GEOLOGY OF THE TRAVERTINE POINT AREA,

DEATH VALLEY, CA: IMPLICATIONS FOR

STRUCTURAL EVOLUTION OF THE

FURNACE CREEK FAULT

ZONE

By

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Thesis Advisor

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Firstly, I would like to sincerely thank my beloved wife, Sheila, for the sacrifices she made during the time that is study was being conducted. She has always been supportive and willing to help with practical matters whenever she could.

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Chapter One

Introduction

The Death Valley region is located in eastern California, bordering Nevada. It is a constituent of the Basin and Range Province which covers a large portion of the Southwestern United States (Fig. 1.1). It is bounded by the Garlock fault zone to the south, the Furnace Creek fault zone to the north, the Funeral Mountains and the Nopah Range to the west, and the Panamint Range to the west (Fig. 1.2). The Cenozoic tectonics of the Death Valley region is characterized by numerous normal faults during the Cenozoic Basin and Range extension. The region also contains strike-slip faults formed in response to the extension. The Furnace Creek Fault zone (FCFZ) is a right-lateral, strike-slip fault trending northwest to southeast for approximately 200 km. within the Death Valley region.

Although the Death Valley region has been mapped in detail within the last 50 years (McAllister, 1970, 1971; Wright and Troxel, 1984), the rocks within the Travertine Point area have remained relatively unstudied (Fig. 1.3). The thesis area is located at Travertine Point, an area along the fault zone just southeast of the central and southern Funeral Mountains (Plate 1). This area contains conglomerate rocks composed of Paleozoic clasts from the following formations: Bonanza King, Nopah, Pogonip, Eureka Quartzite, Hidden Valley, and Ely Springs Dolomite. The origin of these conglomerates is controversial. Noble and Wright, (1951); and McAllister, (1970) concluded that they are Quaternary landslides.

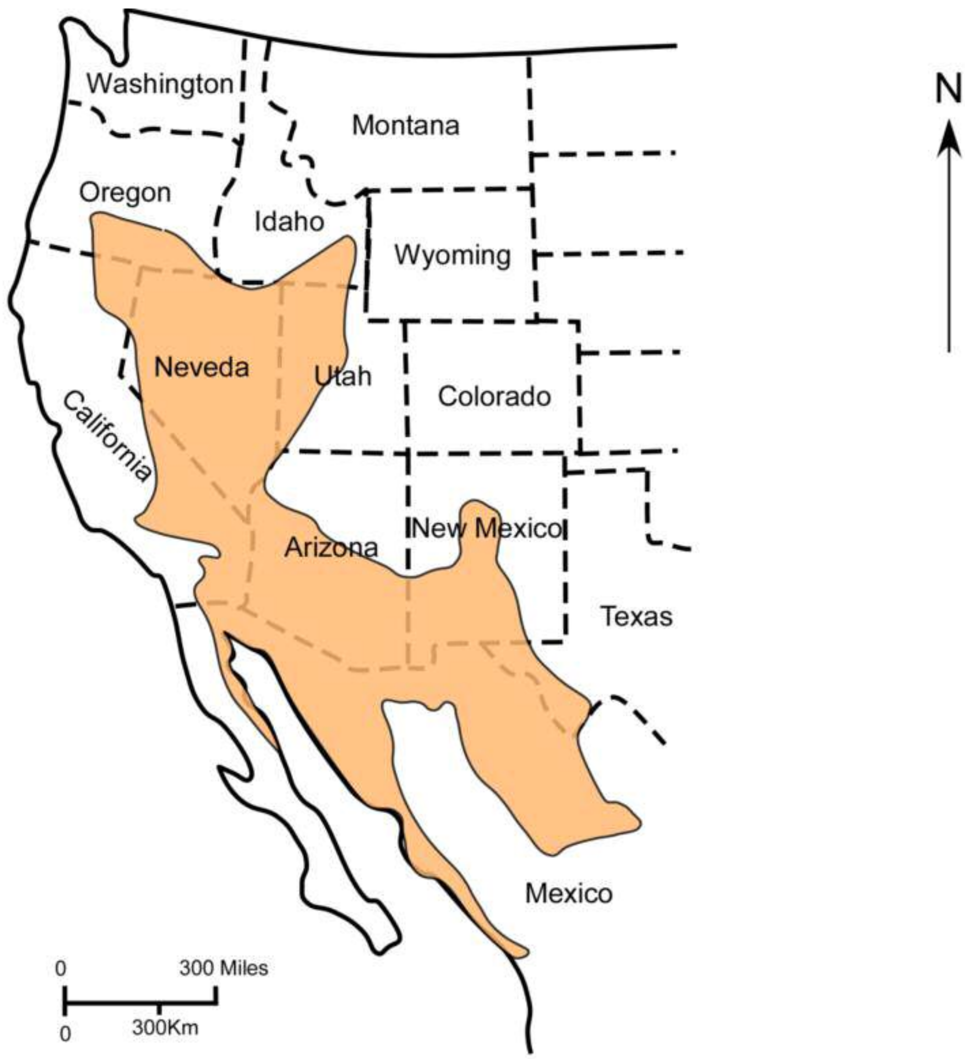


Figure 1.1. The Tan shaded area represents the Basin and Range Province of South Western United States (After Davis and Reynolds, 1996).

