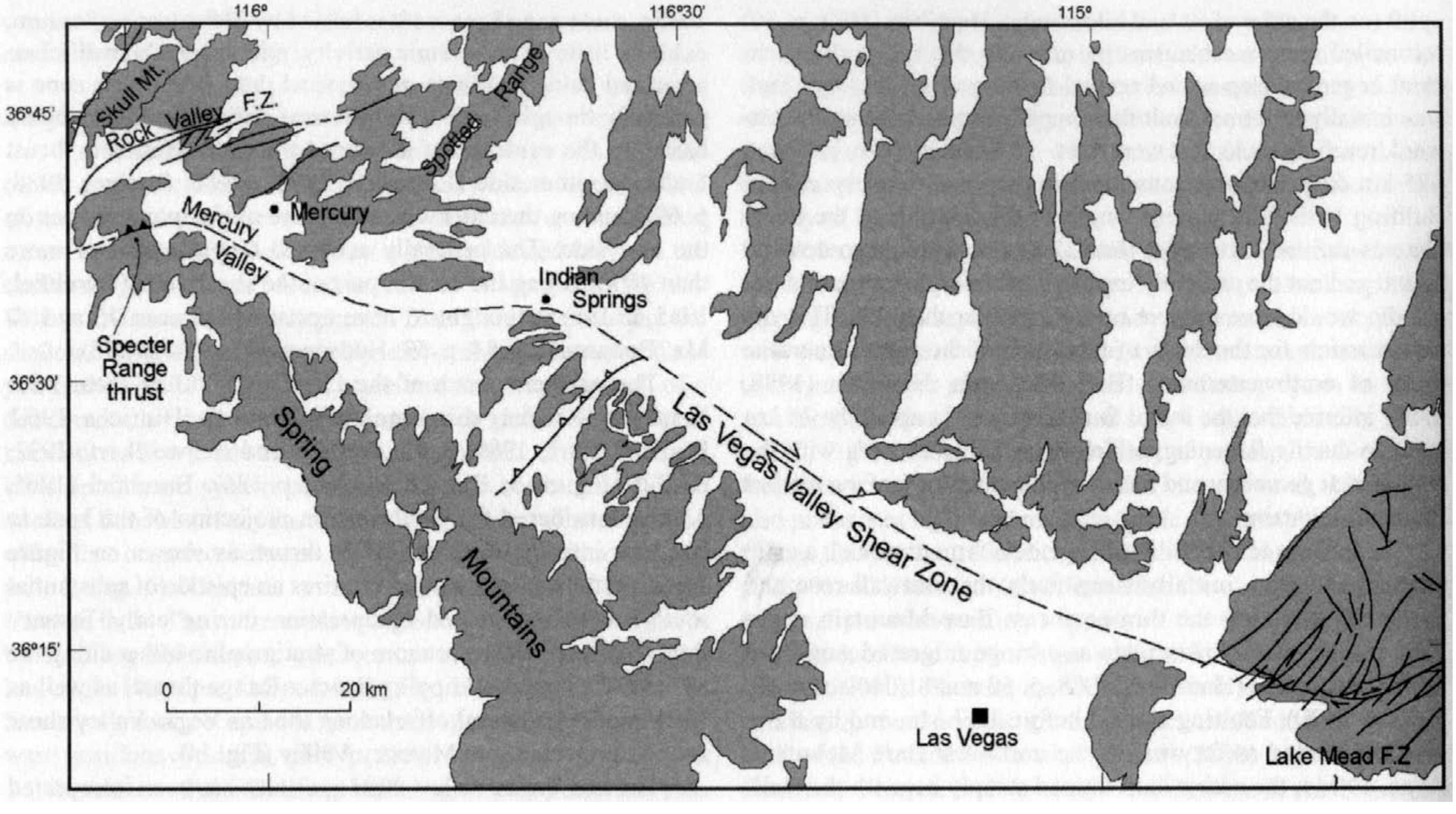


Figure 2.3 Location of the Las Vegas Valley Shear Zone. From Stuckless and O'Leary (2007).

2.2.2.2 Fluorspar Canyon-Bullfrog Hills (FC-BH) Detachment

The FC-BH detachment crops out as a dipping fault plane north of Bare Mountain and east of Beatty, Nevada. The fault may be traced west from the eastern Fluorspar Hills to west of the original Bullfrog Mine. Generally, the fault juxtaposes Neoproterozic and Paleozoic Rocks of the footwall that underlie Bare Mountain against Tertiary volcanic and sedimentary rocks exposed in the Fluorspar Hills and Bullfrog Hills (Monsen et al. 1992; Fridrich et al, 2007). The FC-BH detachment is mapped as part of the Death Valley detachment fault system (Carr and Monsen, 1988; figure 2.4). At the Amargosa Narrows, Maldonado (1990) proposes the development of a second west-trending detachment that accommodates a middle plate of Paleozoic rocks sandwiched between a lower plate of Pre-cambrian basement and an upper plate of Tertiary sediments and volcanics (discussed further below).

In the Bullfrog Hills, the FC-BH the dip of the detachment is shallow and the plane is probably sub-horizontal. This geometry is evident in the Bullfrog Hills, west of the Bullfrog Mine (Maldonado 1990).

Extensional Pulses

Movement along the FC-BH detachment occurred as four pulses recognized by Fridrich (1999a). These pulses were commonly accompanied by eruptions of the SWNVF during peak extension (11.7-10.5 Ma; Fridrich et al. 1999) along the detachment correlates to peak volcanism (12.6-11.45 Ma; Sawyer et al. [1994]). The first pulse occurs between 12.7-11.6 Ma, the interval between the eruption of the Paintbrush Group and the Timber Mountain Group. A second pulse dates at 11.6- ~10.5 Ma, synchronous with the eruption of the Timber Mountain Group. A third pulse between ~10.5-~9.5 Ma is accompanied by the eruption of the Rainbow Mountain Group in the SBH. A fourth pulse recognized by Fridrich (1999a) occurs between ~9.5-~7 Ma. Ages and timing of the pulses are constrained using unconformities and the presence of breccias in the field area (Fridrich et al., 1999).

This study provides evidence that corroborates that of Fridrich (1999a) and speculates that an earlier pulse of extension occurred along the FC-BH detachment, responsible for the opening of Crater Flat and the westward displacement of Paleozoic rocks at Bare Mountain. After the transportation of the Paleozoic strata, volcanic and sedimentary rocks consisting of the Crater Flat Group, Paintbrush Group, and older strata were deposited, covering Bare Mountain.

Although extension occurred in the area prior to 12.7 Ma (Hoisch et al, 1997; Fridrich et al. 1999a), Fridrich argues that stratigraphic and geochemical evidence indicate that motion along the FC-BH detachment did not take place before 12.7 Ma. First, the presence of Paleozoic-clast breccias overlying the 12.8-12.7 Ma Paintbrush Group indicates Bare Mountain must have uplifted between

12.7 and 11.6 Ma (Eng et al. 1996; Hoisch et al. 1997). Secondly, fission track ages of zircons from the lower plate of the detachment indicate rapid cooling of metamorphic rocks between 12.6-11.1 Ma related to uplift accommodated by the FC-BH detachment (Hoisch et al. 1997).

Two detachment surfaces encountered during exploration drilling near Bullfrog Mine (Eng et al., 1996) that revealed a tripartite rock package composed of a lower plate consisting of 1.7 Ga (Hoisch et al. 1997) gneissic basement, exposed only in a low railroad cut in the SBH south west of Rhyolite, a middle plate composed of Paleozoic strata, and an upper plate of Tertiary rocks. Near the Amargosa Narrows, the lower detachment between crystalline gneiss and Wood Canyon (?) cuts gently upward into Cambrian carbonate thereby eliminating the middle plate and resulting in the single detachment in Fluorspar Canyon. Maldonado (1990) characterizes this structural arrangement as a dual detachment fault, originally proposed by Reynolds and Spencer (1985), which accommodates massive extension (on the order of 100% to >275% extension).

12.7-11.6 Ma Pulse

The first major pulse of extension recognized by Fridrich (1999a) occurred above the FC-BH detachment around 12.7 Ma and continued until 11.6 Ma. The Fluorspar Canyon fault-Tate's Wash detachment system cut through the Tertiary units and 5.5 km of underlying previously deformed Paleozoic clastic rocks that

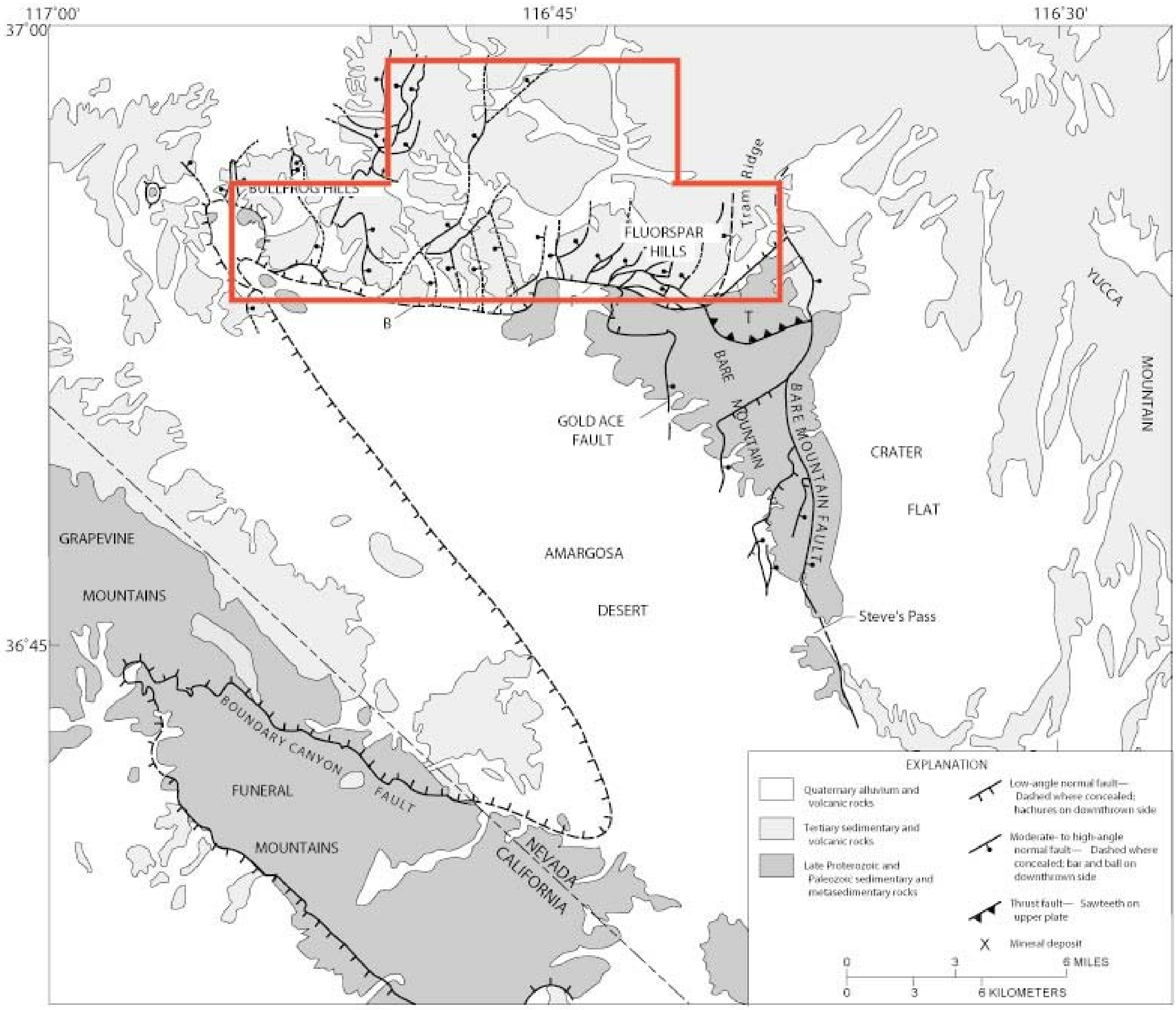


Figure 2.4 Map of the Death Valley Detachment System. B: Bullfrog Hills Detachment; F: Fluorspar Canyon Detachment. Red lines outline the field area. Modified from Hoisch (1997)

compose Bare Mountain. Fridrich (1999a) and Hoisch (2000) proposed that Bare Mountain was uplifted as the footwall of the FC-BH detachment. Pre-12.7 Ma Tertiary hanging wall rocks were tilted ~40° east (Monsen et al. 1992).

Extension along the detachment in the Southeastern Bullfrog Hills (SBH) did not begin until ~11 Ma (Weiss et al. 1996; Hoisch et al. 1997). However, Eng et al. (1996) report a modest angular discordance between the Paintbrush and overlying Timber Mountain in the SBH, indicating extension along the FC-BH detachment occurred, perhaps not as intensely than in the Fluorspar Hills, between 12.7 Ma and 11.6 Ma.

Recognizing 12.7-11.6 Ma extension using stratigraphy is difficult in the Northeastern Bullfrog Hills (NBH) due to the lack of depositional contacts and extensive fault- bounded breccia sheets. Clear stratigraphic relationships are restricted to the area east of Zabriskie Hill where Oligocene conglomerate, at the base of the Tertiary, unconformably overlies Paleozoic rocks. Tertiary units generally dip toward the southeast (Connors et al., 1998), although the dip angles are variable.

This pulse is well constrained in the Fluorspar Hills where tilted pre -12.7 Ma rocks are overlain by 11.7-11.45 Ma volcanics, resulting in an angular unconformity. The same angular unconformity is not as pronounced in the SBH due to the later initiation of extension (Maldonado, 1990; Maldonado and Hausback, 1990).

11.6-~10.5Ma Pulse

Between 12.7 and 11.6 Ma there was no major volcanism in the SWNVF (Sawyer et al. 1994). At 11.7 Ma, in conjunction with the eruption of Timber Mountain Caldera Complex (TMCC), the second pulse of extension began along the FC-BH detachment as shown by fanning dips in the Fluorspar Hills and interfingering breccias within 11.6 Ma tuffs (Monsen et al. 1992; Fridrich et al. 2007). Volcanism from the TMCC continued throughout the duration of the second extensional pulse, gradually tilting the newly erupted Timber Mountain group. Rainbow Basin, a structural basin in the SBH, was formed as the result of 11.6-~10.5 Ma extension, produced from the half-graben formed by the tilting of the Timber Mountain group and older volcanic units.

~10.5-~9.5 Ma Pulse

The 10.5-9.5Ma pulse was synchronous with localized volcanism in the Bullfrog Hills, the products of which were deposited in Rainbow Basin. Fanning dips of basin sediments and volcanic units suggest rotation occurred gradually as the volcanic units were being erupted and extension continued (Maldonado and Hausback, 1990). Strike-slip deformation in the Southeastern Bullfrog Hills occurred after the eruption of the Donovan Mountain tuff and may have been active previously, during the eruption and deposition of the Rainbow Mountain Group and underlying tuffs and sediments (Maldonado and Hausback, 1990).

2.2.2.3 Tate's Wash fault

The Tate's Wash fault (TWF) is a northeast striking, west-dipping fault with apparent left separation active between 13.9 and 12.2 Ma in the Fluorspar Hills. The date of displacement along the fault is constrained by the presence of shallow mineralization of alunite (dated at 12.2 ±4 Ma) in the hanging wall and 13.9 Ma rhyolite porphyry dikes cut by the TWF (Hoisch et al. 1997). The fault dips 50-60 ° (Monsen et al. 1992). The TWF extends north where it is concealed by Timber Mountain Group (11.7-11.45 Ma).

2.2.2.4 Bare Mountain Fault

The Bare Mountain fault bounds Bare Mountain to the east and is the western boundary of Crater Flat (figure 2.5). It is a steeply dipping normal fault; however, seismic evidence indicates at the southern end, the dip shallows to ~65° to the east (Brocher et al., 1998; O'Leary, 2007). Generally, it strikes north with about 1 km of eastward displacement (Stuckless and O'Leary, 2005). It has been interpreted both as a single large fault and as a series of stepped faults (O'Leary, 2005). Displacement is oblique at the southern end of the fault, where its trend changes somewhat to the northwest (Fridrich, 1999b).

2.2.2.5 Hogback fault

The Hogback lineament is a prominent north-south trending feature recognized by aeromagnetic, gravity, and magnetic data (Grauch et al., 1997) located east of the Oasis Mountain Hogback (figure 2.5). Grauch et al. (1997) interpreted this feature as a steep, east-dipping fault. Fridrich et al. (1999) expanded this definition, describing the structure as listric normal fault. Although, generally unexposed, it correlates with a scarp belonging to a major normal fault on the eastern side of the Hogback topographic feature (Fridrich et al., 1999). The Hogback fault serves as the western boundary of the Oasis Valley Basin in which at least 2 km of basin or caldera collapse fill have accumulated (Mankinen et al. 2003). Cross cutting relationships indicate that the Hogback fault had a prolonged history of movement: in the field area, the Hogback fault cuts volcanic rocks of the Timber Mountain Group and younger, suggesting that the Hogback fault was active between 11.2 and ~9.5 Ma. To the north, exposed fault scarps imply emplacement before the eruption of the Rainier Mesa Tuff at 11.6 Ma (Fridrich et al., 1999).

2.2.2.6 Beatty Fault

The Beatty Fault, first recognized by Ransom et al. (1910) is an inferred east-dipping fault that generally strikes north. It merges into the FC-BH detachment north of the Amargosa Narrows (Eng et al., 1996; Fridrich et al. 2007), acting as a structural boundary between the Fluorspar Hill and the Bullfrog Hills domains. The Oasis Valley fault of Connors et al. (1998) is the northern extension of the Beatty fault (Eng et al. 1996). Stratigraphic displacement in the Beatty area is measured to be 3 km (Eng et al., 1996).

2.2.2.7 Thirsty Canyon Lineament

The Thirsty Canyon Lineament (TCL) is a northeast-trending subsurface feature recognized by gravity and magnetic studies (Grauch et al., 1997; Mankinen et al. 1999; Mankinen et al. 2003). The linear feature extends from Pahute Mesa in the NTS southwestward 35 km toward Beatty (figure 2.5). The southwestern terminus of TCL is not exposed, perhaps because it is offset by left-lateral movement (Hildenbrand et al., 1999; Mankinen et al. 1999). The TCL is interpreted as a linear zone 2-3 km in width of en-echelon faults with “step-like incremental displacements typical of a caldera ring fractures system of the Silent Canyon Caldera” (Mankinen et al. 2003; Smith and Bailey, 1968).

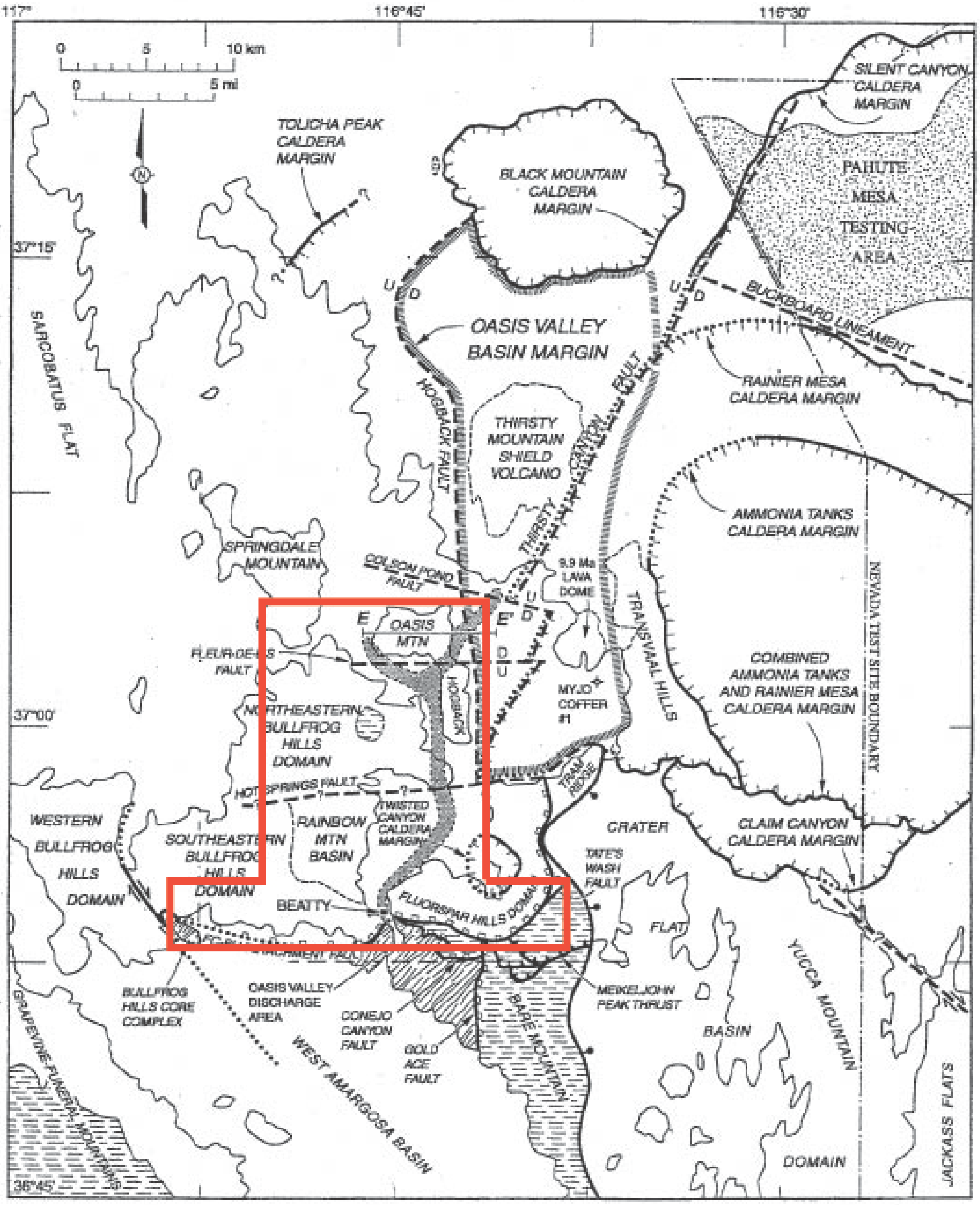
A direct relationship between the TCL and the western margin of the Silent Canyon Caldera Complex suggests that the TCL is an ancient structure related to caldera formation (Grauch et al., 1997). Fridrich et al. (1999) also suggests that the TCL is the western ring fracture zone of the Rainier Mesa Caldera.

The TCL may be a steep and deep fault that penetrates the pre-Tertiary basement (Schenkel et al., 1999), and possibly the deep crust or the upper mantle (Mankinen et al., 2003). The feature's possible extent into the Pre-Tertiary basement and its extension from Pahute Mesa to the Springdale-Beatty region identify it as a potential groundwater pathway that allows water to flow from Pahute Mesa southward (Hildenbrand et al., 1999).

2.2.2.8 Hot Springs Fault

The Hot Springs fault (HSF) is a west trending, near vertical structure inferred by gravity and magnetic data (Grouch et al., 1997). The structure is generally separated into two segments: eastern and western. The eastern segment serves as the southern boundary of Oasis Valley Basin (figure 2.5; Grouch et al. 1997). Gravity, magnetic, and field data suggests the fault dips steeply to the north (Grouch et al. 1997; Fridrich et al. 1999).

The western segment serves as the boundary between the NBH and SBH (Fridrich et al. 1999). Grouch et al. (1997) shows that the western segment of the


117°
116°45'
116°30'
37°15'
37°00'
36°45'
0 5 10 km
0 5 mi
TOLICHA PEAK CALDERA MARGIN
BLACK MOUNTAIN CALDERA MARGIN
SILENT CANYON CALDERA MARGIN
PAHUTE MESA TESTING AREA
BUCKBOARD LINEAMENT
OASIS VALLEY BASIN MARGIN
RAINIER MESA CALDERA MARGIN
SARCOBATUS FLAT
HOGBACK FAULT
THIRSTY MOUNTAIN SHIELD VOLCANO
THIRSTY CANYON FAULT
AMMONIA TANKS CALDERA MARGIN
SPRINGDALE MOUNTAIN
COLSON POND FAULT
9.9 Ma LAVA DOME
TRANSVAAL HILLS
NEVADA TEST SITE BOUNDARY
OASIS MTN
FLEUR-DE-LIS FAULT
MYJO COFFER #1
COMBINED AMMONIA TANKS AND RAINIER MESA CALDERA MARGIN
NORTHEASTERN BULLFROG HILLS DOMAIN
HOGBACK
HOT SPRINGS FAULT
RAM RIDGE
WESTERN BULLFROG HILLS DOMAIN
SOUTHEASTERN BULLFROG HILLS DOMAIN
RAINBOW MTN BASIN
TWISTED CANYON CALDERA MARGIN
CRATER
CLAIM CANYON CALDERA MARGIN
TATE'S WASH FAULT
BEATTY
FLUORSPAR HILLS DOMAIN
FLAT
BULLFROG HILLS CORE COMPLEX
OASIS VALLEY DISCHARGE AREA
CONEJO CANYON FAULT
GOLD ACE FAULT
MEIKELJOHN PEAK THRUST
BARE MOUNTAIN
BASIN
YUCCA MOUNTAIN
WEST AMARGOSA BASIN
GRAPEVINE-FUNERAL MOUNTAINS
DOMAIN
JACKASS FLATS

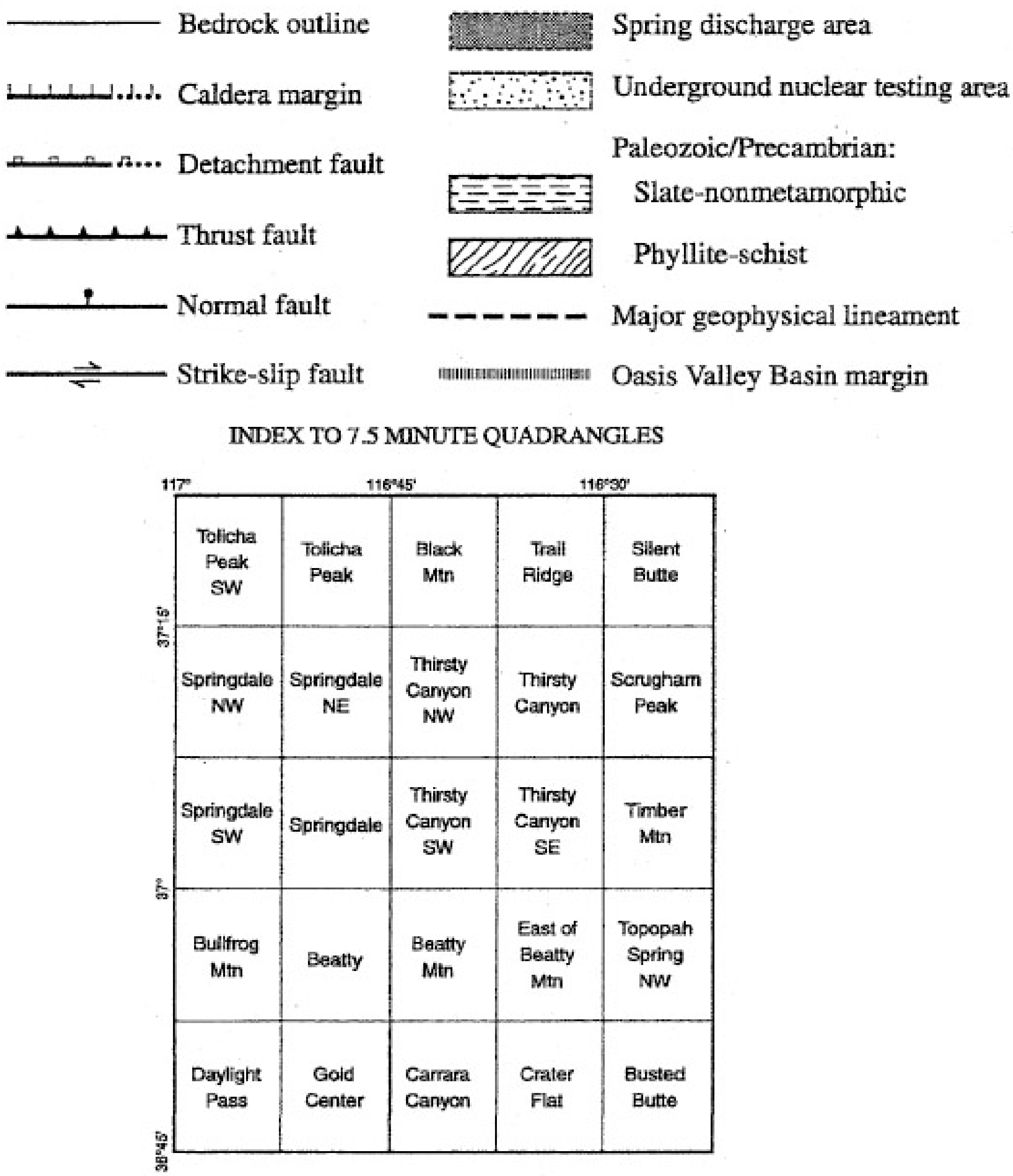


Figure 2.5 Map of Oasis Valley Basin and vicinity. Red box outlines the field area. Modified from Fridrich et al. (1999).

Hot Springs fault is accompanied with a reversal in polarity illustrated by the steep change in gravity to the south.

The polarity difference between the eastern and western segments suggests the Hot Springs fault is not a single structure but may actually be two separate faults (Fridrich et al. 1999; Mankinen at al. 2003).

The linearity of the HSF has been interpreted as a tectonic structure (Grouch et al. 1997). Furthermore, Stewart (1988) suggests east-striking faults in the Excelsior-Coaldale domain of the Walker Lane Belt are reactivated Mesozoic structures. This study applies the same hypothesis to steep, east-west striking structures, such as the HSF.

2.2.3 Structural domains within and adjacent to the study area

2.2.3.1 Crater Flat

Crater Flat is a north-south trending structural basin about 24 km long and 6-11 km wide that lies south of the SWNVF (figure 2.5). The basin formed within a graben (Fridrich, 1999) bounded by normal faults. On the west Bare Mountain fault is an east dipping front range fault along which Late Proterozoic and Paleozoic strata of Bare Mountain are uplifted**.** The eastern boundary of the basin coincides with the concealed Gravity fault, a west dipping fault interpreted from gravity anomalies with a throw of >1 km (Fridrich, 1999a).

In general normal faults record the regional north-south maximum principal stress direction. However, near the SWNVF caldera complex, radial faults probably record local caldera-related stress (Fridrich, 1999a). Within the basin a thick sequence (~3 km) of Tertiary volcanic and sedimentary rocks are preserved (Stuckless and O'Leary 2007).

2.2.3.2 Amargosa Valley

Amargosa Valley is a large, northwest-trending basin located south of the field area. The basin, about 80 km long and as much as 30 km wide, coincides with the Amargosa Desert (Stuckless and O'Leary, 2007) and, separates the field area from the Grapevine and Funeral Mountains bordering Death Valley (figure 2.5).

2.2.3.3 Oasis Valley Basin

The Oasis Valley Basin is a roughly rectangular north-trending Miocene basin that extends for about 10 km north of Bare Mountain (figure 1.6). Although the basin boundaries are not exposed, it is distinguished by gradients in geophysical data (Fridrich et al., 1999). The western boundary coincides with the inferred, north-striking Hogback fault. The southern boundary is the eastern part of the near-vertical, east-striking, Hot Springs fault, which is distinguished by a gravity gradient declining to the north (Fridrich et al. 1999). The northern boundary coincides with the southern margin of the 9.4 Ma Black Mountain caldera (Fridrich et al. 1999; Sawyer et al. 1994).

2.2.3.4 Fluorspar Hills Domain

Rocks in this domain compose the hanging wall of the tilted Fluorspar Canyon-Bullfrog Hills (FC-BH) detachment fault that structurally separates the domain from Bare Mountain to the south (figure 1.6). The domain comprises tilted Tertiary volcanic rocks between the inferred west-dipping Beatty fault and Tram Ridge to the east (Fridrich et al. 1999). The northern boundary is not defined, but may be the west- trending Hot Springs fault that that separates Fluorspar Hills from the Oasis Valley Basin (Fridrich et al. 1999; figure 1.6). In the northern Fluorspar Hills the 11.55 Ma Twisted Canyon caldera is marked by a modest topographic high or wall at its inferred margin (Fridrich et al. 2007).

2.2.3.5 Bare Mountain Domain

Bare Mountain, a small but prominent range composed of folded and faulted Neoproterozoic and Paleozoic clastic rocks in the footwall of the FC-BH detachment comprises the Bare Mountain domain south of the Fluorspar Hills (figure 2.5). Domain boundaries are defined as the FC-BH detachment to the north, the Bare Mountain fault to the east and the Carrara Fault to the southwest (figure 1.6). The Carrara fault is interpreted as a right lateral strike slip fault that strikes northwest (Fridrich, 1999a; Stamatakos et al, 1997; Slemmons, 1997).

Major structures exposed at Bare Mountain include the Mesozoic Meiklejohn Peak thrust, and the Tertiary Gold Ace fault. Meiklejohn Peak thrust separates Mississippian-Devonian rocks on the footwall from Ordovician rocks on the hanging wall. Gold Ace fault is a detachment that strikes north-south and juxtaposes metamorphosed Neo-Proterozoic and Paleozoic rocks in the footwall from unmetamorphosed rock in the hanging wall (Hoisch et al., 1997). The relation of Bare Mountain in the footwall of the FC-BH detachment has led many some workers to compare the small range with turtlebacks related to metamorphic core complex deformation (Fridrich et al., 1999; Fridrich, 1999a).

2.2.3.6 Southeastern Bullfrog Hills Domain

Both the Southeastern Bullfrog Hills (SBH) and Northern Bullfrog Hills (NBH) domains are characterized by extension of 100% perhaps >275% (Maldonado, 1990). The Southern Bullfrog Hills domain west of Beatty comprises sparse exposures of Paleozoic clastic and carbonate strata and extensive Tertiary volcanic rocks. The southern boundary is the unexposed sub-horizontal FC-BH detachment. The Hot Springs fault serves as the northern border, separating the SBH from the NBH (Fridrich et al., 1999). The Beatty Fault is the eastern boundary of the SBH with the Fluorspar Hills domain. The western boundary is a north-west trending, right lateral strike slip fault that separates the SBH from the Western Bullfrog Hills domain (Fridrich et al, 1999; figure 1.6). Volcanic rocks tilted eastward rest upon the FC-BH detachment throughout the domain. The domino-like blocks formed above north striking, west dipping listric normal faults during Miocene extension (Maldonado, 1990). The faults merge into the underlying detachment (Maldonado, 1990). Crystalline basement crops out south of the SBH as the footwall of the FC-BH detachment.

Rainbow Basin

Rainbow Basin is a structural basin within the SBH (figure 1.6; Fridrich et al., 1999). The basin contains volcaniclastic strata, slide masses, and ignimbrite deposits that accumulated after the Ammonia Tanks formation (section 2.3.2.6) and synchronously with eruption of the volcanic Rainbow Mountain Group. General basin boundaries include: (1) southern boundary represented by an inferred, north dipping normal fault that separates rocks of the Timber Mountain, Paintbrush, and Crater Flat Groups to the south from rocks of the Rainbow Mountain Group to the north; (2) a west-trending fault south of Zabriskie Hill that is marked by steep and shallow faults and common allochthonous blocks; (3) the Beatty fault to the east; and (4) north-striking normal faults that down-dropped the Pre-Rainbow Mountain volcanics, i.e. Ammonia Tanks.

2.2.3.7 Northeastern Bullfrog Hills Domain

The Northeastern Bullfrog Hills (NBH) domain is characterized by masses of breccia interpreted as landslide and talus breccias (Minor et al. 1997; Connors et al. 1998). Some large blocks of coherent breccia (discussed in detail in Chapter 3) are composed of monolithic masses. This domain is bounded by the Hot Spring Fault to the south, the Hogback fault to the east, and the Sarcobatus Flats to the west (Fridrich et al. 1999; Mankinen et al. 2003; figure 1.6).

Oasis Mountain and the Oasis Mountain hogback (figure 1.1) are prominent features within the NBH domain. Oasis Mountain, which lies east of Highway 95, is composed of tilted and possibly folded Ammonia Tanks Tuff, estimated to be more than 1000 m thick (Fridrich et al. 2007).

South of Oasis Mountain, the north-trending Oasis Mountain hogback (referred to as the Hogback) is underlain by east-dipping volcanic rocks of the Timber Mountain Group and the Tuff of Cut Off Road bounded to the east by the Hogback fault. Eastward dips of 30-18° suggest the presence of a north-striking, west-dipping listric normal fault east of the hogback. The Hogback fault does not accommodate this geometry as it dips east (Mankinen et al. 2003). The location and identity of the fault responsible for the Hogback's geometry is unknown and may be concealed by younger volcanics and alluvium.

2.3 STRATIGRAPHY

The stratigraphic units exposed in the field area range from Proterozoic gneissic basement to Quaternary gravel and alluvium. Stratigraphic columns of the Fluorspar Hills and Northern Bare Mountain NBH, and SBH are included as figures 2.6, 2.7, and 2.8 respectively. In this section, Quaternary units are not described because they do not reflect Miocene extension; for the description of Quaternary units, refer to Maldonado and Hausback (1990), Monsen et al. (1992), Minor et al. (1997), Connors et al. (1998), and Fridrich et al. (2007).

2.3.1 Pre-Tertiary Rocks

Pre-Tertiary rocks, mainly Paleozoic and sparse Proterozoic units, crop out in the footwall of the FC-BH detachment. They also crop out above the detachment in the Bullfrog Hills where they are preserved as large blocks and brecciated masses e.g. at Zabriskie Hill, and north of Pioneer Mine.

At Bare Mountain, in the footwall of the east verging Gold Ace Fault, Proterozoic and Cambrian strata have been metamorphosed to the greenschist facies (Monsen et al. 1992).

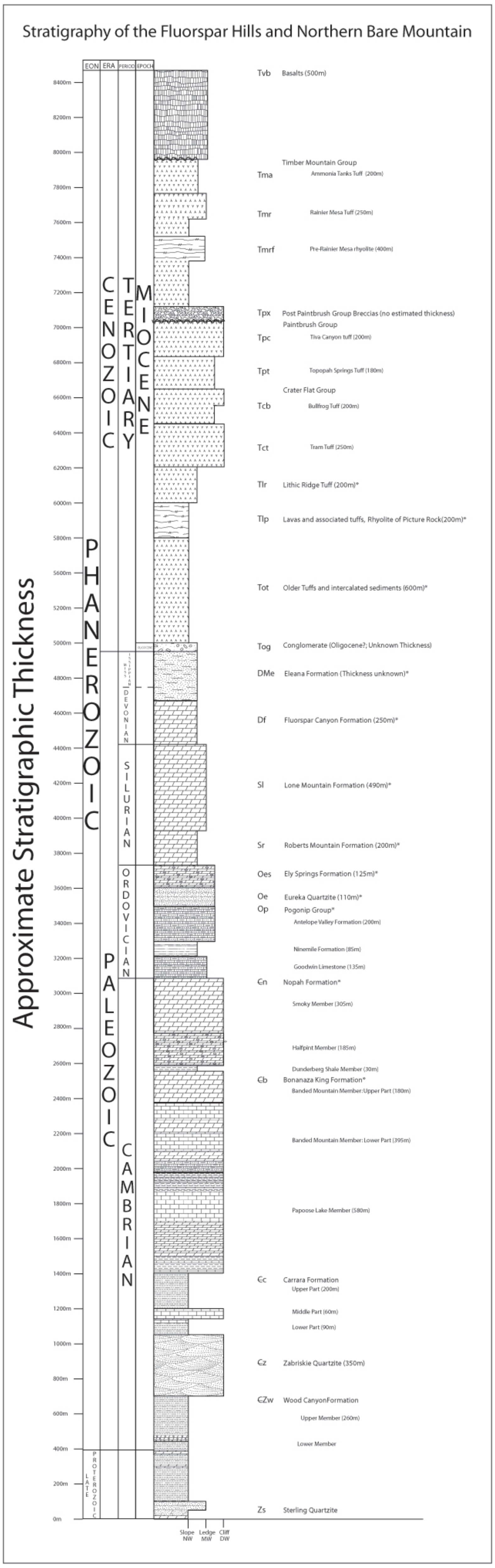


Figure 2.6 Stratigraphic column of the Fluorspar Hills and Northern Bare Mountain. Abbreviations of NW, MW, and DW at the bottom of the column refer to volcanic rocks and indicate if the unit is non-welded, moderately welded, or densely welded respectively. Wavy line indicates the presence of an unconformity. Units with an asterisk indicate that the unit is not formally described in the text. For detailed description of these units, refer to Monsen et al. (1992) and Fridrich et al., (2007)

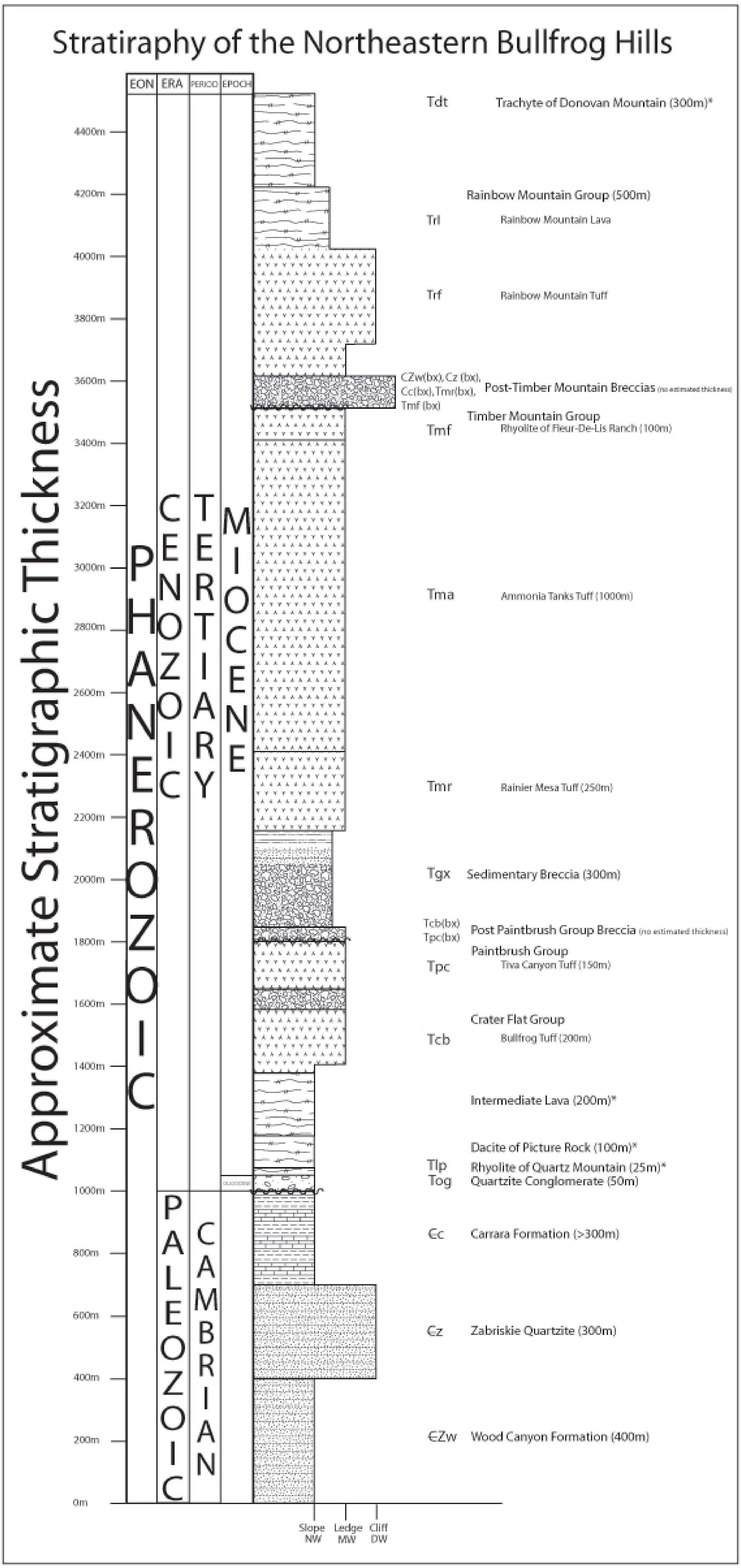


Figure 2.7 Stratigraphic column of the Northeastern Bullfrog Hills. Abbreviations of NW, MW, and DW at the bottom of the column refer to volcanic rocks and indicate if the unit is non-welded, moderately welded, or densely welded respectively. Wavy line indicates the presence of an unconformity. Units with an asterisk indicate that the unit is not formally described in the text. For detailed description of these units, refer to Minor et al. (1997), Connors et al. (1998), and Fridrich et al. (2007).

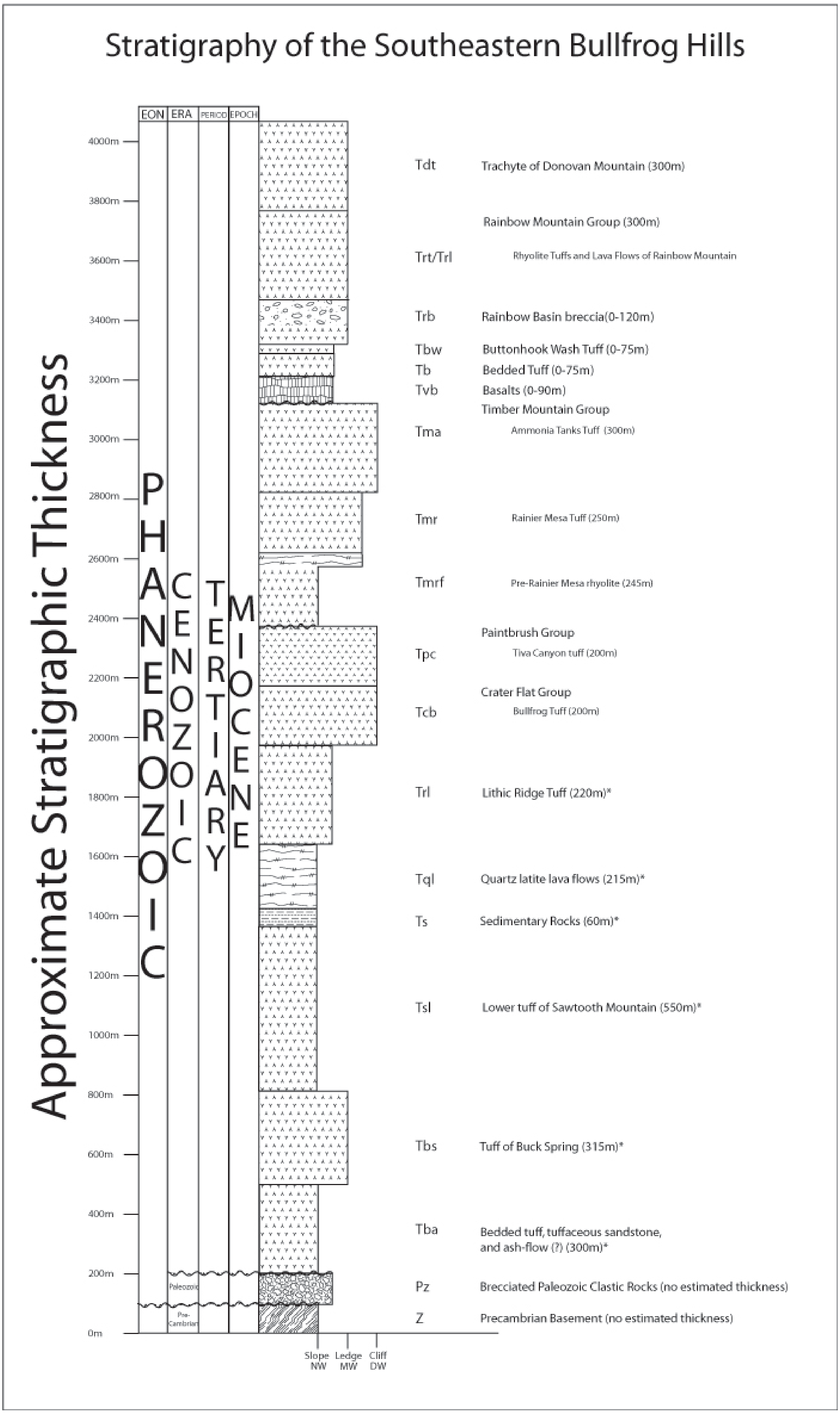


Figure 2.8 Stratigraphic column of the Southeastern Bullfrog Hills. Abbreviations of NW, MW, and DW at the bottom of the column refer to volcanic rocks and indicate if the unit is non-welded, moderately welded, or densely welded respectively. Wavy line indicates the presence of an unconformity. Units with an asterisk indicate that the unit is not formally described in the text. For detailed description of these units, refer to Maldonado and Hausback (1990), Connors et al. (1998), and Fridrich et al. (2007).

2.3.1.1 Crystalline Basement (Proterozoic)

Crystalline basement includes gneiss and schist metamorphosed to amphibolite facies. Outcrops are known from railroad cuts through low hills in the southern Bullfrog Hills 5.5 km west of Rhyolite, Nevada (Maldonado, 1990). Fresh exposures along an abandoned railroad reveal gneiss composed of quartz, plagioclase, biotite, ± muscovite or chlorite. These rocks are cut by amphibolite dikes, folded granitic pegmatite, and unfoliated diabase dikes which may be of Tertiary age (Eng et al. 1996). U-Pb dates of 1.7 Ga for an amphibolite dike (Hoisch et al. 1997) indicates that the host rock does not correlate with the Upper Proterozoic Johnnie Formation as proposed by Maldonado (1990). Although weak mylonitic foliation in quartz and small boudins are present the lack of strong c/s foliation observed in this study suggests that these rocks were not metamorphosed during a metamorphic core complex event as proposed by numerous authors (McKee, 1983; Fridrich 1999a).

2.3.1.2 Sterling Quartzite

The Sterling Quartzite comprises four members (Fridrich et al. 2007), from top to bottom, of which two crop out at Bare Mountain. These two, exposed in the footwall of the FC-BH detachment, comprise about 60 m of section (Fridrich et al. 2007). The D member contains an upper part composed of interbedded medium to thick light brown, fine grained quartzite and micaceous quartzite, yellow brown dolomite and sandy dolomite, and pale green siltstone. Dolomite beds become more abundant down-section. The exposed thickness is 50 m. The C member comprises pale green siltstone containing rare thin beds of micaceous quartzite, limestone, and dolomite. The thinly bedded siltstone is platy and slightly metamorphosed. The base is not exposed. The top of the section grades into Unit A of the Lower Wood Canyon Formation; Sterling Quartzite begins when quartize becomes the dominant lithology. The exposed thickness is 17.4m (Stewart, 1970).

2.3.1.3 Wood Canyon Formation (Upper Proterozoic- Lower Cambrian)

The Wood Canyon Formation mainly crops out in Bare Mountain and the Amargosa Narrows (figure 2.9). Small exposures in the northern Bullfrog Hills, on the west side of Zabriskie Hill, comprise a short stratigraphic section along with overlying Zabriskie Quartzite and Carrara Formation.

The lower contact of the Wood Canyon Formation with the Sterling Quartzite is gradational and is defined where quartzite becomes the dominant rock type. The upper contact with Zabriskie Quartzite grades from quartzite to pelitic rocks of Wood Canyon (Monsen et al. 1992).

The Wood Canyon Formation is divided into lower and upper members (Monsen et al., 1992). The lower Member (Late Proterozoic) is composed of 4 mappable units. At the top, unit D contains thickly bedded, very fine grained, micaceous, quartzite with rare interbeds of light green siltstone. The top of the underlying Unit C is marked by 25 m of pale-orange dolomite and limestone. Dolomite and limestone grade down section into interbedded very fine grained micaceous quartzite and siltstone. Total unit thickness is 80 m. Unit B consists of 20 m of pale-orange, medium-thick bedded dolomite and limestone in the uppermost part and grades downward to thick to medium interbeds of very fine grained quartzite, micaceous quartzite, and siltstone. At the base, Unit A, comprises 10 m of pale-orange medium- to-thick bedded dolomite and limestone with intercalated beds of sandy dolomite and quartzite that overlies very fine grained thin to medium bedded micaceous quartzite and siltstone. Quartzite is more abundant in the lowermost part of Unit A. The lower member is 335 m thick (Monsen, 1983).

The Upper Member (Cambrian) is a slope-forming package of interbedded quartizite and siltstone with thin beds of orange oolitic dolomite. The upper member is about 260 m thick.

2.3.1.4 Zabriskie Quartzite (Cambrian)

The Zabriskie quartzite is medium-grained, laminated, cross bedded orthoquartzite (Monson et al. 1992). *Scolithus*, a trace fossil shown by tube-like channels perpendicular to bedding, is common in the lower part of the unit (Monson et al 1992; Minor et al. 1997). At Bare Mountain, the quartzite is generally white and highly fractured. In the NBH, the Zabriskie Quartzite comprises commonly brecciated, pale pink to white quartzite that underlies large prominent hills with steep sides (e.g. Zabriskie Hill; figure 2.9), The Zabriskie Quartzite is 347.7 m thick at Bare Mountain (Stewart, 1979) and about 300 m thick in the NBH (Minor et al. 1997). The Zabriskie quartzite has a gradational basal contact with the Wood Canyon Formation; it is marked by a sharp change in slope and a conformable upper contact with the Carrara Formation (Monsen et al. 1992).

2.3.1.5 Carrara Formation (Cambrian)

The Carrara Formation crops out at Bare Mountain and in the NBH where it is incomplete and unmetamorphosed (Minor et al. 1997). The unit is predominantly composed of siltstone, dark gray limestone, and quartzite. The basal contact with Zabriskie Quartzite is defined where quartzite becomes dominant. The upper contact with Bonanza King Formation is gradational and marked at the contact between white, silty limestone and dolomite of Bonanza King overlying dark gray limestone of the Carrara (Monsen et al. 1992).

The Carrara is divided into three parts: the Upper part, upon which slopes form, is underlain by medium-dark gray-limestone intercalated with thin- to medium-bedded dark-greenish-gray siltstone and micaceous quartzite that becomes more abundant down section. The unit is 200 m thick (Monson et al. 1992). In the

Northern Bullfrog Hills, limestone in the upper part of the Carrara generally crops out (Minor et al. 1997).

At Bare Mountain, the contact between the Upper and Middle Carrara is sharp and recognized as the resistant dark gray limestone of the middle part (Monsen et al. 1992).

The middle unit consists of cliff –forming, dark-gray, thickly bedded, limestone containing *Girvenella* (Monson et al. 1992). In the Northern Bullfrog Hills, the middle part of the Carrara, 62 m thick, has been cut away by faulting (Minor et al. 1997).

The lower part of the formation, 87 m thick (Palmer and Halley, 1979), is similar to the upper part. The upper contact with the middle part is sharp (Monsen et al. 1992). In the Bullfrog Hills some beds may contain trilobite debris (Minor et al. 1997).

2.3.1.6 Cambrian-Mississippian Limestone, Dolomite, and clastic rocks

Thousands of meters of Paleozoic limestone and dolomite commonly intercalated with siltstone and argillite, which range in age from Cambrian to Mississippian, overlie the Carrara Formation. These rocks mainly crop out at Bare Mountain where they include the Bonanza King Formation, Nopah Formation, the Pogonip Group, Lone Mountain Formation, Ely Springs Formation, Roberts Mountain Formation, Fluorspar Canyon Formation, and the Eleana Formation

(Fridrich et al., 2007; Monsen et al., 1992; figure 2.6). Additionally a few small exposures of Paleozoic in the Southern Bullfrog Hills west of Rhyolite are identified as the Pogonip Group and Eureka quartzite (Maldonado and Hausback, 1992). These exposures are in the middle plate of the zone of detachment faults recognized by Maldonado (1990). General lithologic details for these units are available in figure 2.8.

Uplift and erosion after the Late Permian precluded deposition of Mesozoic age rocks in the field area (Stuckless and O'Leary, 2007).

2.3.2 Tertiary Rocks

Tertiary age rocks in the field area are volcanic with common sedimentary units. The source of these volcanic deposits is the Southwest Nevada Volcanic Field (SWNVF) (figure 2.1), a multicaldera complex of overlapping, silica-rich volcanic units (Sawyer et al. 1994). Overlapping caldera boundaries in the SWNVF make defining margins of individual centers difficult; however, boundaries have been estimated using geophysical methods (Mankinen et al. 1999; Mankinen et al. 2003, Grauch et al. 1997). Boundaries have been estimated for the Silent Canyon (including Grause Canyon and the Area 20 Caldera), the Timber Mountain Caldera Complex (Rainier Mesa Caldera and the Timber Mountain Caldera), and Claim Canyon Caldera (figure 2.1). Sawyer et al. (1994) determined ages for most of the volcanic units exposed in the study area using the $^{40}Ar/^{39}Ar$ method. They also distinguished the volcanic source caldera for each unit based on outcrop and drill-hole data.

Volcanism peaked in the SWNVF between 12.8-11.4 Ma coinciding with peak extension between 12.7 and 11.6 Ma (Fridrich, 1999b). During this time, the Paintbrush and Timber Mountain Groups, two high-volume rhyolitic ash flow units, erupted from the SWNVF (Sawyer et al. 1994).

Figure 2.10 provides the location of referenced field stops.

2.3.2.1 Conglomerate (Oligocene)

The base of the Tertiary section is commonly marked by outcrops of pebble conglomerate that rest unconformably on Paleozoic units. In the eastern Fluorspar Hills the conglomerate, composed of rounded-subrounded clasts of Paleozoic quartzite, limestone, and chert in a gray silicified matrix (figure 2.11), is interpreted to be a fluvial deposit of Oligocene age.

In the NBH, the conglomerate unconformably overlies Proterozoic and Cambrian rocks north of Pioneer Mine (Minor et al. 1997). East of Zabriskie Hill, unconsolidated, well rounded, pebble-cobble sized clasts of white and weathered brown Zabriskie quartzite (figure 2.12) are probably derived from weathered conglomerate.

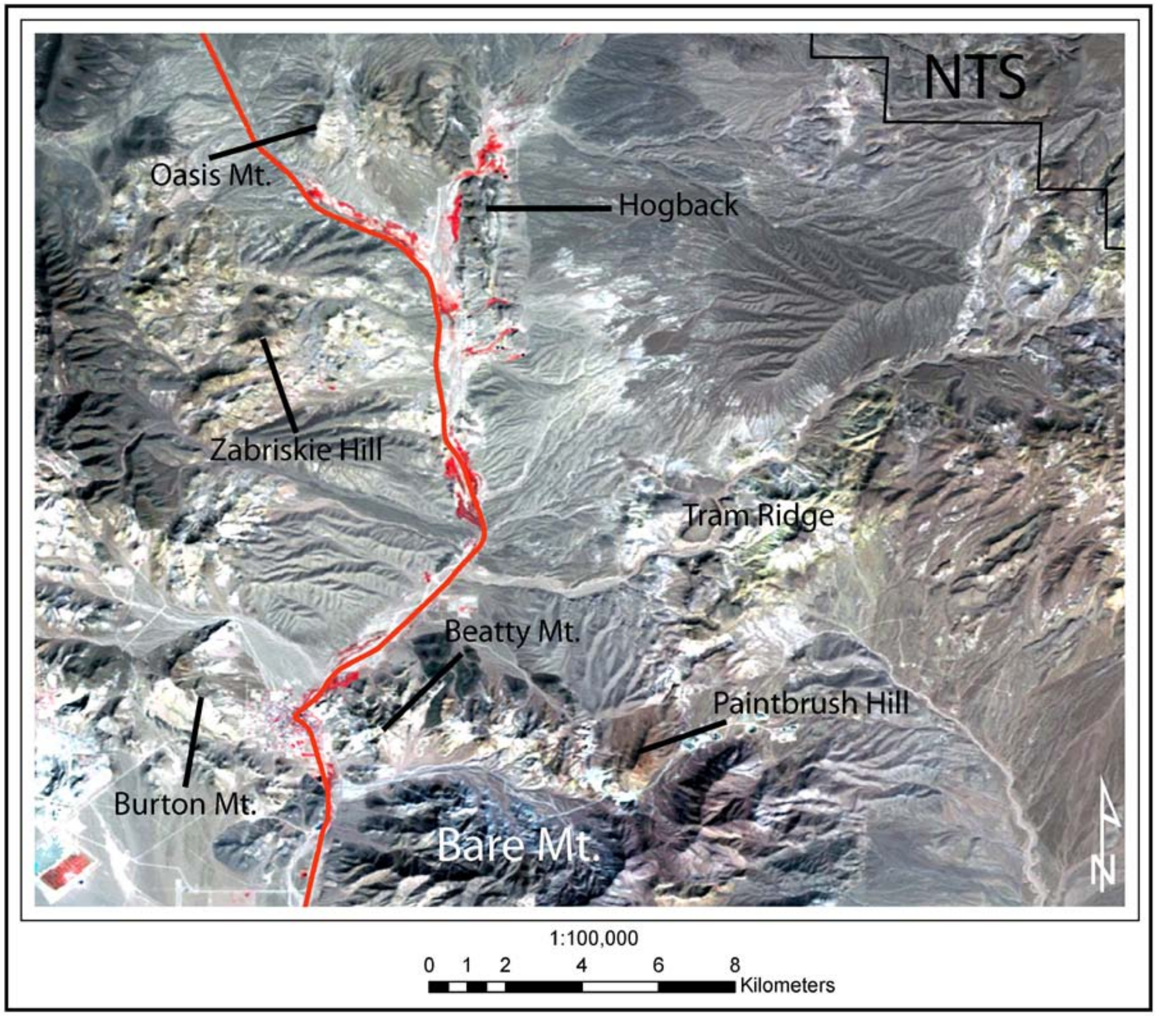


Figure 2.9 Map of the local topographic features within the field area.

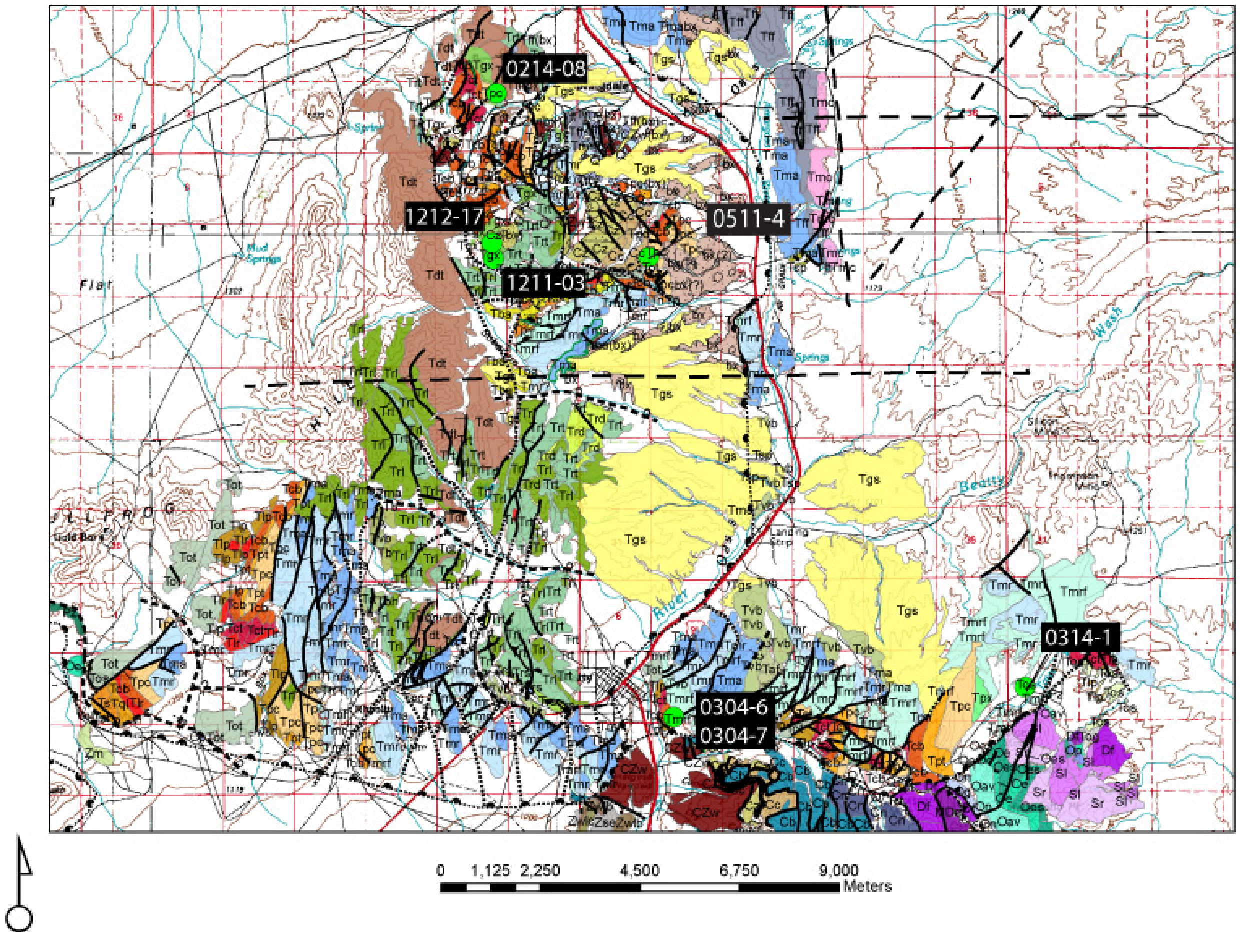


Figure 2.10 Map of the field area. Bright green circles represents a field stop referenced in the text. For the detailed map explanation, refer to the geologic map associated with this study.

Figure 2.11 Oligocene conglomerate exposed in the Fluorspar Hills at field stop 0314-1. Clasts of Paleozoic rocks are supported in a siliceous matrix.

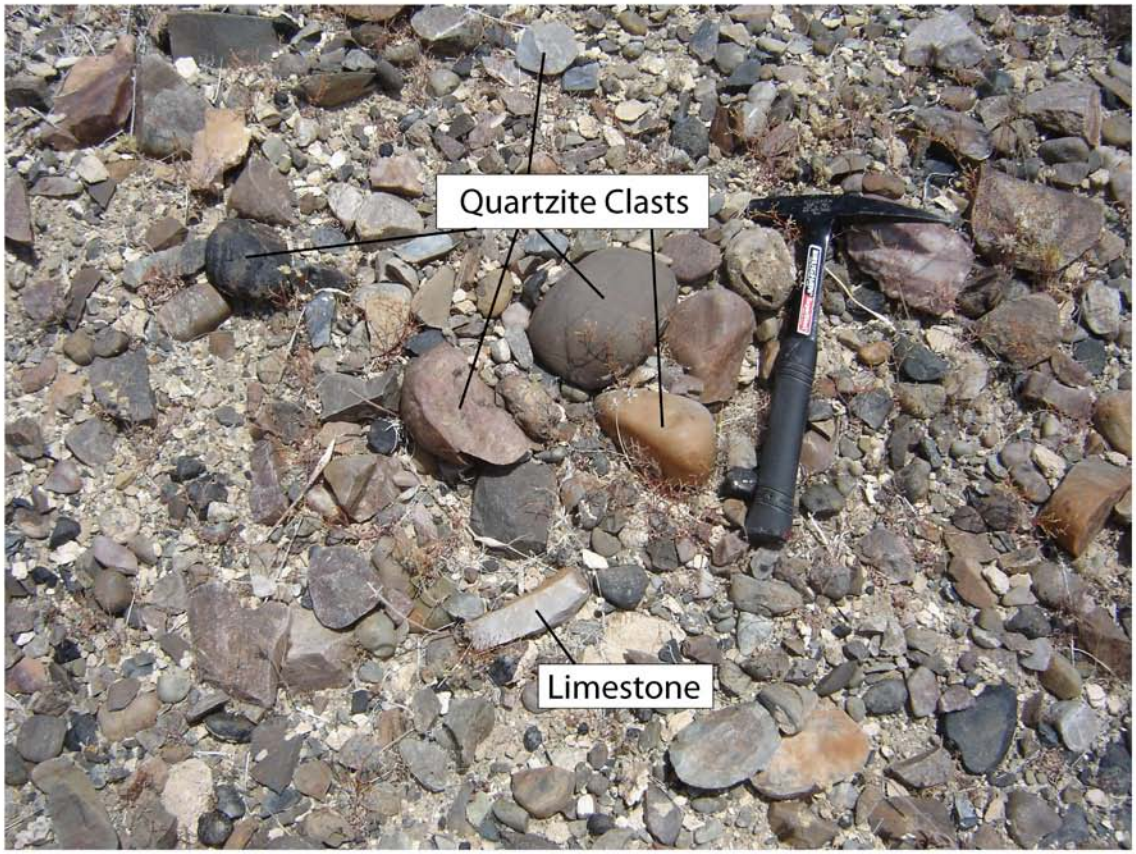


Figure 2.12 Oligocene conglomerate exposed in the Northern Bullfrog Hills at field stop 0511-4.

2.3.2.2 Crater Flat Group (Miocene)

The lowest discussed volcanic unit in the field area, called the Tram Tuff, comprises light gray to pink, moderately to densely welded, rhyolite ash flow tuff that contains about 10% phenocrysts of plagioclase, sanidine, quartz, and biotite. The tuff erupted at 13.4 Ma (Fridrich et al., 2007) possibly from the Prospector Pass Caldera Complex (Sawyer et al., 1994). The tuff, 245 m thick, is exposed only in the Fluorspar Hills domain.

Overlying the Tram is the Bullfrog tuff, a dense to poorly welded ash flow tuff that erupted from the Area 20 Caldera at 13.25 Ma (Sawyer et al. 1994). It contains 13% phenocrysts of quartz, sanidine, plagioclase, and rare biotite and hornblende. Its maximum exposed thickness is about 200 m.

2.3.2.3 The Paintbrush Group (Miocene)

The Paintbrush Group erupted from the Claim Canyon Caldera between 12.8-12.7 Ma (Sawyer et al. 1994). The Topopah Springs tuff is a non-welded to densely welded ash flow tuff that erupted at 12.8 Ma. It crops out only in the Fluorspar Hills, but Connors et al. (1998) mapped the unit between Pioneer Road and Sober Up Gulch. In this same location, Maldonado and Hausback (1990) map the rock as the younger Tiva Canyon Tuff. Fridrich et al. (2007) divides the unit into two parts: (1) an upper crystal rich trachyte containing 11 % phenocrysts of sanidine, plagioclase, biotite, clinopyroxene, traces of sphene, fayalite, and rare hornblende and quartz and (2) a lower crystal poor, high silica rhyolite with <1% phenocrysts. The unit is about 180 m thick (Fridrich et al., 2007).

Overlying the Topopah Springs tuff is the Tiva Canyon Formation that erupted at 12.7 Ma. The tuff is distinguished from the Topopah Springs tuff by the absence of sphene and lower phenocryst abundance (Fridrich et al., 2007). Like the Topopah Springs, the Tiva Canyon is divided into two parts (Fridrich et al., 2007): (1) an upper crystal-rich trachyte with phenocrysts that include mostly alkali feldspar, plagioclase, and trace quartz, clinopyroxene, hornblende, and sphene ; and (2) lower, crystal-poor, high silica rhyolite. Its maximum exposed thickness is 200m (Fridrich et al., 2007).

2.3.2.4 Post Paintbrush Group Breccias or Conglomerate

Carbonate Clast Breccia

Angular clasts of carbonate deposited on the Tiva Canyon are located on the southeastern flank of Paintbrush Hill (figure 2.9). This unit is discussed and described in detail in Chapter 3.

Basal Conglomerate (Miocene)

In the western Fluorspar Hills, east of Beatty Mountain (figure 2.9), steeply dipping conglomerate underlies steeply dipping pre-Timber Mountain Group rocks (figure 2.13). This unit is discussed and described in detail in Chapter 3.

Post-Paintbrush Monolithic Breccias

In the Northern Bullfrog Hills, Post-Paintbrush breccia is generally monolithic, and composed of angular to sub-rounded clasts of Bullfrog tuff or Tiva Canyon tuff with rare clasts of Zabriskie Quartzite (figures 2.14). This unit is discussed and described in detail in Chapter 3.

2.3.2.5 Sedimentary Breccia and Sandstone

Located in the NBH, a thick sequence of cobble breccia and pebbly sandstone overlies the post-Paintbrush breccia. The breccia is polylithic, containing clasts of Zabriskie quartzite, Bullfrog tuff, Tiva Canyon tuff, and rare Carrara and Wood Canyon in a brown sand-silt matrix commonly altered red. Near the Mayflower Mine, the sediments show poor to moderate bedding that is commonly graded (figure 2.15). North of Zabriskie Hill, south of Springdale Mountain, the breccia is composed exclusively of angular pebbles and cobbles of Zabriskie quartzite in a red sand matrix (figure 2.16). Minor et al. (1997) mapped this unit (Tgx) as underlying the Rainbow Mountain Group; however, lack of contact exposures and the absence of Rainier Mesa clasts within the unit suggests deposition after Paintbrush and before Timber Mountain eruptions. The unit is about 300 m thick.

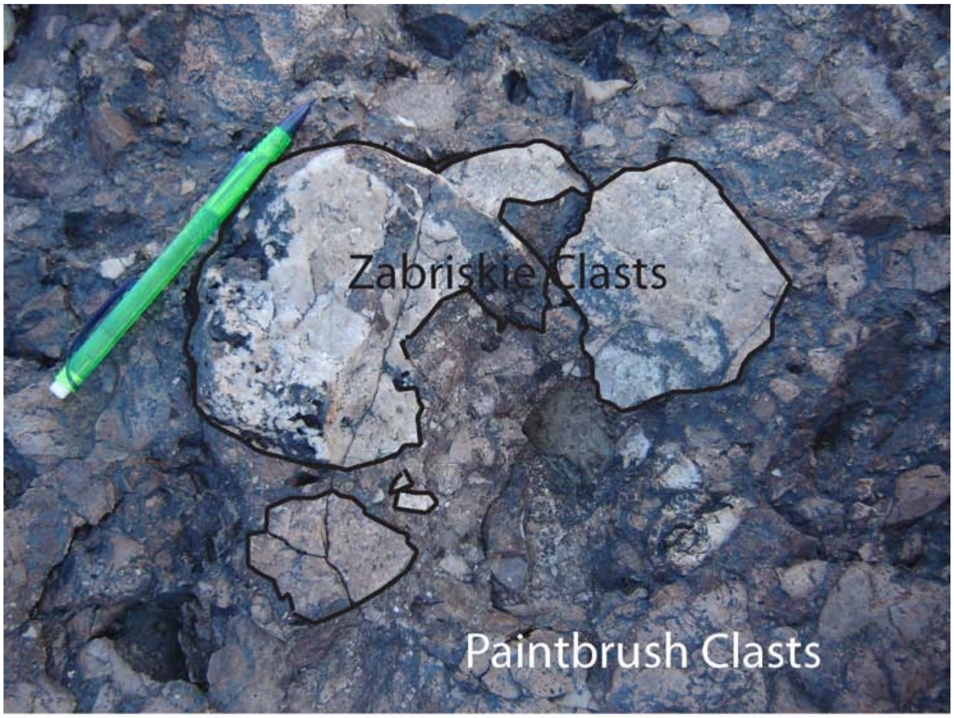
2.3.2.6 Timber Mountain Group (Miocene)

The Timber Mountain Group is a thick sequence of rhyolitic ash flow tuffs and lavas erupted between 11.62 and 11.45 Ma from the Timber Mountain Complex caldera (Sawyer et al, 1994). In the Fluorspar Hills, this group is extensively exposed and exhibits fanned bedding dips, suggesting eruption was synchronous with gradual rotation against listric normal faults (Fridrich et al. 2007, Monsen et al., 1992). The sequence unconformably rests on the Paintbrush Group tuff and/or post-Paintbrush breccia (where present).

Pre-Rainier Mesa rhyolite

Pre-Rainier Mesa rhyolite is composed of a thick sequence of ash-flow, ash-fall, and water-laid tuffs, and gray lava flows erupted between 11.62 and 11.7Ma. The tuff layers are generally white or pink, except in the western Fluorspar Hills where they are light green. Most of the unit is crystal poor (5.5% total phenocrysts [Fridrich et al. 2007]). Some tuff and lava are petrographically similar to the first-erupted part of the Rainier Mesa tuff (Fridrich et al. 2007). Lithic fragments are

Figure 2.13 Post-Paintbrush Group conglomerate exposed at field stops 0304-6 and 0304-7



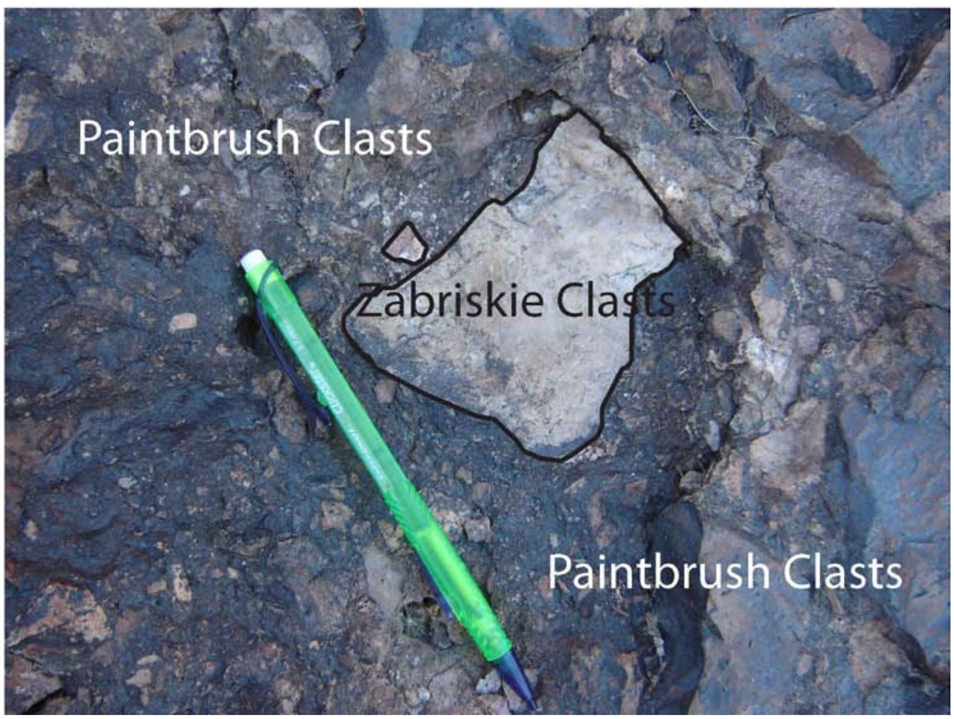


Figure 2.14 Post-Paintbrush breccia exposed at field stop 1211-03. This breccia is generally monolithic, but does contain rare clasts of Zabriskie

Figure 2.15 Normally graded bedding in the Sedimentary breccia unit, NBH at field stops 0512-2 (first and second images) and 1212-17 (third image).

Figure 2.16 Sedimentary breccia composed of clasts of Zabrsikie quartzite in a red sand matrix the NBH at field stop 1214-08.

common in the tuff units and include pumice and a black vitrophyre originating from the underlying Paintbrush Group tuffs. The average clast size is about 1 cm. At the base of the unit, large, elongate clasts up to 0.5 m long of the Paintbrush Group tuff are present. In addition to fanned dips, further evidence for syntectonic eruption of this unit is provided by the presence of interfingered breccias (Fridrich et al. 2007, Monsen et al. 1992). The Pre-Rainier Mesa rhyolite has a maximum exposed thickness of approximately 400 m, but is thinner (0-120 m) in the Bullfrog Hills (Fridrich et al., 2007; Maldonado and Hausback, 1990).

Rainier Mesa Formation

Crystal-rich ash flow tuff comprising the Rainer Mesa Formation erupted from the Rainier Mesa Caldera 11.6 Ma ago (Sawyer et al. 1994). The base of the unit is marked by thick pyroclastic layers. The overlying main eruptive deposit is a brown, high silica rhyolite that contains approximately 10% phenocrysts of sanidine, quartz, plagioclase, and trace hornblende. An overlying pink, more crystal-rich, quartz trachyte contains about 24% phenocrysts of sanidine (~10%), plagioclase (~9%), quartz (~3%), sparse biotite and clinopyroxene, and traces of hornblende and orthopyroxene (Fridrich et al. 2007; Minor et al. 1997). The lack of sphene, high quartz content, and reverse magnetic polarity distinguishes the Rainier Mesa tuff from the overlying Ammonia Tanks tuff. The thickness of the Rainier Mesa formation is about 250 m.

Ammonia Tanks Formation

The Ammonia Tanks tuff of the Timber Mountain group is a crystal rich ash flow tuff that erupted from the Ammonia Tanks caldera 11.45 Ma ago (Sawyer 1994). Fridrich et al. (2007) divides the Ammonia Tanks into two parts: 1) a lower, high silica rhyolite that contains about 17.5% phenocrysts that include sanidine (~11%), quartz (~4%), plagioclase (~2%), biotite, and traces of clinopyroxene and sphene and 2) an upper quartz trachyte with about 25% phenocrysts of sanidine (~13), plagioclase (~7.5%), quartz (~3), biotite (~1%), sparse clinopyroxene, and rare sphene.

The Ammonia Tanks is characterized by strong rheomorphic lineations and granophyric texture at Oasis Mountain and abundant lithic clasts on the Hogback (Connors et al., 1998). Ammonia Tanks is distinguished from the underlying Rainier Mesa tuff by stratigraphic position, the presence of sphene, and chatoyant sanidine. Its thickness ranges from about 200 m in the Fluorspar Hills (Monsen et al. 1992) to more than 1000 m at Oasis Mountain (Fridrich et al. 2007; figure 2.9), where it may be folded.

Fleur-de-Lis Ranch tuff

Fleur-de-Lis-Ranch tuff and flows crop out only in the NBH and at the Oasis Mountain hogback. It is light-brown ash-flow tuff and rhyolite lava flows that erupted at about 11.4 Ma on the west side of the Timber Mountain caldera complex

(Minor et al. 1997). The unit is divided into three parts: Upper tuff of Fleur-de-Lis Ranch, lavas of Fleur-de-Lis Ranch and West Cat Canyon, and lower tuff of Fleur-de-Lis Ranch. The upper and lower tuff units are petrographically indistinguishable with 15% phenocrysts composed of abundant plagioclase, biotite, and sparse clinopyroxene. The lower tuff has reverse magnetic polarity. Exposed thickness ranges from 100 m in the NBH to 600 m in the Oasis Valley region.

2.3.2.7 Post Timber Mountain Group Breccias (Miocene)

North of Zabriskie Hill in the NBH, monolithic breccia composed of locally derived clasts (mapped as Tyx by Fridrich et al., 2007) is widespread. Minor et al. (1997) identified and described these deposits based on the lithologic unit from which the clasts were derived. Clasts in these breccias originated from the Wood Canyon, Carrara, Zabriskie, Bullfrog Tuff, Rainier Mesa, and Fleur -de-Lis Ranch Formations. Breccias are commonly bounded by slide surfaces (Minor et al. 1997). Chapter 3 provides a detailed description of the breccia sheets.

2.3.2.8 Basalt Lava Flow (Miocene)

This purplish-black, dense to vesicular porphyritic basaltic lava flow is exposed in the Bullfrog hills, south of Pioneer Road. It contains phenocrysts of olivine, plagioclase, pyroxene, and Fe-Ti oxides that can be up to 4mm in length. Porphyries are contained in a fine trachytic to hyalopilitic fine grained groundmass composed of plagioclase, olivine, Fe-Ti oxides, and glass (Connors et al. 1998). This unit is mapped in the Bullfrog Hills as overlying the Ammonia Tanks tuff. Ages of the basalt lie within the interval of 11.4-10.6 Ma based on stratigraphic and radiometric dating constraints. Its thickness ranges from 0-90 m in the SBH to about 500 m in the Fluorspar Hills (Fridrich et al., 2007; Maldonado and Hausback, 1990).

2.3.2.9 Bedded Tuff

Adjacent to the basalt in the western margin of the Rainbow Basin is 0-75 m of bedded tuff, referred to as Bedded tuff #6 by Maldonado and Hausback (1990). Other mappers (Connors et al. 1998 and Fridrich et al. 2007) incorporate this unit and its overlying unit (the Buttonhook Wash tuff) as the base of the Rainbow Mountain Group. This study considers the bedded tuff and Buttonhook Wash separate mapable units. The bedded tuff is only exposed in the SBH where it is useful in outlining the Rainbow Basin. The bedded tuffs is a white, light pink/purple, thin-bedded to massive volcaniclastic (Maldonado and Hausback, 1990) lithic-rich crystal tuff with a white ash matrix. Lithics consist primarily of tuffs, ranging from boulders to granules, and rare metamorphic and siltstone clasts. Crystals include quartz, feldspar, and biotite. Its maximum exposed thickness of 75m (Maldonado and Hausback, 1990).

2.3.2.10 Buttonhook Wash Formation

The Buttonhook Wash formation is a red-brown to orange, nonwelded to moderately welded ash flow tuff only mapped in the SBH. It contains 0-10% pumice lapilli, 10-20% crystals of quartz, sanadine, plagioclase, and biotite, and 2-5% lithics originating from the underlying Paintbrush and Timber Mountain groups, basalt, and sparce metamorphics. It has a thickness of 0-30 m (Maldonado and Hausback 1990). An $^{40}Ar/^{39}Ar$ age of 10.56 Ma ±0.022 from sanidine has been determined (Eng et al. 1996).

2.3.2.11 Rainbow Basin Breccia and Ash-Fall Tuff (Miocene)

Connors et al. (1998) and Maldonado and Hausback (1992) mapped the Rainbow Basin breccia and Ash-fall tuff in the Southern Bullfrog Hills, where it is composed of basin-fill sediments including beds of red polylithic breccia and lapilli tuff. Beds are generally thin and are normally graded. Clasts consist of angular to subangular volcanic rocks that generally range from course sand to large pebbles. The clastic debris encloses large casts (commonly >5 m in length) of volcanic and sedimentary rock. Overlying the thick breccia sequence is a thin layer (1 m thick) of distinctive green lapilli ash tuff which is, in turn, overlain by a thin sequence (<1 m) of additional breccia. In the SBH, the exposed thickness is 0-120 m.

2.3.2.12 Rainbow Mountain Group (Miocene)

The Rainbow Mountain group is a series of ash fall tuffs and lava flows erupted from local vents in the Bullfrog hills (Connors et al. 1998 and Minor et al. 1997). Connors et al. (1998) divide the group into five separate subunits; however, Fridrich et al. (2007) separate the group into older rhyolite ash-flow tuffs commonly interbedded with rhyolite lavas. The rocks formed between 10.56 and 10.33 Ma as indicated by ages of units overlying and underlying the Rainbow Mountain Group. The maximum exposed thickness is at least 400 m.

Rhyolite Tuffs of Rainbow Mountain

The lower part of the Rainbow Mountain tuffs, mapped specifically in the southern end of Springdale Quadrangle (Minor et al. 1997), consists of light gray to buff well bedded ash-fall and water-laid tuff and sedimentary rocks. It pinches out northward. The upper part is white crystal rich non-welded ash flow tuff containing phenocrysts of abundant quartz, common sanidine and plagioclase, sparse biotite, and rare iron oxides and ilmenite. Lithic fragments of pumice are also abundant. Characteristically, the tuffs weather to form caverns.

Rhyolite Lava of Rainbow Mountain

Overlying the rhyolite tuff is dark gray to black, vitric, banded lava flow that forms steep scarps. Phenocrysts in the lava include quartz (abundant), plagioclase, sanidine and hornblende (which are commonly absent), and sparse biotite.

3.0 FIELD INVESTIGATIONS

3.1 METHODOLOGY

Field data were collected for 13 weeks over a span of two years from the summer of 2007 to the summer of 2009. Geographic coordinates of significant field stops were received and recorded using a handheld geographic positioning system (GPS) unit. Coordinates were recorded in the universal transverse Mercator (UTM) coordinate system on the NAD27 Earth Model. The field area is located in UTM zone 11N. Attitude measurements of geologic units and structures were acquired using a standard quadrant-style Brunton transit compass calibrated to the magnetic declination of 16.5° E. Coordinate and structural data were combined and mapped using ArcGIS (Geographic Information System), a computer based mapping software issued by ESRI.

A geologic map was constructed using the field data collected throughout the project (Plate 1). ArcGIS was used to map geologic contacts and structures.

3.2 FIELD STUDY OF THE FC-BH DETACHMENT AND ADJOINING TATES WASH FAULT

The north-dipping Fluorspar Canyon-Bullfrog Hills (FC-BH) detachment separates tilted Tertiary strata of the Southwest Nevada volcanic field from Paleozoic units underlying the northern part of Bare Mountain to the south (figure 2.4). The detachment, together with the adjoining northeasterly striking Tates Wash fault (TWF), comprises the principal structure in the Beatty region. From east to west the two joined faults cut down section for 1000s of meters through Middle and Early Paleozoic and underlying Neoproterozoic strata. Preserved hanging wall rocks, consisting of Tertiary volcanics of the Bullfrog and overlying formations, commonly dip moderately to steeply east (Monsen et al. 1992). Strongly fractured and brecciated Middle Paleozoic rocks and rare megablocks of lower Paleozoic units crop out above the detachment in the Bullfrog Hills.

In the Amargosa Narrows, the FC-BH detachment is not exposed; however, the fault may be inferred by volcanic layers mapped as Timber Mountain Group (Monsen et al., 1992) that dip steeply toward the metamorphosed and folded Wood Canyon Formation in the footwall at field stop 0619-5 (figures 3.1 and 3.2).

Sub-vertical dips of volcanic layers into the subhorizontal fault suggest rotation related to movement along the FC-BH detachment and the development of a rollover antiform (figure 3.3). West of the Amargosa Narrows, units of the Timber Mountain Group and underlying volcanic rocks dip moderately east. Nevertheless, the layers close to the fault plane have steep dips.

3.2.1 The Fault Plane

In the field area, the FC-BH detachment crops out in the southernmost Fluorspar Hills (field stop 0607-1; figure 3.1). In places, the fault is very well exposed. Along the gently dipping segment of the fault, the Bonanza King Formation in the footwall is juxtaposed against Timber Mountain Group (11.6-11.4 Ma) in the hanging wall (Monsen et al. 1992).

South of Paintbrush Hill, at field stop 0607-1, the striated, planar fault that cuts Devonian Fluorspar Canyon Formation in the footwall (figure 3.4) strikes N85E and dips 41°NW. Slickenlines on the surface plunge 25° S70W. Microbrecciation in carbonate rocks of the footwall is common. The detachment can be traced about 10 m before it disappears into low-lying hills. At field stop 0619-8, the fault is revealed spectacularly by collapse of an abandoned open pit wall, exposing the fault plane between footwall and hanging wall (figure 3.5). At this location, the detachment surface strikes E-W, and dips 39°N. The geometry and Miocene age of the FC-BH fault are compatible with the interpretation that it

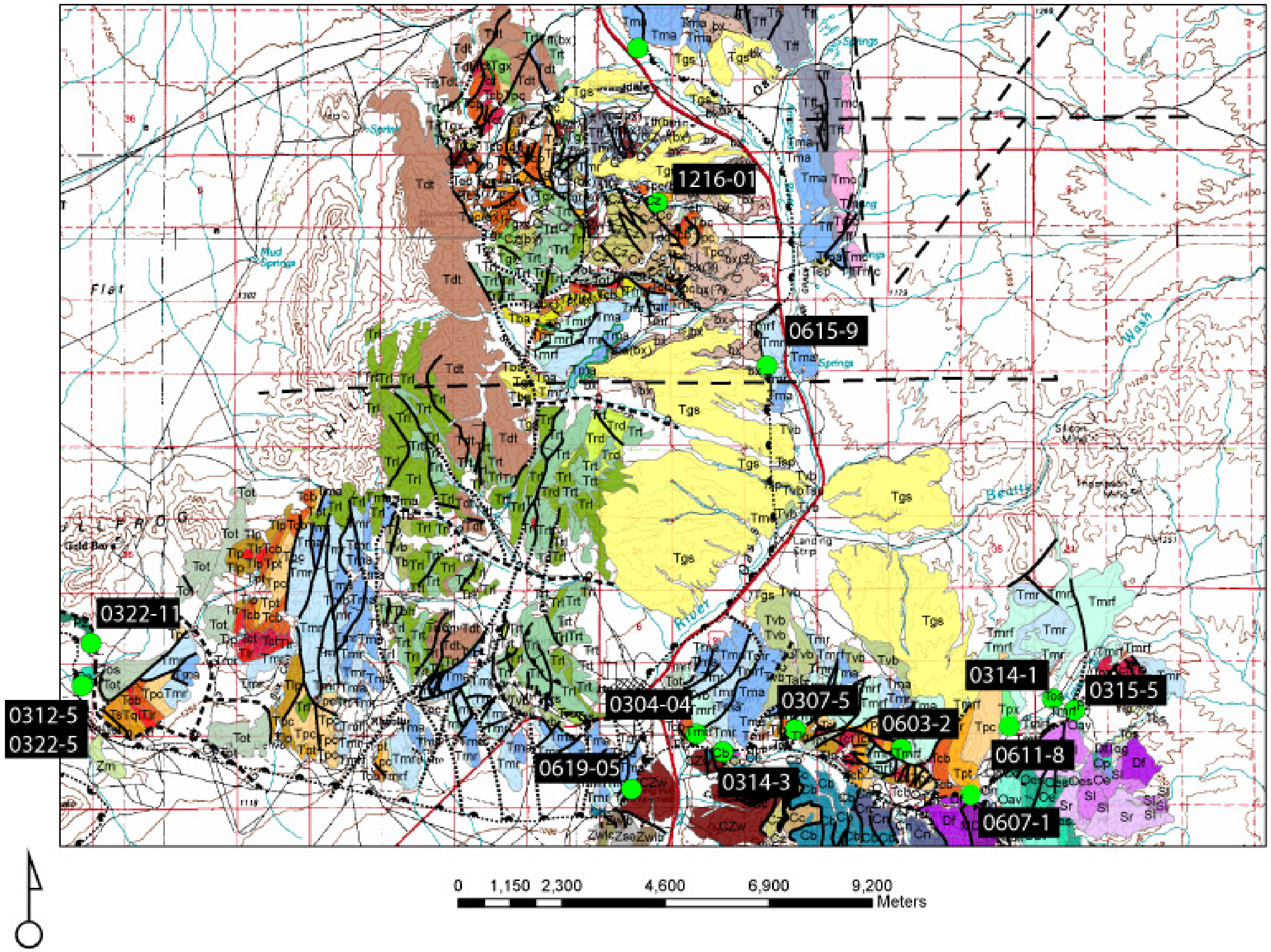


Figure 3.1 Geologic map of the field area. Bright green circles represent field stops referenced in the text. For the detailed map explanation, refer to the geologic map associated with this study.

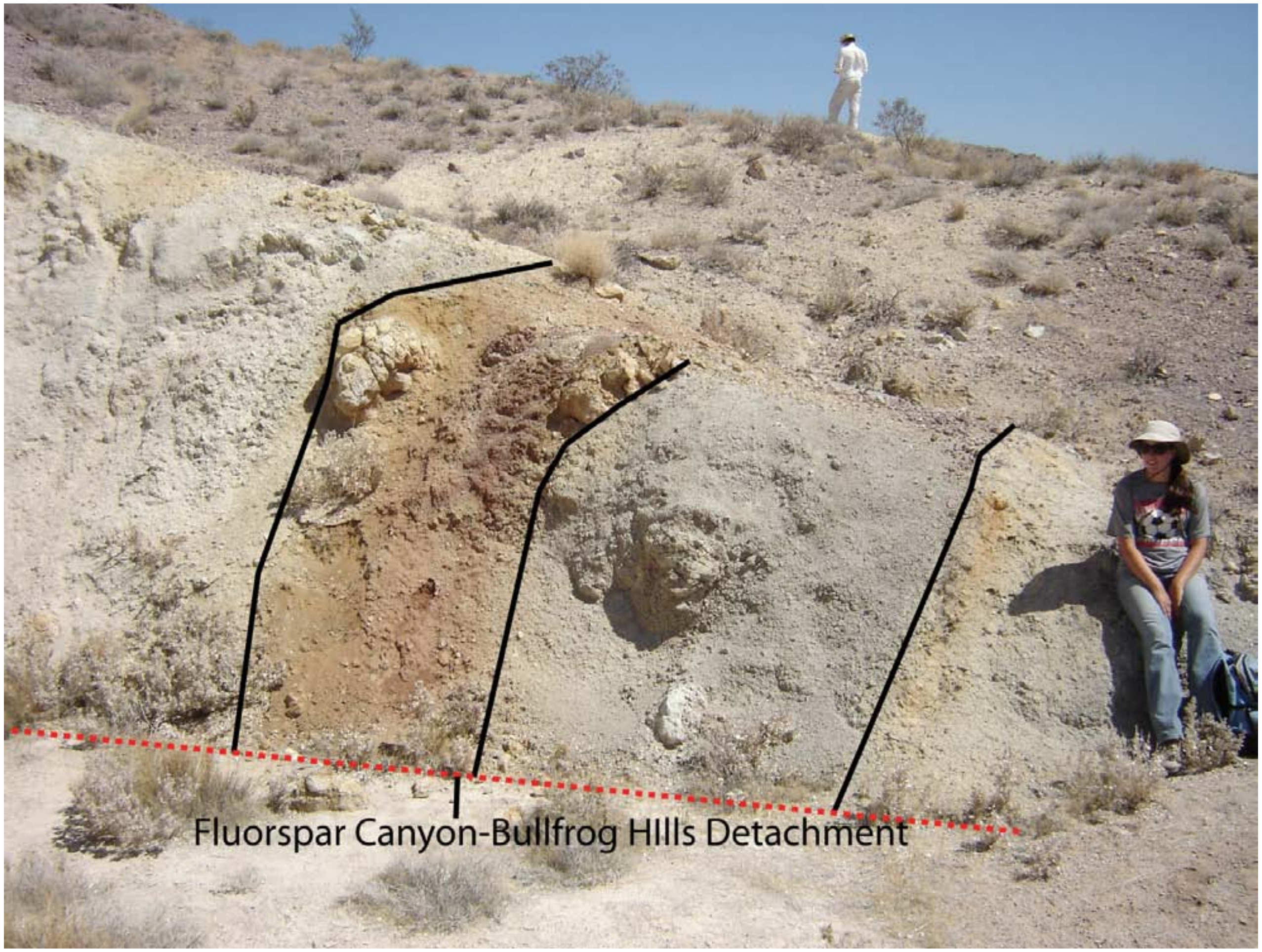


Figure 3.2 Beds of the Timber Mountain Group dip steeply into the inferred FC-BH detachment at field stop 0619-05. The FC-BH detachment is represented by the red dashed line. Black lines represent bedding in the Timber Mountain Group.

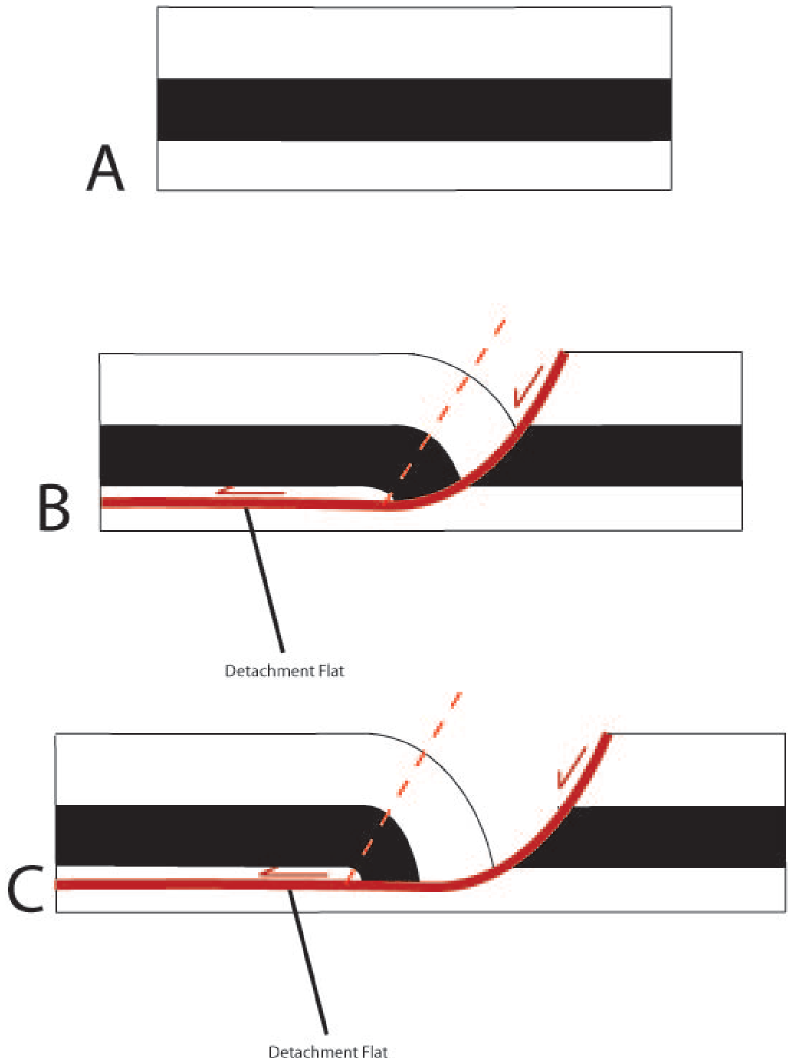


Figure 3.3 General diagram of bed rotation along a listric normal fault and related detachment. A) Undisturbed strata B) Listric normal fault forms, curving with depth until a flat detachment surface forms. Hanging wall beds proximal to the fault slides along the curved structure, rotating. Rotation of these beds forms an antiform in relation to the adjacent unrotated beds. Unrotated beds remain flat due to transportation along the detachment flat. C) Further movement along the fault continues to rotate the hanging wall until these rocks reach the detachment fault where rotation no longer takes place.

is part of a regional detachment originally horizontal in the Fluorspar Hills (Carr and Monsen, 1988). The northward dip of the detachment is attributed to tilting during shortening related to west-directed Miocene extension (cf. Bohannon, 1979). During contraction both hanging wall and footwall were pushed southward and upward toward Amargosa Valley where movement was probably accommodated by the proto-Carrara fault. Along strike to the east, comparable uplift is recorded by volcanic rocks at the southern margin of Crater Flat.

In the Fluorspar Canyon region, the northerly dipping FC-BH detachment links with the Tate's Wash Fault, a moderately to steeply dipping fault that strikes N04W, 52SW and shows apparent right-lateral (down to the west) offset. Movement began along this fault began between 13.9 and 12.2 Ma (Hoisch et al. 1997) and may have ended as recently as the Quaternary (Monson et al. 1992). If the tilted BH-FC detachment is restored to horizontal, then the Tate's Wash Fault is revealed as a listric normal fault that shallows as it cuts downward through Paleozoic limestone at Bare Mountain (Eng et al. 1996). In a mining pit at field stop 0315-5 (figure 3.1), where Tate's Wash fault is exposed, the footwall is composed of folded Paleozoic limestone and the hanging wall consists of a thick sequence of bedded Pre-Rainier Mesa Rhyolite oriented N49E, 36NW (figure 3.6).

The fault zone is 1-1.5 meters thick. Adjacent to the fault plane is a layer of black gouge in the footwall and brown, purple, and pink fractured volcanic rocks in the hanging wall (figure 3.7). The volcanic rocks close to the fault are heavily fractured and bedding planes are rare. Within the fault zone, is a shorter (~1 m in length) steep normal fault related to the TWF that displaces beds. Bedding in the fault zone is highly disrupted and displacement could not be measured; however, present drag along this fault illustrates right lateral displacement (figure 3.7). The footwall is composed of faulted and folded dark gray, platy Paleozoic limestone with beds of sandstone. Moderately dipping (dips of 52-66° NE) normal faults of left lateral displacement cut the beds (figure 3.8). Closer to the TWF fault, open and gentle folds in Paleozoic limestone have hinges plunging in diverse directions. The TWF fault may represent a break-away structure of the FC-BH detachment system.

To the east of the TWF is a normal fault oriented at N20W, 64NE that juxtaposes older Tertiary tuffaceous sediments in the hanging wall against the Paleozoic limestone in the footwall (figure 3.8). The age of this fault has not been determined relative to the TWF, but may be younger than the TWF.

Carbonate rocks in the footwall of the FC-BH detachment are brecciated. At field stop 0315-1 (figure 3.1), the base of the detachment is marked by recrystallized limestone of the Bonanza King Formation broken into angular clasts that range from boulders to granules (figure 3.9). The intensity of brecciation varies throughout the outcrop with some exposures consisting of granular clasts whereas

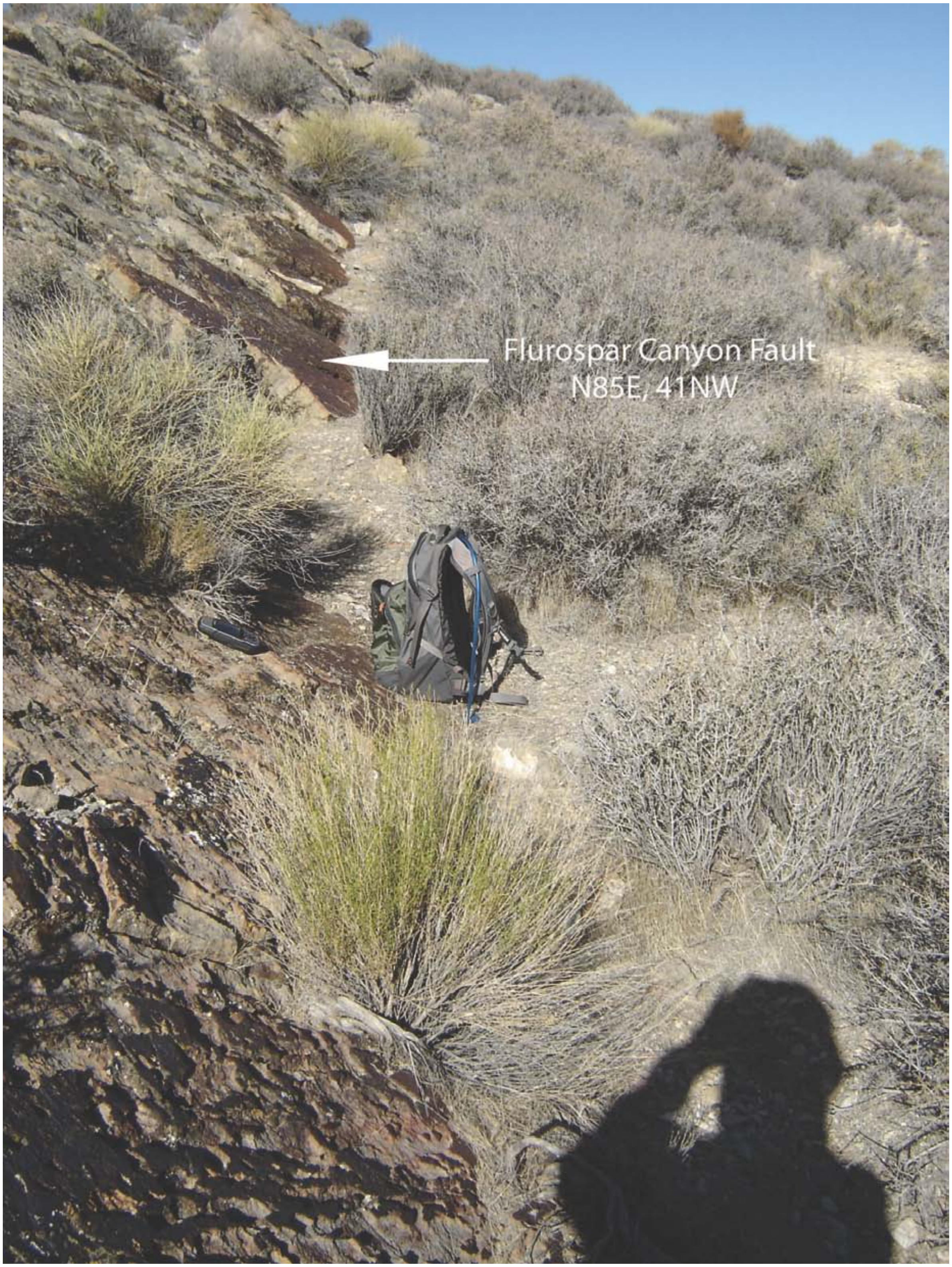


Figure 3.4 Fluorspar Canyon detachment fault plane at field stop 0607-1

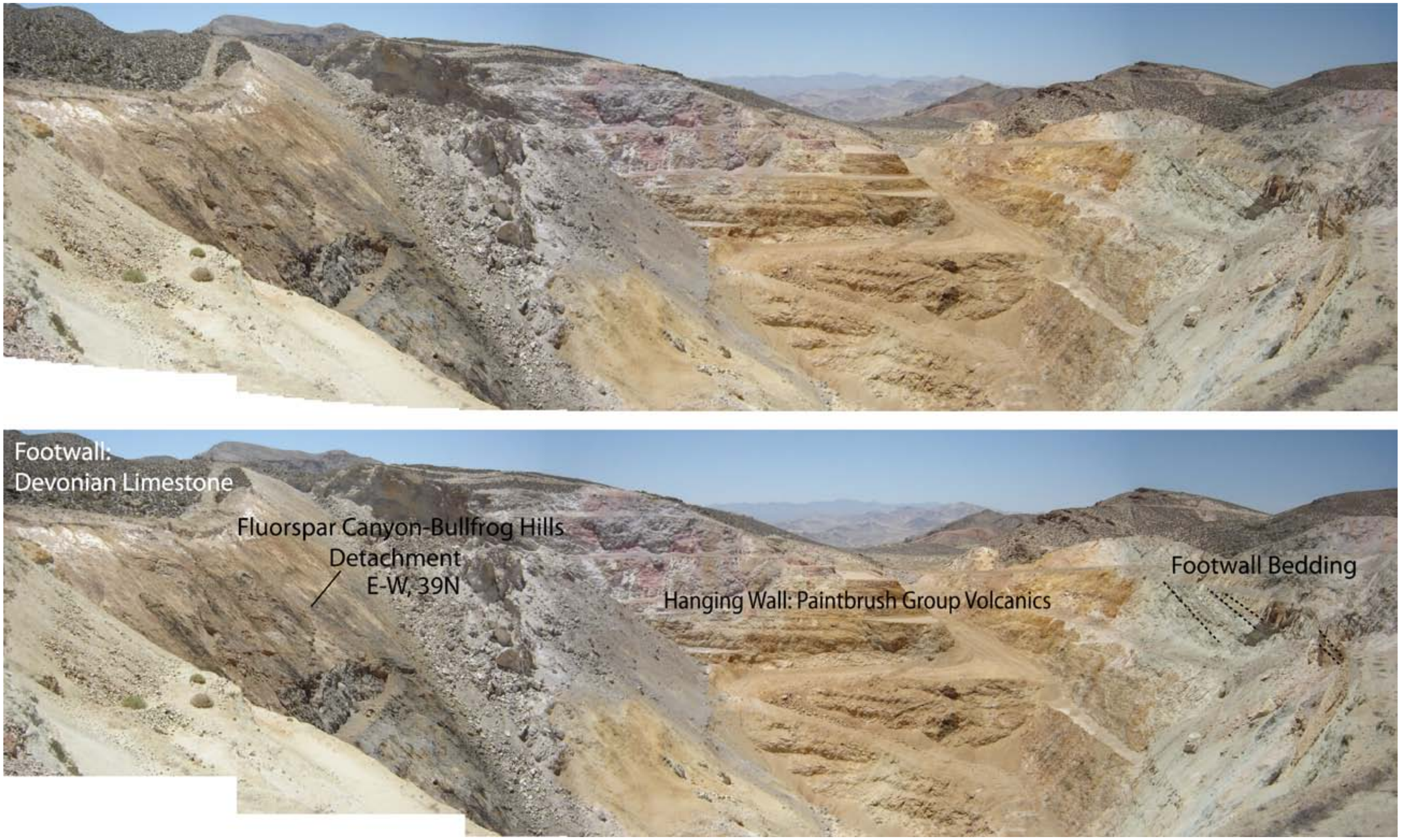


Figure 3.5 The Fluorspar Canyon Detachment exposed in an open pit south of Paintbrush Hill. Black lines in the hanging wall represent bedding planes of the Bullfrog Tuff.

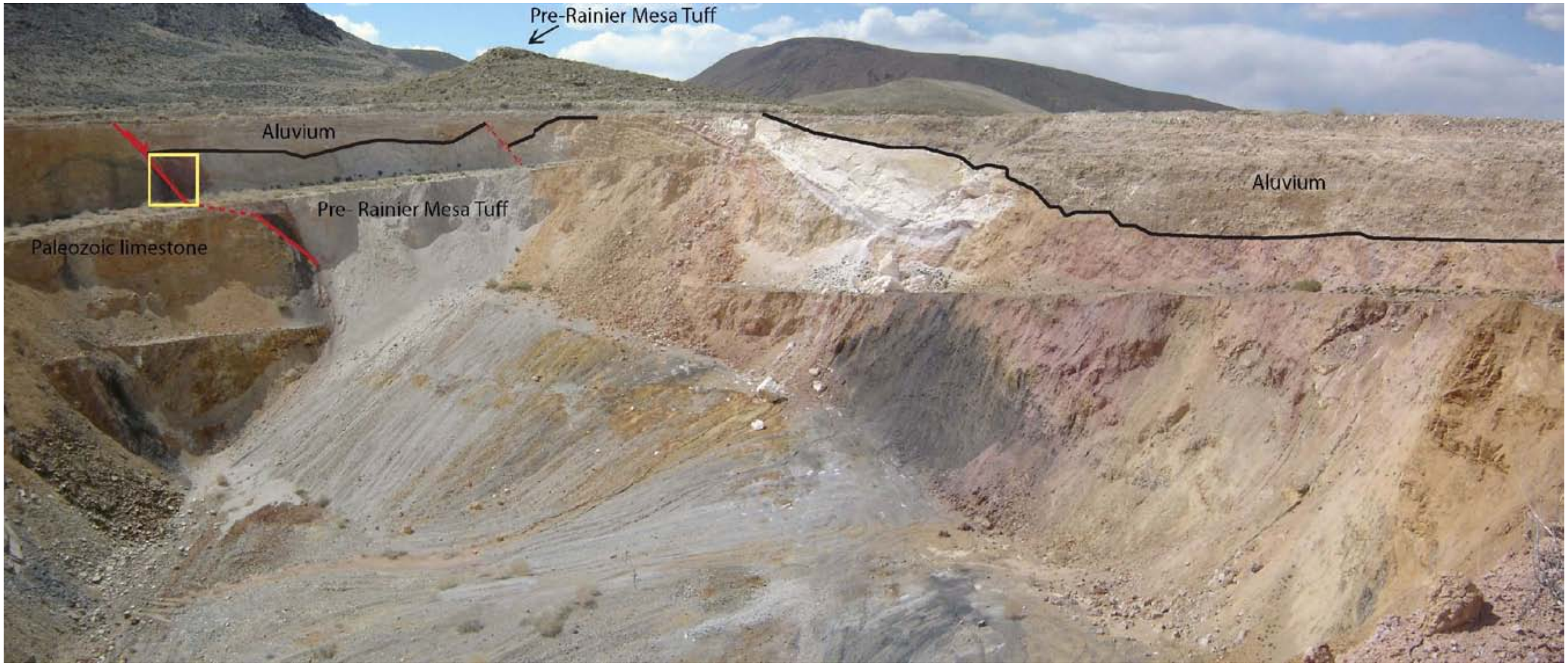


Figure 3.6 Exposure of the Tate's Wash fault in a pit at field stop 0315-5 . The footwall consists of folded and faulted Paleozoic limestone. Faults are represented by the red lines (dashed where approximate) with displacement direction illustrated by red arrows. Black lines represent the contact between the Pre-Rainier Mesa Tuff and overlying alluvium.

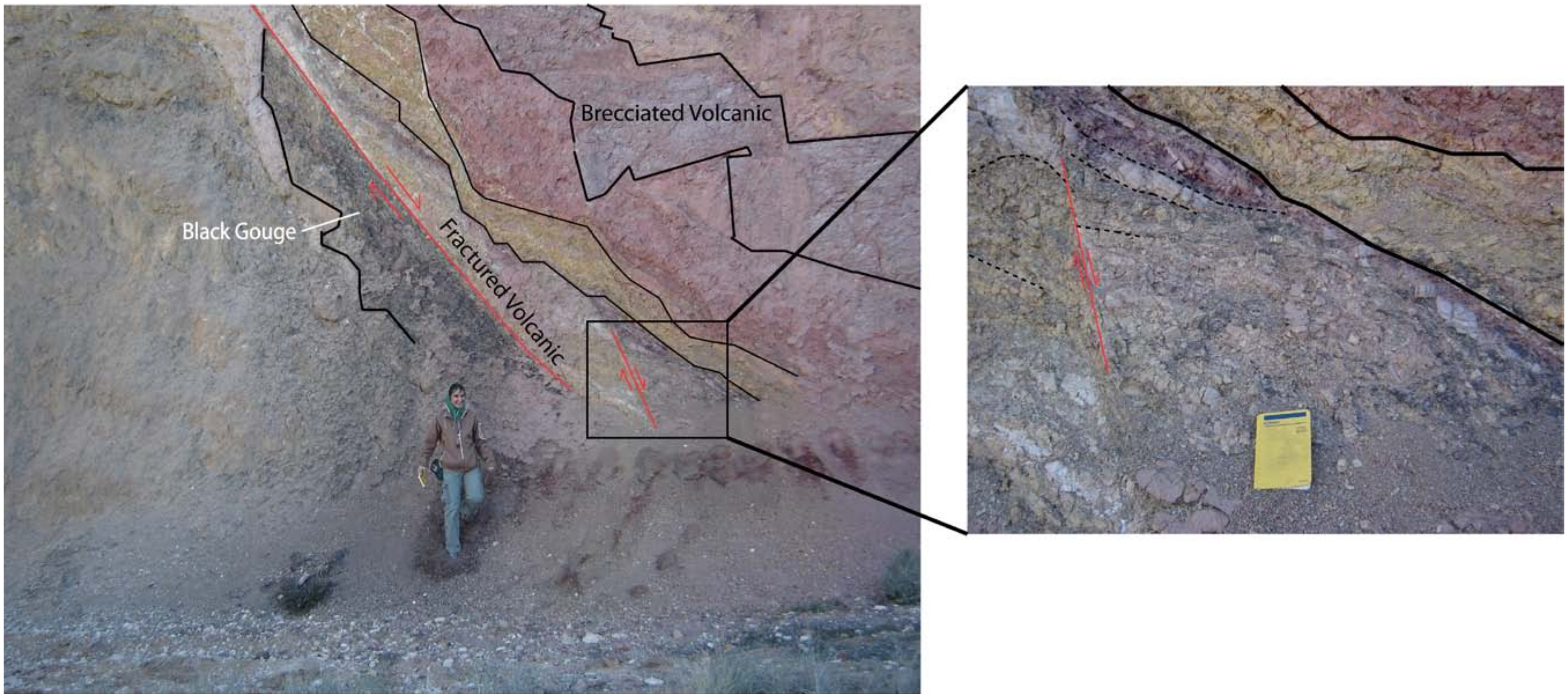


Figure 3.7 Tate's Wash Fault exposed in an open pit. Red lines represent fault planes with red arrows indicating displacement sense. Solid black lines indicate contacts between rock units in the fault zone. Dashed black lines represent bedding in the footwall and hanging wall of the smaller right lateral normal fault (right photo).

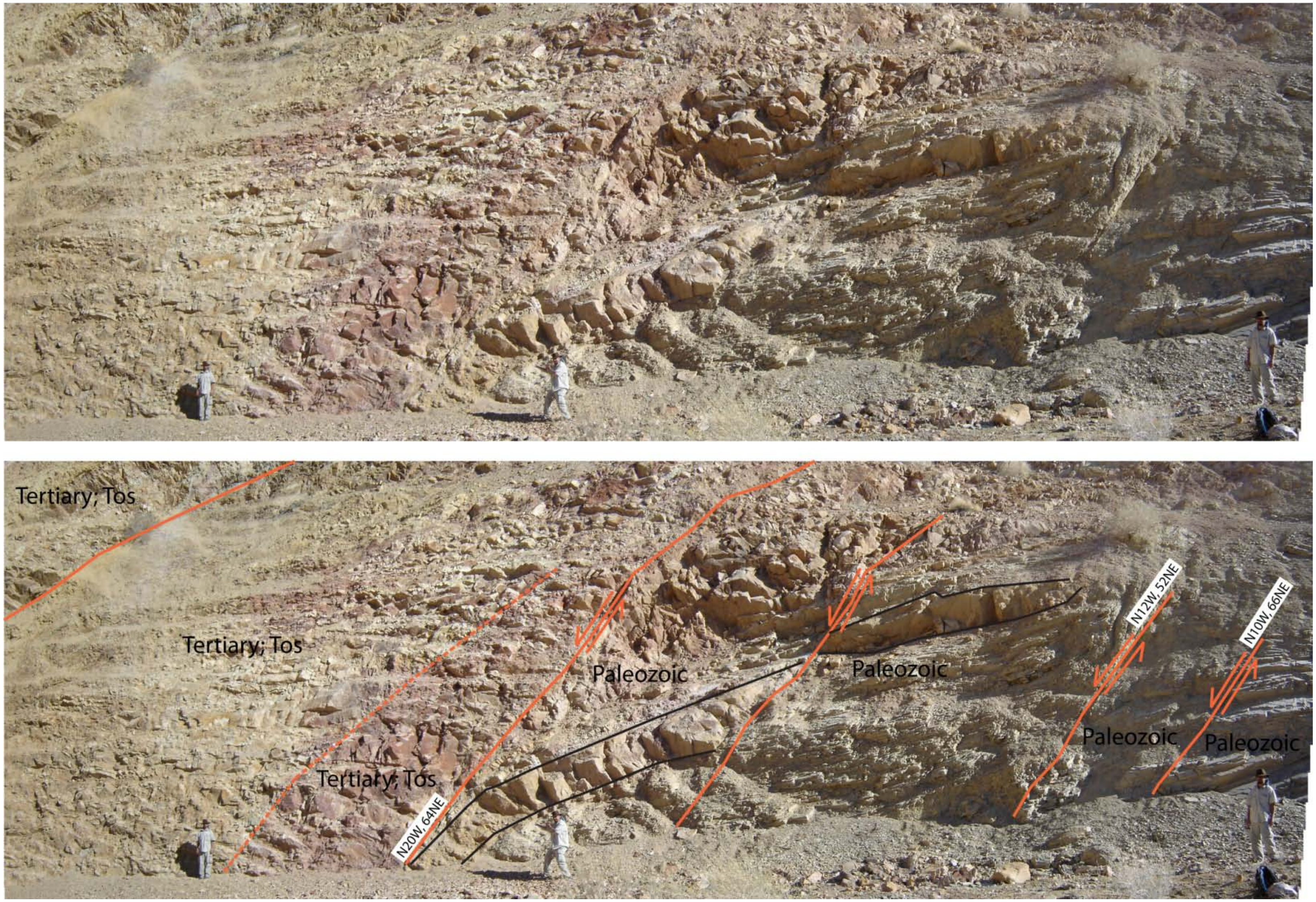


Figure 3.8 The footwall of the Tates Fault, cut by several normal faults.

other exposures contain poorly sorted larger clasts in an finer matrix. Some layers of the Bonanza King may record foliation near the detachment.

In the western Bullfrog Hills, Maldonado (1990) identified the Bonanza King Formation, Pogonip Group, Eureka Quartzite**,** Ely Springs Dolomite, Hidden Valley Dolomite and Lost Burro Formation (not exposed at Bare Mountain), and Eleana Formation. Most of these formations correlate with units cut by the Tates Wash fault in the Fluorspar Hills. They may represent the remnants of hanging wall rocks formerly beneath the volcanic section.

West of the town of Rhyolite, these hanging wall remnants are strongly deformed and may be part of a fault-bound sliver. Distinctive Eureka quartzite crops out in a hill (field stop 0321-5 [figure 3.1] in the SBH where it is broken into angular to subangular to subrounded clasts ranging from granules to small cobbles supported in a coarse grained matrix of poorly sorted quartz sand (figure 3.10). Brecciation varies in intensity throughout the exposure and locally, steep beds are preserved (figure 3.11).

Brecciated carbonate is commonly present as slightly fractured dark gray dolomite (?) cut by fractures with diverse orientations. This rock is separated from less resistant limestone breccia by an irregular relict depositional contact (figure 3.12). The limestone breccia consists of angular boulder to granular clasts of limestone in a coarse limestone sand matrix.

10 km northeast of the exposures of the detachment near Rhyolite, are additional outcrops of Paleozoic and Neo-Proterozoic rocks. Exposures exist as prominent hills north of Pioneer Road in the Springdale Quadrangle. One such hill is composed of Zabriskie Quartzite, Wood Canyon, Zabriskie, and Carrara Formations (Minor et al. 1997) and is referred to as Zabriskie Hill (figure 2.2). Rocks have a general eastward tilt and are dipping 40-70°.

The Wood Canyon Formation is folded, whereas Zabriskie Quartzite on the north side of the hill is brecciated into angular, boulder to granular clasts of quartzite supported in a silicified matrix (figure 3.13). The breccias may occur in a discrete zone. The siliceous matrix commonly shows black veneer on exposed surfaces. Because (1) these rocks are not as brecciated as the Paleozoic units further southwest ,and (2) previously mapped Tertiary rocks (Maldonado and Hausback, 1990; Minor et al. 1997, Connors et al. 1998, Fridrich et al. 2007) unconformably overly the hill, the Cambrian rocks must have been exposed during the Tertiary.

The Paleozoic and Neo-Proterozoic rocks present in the Springdale Quadrant that may be part of the fault-bounded sliver are enigmatic. A speculative interpretation is that they may have comprised the hanging wall of a Mesozoic thrust that was lowered onto the FC-BH detachment as a coherent block during extension.

3.2.2 The Beatty Fault

The Beatty fault, a structure that generally strikes north through Oasis Valley, is a major steep fault that separates the Fluorspar Hills and the Bullfrog Hills domains. This west dipping structure is recorded by brecciated Timber Mountain volcanics immediately north of Sober Up Gulch and west of Highway 95 (figures 3.1 and 3.14). The breccia consists of angular granular to boulder size fragments of densely welded Timber Mountain tuff (either from the Rainier Mesa or Ammonia Tanks Formations). Clasts are silicified perhaps by quartz veins that fill fractures. To the west, breccia mapped by Connors et al. (1998) and Fridrich et al. (2007) form rounded hills and have no sufficient exposure of rock to examine.

Figure 3.9 Brecciated Bonanza king in the footwall of the Fluorspar Canyon-Bullfrog Hills Detachment in the Fluorspar Hills at field stop 0314-3.

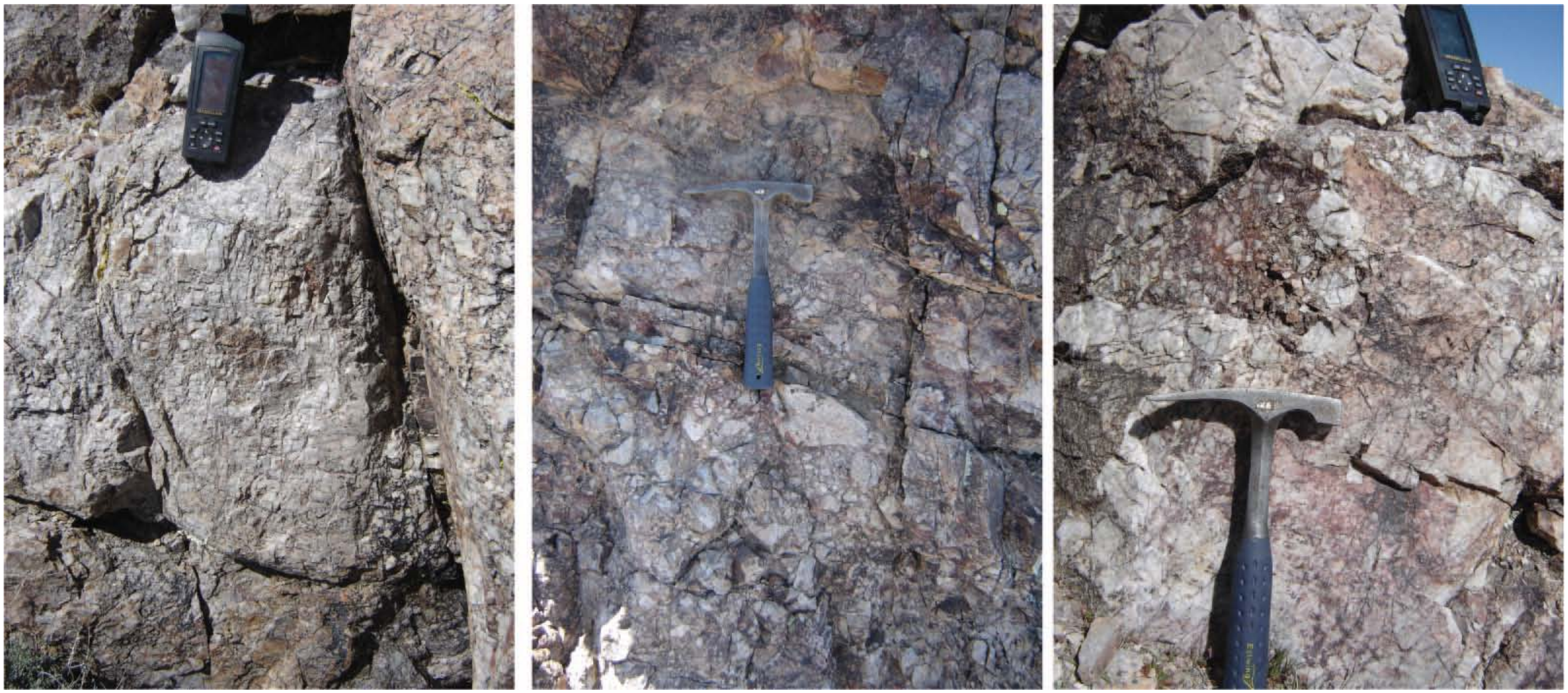


Figure 3.10 Brecciation in the Eureka Quartzite in the crush zone between the upper and lower plates of the FC-BH detachment in the SBH at field stop 0322-5.

Figure 3.11 Bedding in the Eureka Quartzite in the SBH at field stop 0312-5. Bedding is indicated by red lines.

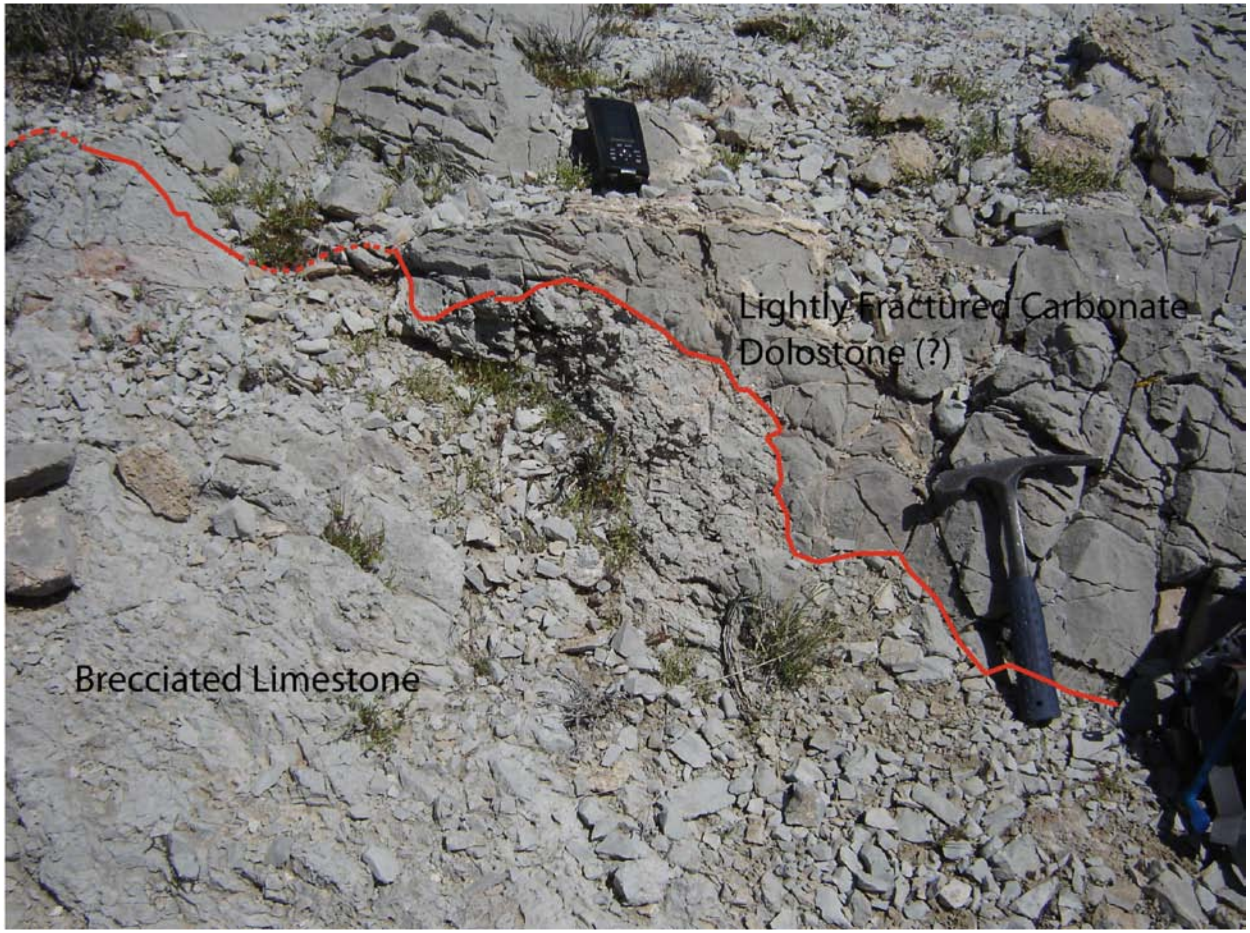
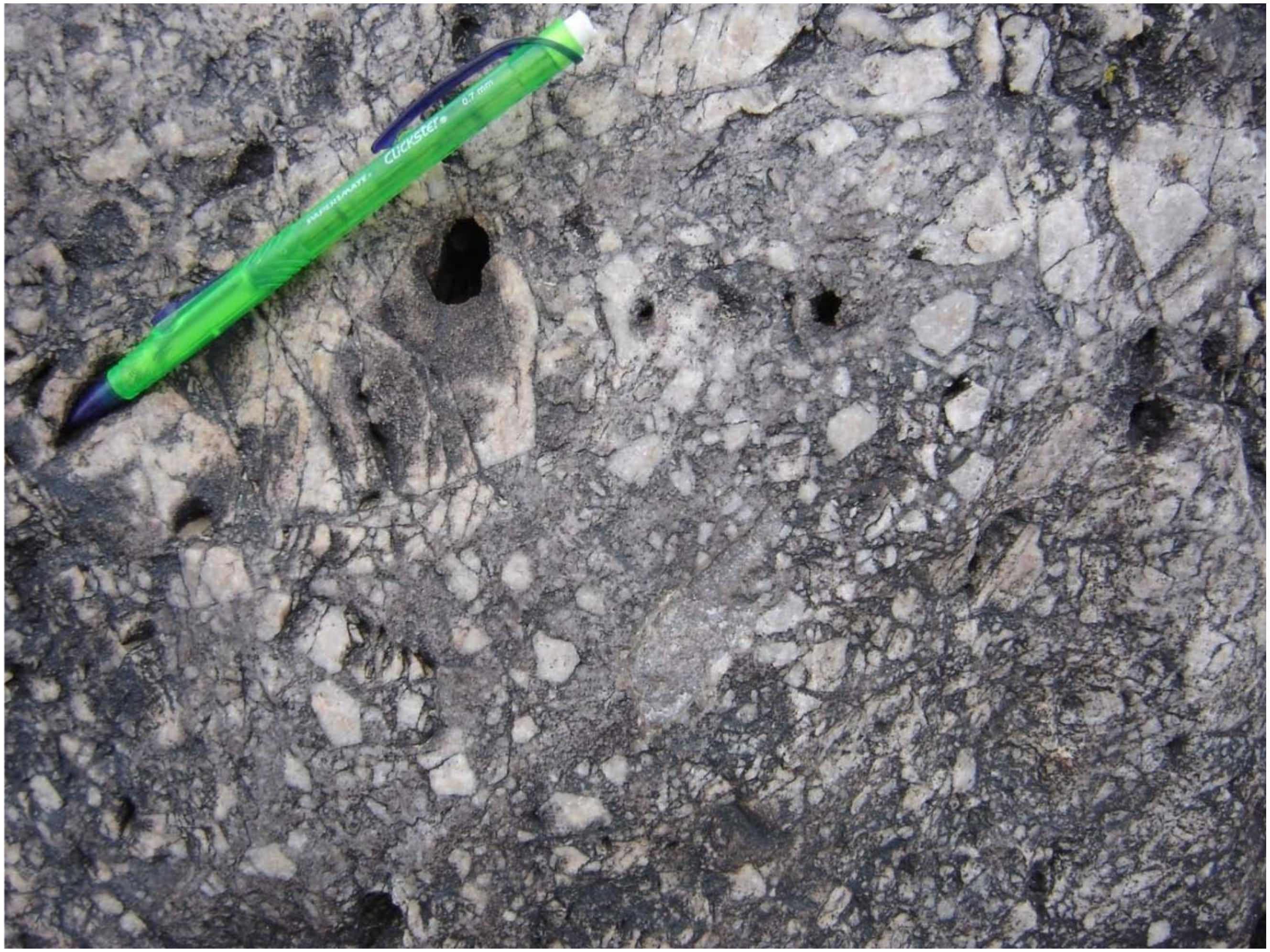


Figure 3.12 Brecciation in Paleozoic limestone within the rock sliver between the upper and lower detachment plates at field stop 0322-11. The light gray limestone is moderately brecciated. The dark gray carbonate, probably dolostone, is less fractured. The red line marks the contact between the two units and is dashed where approximate.



Figur 3.13 Angular clasts of Zabriskie Quartzite at the northern margin of Zabriskie Hill in the northeastern Bullfrog Hills at field stop 1216-01

Figure 3.14 Brecciated Timber Mountain Group north of Sober Up Gluch and west of Highway 95 at field stop 0615-9

3.3 EVALUATION OF PREVIOUSLY MAPPED BRECCIAS

Breccia that may serve as a fast pathway for groundwater movement is an important study focus of this thesis. Several extensive breccias have been mapped in the field area (Connors et al., 1998; Fridrich et al., 2007; Maldonado and Hausback, 1990; Minor et al., 1997). The breccia units have been assessed with the intention of distinguishing the formation of each and the potential of each to facilitate water movement. Some of the breccias are gravity-driven slide masses that were brecciated during transport into low areas. Many of the slides, mapped as thrusts (Maldonado and Hausback, 1990), are re-interpreted in this study as low-angle structures that accommodated the movement of rock from higher elevations to lower elevations.

3.3.1 Fluorspar Hills

3.3.1.1 Quartzite Breccia (Fridrich et al., 2007)

East of Paintbrush Hill, silicified brecciated quartzite, probably derived from Eureka or Zabriskie Quartizite, comprises a small, isolated, outcrop. Clasts consisting of granules to cobbles reside in a siliceous matrix that is commonly covered by desert varnish (figure 3.15). The siliceous rock is mapped as "silicified gravel” by Monsen et al. (1992) in the Fluorspar Hills and as breccia by Fridrich et al. (2007) in the NBH. Examination of the exposure shows that a transition exists between strongly fractured quartzose rock and quartzite-clast cobble conglomerate. The less fractured part of the exposure resembles quartzite clast conglomerate that rests on the Eureka quartzite west of Mercury, Nevada. The fractured quartzose rock likely forms the base of the Oligocene section described in Chapter 2.

East of Paintbrush Hill, the matrix of the conglomerate is silicified and resistant to weathering, whereas in the NBH, the matrix has been weathered, leaving behind well rounded clasts of limestone and quartzite.

In places rounded clasts are difficult to identify because of extensive fracturing but small angular pebble and granule clasts are present.

3.3.1.2 Carbonate-clast sedimentary breccia

Along the eastern slope of Paintbrush Hill in the Fluorspar Hills, poorly exposed carbonate-clast breccia overlies Tiva Canyon tuff (figure 3.16). The breccia is composed of angular pebbles of carbonate and sandy/silty carbonate in a sandy matrix**.** Some clasts are fractured and the rock is hydrothermally altered to red color.

Clasts were probably derived from Paleozoic units exposed in the high-standing footwall of the the Tates Wash normal fault (see above) (Fridrich et al. 2007). The exposure may have been part of talus or an alluvial fan that accumulated in a half-graben that formed between 12.7 and 11.6 Ma ago. Paleozoic clast avalanche breccias of the same age overlying the Tiva Canyon tuff has been reported in Crater Flat (Carr and Parish, 1985). The presence of these deposits suggests the Paleozoic footwall was exposed by 11.6 Ma ago (Hoisch et al.1997).

3.3.1.3 Volcanic-clast conglomerate

In the central and western Fluorspar Hills, conglomerate containing volcanic clasts that accumulated after the eruption of the Paintbrush Group were mapped as breccias by Fridrich et al. (2007).

West of Beatty Mountain, the volcanic clast conglomerate overlies a stratigraphic section consisting of Older tuffs and sediments (Tot), Lithic Ridge tuff, Crater Flat Group, and Paintbrush Group immediately east of Beatty, NV (Monsen et al 1992; Fridrich et al. 2007). At this location, the older volcanic and sedimentary section is locally vertical to overturned and strikes northeast. The dips of this unit are significantly steeper than those of the tilted section to the east (e.g. Paintbrush Hill, where the rocks dip ~40°E). The overlying conglomerate strikes north and has vertical to steep dips. The unconformably underlying rocks must have been tilted during early tilting of Paintbrush and older Tertiary units or are part of an overturned fold limb. As no evidence suggests the presence of a fold, it is assumed that these rocks record at least one additional episode of normal faulting that caused rotation before accumulation of the conglomerate.

The disconformably overlying the volcaniclast conglomerate that marks the base of the Pre-Rainier Mesa tuff has been rotated to 88°. The contact between the conglomerate and pre-Rainier Mesa (stop 0304-3; figure 3.1) is distinguished by a sharp color contrast between the purple-red conglomerate and the light green Pre-Rainier Mesa tuff (figure 3.17). The contact is sharp but irregular. The overlying tuff fills in the low pockets created by the irregular surface of the underlying conglomerate. This is illustrated by bedding that terminates against the upper contact of the conglomerate and pre-Rainier Mesa tuff (figure 3.18) at field stop 0304-3 (figure 3.1).

Stratigraphic relationships are clearly exposed at field location 0307-6 (figure 3.1) where the conglomerate overlies steeply dipping beds of the Paintbrush Group and underlies the well to moderately bedded pre-Rainier Mesa tuff. The average size of clasts at this location is less than and they are more rounded than, those at field stop 0304-3. Clasts are abundant at the base of the unit, where they comprise 80-90% of the unit (figure 3.19). Upward from the base, the conglomerate contains fewer clasts and is matrix supported. A distinct, but irregular contact separates the clast-supported conglomerate from the matrix-supported conglomerate (figure 3.19).

In the SBH, neither conglomerate nor breccia overlie Paintbrush units at the angular unconformity between Paintbrush and Timber Mountain Groups.

3.3.1.4 Breccias interfingering in the Pre-Rainier Mesa Rhyolite

Layers of cobbly sedimentary breccia form interbeds within pre-Rainier Mesa Rhyolite (Figure 3.20). A well exposed layer has a sharp, but irregular, upper contact with the Pre-Rainier Mesa Rhyolite. The upper contact contrasts with a transition from tuff to breccia at the base. The breccia layer is approximately 1.5 m thick. Clasts are angular pieces of the Paintbrush Group supported in a white, fine to coarse grained, poorly sorted, sand matrix. At the basal contact, the matrix is ashy.

3.3.2 Northeastern Bullfrog Hills

The breccias in the NBH consists of both monolithic and polylithic rocks. Minor et al. (1997) mapped the Springdale Quadrangle and distinguished among the monolithic breccias, identifying the units based on the formation from which the clasts were derived. Later mapping by Connors et al. (1998) grouped the monolithic and polylithic breccias together as one unit, but did recognize and document distinct areas where monolithic breccias crop out. Fridrich et al., (2007)

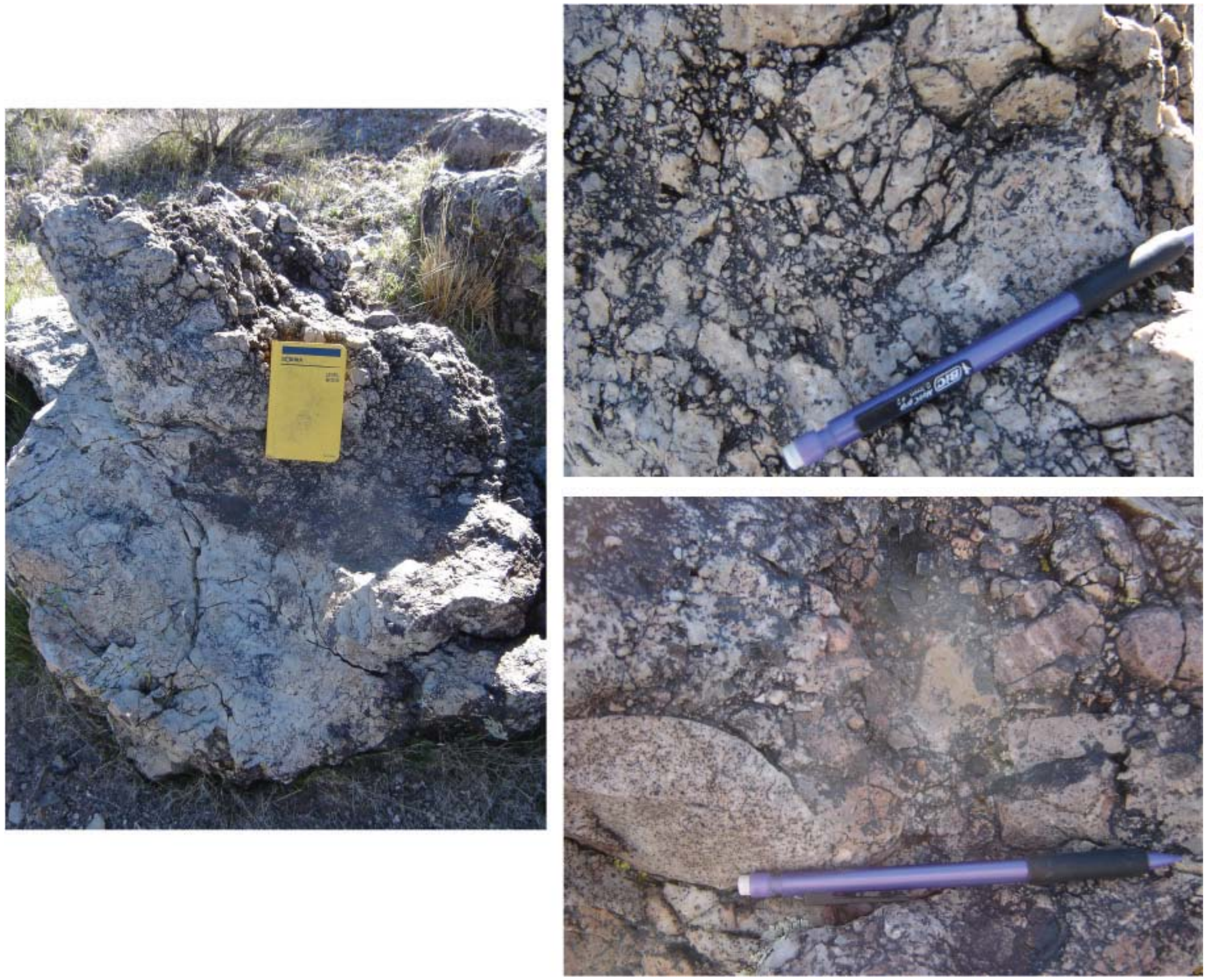


Figure 3.15 Brecciated Quartzite underlying the underlying the Eocene-age conglomerate in the Fluorspar Hills at field stop 0314-1.

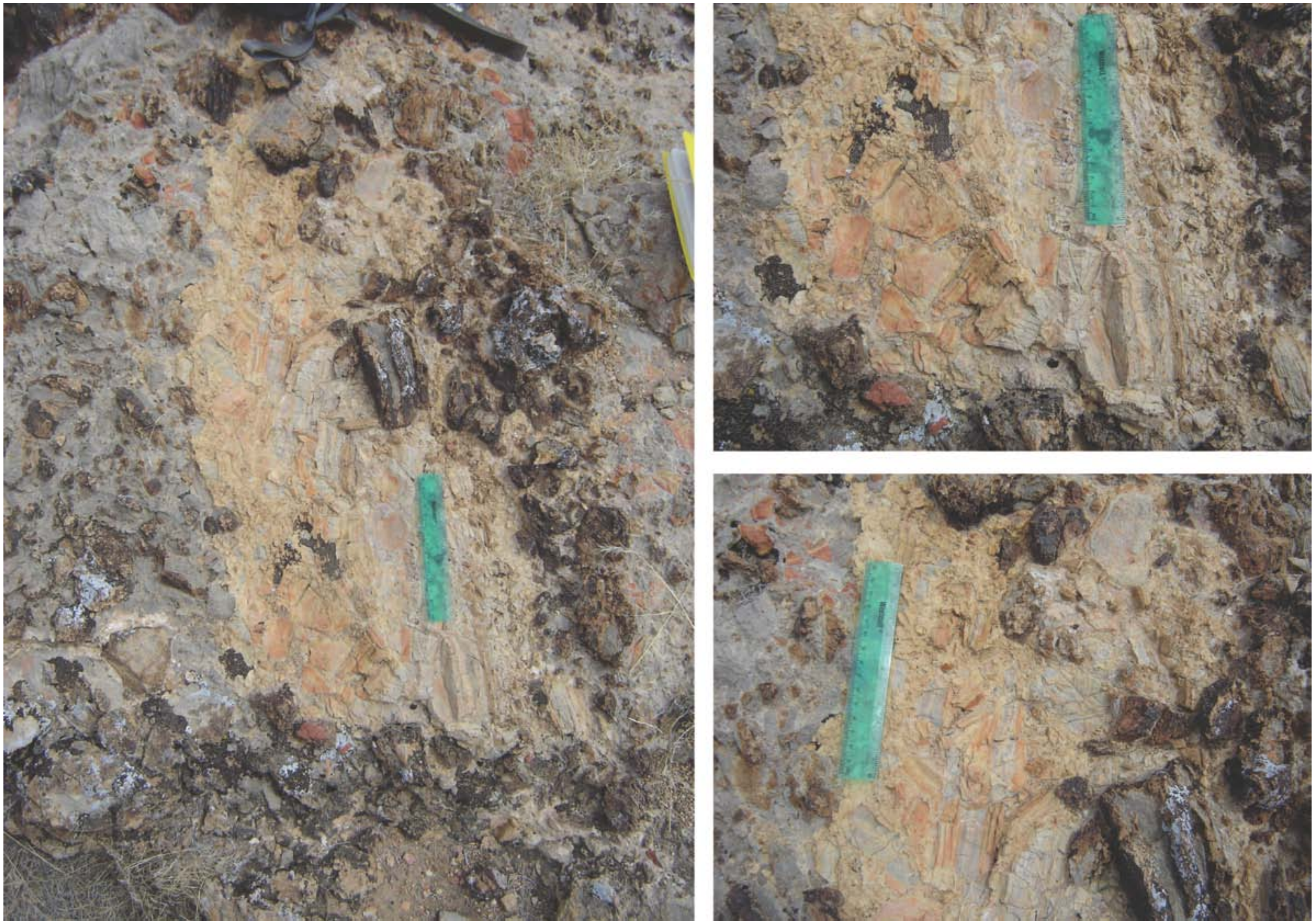


Figure 3.16 Post-Paintbrush breccia that crops out on the east face of Paintbrush Hill in the Fluorspar Hills at field stop 0611-8.

Figure 3.17 Contact (black line: solid where certain, dashed where approximate) between the coarse post-Paintbrush sedimentary breccia and the Pre-Rainier Mesa Tuff (field stop 0304-4). The black box outlines the area of Figure 3.18.

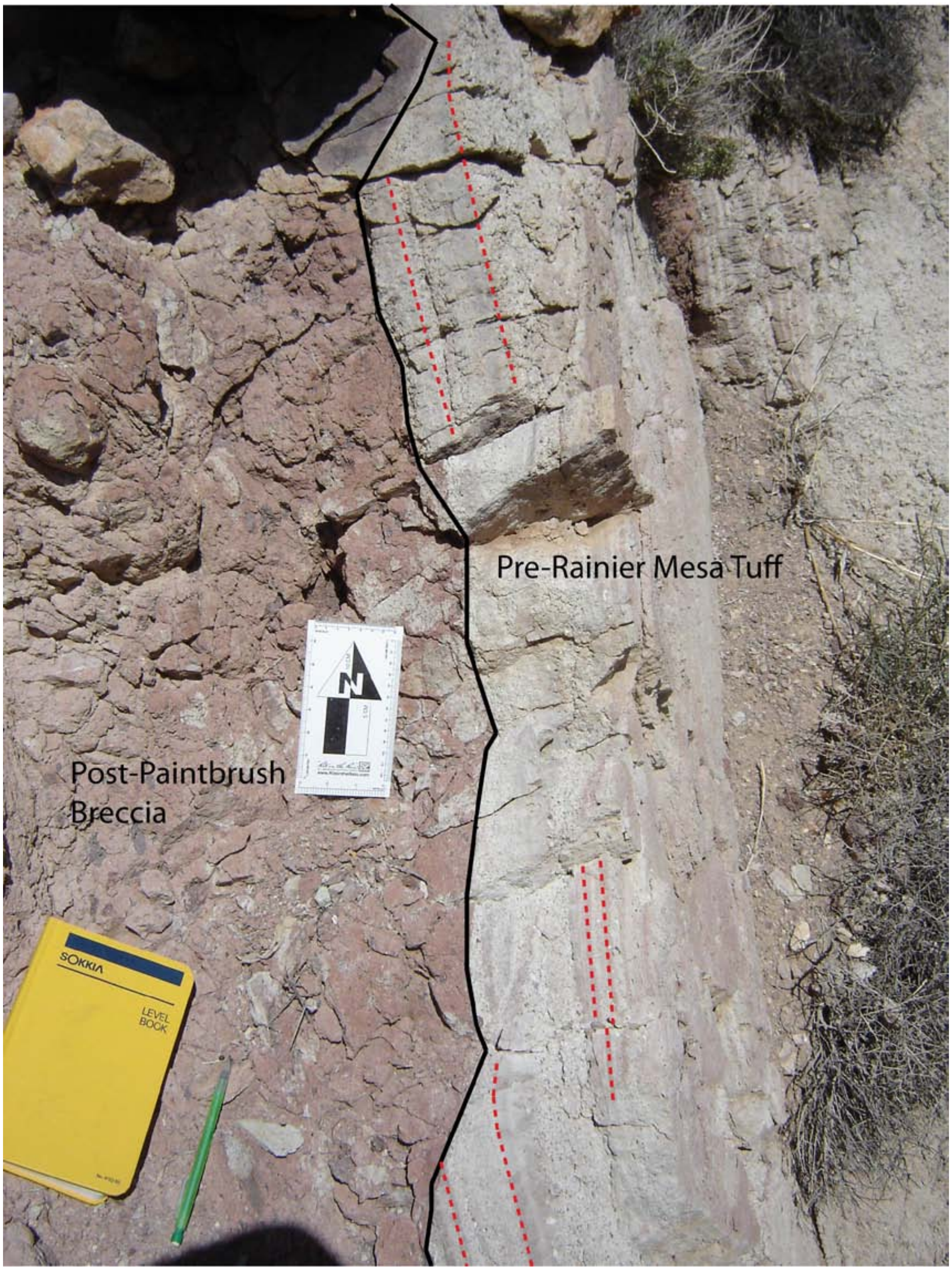


Figure 3.18 Contact between the post-Paintbrush Breccia and overlying pre-Rainier Mesa tuff (field stop 0304-4). Solid black line coincides with the depositional contact and dashed red lines trace bedding in the pre-Rainier Mesa tuff.

mapped the breccias in the NBH and part of the SBH as one unit (Tyx) without distinguishing the specific monolithic breccias. Minor et al. (1997) considered the monolithic breccias to be the same age, underlying a mappable sedimentary breccia unit (mapped as Tgx by Minor et al. 1997).

The relative ages of breccia units in the Springdale Quadrangle are constrained by their stratigraphic relations and extent in the NBH. An attempt was made to identify distinguishable structural domains in the NBH based on stratigraphic patterns of breccias. Emplacement of masses of volcanic breccia as slide masses among tuffs synchronous with the eruption of Rainbow Mountain Group obscures many of the older faults. This overprint makes it difficult to ascertain relative ages of faulting in the area. Eight breccia groups are recognized based on clast content and relatively dated based cross-cutting relations. These are: Post-Paintbrush breccias ([1] Bullfrog-clast and [2] Paintbrush-clast breccias of Minor et al., 1997), (3) Sedimentary breccia and sandstone (unit described in section 2.3.2.5;Tgx of Minor et al., 1997), and the younger (11.4-10.56 Ma) monolithic Post-Timber Mountain Group breccias monolithic ([4]Wood Canyon-clast, [5] Zabriskie-clast, [6] Carrara-clast, [7] Rainier Mesa-clast, [8] Fleur-di-Lis-clast breccias of Minor et al., 1997).

Figure 3.21 is a map of the field area with the location of referenced field areas in section 3.3.2.

3.3.2.1 Post-Paintbrush Group talus breccias (12.7-11.7Ma)

As in the Fluorspar Hills, extension between 12.7 and 11.6 Ma tilted the Paintbrush Group and older units. Tilting took place during formation of a half graben where monolithic breccias accumulated. These breccias commonly rest upon source rocks that must have been exposed as the footwall at the surface. For example, breccias containing clasts of the Paintbrush Group commonly overly the Paintbrush Group volcanics. At least three types of monolithic breccias of this age exist: Zabriskie-clast breccia, Bullfrog Formation clasts breccia and Tiva Canyon clast breccia. These breccias contain angular to sub-rounded cobbles, pebbles and granules (figure 3.22).

Evidence of post-lithification deformation is recorded in the Paintbrush-clast breccias by variously oriented slide surfaces (figure 3.23).

3.3.2.2 Sedimentary breccia and sandstone

A thick section (~300 m) of graded breccia and immature sandstone overlies the sedimentary (talus) Bullfrog and Paintbrush-clast breccias in the southern part of the Springdale Quadrangle and about 5 km southwest of Oasis Mountain. North of Pioneer Mine, the sedimentary unit is poorly exposed, only cropping out beneath the contact with the Rainbow Mountain Group.

In the southern section of the quadrangle, an angular unconformity represents the uppermost sandy sedimentary unit from the overlying Rainbow Mountain Group (Minor et al., 1997). The angular discordance between these two units is between 10 and 20°. Layers in the graded breccia sub-unit are thin to moderately bedded. Beds are normally graded, are poorly sorted, and have large clast size. Dips of bedding range from 45-31°E in the southern part of the Springdale Quadrangle. Clasts within the unit are derived from locally exposed units including the Bullfrog and Paintbrush Groups with abundant Zabriskie Quartzite clasts. Clasts of Wood Canyon and/or Carrara are rare.

North of Pioneer Mine, the breccia is composed of angular to subangular pebbles and cobbles of Zabriskie Quartzite supported in a red, hydrothermally altered, fine grained sand matrix in the central part of the quadrangle (figure 2.16) Poor exposure precludes determination of sedimentary characteristics such as grading .

Minor et al. (1997) consider the sandstone and breccia to be post-Rainier Mesa; however, a depositional contact between this unit and the Rainier Mesa has not been mapped. Also, there are no clasts of Rainier Mesa within breccia.

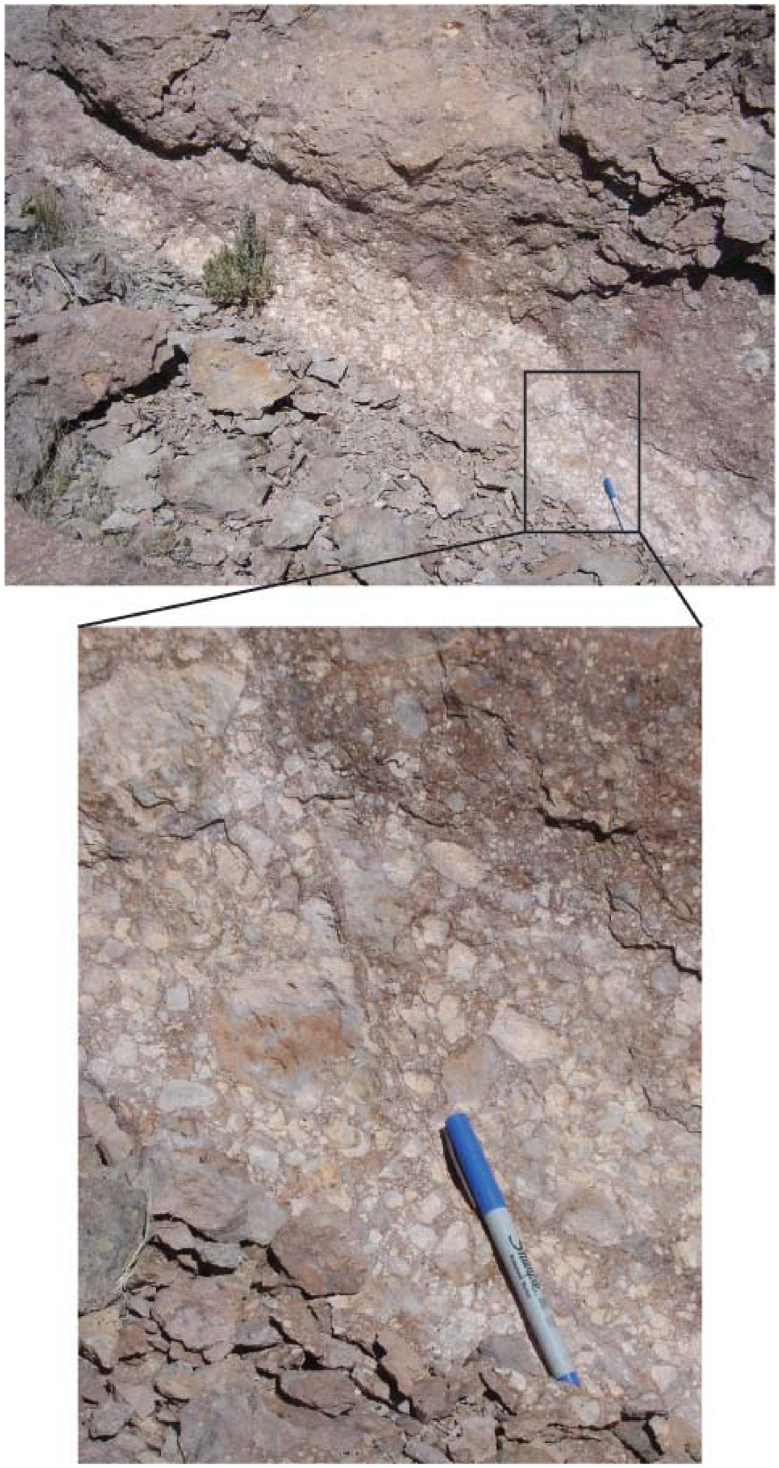


Figure 3.19 Post-Paintbrush Group sedimentary breccias containing clasts of volcanic rock derived from the Paintbrush and Crater Flat (?) Groups. Rock crops out at field stop 0307-5.

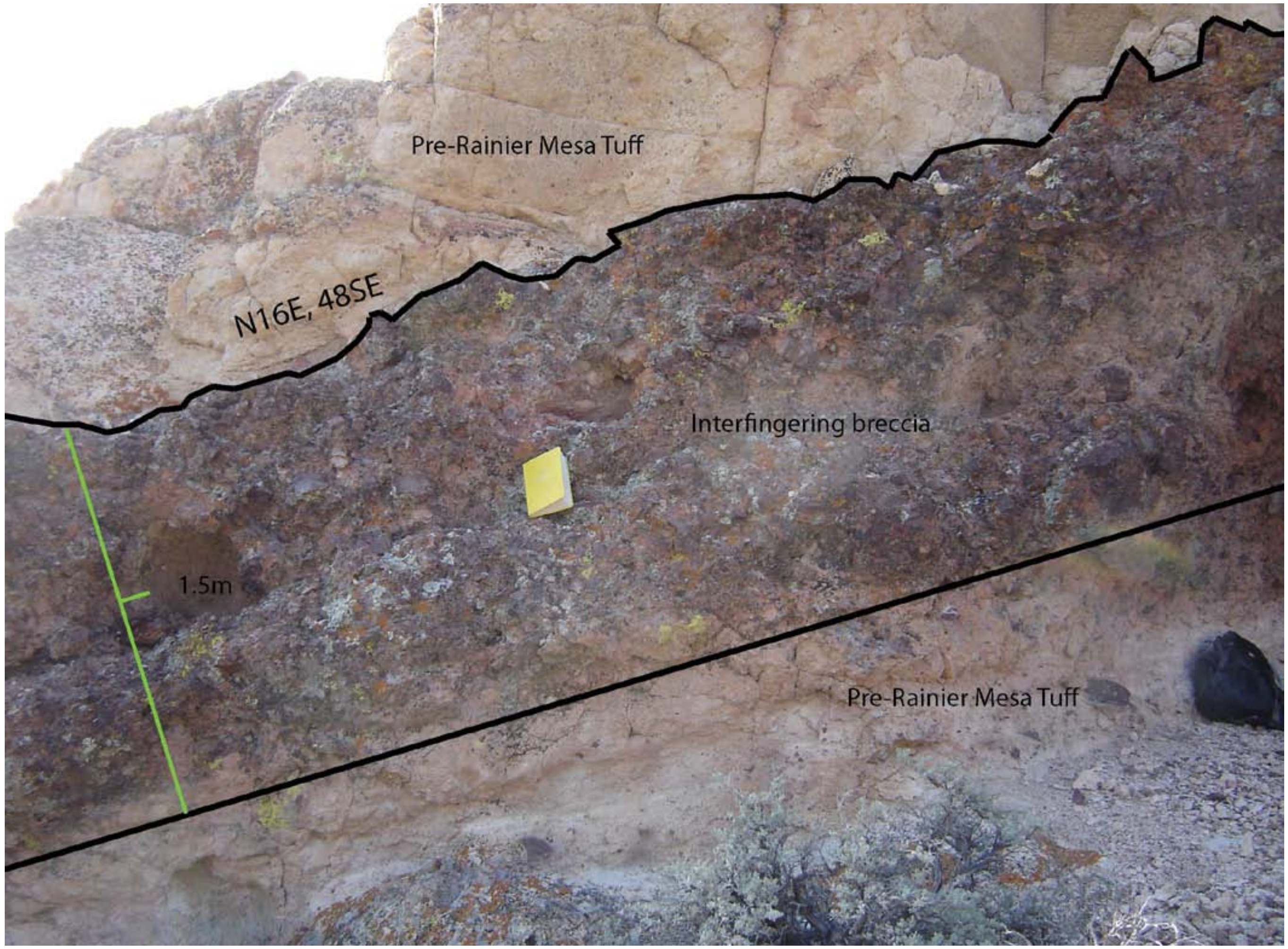


Figure 3.20 Interfingering breccias within the Pre-Rainier Mesa Tuff in the Fluorspar Hills at field stop 0603-2. Clasts are derived from the Paintbrush Group.

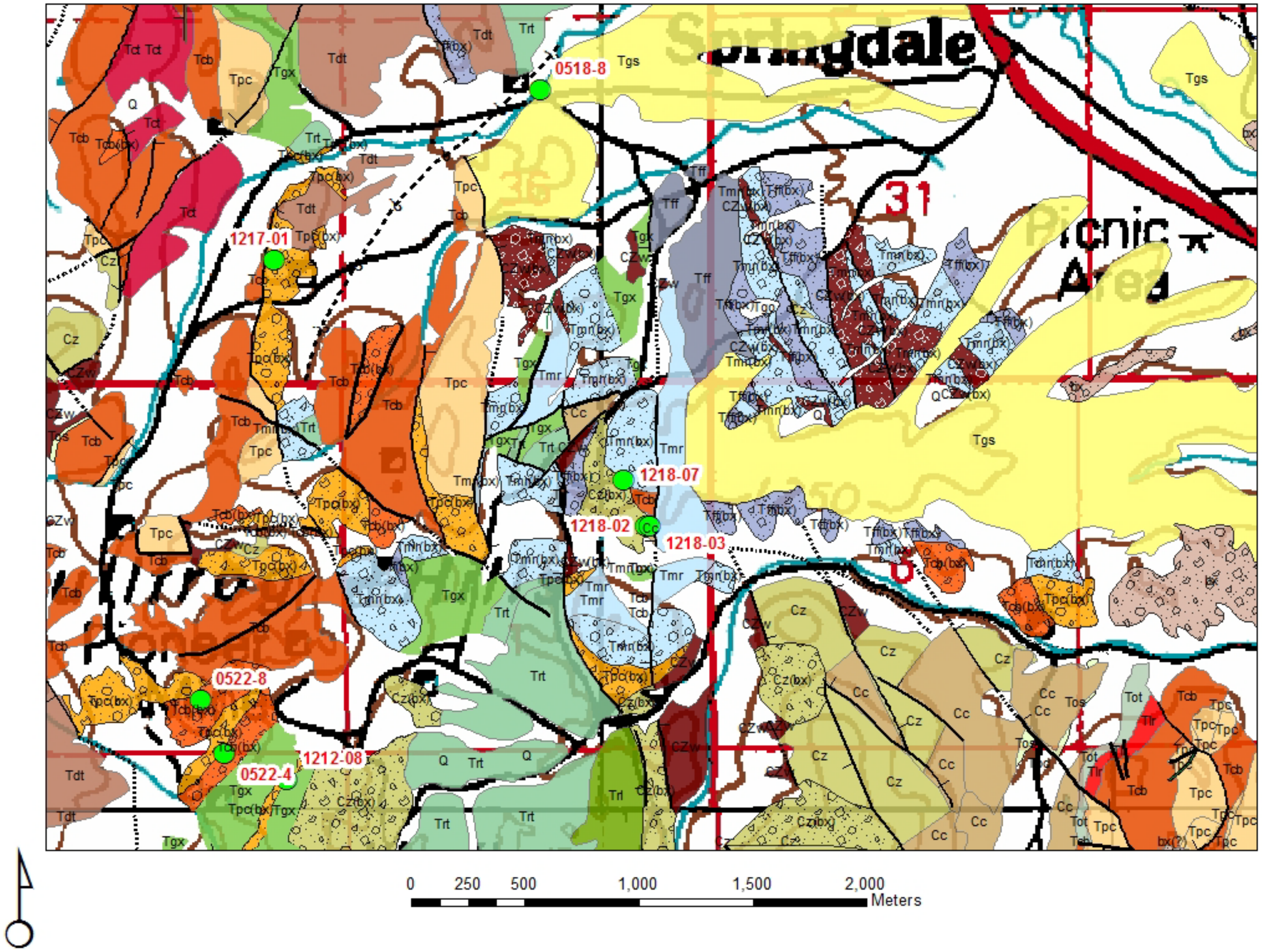


Figure 3.21 Geologic map of the NBH. Bright green circles represent referenced field stops in section 3.3.2. For the detailed map explanation, refer to the geologic map associated with this study.

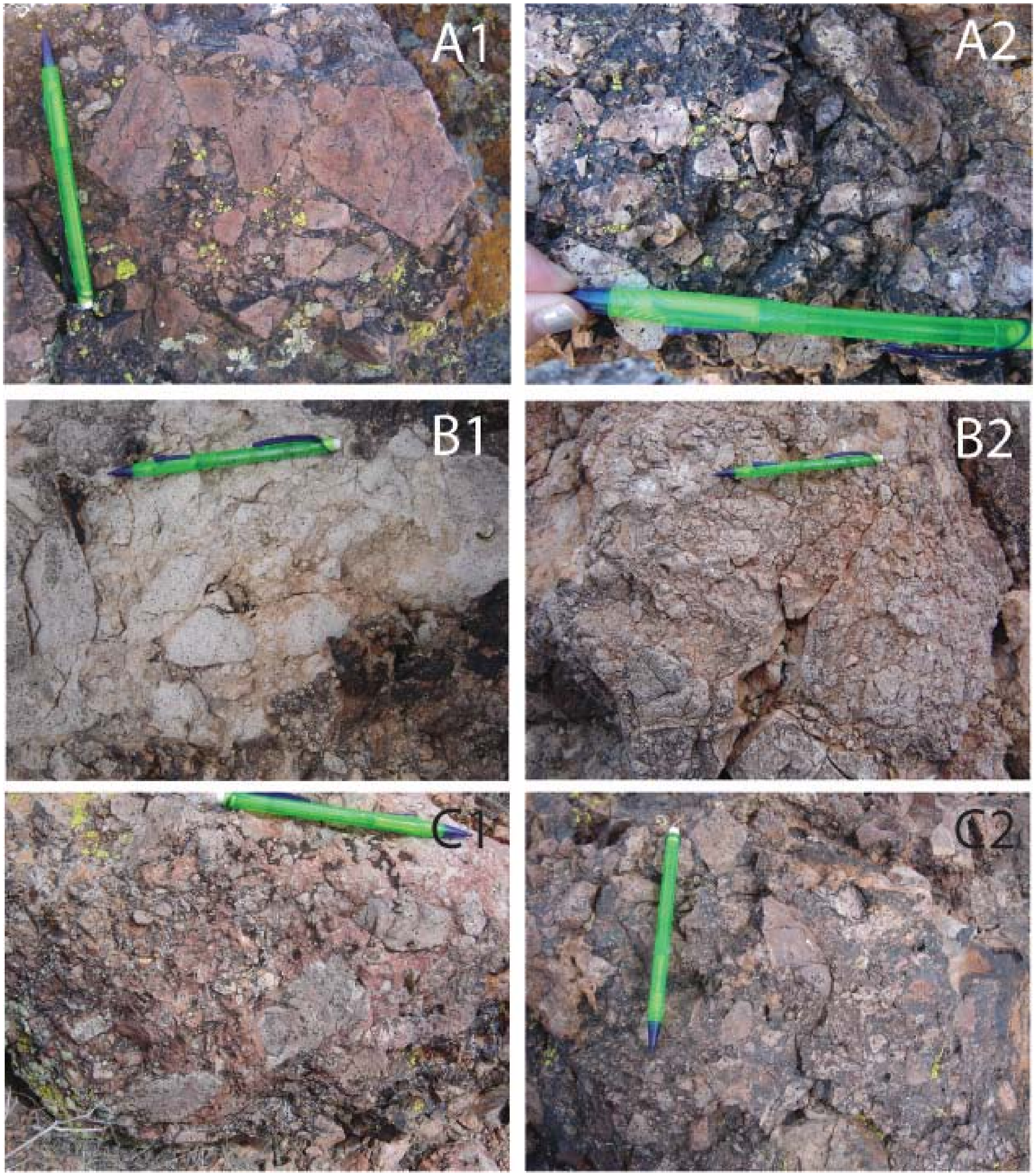


Figure 3.22 : Post Paintbrush breccias in the NBH. Photos A1 and A2 are Paintbrush-clast breccias located at field stop 1212-08. Photos B1 and B2 are Bullfrog-clast breccias at field stop 0522-4. Photos C1 and C2 are Paintbrush-clast breccias at field stop 0522-8.

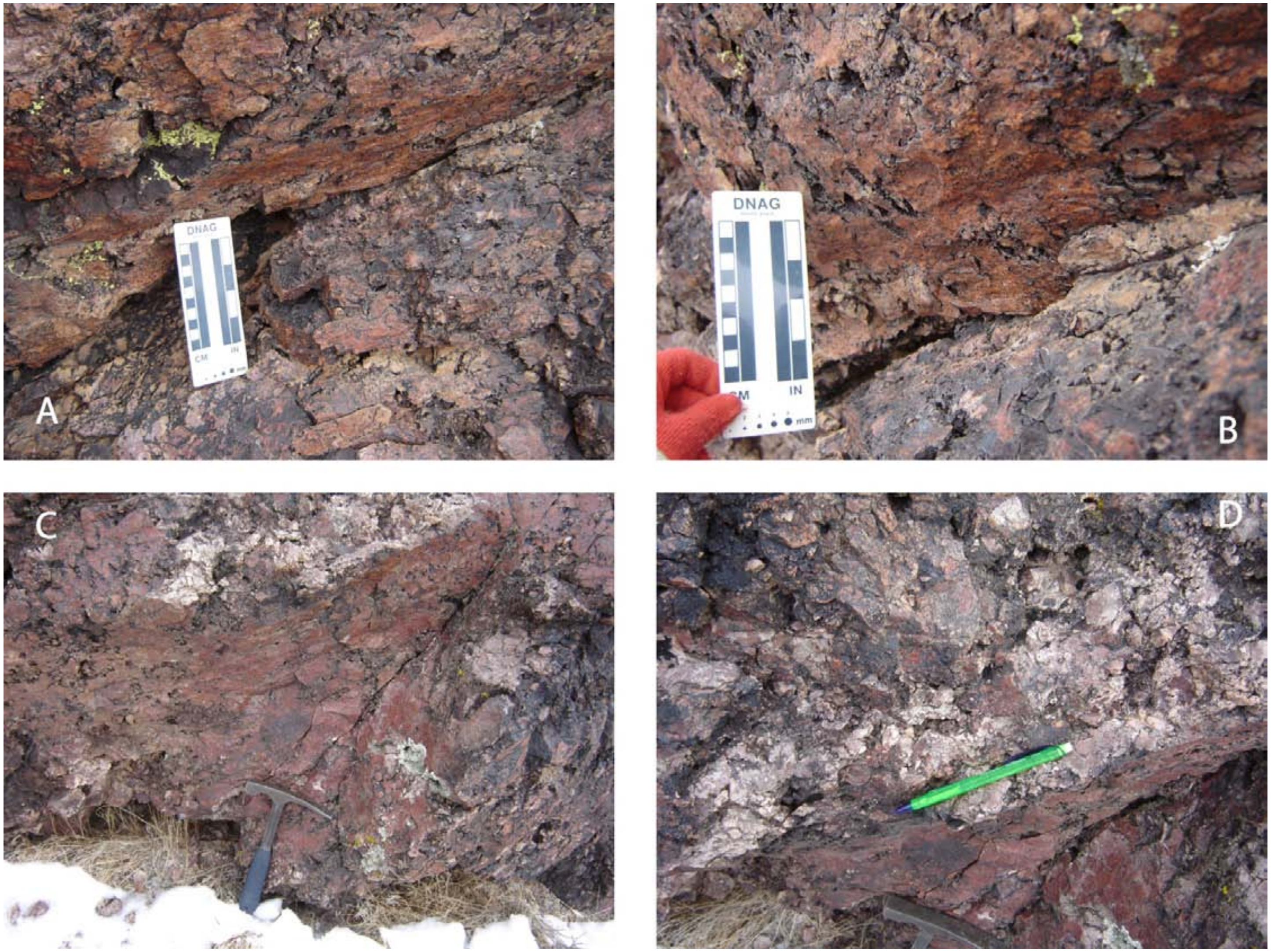


Figure 3.23 Slickensided surfaces in Paintbrush clast breccia at field stop 1217-01.

Therefore, it is proposed that this unit was deposited post-Paintbrush into a half-graben that formed during the 12.7-11.6 Ma extensional pulse.

3.3.2.3 Post Timber Mountain Group breccias (11.4-10.56 Ma)

Extension resulted in a large accumulation of monolithic breccias after the eruption of the 11.4 Ma Fleur-de-lis Ranch Formation present in the NBH. Clasts are derived from local units of the Wood Canyon, Zabriskie, Carrara, Rainier Mesa, and Fleur-de-lis Ranch Formations. These breccias are mapped adjacent to each other and for the most part, do not include Paintbrush or Bullfrog-clast breccias. The presence of Fleur-de-lis clast breccias and the lack of Rainbow Mountain Group clast breccias suggests these deposits were accumulated between 11.4 and 10.54 Ma ago, the interval between the eruption of the Fleur-de-lis Ranch Formation and the Rainbow Mountain Group.

Clasts are derived from the Wood Canyon, Zabriskie, Carrara, Rainier Mesa, and Fleur -de-lis Ranch Formations. Minor et al. (1997) and Fridrich et al. (2007) interpret these rocks as landslide deposits originating from the east at Oasis Mountain Hogback (Fridrich, 1999). In most cases, these deposits crop out on the low topography west of Springdale; therefore, exposures are rare and not of high quality.

Wood Canyon-clast breccia

Exposures of Wood Canyon-clast breccia are sparse; most of the rock is exposed as unconsolidated material, commonly silty breccia composed of angular pebbles and granules of medium gray limestone supported in a fine grained calcareous matrix (figure 3.24). This breccia crops out at field stops 0518-8 and 0519-2 (figure 3.21). At field stop 0519-3, heavily fractured Wood Canyon siltstone crops out. Wood Canyon-clast breccia commonly crops out adjacent to the Rainier Mesa-clast and Fleur-di-lis-clast breccias although the contacts between the units are northwest-striking normal faults or gravity-slide surfaces (Minor et al., 1997).

Zabriskie Clast Breccia

Breccia composed of angular clasts of Zabriskie Quartzite are exposed in numerous places within the NBH. Angular boulder to granule-sized clasts are generally clast supported; however, in places clasts are supported by a small amount of yellowish-white siliceous matrix (figure 3.25).

Carrara Clast Breccia and Slide Blocks

A large block of dark gray limestone belonging to the Carrara Formation is present at field stop 1218-02 (figure 3.21) and is interpreted as a slide block because, unlike the surrounding units, it is unbrecciated and generally coherent (figure 3.26). The exposure is approximately 1.5-2 m thick and exhibits thin to moderate bedding that strikes to the southeast. Adjacent to the block is Zabriskie-clast breccia that is faulted against the Rainier Mesa Formation (Minor et al. 1997).

Rainier Mesa-clast breccia

At field stop 0519-4 (figure 3.21), Rainier Mesa Clast breccia is composed of angular to sub-rounded clasts of Rainier Mesa formation. At some locations it is supported by red, fine grained, poorly sorted, sandy matrix with a matrix to clast ratio of roughly 40-60% (figure 3.27a). Other outcrops are composed of clast supported breccia (figure 3.27b). The Rainier Mesa-clast breccia is commonly found adjacent to the Flur-di-lis Ranch-clast, Wood Canyon-clast breccia, and the sandstone and breccia of the NBH (Minor et al. 1997). These units are bounded by northwest striking normal and gravity-slide surfaces (Minor et al., 1997).

Fleur di-Lis Clast Breccia

The Fleur di-Lis breccia is not well exposed in the field area and generally does not crop out as a coherent mass of rock. At the surface, the unit is only exposed as unconsolidated angular Fleur di-Lis clasts. Previous mapping indicates the Fleur di-Lis breccia overlies the only occurrence of the Fleur-di-Lis Ranch Formation, a stratigraphic relationship similar to the Tiva Canyon and Bullfrog

Figure 3.24 Wood Canyon-clast breccia in the NBH. Clasts consists of angular limestone in a calcareous matrix. Unit crops out at field stop 0518-8.

Figure 3.25 Zabriskie Quartzite-clast breccia in the NBH at field stop 1218-03.

Figure 3.26 Dark gray limestone of the Carrara formation at stop 1218-02. This is interpreted as a slide block where bedding has been preserved.

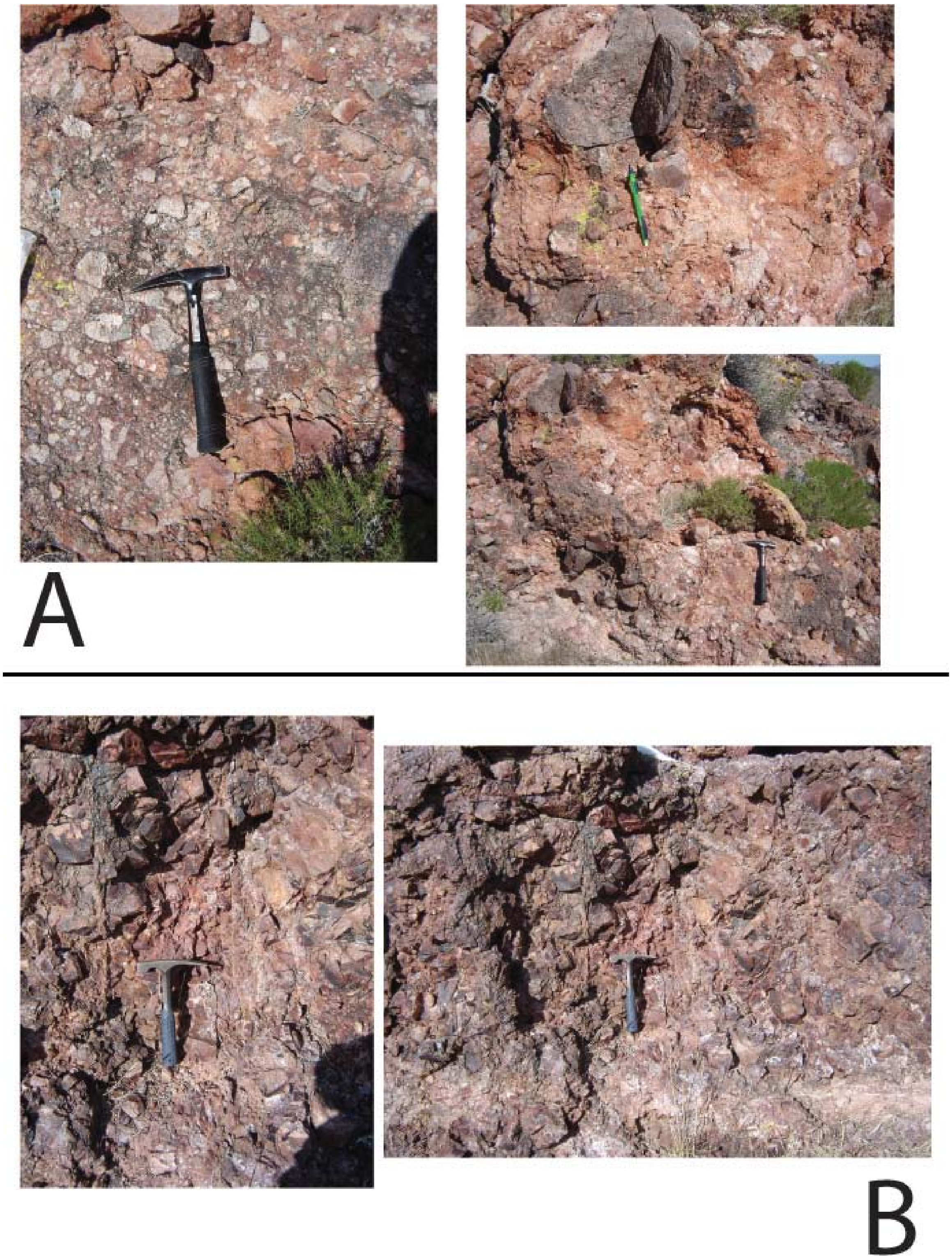


Figure 3.27 Rainier Mesa-clast breccia in the NBH. Section A contains photos from field stop 0519-04 and section B contains photos from field stop 1218-07.

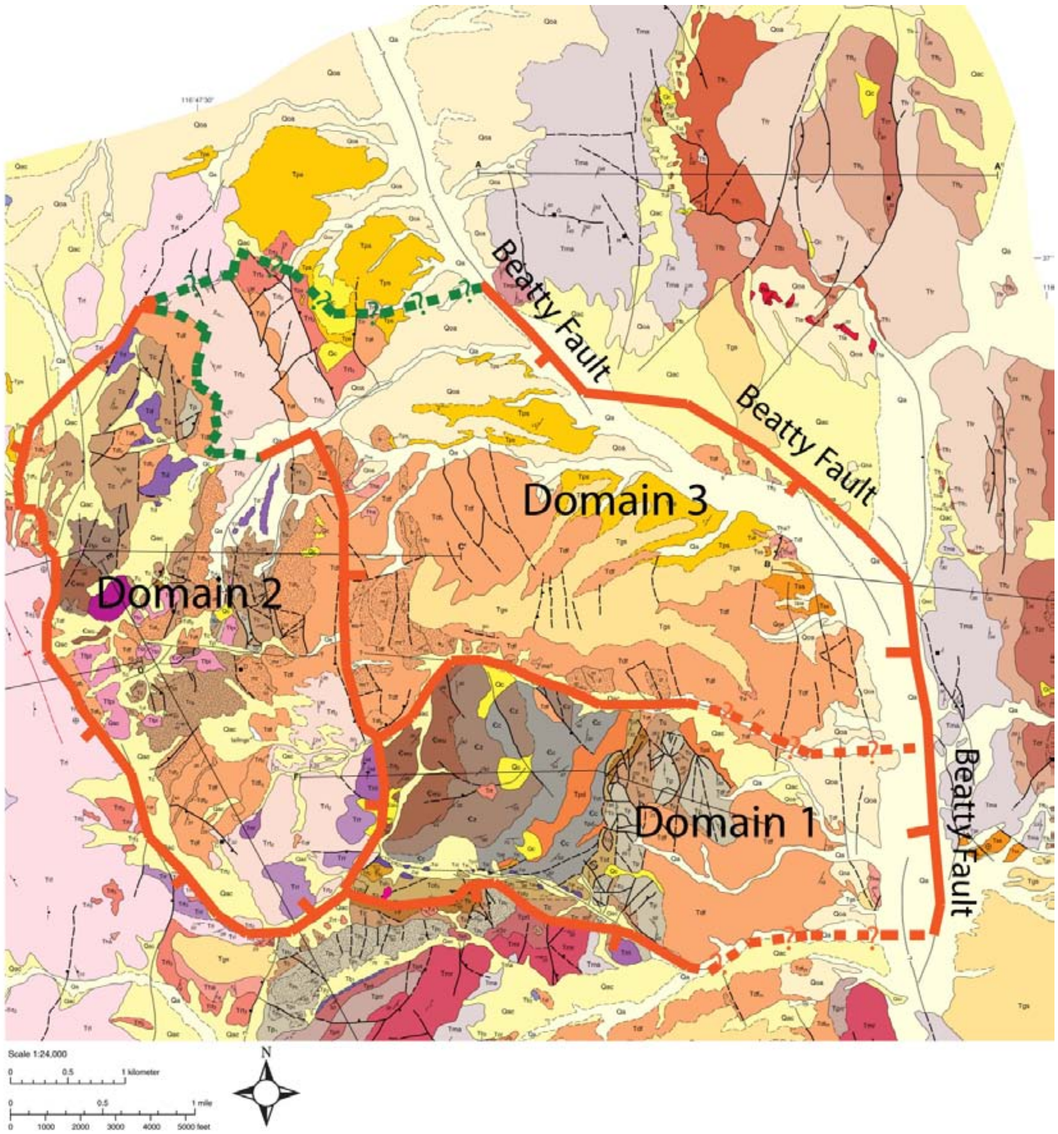


Figure 3.28 Map of the NBH and discussed “brecciad domains.” Domain boundaries are represented by red and green lines. Red lines represent fault boundaries (red tick mark is on the hanging wall side), solid where known and dashed where inferred. Green dashed lines represent boundaries that are stratigraphic boundaries. Dashed green lines with “?” are inferred boundaries. Domains are based on the location of rocks older than 10.5 Ma (pre-Rainbow Mountain Group). Map modified from Connors et al., 1998.

clast breccias (Minor et al., 1997). In other areas, the Fleur-di-Lis clasts breccia shares gravity slide contacts with the Rainier Mesa and Wood Canyon clast breccias (Minor et al., 1997).

Three domains in the NBH have been recognized based on the predominant strata and breccias present (figure 3.28):

1. The domain of Zabriskie Hill and the surrounding rocks. The Cambrian and Precambrian rocks are overlain by Tertiary sedimentary and volcanic rocks to the east and south.

   Previous mappers (Connors et al., 1998; Fridrich et al., 2007) interpret the contact between the Tertiary rocks and the Pre-cambrian and Cambrian strata as a detachment. This study suggests that there is no evidence for a detachment structure and the Tertiary rocks may have accumulated unconformably upon the rocks that comprise Zabriskie Hill, which was a topographic high during the Oligocene. Overlying the Tertiary volcanics are breccias (Connors et al., 1998; Fridrich et al., 2007) of unknown description. These breccias could not be examined further due to the lack of outcrops and low topography.

   This domain is bordered by inferred west-striking faults to the north and south which may have served as tear faults that accommodated the movement of Zabriskie Hill. The rocks at the southern portion of the domain consists of older tuffs and sediments (Tot of Fridrich et al., 2007), Lithic Ridge tuff, Lower tuff of Buck Spring, and Bullfrog tuff (Maldonado and Hausback, 1990; Connors et al., 1998). These units are strongly deformed by faults and are difficult to identify and interpret.

The western boundary is a north-striking normal fault. There is no clear eastern boundary; however, the Beatty fault may serve as this margin.

2. The domain of the Post-Paintbrush graben in the western part of the NBH.

Down dropped footwall blocks of normal faults in the NBH after the eruption of Paintbrush Group formed a series of half-grabens where clasts of Paintbrush and Bullfrog tuff accumulated as monolithic deposits. These Post-Paintbrush monolithic breccias represent a reverse stratigraphy in that Paintbrush-clast breccia is overlain by Bullfrog-clast breccia. Overlying the Post-Paintbrush breccia is the Sandstone and sedimentary breccia. Other sparse exposures include Wood Canyon-clast, Zabriskie-clast, and Carrara-clast breccias. Some Rainier Mesa-clast breccias are present, but may have been emplaced or displaced by younger faulting.

Tuffs and lavas of the Rainbow Mountain Group overly the clastic deposits unconformably. Later deformation tilted the Rainbow Mountain Group rocks about 30-35° E in the southern part of the Springdale Quadrangle.

Domain boundaries include north-striking normal, west dipping faults to the east and west. The domain extends north to the point where the breccias are truncated by a young (post-Rainbow Mountain Group) northeast striking, northwest-dipping normal fault. The southern boundary is the area where both the eastern and western are inferred to curve and meet at a point (Connors et al., 1998; Fridrich et al., 2007)

3. The domain north of Zabriskie Hill. This domain is dominated by monolithic breccias that include clasts primarily from the Wood Canyon, Zabriskie, and Carrara Formations, and Timber Mountain group. Few exposures Bullfrog and Paintbrush Group-clast breccias are present in the domain. Overlying the monolithic breccias is the moderately tilted Rainbow Mountain Group. Stratigraphic relationships in this domain suggests that the breccia accumulated after eruptions of the Timber Mountain Group (11.4 Ma) and before eruption of the Rainbow Mountain Group (10.56 Ma).
The domain boundaries are: an inferred west striking fault on the south, a north striking normal fault to the west, probably the Beatty fault to the east, and an undetermined boundary to the north.

The proposed boundary between domains 1 and 3 is along a north-striking normal fault (figure 3.27) juxtaposing the Tiva Canyon tuff against a Wood Canyon and Rainier Mesa-clast breccias. To the west of this fault, few exposures of Rainier Mesa- and Fleur-de-lis-clast breccias are mapped near Paintbrush- and Bullfrog-clast breccias. After emplacement by gravity slide faults, the younger breccias may have been displaced westward by movement along a NW-striking, right-lateral strike-slip fault. Blocks of the sandstone and sedimentary breccia have also been displaced during 11.6-10.5Ma deformation.

Faulting in this domain is dominated by northwest-striking, right-lateral faults that cut the breccias (specifically the Wood Canyon- clast, Rainier Mesa-clast, and Fleur de Lis-clast breccias) and extend south into the second domain.

3.3.3 Southeastern Bullfrog Hills

3.3.3.1 Sediments and tuffs of Rainbow basin

Red, pebbly, volcanic-clastic conglomerate and sandstone, along with tuff units, comprise the basal, coarse fill of Rainbow Basin. Named the Rainbow Mountain conglomerate, it is only exposed at the southern margin of Rainbow Mountain, south of Burton Mountain where is overlain by the Rainbow Mountain Group tuffs.

The sediments are moderately to poorly layered and commonly exhibit graded sequences. Clasts are gray to brown and contain abundant quartz and sanidine; these are characteristic of the Timber Mountain Group volcanics. A more detailed description of the Rainbow Mountain conglomerate is available in Chapter 2.

Adjacent to the Rainbow basin breccia is a 10.3 Ma olivine porphyry basalt and the overlying unit is the Rainbow Mountain Group (Connors et al. 1998; Maldonado and Hausback, 1990). These relationships indicate that after the faulting of the Timber Mountain Group, a large structural basin formed in the SBH. Prior to sedimentary deposition, basalt and lesser tuffs (bedded tuff and the Buttonhook Wash Formation) settled in the basin. At about 10.5 Ma, the Rainbow Mountain Group erupted and accumulated outside of Rainbow basin as well as on top of the sediments and tuffs of Rainbow basin.

Slide masses, some of which contain brecciated volcanic rock, have been previously mapped as breccia (Connors et al., 1998; Fridrich et al., 2007; Maldonado and Hausback, 1990). These masses are entrained throughout the Rainbow Mountain Group and are described in detail below. As previously mentioned, these slide masses were mapped as the hanging wall of thrust faults (Maldonado and Hausback, 1990). This study interprets the masses as comprising part of the hanging wall of a listric normal fault. Isolated blocks of volcanic breccias entrained in tuff suggest that gravity sliding accommodated the movement of the rock into a half-graben basin.

3.4 RAINBOW BASIN

Rainbow Basin is a structural basin in the SBH that formed after the eruption of the Timber Mountain group and synchronous with the eruption of the Rainbow Mountain group. The walls of the basin are composed of the Timber Mountain group and underlying Paintbrush and Crater Flat groups. The opening of the basin occurred along north striking, west dipping listric normal faults that merge into the underling FC-BH detachment (Maldonado 1990). Movement along the listric fault is responsible for the eastward dips of the basin wall rocks.

The southern boundary of the basin is mapped as a west-striking normal fault that dips north (Maldonado and Hausback 1990). It is unclear how this fault formed in conjunction with the opening of Rainbow Basin.

3.4.1 Stratigraphy

Within the basin is a sequence of rocks, some of which are exclusive to the area of Rainbow Basin. An olivine-bearing basalt is the oldest unit, deposited on the basin floor, possibly taking advantage of the pre-existing structures to erupt at the surface. Adjacent to the basalt is about 200 m of lesser tuffs (bedded tuffs and the Buttonhook Wash tuff) and graded Rainbow Basin conglomerate. The rocks then become more volcanic in nature as the Rainbow Mountain group was deposited. Figure 3.29 is a photograph of Rainbow and Burton Mountains. In the foreground is the Rainbow Basin conglomerate, which represents the bottom of the basin. The Rainbow Mountain group, which comprises Rainbow and Burton Mountains, represents the youngest rocks deposited in Rainbow Mountain basin. Overall, about 625 m of material was deposited into the basin. Fanned bedding at Burton Mountain (within the Rainbow Basin) suggests the eruption of the Rainbow Mountain Group was synchronous with extension (Maldonado and Hausback 1990).

3.4.2 Gravity slide masses

Within the Rainbow Basin strata, low angle faults, interpreted as detachment faults, accommodate the transport of slide masses into the basin. These slide masses are commonly coherent stratigraphic blocks or brecciated rocks composed of fractured pieces from the basin walls.

The first slide crops out at field stop 0508-8 (figures 3.30 and 3.31). At this location, a massive block of unidentified rock has been transported along a complex series of low angle faults. In the footwall is the Rainbow Basin

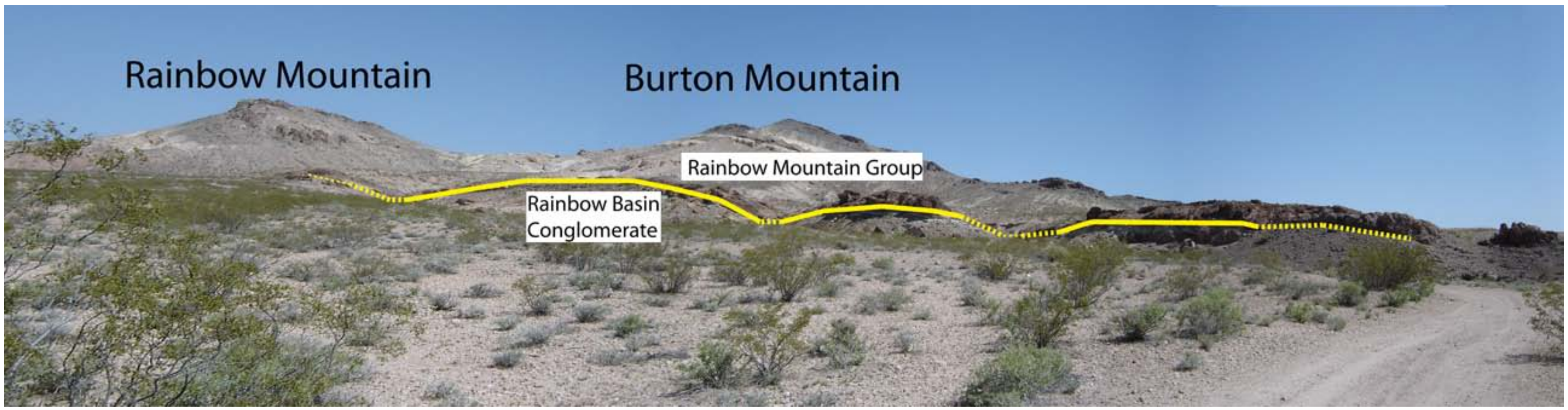


Figure 3.29 Photograph of Rainbow and Burton Mountains (roughly from the south) in the SBH. The yellow line represents the contact between the Rainbow Mountain conglomerate and the Rainbow Mountain Group (solid where certain, dashed where inferred).

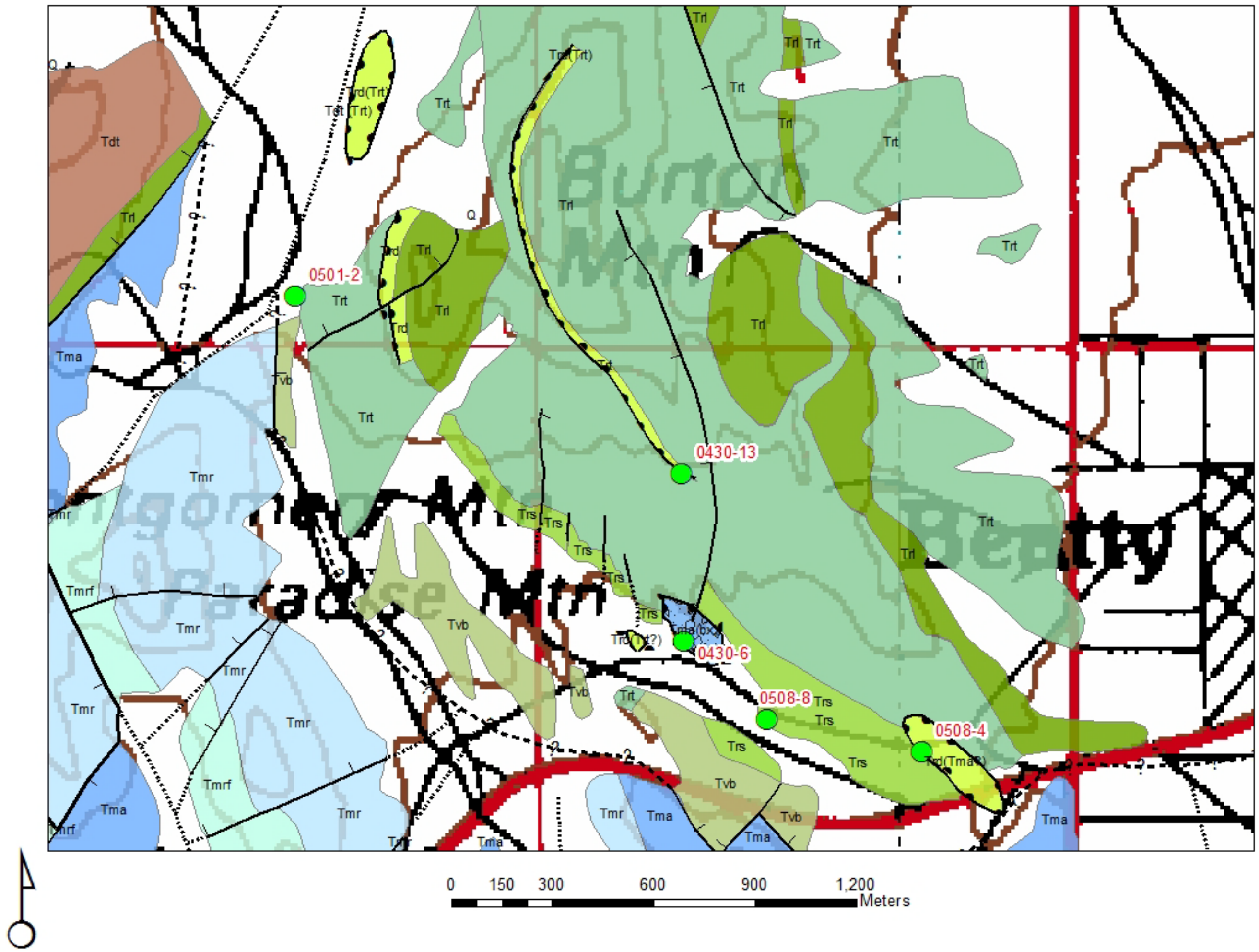


Figure 3.30 Geolgoic map of Burton Mountain in the SBH. Bright green circles represent field stops referenced in section 3.4.2. For the detailed map explanation, refer to the geologic map associated with this study.

conglomerate, which has been cut by the overriding plate. Between the conglomerate and the slide mass is an irregular contact where displacement within the block can be identified using the thin layer of platy rock as a stratigraphic marker.

Next, a series of detachments crops out at field stop 0508-4 and vicinity (figure 3.30) within the Rainbow Mountain Group tuff. Here, slide masses are continuously cut by subsequent slide blocks. These slide surfaces were inferred between discontinuous portions of rocks at the outcrop. The first slide mass, represented by a thin sequence of volcanic-clast rock and overlying white and pink tuff, was transported above a moderately bedded lapilli tuff. This mass forms a small, intermediate, fold plunging at 22°, N87W, defined by the basal volcaniclastic unit (figure 3.32). Possibly penecontemporanious in nature, the fold may have been formed during sliding where the sediments and volcanic clasts were saturated with fluids. Collision of the saturated mixture with a barrier resulted in an intermediate fold. This folded package of rock is then cut by a second low angle structure that accommodates the movement of a pink tuff and brecciated volcanic of unknown origin. A third detachment, consisting of a brown unidentified rock in the hanging wall, truncates the previous slide sequences which is then cut by a fourth and final detachment in this location. This youngest slide is composed of a block of brecciated Timber Mountain Group volcanics derived from the basin walls.

This series of slides can be seen more clearly 10 m east of field stop 0508-4 where an abandoned railroad cut offers a cross sectional view of the slides (figure 3.33). The youngest slide, composed of brecciated Timber Mountain volcanics, slices the top of the older slide masses. At this location is the occurrence of an unknown brown rock (possibly volcanic) that has been crushed and manipulated into a fold-like structure.

At field stops 0430-13 and 0430-14 (figure 3.30), a dark purple, matrix supported polylithic breccia (figure 3.34) is deposited in between tuffaceous eruptions of the Rainbow Mountain vents. Clasts are angular to sub-rounded and supported in a glassy or siliceous matrix. Based on crystal content, the clasts were not derived from the Timber Mountain Group. The basal contact with the Rainbow Mountain Group is faulted, represented by a planar, low angle fault surface (figure 3.35.). Adjacent to the fault, in the footwall, is a thin (ranging from 5 cm-15 cm) layer of fault gouge, Underlying the gouge is a brecciated zone of unknown thickness (figure 3. 35).

Immediately west of Burton Mountain, at field stop 0501-2 (figure 3.30), 1.5-2 m sedimentary sequence forms a moderate cliff within the slope forming tuffs of the Rainbow Mountain Group (figure 3.36). The base of the sequence is an immature coarse grained sandstone containing ~80% quartz grains. Overlying the base unit is a thin coarsening upward sequence of sandstone. The upper unit is a matrix supported pebble-clast breccia composed of clasts of the Timber Mountain Group, probably derived from the basin walls. The depositional contact between the course sandstone and breccia is very irregular. A moderately dipping reverse fault within the unit displaces the sandstone and lower part of the breccia. The reverse sense of displacement is anomalous with the normal sense of displacement recorded in the field area during the Miocene. Displacement along the ~1 m fault is right lateral and about ~10 cm. The monolithic clasts are derived from the Timber Mountain group. The energy of the transportation may have resulted in underthrusting of the sediments beneath the monolithic clasts resulting in a reverse fault penetrating the upper part of the sand layer and the lower portion of the breccia bed. To the north and south, the unit pinches out abruptly (figure 3.37; Maldonado and Hausback, 1990). Overlying the sediments is the continuation of the Rainbow Mountain tuffs. There are no clear upper or lower contacts exposed and the unit does not appear to continue laterally (figure 3.37); therefore it is difficult to determine if this mass is a depositional feature or transported from another location.

Breccia at field stop 051109-8 is a cobble-pebble volcanic clastic unit, composed of subangular-subrounded clasts of the Timber Mountain and Paintbrush

Groups supported in an ashy and crystal rich matrix. Underlying and overlying these breccias is the tuffaceous Rainbow Mountain Group.

Eruption of the Dacite of Donovan Mountain into the basin followed sliding and the eruption of the Rainbow Mountain Group. There have been no massive slide blocks or sedimentary deposition mapped during the eruption, suggesting that extension was less intense than that between 11.6 and 10.5 Ma. Gentle dips of about 10° in the SBH in within the basin support this claim.

3.4.3 Younger faulting within the Rainbow Basin strata

3.4.3.1 Younger strike slip faults (10.5-? Ma)

Further deformation of the SBH and consequently Rainbow Basin was accommodated by northeast striking left lateral strike slip faults. Displacement along these faults can be traced using the basalt, Buttonhook Formation, and Pre-Buttonhook tuff as reference units. Along the major strike slip fault, apparent displacement of the basalt is about 2.5 km. The fault is inferred to take a left step and is concealed by alluvium.

In outcrop (field stop 0430-6; figure 3.30), a strike slip fault cuts a breccia deposited in the Rainbow Basin. The fault plane, oriented N41W 55°NE, is smooth and contains at least 3 sets of slickenlines (figure 3.38) suggesting multiple directions of movement along the fault. The amount of displacement along this fault is undetermined because the exposed segment of the fault cuts a massive breccia unit.

3.4.3.2 Hot Springs Fault

Gravity data suggests the Hot Springs fault strikes west through Sober Up Gulch. Displacement along the Hot Springs fault is apparently right lateral, transporting the Timber Mountain Group and older rocks about 2 km to the west. Deformation along this fault is young because it cuts the rocks in Rainbow Basin; however, this may be a reactivated structure.

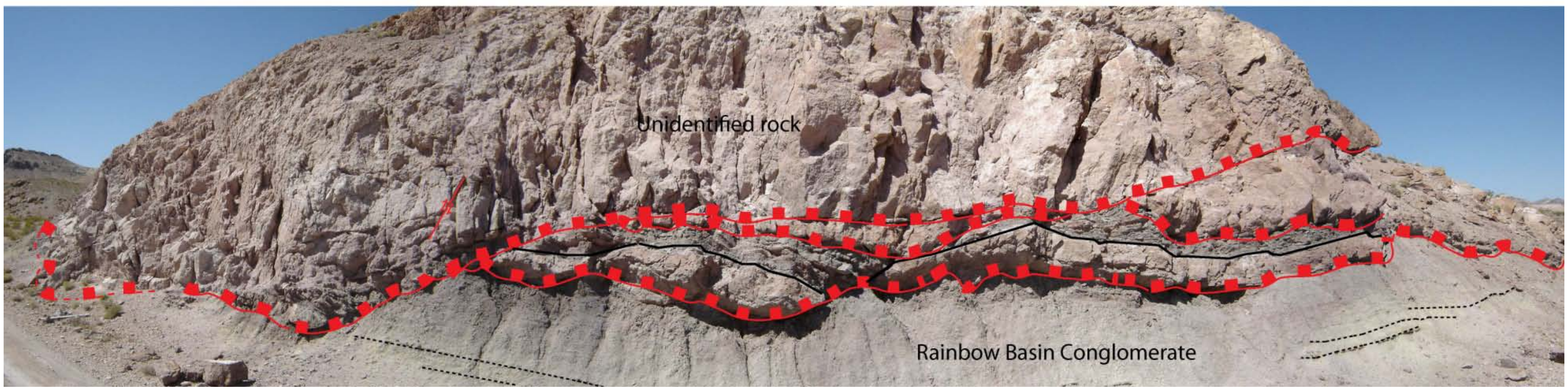


Figure 3.31 Large slide mass that cuts the Rainbow Mountain conglomerate at field stop 0508-8. The detachment surfaces (red lines with square hatch marks on the hanging wall) are irregular and cut by younger faulting. Black lines in the conglomerate are bedding traces.

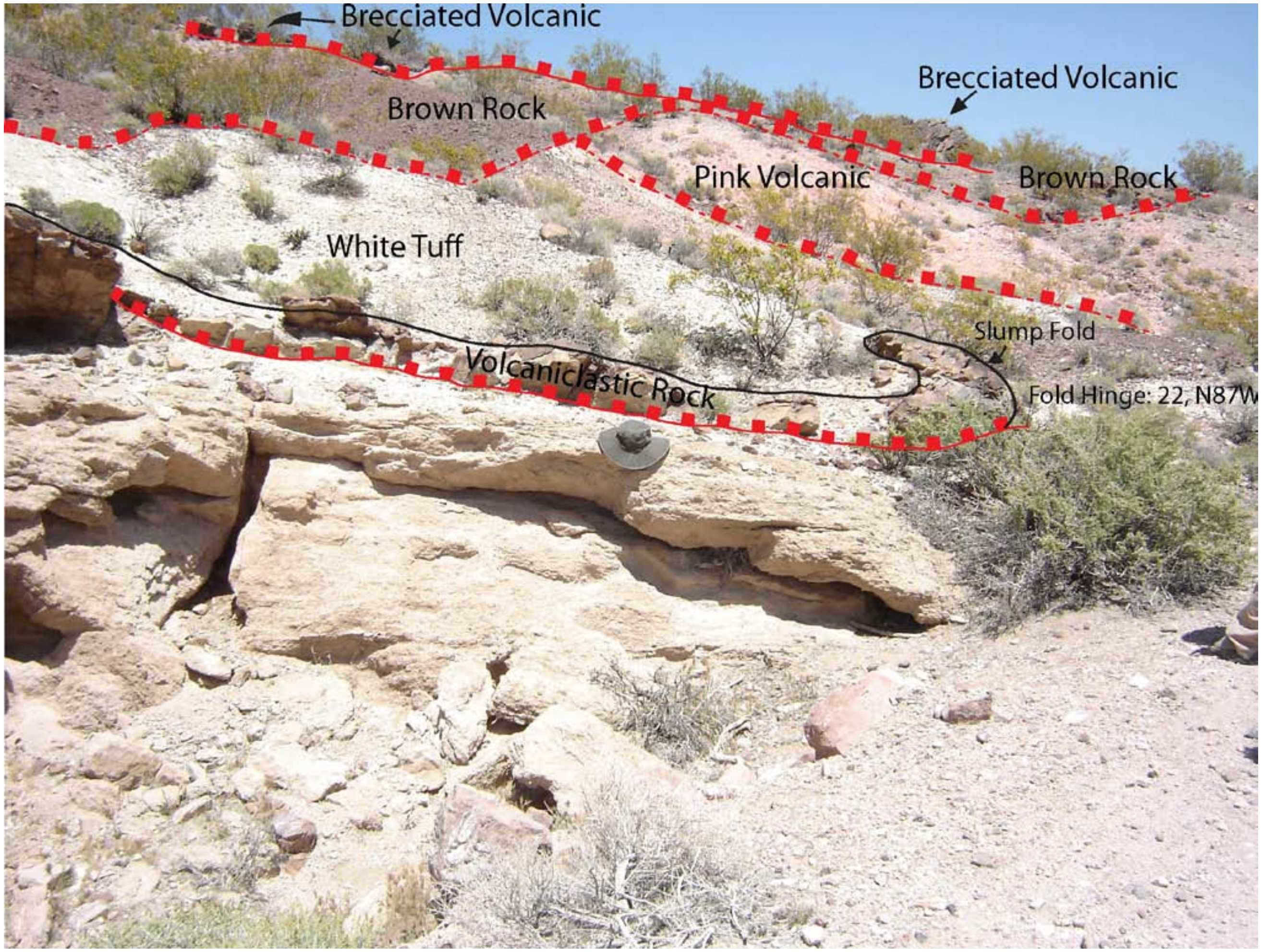


Figure 3.32 Multiple detached slide masses that accumulated in the Rainbow Basin at field stop 0508-4. Red lines with square hatch marks are detachment surfaces (dashed where detachment location is approximated). Black line represents the deformed contact between two intraslide units.

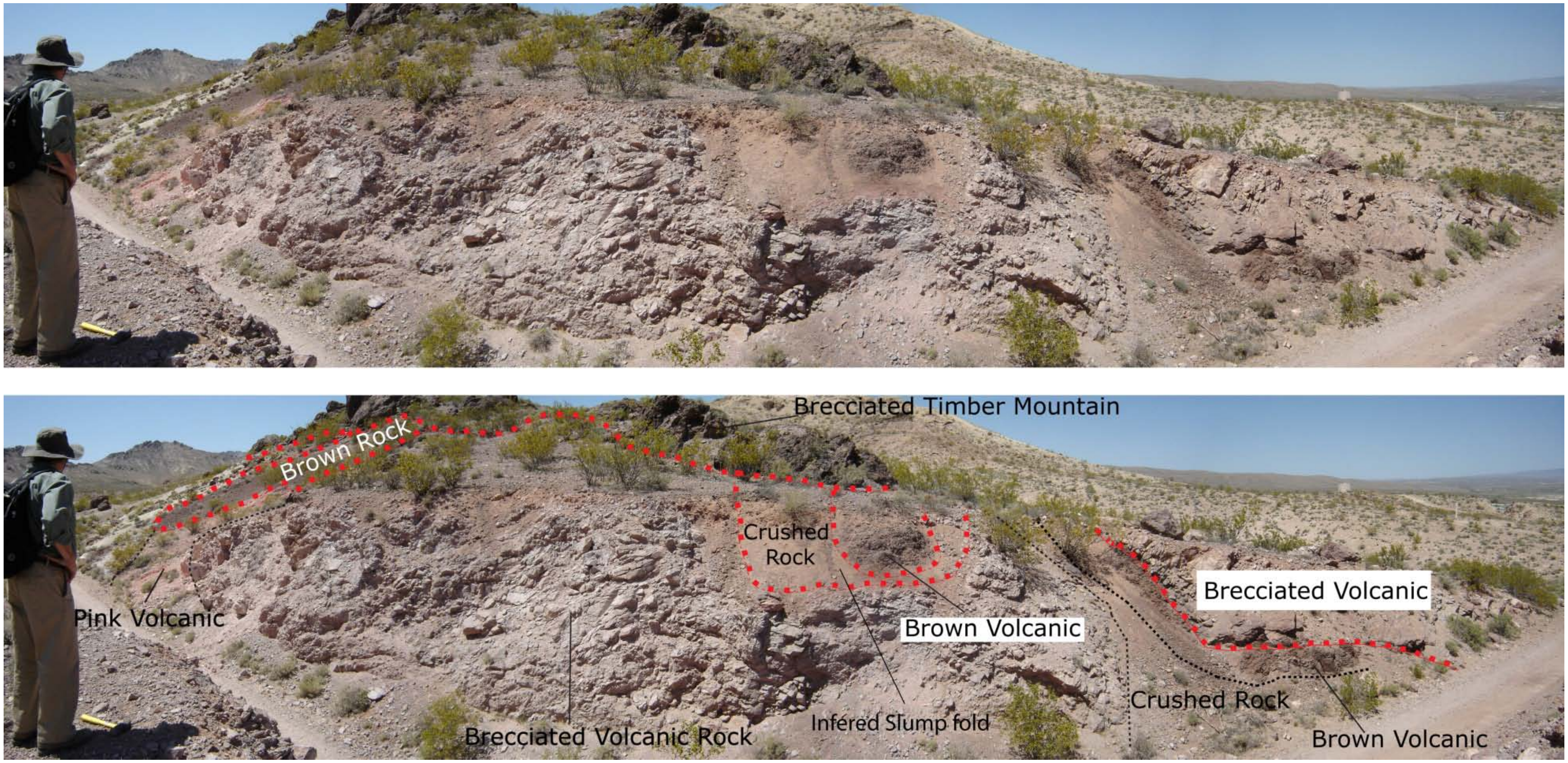


Figure 3.33 A cross sectional view of slide masses exposed in an abandoned railroad cut about 10 meters east of field stop 0508-4. Black lines represent stratigraphic contacts (dashed where inferred). Red lines with square hatch marks are inferred slide surfaces (dashed where approximate) with the hatch marks on the hanging wall of the slide.

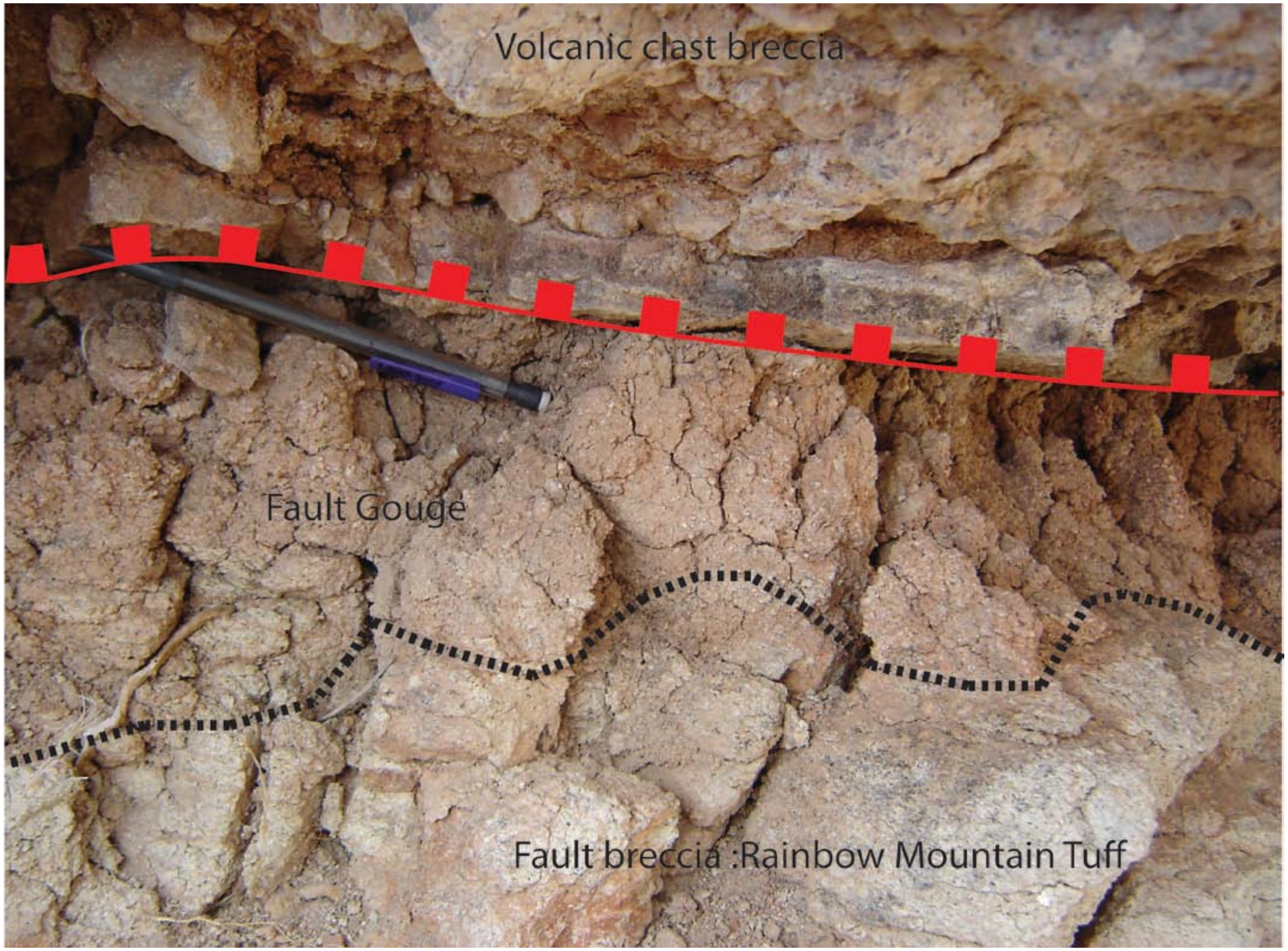


Figure 3.34 Detachment fault zone at field stop 0430-13. Red line with hatch marks represents the detachment surface (hatch marks are on the hanging wall) and the dashed black line is the approximate contact between fault gauge and fault breccia in the Rainbow Mountain tuff that composes the footwall.

Figure 3.35 A) Detachment (represented by the red line with hatch marks on the hanging wall) identified by the resistant planar feature. The hanging wall is a volcanic clast breccia. The footwall is Rainbow Mountain tuff, brecciated in the fault zone. B) Close up of the brecciated footwall of the detachment in photo A. Rocks crop out at field stop 0430-13.

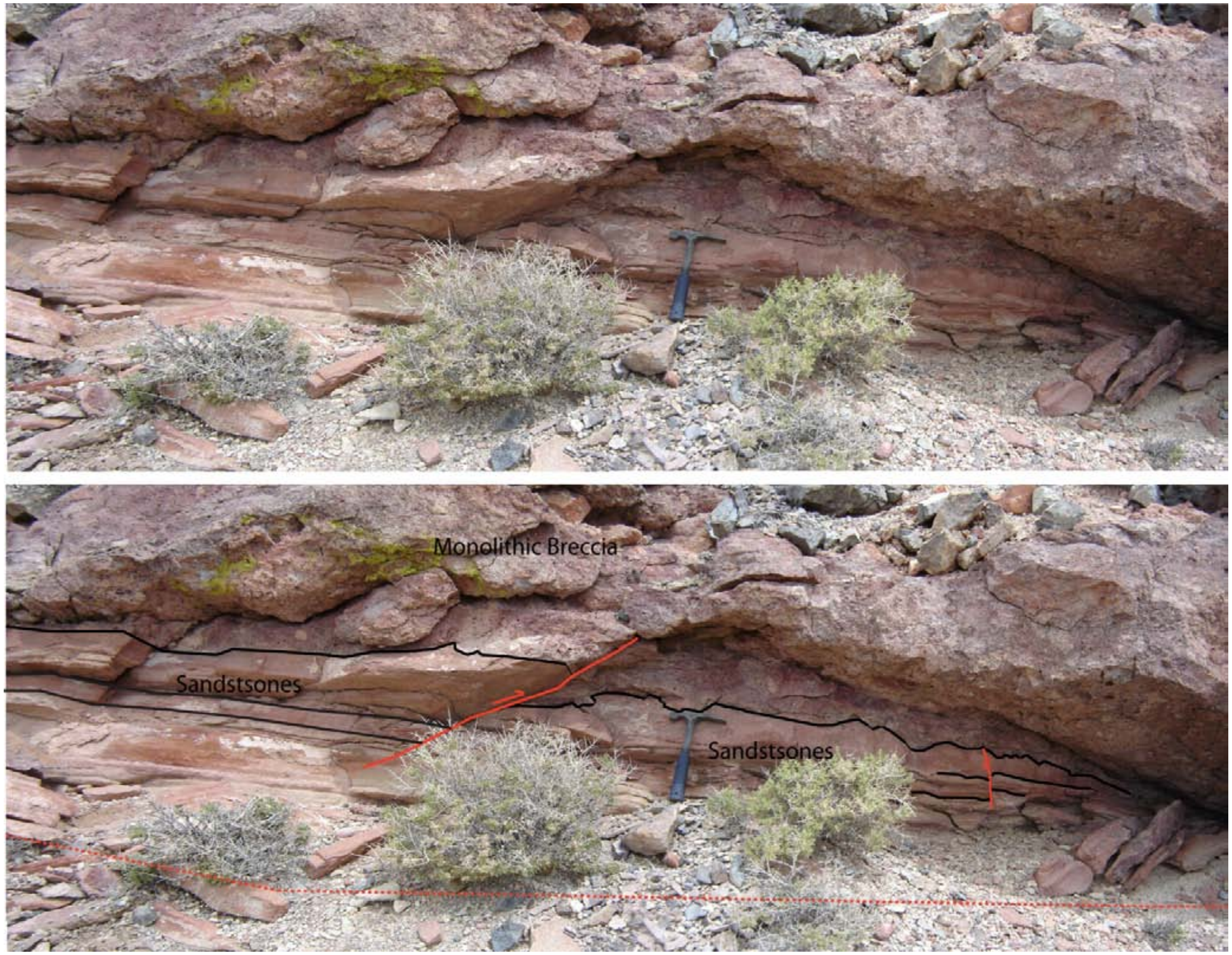


Figure 3.36 Coarsening upward sequence of clastic rocks located west of Burton Mountain in the Southeastern Bullfrog Hills at field stop 0501-2. The monolithic breccias contains clasts of Timber Mountain Group volcanics. Reds lines are faults with arrows indicating the sense of movement. Black lines are contacts. Dashed black lines are bedding traces.

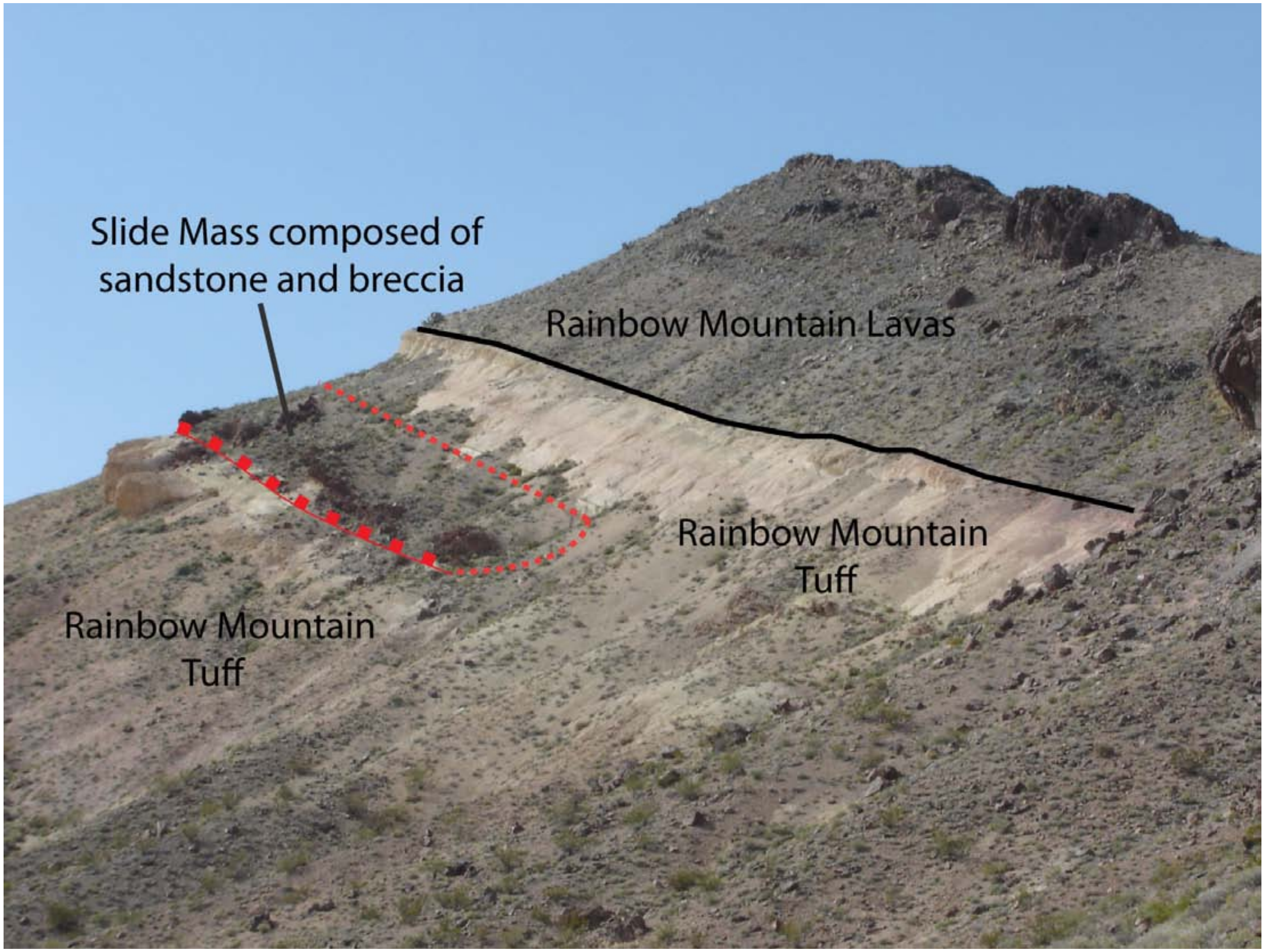


Figure 3.37 Photograph of the western face of Burton Mountain. Red lines indicate the area of the slide mass, solid where certain, dashed where inferred. Line with tick marks represents the slide surface. Thick marks are on the hanging wall.

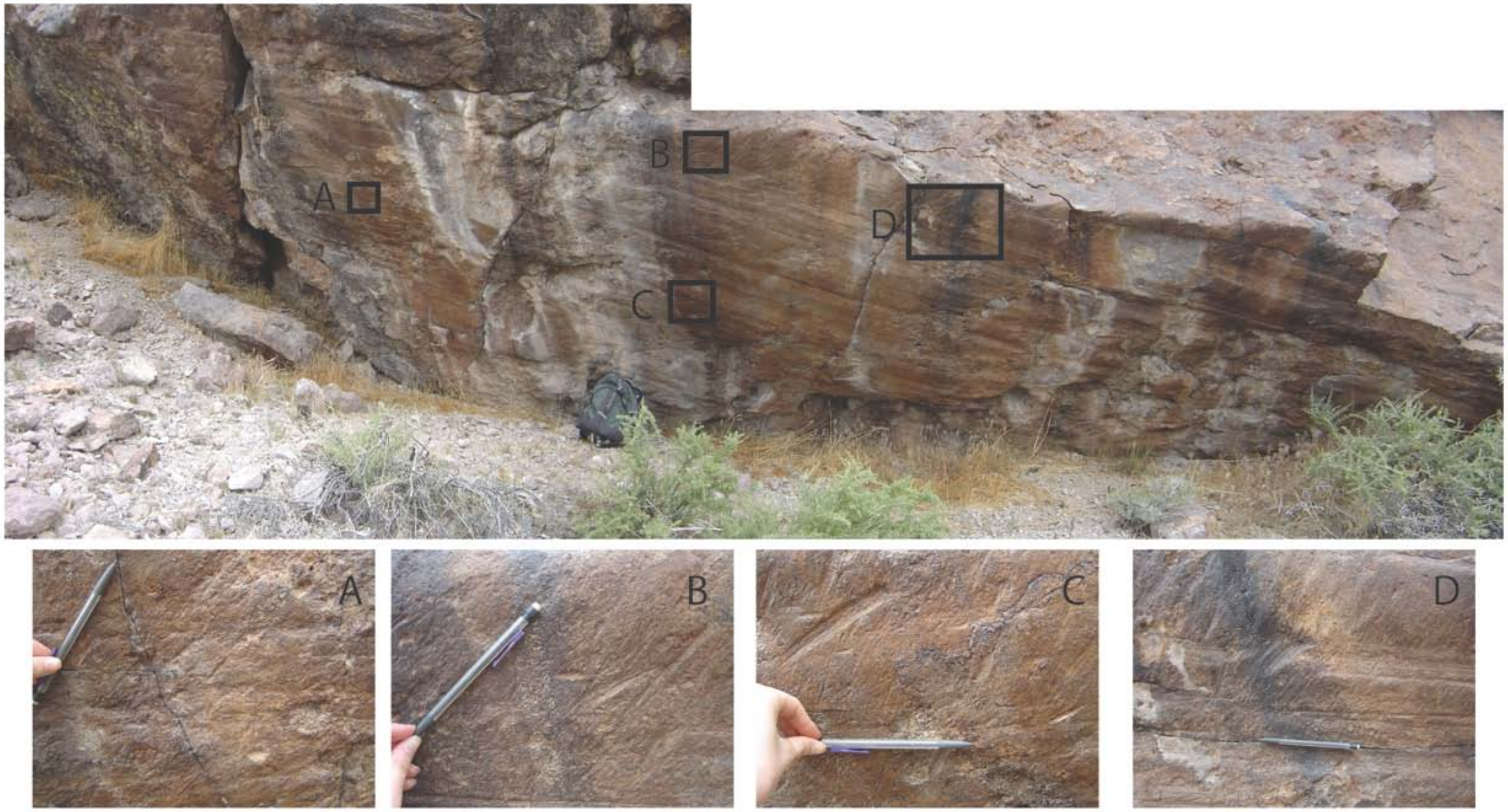


Figure 3.38 Strike slip fault cuts a breccia unit within the Rainbow Mountain group at field stop 0430-6. The fault has two recognizable and consistant sets of slickenlines

4.0 DISCUSSION

4.1 BRECCIAS

This study groups previously mapped breccia units in the study area into four categories:

1. Conglomerate and sedimentary breccia
2. Breccia derived from lithification of talus
3. Breccia formed from disruption of rock masses, some composed of volcanic breccia, during gravity-driven emplacement of slides
4. Fault breccia related to tectonism

Primary volcanic breccias such as caldera collapse breccias, block-and-ash flows, and co-ignimbrite lag deposits were not recognized as mappable unmits.

Plate 2 is a collection of figures used during the discussion of breccias in the previous chapters.

4.1.1 Conglomerate and sedimentary breccia

The following units are interpreted as forming in response to sedimentary processes such as fluvial deposition, high energy water deposition, mudflows, and gravity deposition. Breccias include:

1. Conglomerate of Oligocene age (Fluorspar Hill and Northeastern Bullfrog Hills [NBH] Plate 2, photo A). This unit was previously mapped as breccia by Fridrich et al. (2007). Although the conglomerate is locally brecciated, well rounded, pebbles and cobbles of quartzite and limestone derived from Paleozoic strata are distinct and indicate probable rounding in a fluvial environment. This unit is identified as Quartzite conglomerate of Minor et al. (1997) and the Gravel member of the Rocks of Joshua Hollow formation of Monson et al (1992).
2. Post-Paintbrush breccia in Fluorspar Canyon (Plate 2, photo B). Angular to subrounded volcanic clasts supported in fine grained matrix suggests a formation from a mud flow.
3. Sedimentary breccia and sandstone in the NBH (Plate 2, photo C) comprises a section of poorly graded pebble-cobble breccia and overlying immature sandstone. The angularity of clasts, poor sorting, and large clast size of the rock suggests a proximal source. Repetitions of graded beds record multiple

depositional events involving water. This Miocene unit was deposited in an alluvial environment where high energy, torrential water transported clasts ranging from small grains to talus boulders a short distance from alluvial fans to a low area.

4. Breccias interfingering with pre-Rainer Mesa Formation in the Fluorspar Hills (Plate 2, photo D) are characterized by large clasts and poor rounding of Paintbrush Group fragments derived from a proximal source with minimal transportation. Accumulation of clasts took place between eruptions of the Pre-Rainier Mesa formation. After deposition, eruption of Pre-Rainier Mesa tuff resumed, covering the breccia. Fridrich et al. (2007) concluded that the interfingering breccia layers atop the Paintbrush Group were deposited as a result of collapse of steep rock faces formed during faulting synchronous with the eruption of Pre-Rainier Mesa Formation.
5. Breccia of Rainbow Basin. In the Southeastern Bullfrog Hills (Plate 2, photo E), the breccia is composed of graded, angular to subangular pebble conglomerate and lesser tuffs. Graded bedding suggests water was involved during deposition and the angularity of the clasts suggests they were not deposited far for the source. The clasts were derived from nearby basin walls, which consist of Timber Mountain and Paintbrush Group volcanic rocks. Transport of clasts occurred in a similar manner to that of the

sedimentary breccia and sandstone in the NBH. During high water energy events the clasts were carried into Rainbow Basin from the basin walls. The base of the basin may have contained a moderate amount of water where the clasts settled into a graded pattern.

4.1.2 Talus Breccias

Talus breccias accumulated at the bases of steep rock faces that formed in response to movements along steep fault planes. The resulting relief favored development of talus in structural half-grabens (figure 4.1). Angular clasts indicate that transport has been minor. The depositional sequence is that of a reverse stratigraphic sequence as the young rocks at high elevation provide debris found stratigraphically low in the basin. This process is difficult to see in the NBH, but may be present north of Zabriskie Hill where Wood Canyon, Rainier Mesa, and Fleur de-Lis clast breccias have an apparent reverse stratigraphic order.

Breccias interpreted as derived from talus include:

1. Carbonate-clast breccia that crops out on the east flank of Paintbrush Hill (Plate 1, photo F). Angular carbonate clasts must have accumulated close to their source as suggested by their very angular nature and proximity to the Paleozoic footwall of the Tates Wash normal fault. Accumulation occurred

on top of the Paintbrush Group that comprises the hanging wall of a half-graben.

2. Monolithic-clast breccias in the NBH (Plate 2, photos G and H). The angular to subrounded nature of the clasts, the clast supported texture of the rock, grain size (often containing boulders) and stratigraphic position suggests deposition close to the source.

4.1.3 Slide Masses

Slide masses composed of coherent blocks of rock and/or brecciated rock crop out in the SBH. Rock units interpreted as slide masses include:

1. Brecciated Timber Mountain group. This exposure of angular fragments of Timber Mountain group occurs near the Rainbow basin wall. After the deposition of the sediments and lesser tuffs of Rainbow Basin, blocks of the basin wall, composed of Timber Mountain Group, slid into the basin, accommodated by detachments. Brecciation of the block was syntransportational. Previous mapping (Maldonado and Hausback, 1990) map these blocks as thrust of brecciated Timber Mountain onto the younger sediments.
2. Masses occurring within the Rainbow Mountain group. Breccias include the Rainbow Mountain-clast breccia (field stop 0430-13), the sedimentary

sequence west of Burton Mountain, as well as Rainbow Basin breccia and blocks of volcanic rock within (Plate 2, photo I). Sliding of this block is accommodated by low angle surfaces. A thin layer of platy rock, probably a shale at the base of the block, suggest the hanging wall may be sedimentary.

3. Railroad cut slide sequence (Plate 2, photo J). This series of slides consists first of water saturated volcanic-clastic sediment colliding and consequently creating a slump fold. This fold is interpreted as a penecontemporaneous structure. Subsequent slides of volcanic rock cut the saturated sediments. The rocks on the hanging wall of these slides are brecciated and sometimes crushed into powder. Brecciation and crushing of slide masses occurred during the faulting process, breaking the rocks into small, angular clast or gouge. This slide sequence is then cut by a block of Timber Mountain group derived from the Rainbow basin wall.
4. Detachment of Rainbow Mountain clast breccia (Plate 2, photo K). This slide mass is composed of matrix supported Rainbow Mountain clasts that were originally deposited as a mudslide. After lithificiation, the breccia was transported along a low angle structure, interpreted as a detachment. Sliding caused grinding of the Rainbow Mountain tuff of the detachment footwall, resulting in a thin layer of fault gouge and fault breccia.

5. Sedimentary sequence west of Burton Mountain (Plate 2, photo L). The sedimentary sequence is interpreted as a slide mass transported onto the Rainbow Mountain group. Sediments and clasts originally accumulated on an unstable volcanic vent near the flank of Rainbow Basin where angular clasts of Timber Mountain were available. Sliding was then initiated between eruptions of the Timber Mountain group. Minor reverse faulting within the sequence occurred during sliding, perhaps in response to contact with a barrier or irregularities of the detachment surface.

4.1.4 Tectonic breccias

Breccias interpreted as fault or tectonically derived include:

1. Brecciated Bonanza King in the Fluorspar Hills (Plate 2, photo M). Angular clasts of Bonanza King in the footwall of the FC-BH detachment
2. Microbrecciation in the Devonian footwall in the Fluorspar Hills (Plate 2, photo N). Also part of the FC-BH detachment footwall, the Fluorspar Canyon formation is brecciated into granules in a fine grained carbonate matrix. It is unclear whether the microbreccia records grinding produced by movement along the FC-BH detachment, if it is a more ancient brecciation caused by thrusting during the Mesozoic, or if it is a combination of both processes.

3. Sporadic hills of Paleozoic rocks in the SBH (Plate 2, photo O). These rocks are interpreted as a sliver of Paleozoic strata caught between the hanging wall and footwall of the FC-BH detachment system. Grinding of the fault blocks deforms the Paleozoic sliver, fracturing the rock into angular clasts.

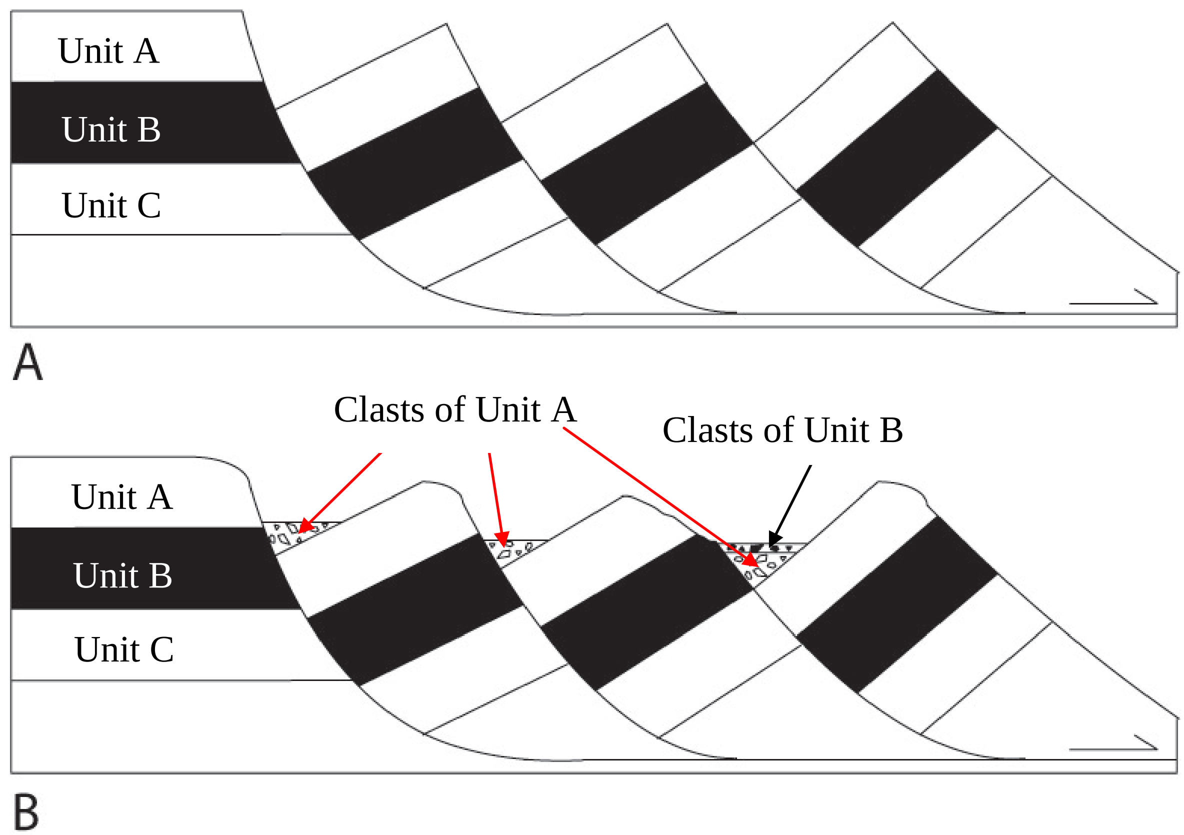


Figure 4.1 General diagram of accumulation of monolithic clasts in half grabens. Diagram A is after domino-style faulting occurs, tilting the rocks in the hanging wall. Down-dropped and tilted blocks create half grabens. Diagram B illustrates accumulation of monolithic clasts derived from the erosion of steep terrain caused by faulting. Unit A erodes first with clasts falling into the half graben. Erosion wears down Unit A, exposing Unit B to weathering. Now exposed, clasts from older layers fall into the half graben on top of Unit A's clasts.

5.0 CONCLUSIONS

This study focuses on previously mapped breccias mainly within the Oasis Valley Discharge area (Connors et al., 1998; Fridrich et al. 2007, Maldonado and Hausback, 1990; Minor et al., 1997; Monsen et al., 1992) in southwestern Nevada. The breccia units were examined to determine the relationship (if any) to deep structures that may influence southwesterly groundwater flow from Pahute Mesa into the Springdale and Beatty region. The porosity and permeability of breccia commonly facilitates the flow of groundwater. In the study area, understanding the conditions that may lead to movement of possibly contaminated groundwater from the NTS toward Springdale and Beatty, where the water is used for consumption, is a principal objective.

Each of the breccia units formed directly in response to tectonic extension in the hanging wall above the locally tilted FC-BH detachment.

5.1 CONCLUSIONS ABOUT BRECCIAS AND THEIR POSSIBLE INFLUENCE ON THE MOVEMENT OF GROUNDWATER

Talus breccias and sedimentary breccia suggest topography in the Miocene was high and steep. Steep topography was produced structurally during extension or by local volcanic uplift as in the SBH. Low areas where clasts accumulated are half-grabens produced by the tilting of strata above normal faults. Steep terrain promotes the high energy clast deposition that produces graded strata in the NBH and SBH.

Sliding of large blocks of rocks and sedimentary layers into Rainbow Basin was activated by extension and concomitant local volcanic eruptions. Eruptions adjacent to a steep basin wall destabilized pre-existing volcanic and sedimentary units and triggered basinward movement, allowing transport of Timber Mountain and Rainbow Mountain volcanics from the basin wall into the basin. Another possible source of slide masses are vents located on the flank of Rainbow Basin. Syntectonic eruptions in the SBH caused unstable surfaces to rupture, detach, and slide into Rainbow Basin (figure 5.1).

In relationship to groundwater flow in the region, this study concludes that the majority of these mapped breccias are not related to structures that cut the FC-

BH detachment system. Therefore, water flowing southwest from Pahute Mesa will not reach these deposits.

5.2 CONCLUSIONS ON STRUCTURES SIGNIFICANT TO GROUNDWATER FLOW

5.2.1 East-trending faults

The Hot Springs fault may provide insight into groundwater flow and the crystalline basement. As a Mesozoic feature, the HSF may have accommodated strike slip movement of Paleozoic rocks (Stewart, 1988). Penetration reached into the crystalline basement. Later faulting during the Tertiary cut through and detached the Paleozoic section and moved it west above crystalline basement.

After the eruption of volcanic units and detachment faulting along the FC-BH detachment, normal (Grauch et al.,1997) and apparent right-lateral reactivation of the HSF occurred. Reactivation occurred from the crystalline lower plate of the FC-BH detachment and penetrated through the overlying volcanic upper plate.

This fault is, therefore, a deep structure, and groundwater could use the fault as a pathway to reach basement rocks. In the SBH, the Indian and Crystal springs are near to the fault.

Other east-trending faults that may be reactivated Mesozoic structures are the Fleur-di-Lis fault and the Colson Pond fault.

This study concludes that the breccias discussed are not related to east-west trending structures in the Oasis Valley discharge area.

5.2.2 Other faults

Springs along the footwall of the Hogback fault follows the general strike of the structure. Additional springs are present in the hanging wall of the Beatty fault, but the springs, as mapped by Fridrich et al. (2007) do not follow the strike of the structure. The springs could be structurally controlled and related to the Beatty fault; therefore, the Beatty fault is mapped in this study as a more northwest trending structure in the Oasis Valley Drainage system.

The location of the springs on the footwall of the Hogback fault is slightly anomalous. Groundwater flowing from Pahute Mesa must flow through the thick gravel aquifer above the down dropped Hogback hanging wall then passes through the gravel material until it reaches the less permeable volcanic rocks in the Hogback footwall where the water must move upward to the surface.

Geophysical studies have shown the importance of the northeast-striking Thirsty Canyon lineament to groundwater flow (Mankinen et al. 1999; Mankinen et al. 2003). At the southern margin of the Hogback, the TCL and Hogback fault are within ~500 m of each other. If the TCL is a major influence on water flow, this intersection may be an important area to monitor.

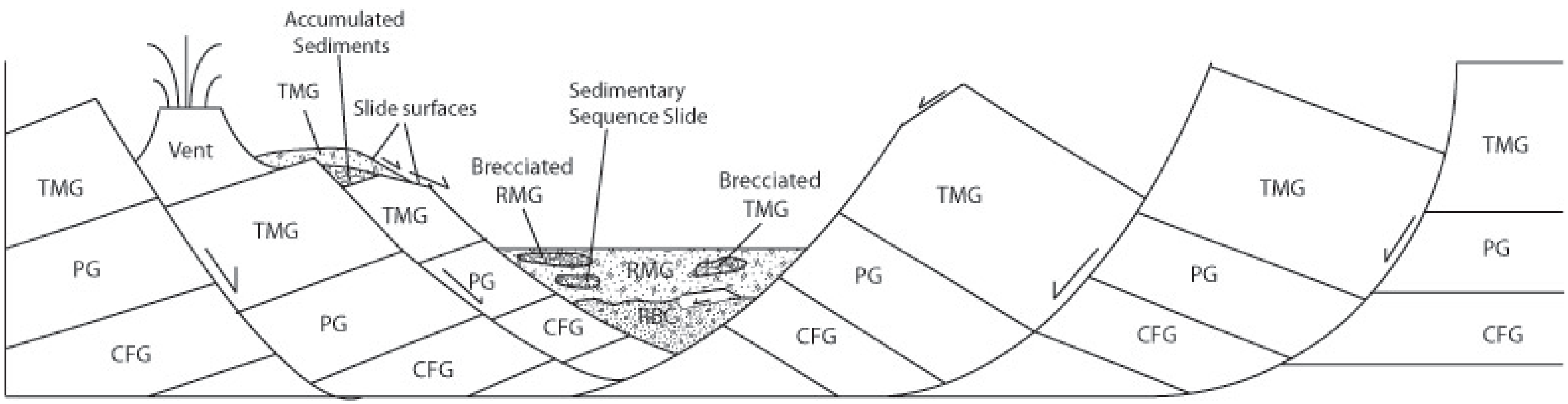


Figure 5.1 Diagram illustrating the emplacement of slide masses into Rainbow Basin. TMG: Timber Mountain Group, PG: Paintbrush Group, CFG: Crater Flat Group, RMG: Rainbow Mountain Group, RB: Rainbow Basin Conglomerate.

6.0 SUMMARY OF THE EXTENSION ABOVE FC-BH DETACHMENT

6.1 THE LAS VEGAS VALLEY SHEAR ZONE (LVSZ)

The general N60W strike of the LVSZ is disturbed by right and left steps in the strike. These deviations produce releasing and restraining bends, respectively. Previous studies south of Skull Mountain (Deemer, 2003) and the Specter range (Piaschyk, 2005) reveal a restraining bend associated to a left step in the LVSZ.

This study hypothesizes the FC-BH detachment is just one component of a larger detachment system generated by a right step of the LVSZ. The LVSZ takes the right step at the Calico Hills before ~14 Ma (figure 6.1), creating a large breakaway fault that displaced thousands of meters of Paleozoic and Proterozoic rocks to the west that now compose Bare Mountain. Extension of Paleozoic rocks from present day Bare mountain occurred before 14 Ma (Fridrich 1999b), and transported the rocks westward to what is now the Grapevine Mountains.

Explosive volcanic eruptions of the SWVF and accumulation of earlier sediments buried the exposed Paleozoic rocks and Crater Flat. Igneous intrusions related to volcanic activity of the SWNVF may have strengthened the crust, resulting in an abrupt westward migration of extension and the formation of the FC-BH detachment system. Major uplift of Bare Mountain occurred during the major extensional pulse along the FC-BH detachment fault 12.7-11.6 Ma ago (Fridrich, 1999b; Hoisch et al. 1997). The Tate's Wash fault serves as the break-away fault of this detachment system, extending northeast until it is buried by Timber Mountain volcanics. The TW-FC system cuts through the Paleozoic and Proterozoic rocks in Fluorspar Canyon and then into crystalline basement in the SBH.

Transport along the FC-BH detachment occurs in pulses described in detail by Fridrich (1999a). Angular unconformities and breccias, such as those described in chapter 3, aid in constraining the ages of extensional pulses. As previously discussed, talus breccias and sedimentary units, as well as angular unconformities in Fluorspar Canyon and NBH, mark the boundary between the first pulse (12.7-11.6 Ma) and the deposition of Timber Mountain Group (11.6-11.4 Ma). First pulse extension was not as strong in the SBH, creating small angular unconformities (Eng et al. 1996; Fridrich et al. 1999).

The second extensional pulse at 11.6 to ~10.5 Ma was synchronous with the eruption of Timber Mountain group, as suggested by fanned dips and interfingering breccias. During this pulse, Pre-Timber Mountain strata experienced additional rotation, creating steep beds and complicated geometries east of Beatty

Mountain. Second pulse extension was immense in the Bullfrog Hills after the eruption of Timber Mountain group. In the NBH, high topography was generated by blocks down-dropped by normal faults, and talus breccias accumulated in half grabens.

In the SBH, domino-style faulting formed Rainbow Basin. The Rainbow basin is a structurally controlled basin in the SBH. Basin walls are composed of Timber Mountain Group that has been down-dropped by north trending, west dipping normal faults above the FC-BH detachment. The probably northern boundary of the basin may be a poorly exposed west-striking, south dipping normal fault located south of Pioneer Road. This fault cuts through older (mostly Pre-Crater Flat) rocks. The complicated geometry of this area is interpreted to be the result of complex faulting during the formation of Rainbow Basin.

Extension in the Fluorspar Hills ceased around ~10.5 Ma (Fridrich et al. 1999), but continued in the Bullfrog Hills, tilting Rainbow Mountain group. In Rainbow Basin, slide masses and angular clasts of rock accumulated in between volcanic eruptions. This debris and the dips of Rainbow Mountain strata that shallow upsection indicate extension was synchronous with volcanism in the SBH.

Deformation of basin fill and walls occurred after the Rainbow Mountain eruption and was accommodated by northeast- striking, left-lateral strike slip and north- striking normal faults displacing basin material. Strike slip displacement is measured using the basalt and is approximately 2 km (Maldonado and Hausback, 1990). A concealed normal fault, proposed by Maldonado and Hausback (1990), is located west of Beatty and rotates basin material, creating east directed dips after or synchronous with the eruptions of the Rainbow Mountain Group.

Overall, Rainbow Basin accumulated approximately 300 m of basin fill with basalt, lesser tuffs, and conglomerate accumulated at the bottom of the basin. Volcanics of the Rainbow Mountain Group may have been deposited by a vent located near the edge of the basin, allowing thick deposits of volcanic rock to settle. In between eruptions, deposition of breccias and slide masses (described in section 4.1.3) occurred.

Movement along the FC-BH detachment in the Bullfrog Hills ceased ~ 9.5 Ma ago (Fridrich et al. 1999).

The total amount of extension accommodated by the detachment system is on the order of 58.7 km. As much as 35 km of extension occurred before 14 Ma with the movement of Paleozoic and Proterozoic rocks westward. Approximately 20 km of extension occurred in the formation of Crater flat and Yucca Mountain beginning at 14 Ma- 10 Ma, and 3.7 km occurred between 12.7 to ~9.5 Ma in the SBH (Maldonado, 1990).

6.2 LOCAL NORTHWARD TILTING OF THE FC-BH DETACHMENT

The dip of the FC-BH detachment exposed in Fluorspar Canyon suggests the system in Fluorspar Canyon has been tilted north approximately 40°. Tilting probably records north-south contraction compatible with east-west extension (figure 6.2).

The tilted clastic aquitards of the FC-BH footwall may form a barrier to southward movement of water east of the Hogback fault. However, if the north-striking Gold Ace fault that cuts the footwall is permeable, it may provide a pathway that accommodates southward movement of groundwater.

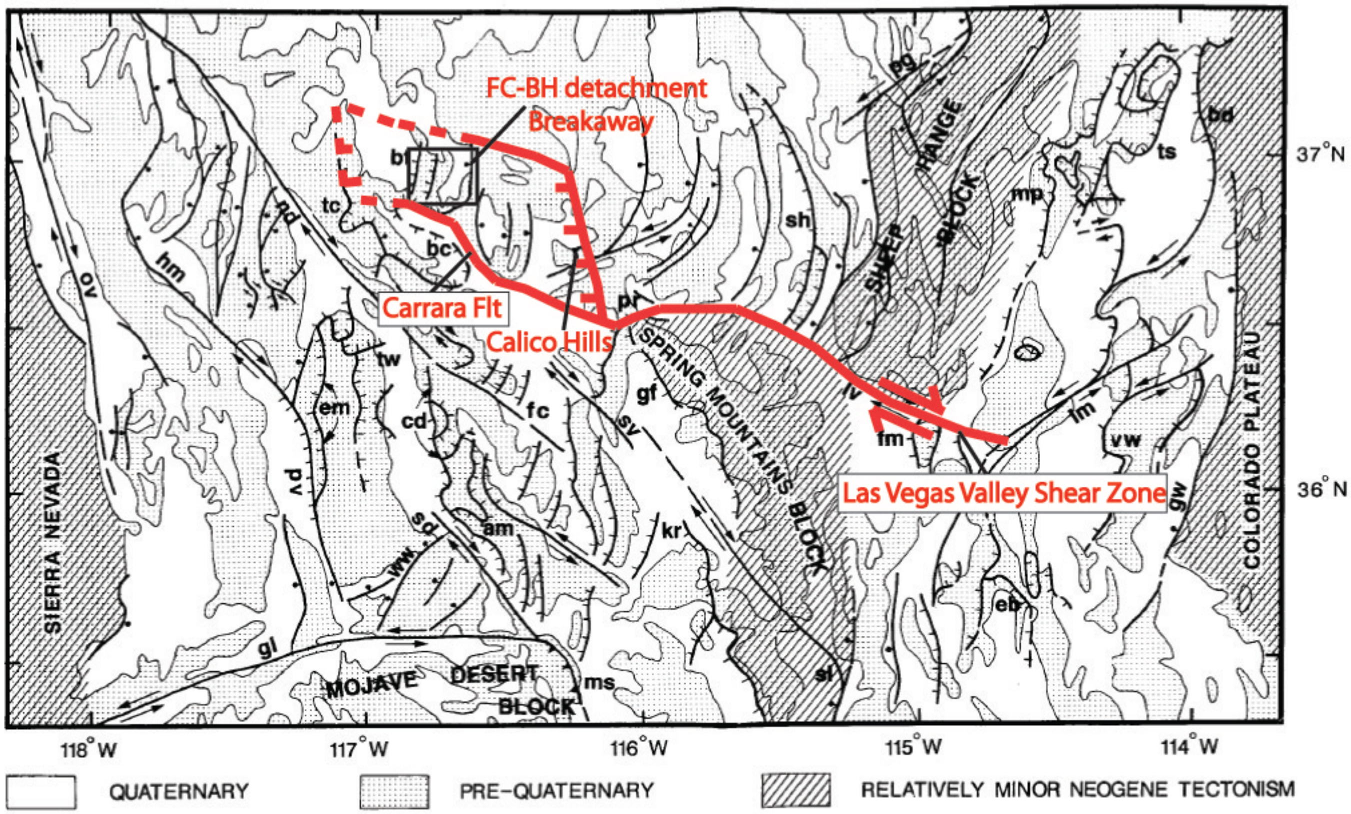


Fig. 1. Generalized tectonic map of Cenozoic faults in the central Basin and Range (heavy lines), including strike-slip faults (arrows), steep normal faults (bar and ball symbols), low-angle normal faults (tick marks) and thrusts (teeth). Strike-slip faults: Furnace Creek-**fc**, Garlock-**gl**, Hunter Mountain-**hm**, Lake Mead-**lm**, Las Vegas Valley-**lv**, northern Death Valley-**nd**, Owens Valley-**ov**, Pahranagat-**pg**, Rock Valley-**rv**, southern Death Valley-**sd**, Stateline-**sl**, Stewart Valley-**sv**. Normal faults and detachments: Amargosa-**am**, Boundary Canyon-**bc**, Beaver Dam-**bd**, Bullfrog-**bf**, central Death Valley-**cd**, Eldorado-Black Mountains-**eb**, Emigrant-**em**, Frenchman Mountain-**fm**, Grapevine-**gf**, Grand Wash-**gw**, Kingston Range-**kr**, Mormon Peak-**mp**, Point of Rocks-**pr**, Sheep Range-**sh**, Titus Canyon-**tc**, Tule Springs-**ts**, Tucki Wash-**tw**, South Virgin-White Hills-**vw**, Wingate Wash-**ww**. Thrust fault: Mule Springs-**ms**.

Figure 6.1: Map of the Las Vegas Valley Shear Zone that takes a right step, creating a large pull-apart basin responsible for the formation of the FC-BH detachment . Red line represent faults. Normal faults are represented by red tick marks on the hanging wall. Dashed fault lines indicate the inferred geometry of the Pull-Apart basin. Modified from Snow and Wernicke (2000).

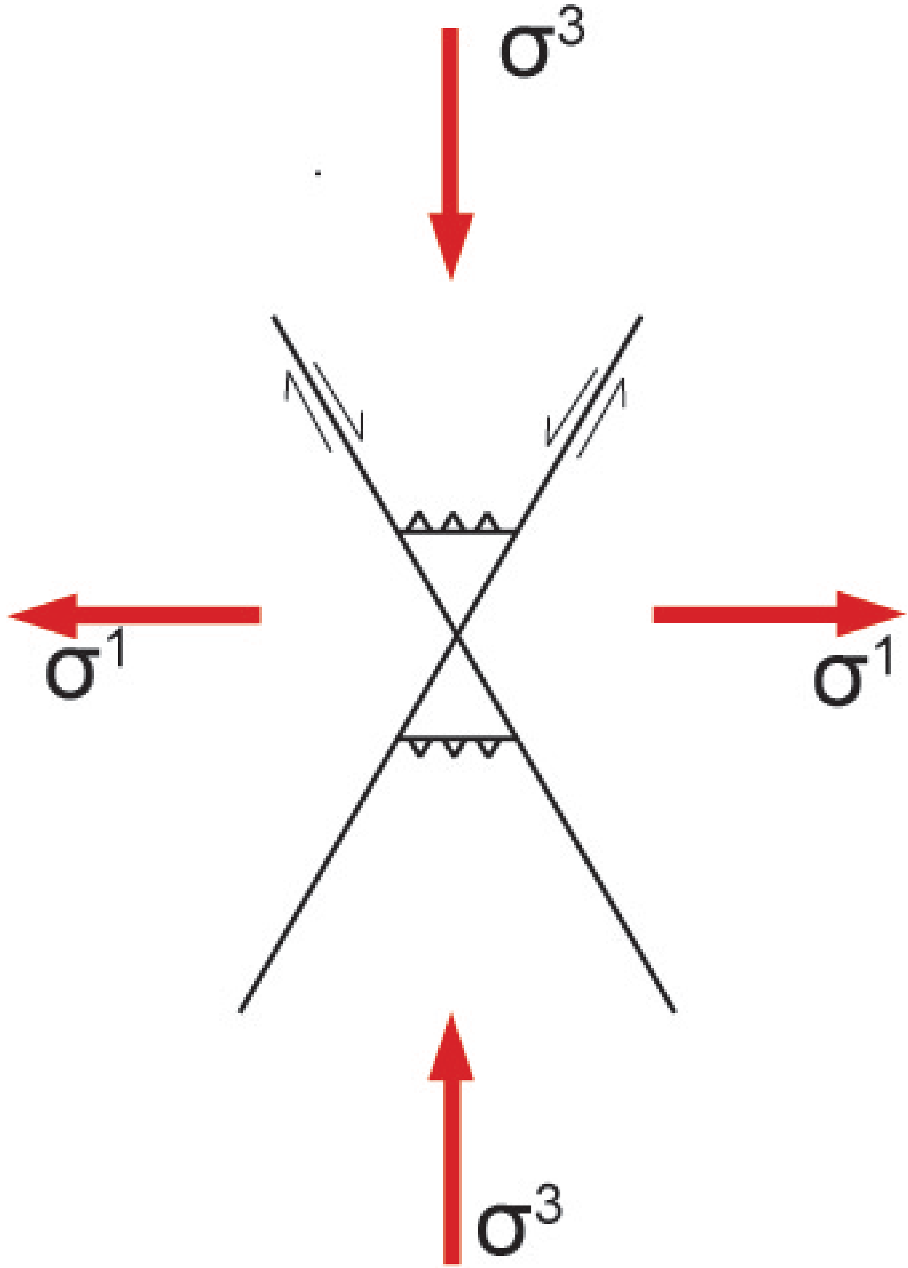


Figure 6.2 Kinematic diagram illustrating thrusting in response to large scale extension.

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