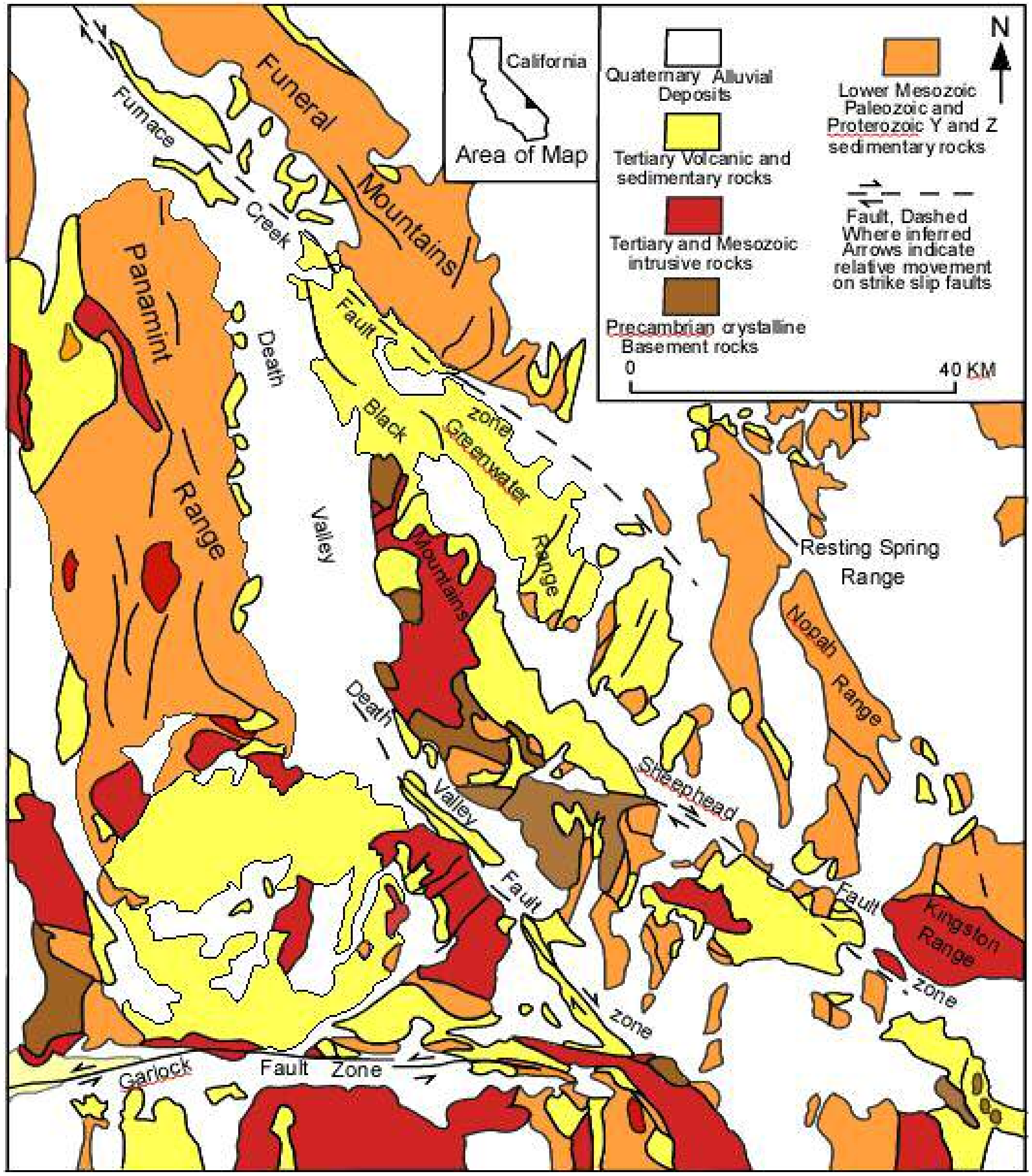


Figure 1.2. Generalized geologic map of the Death Valley Region area, California (Steward, 1983).

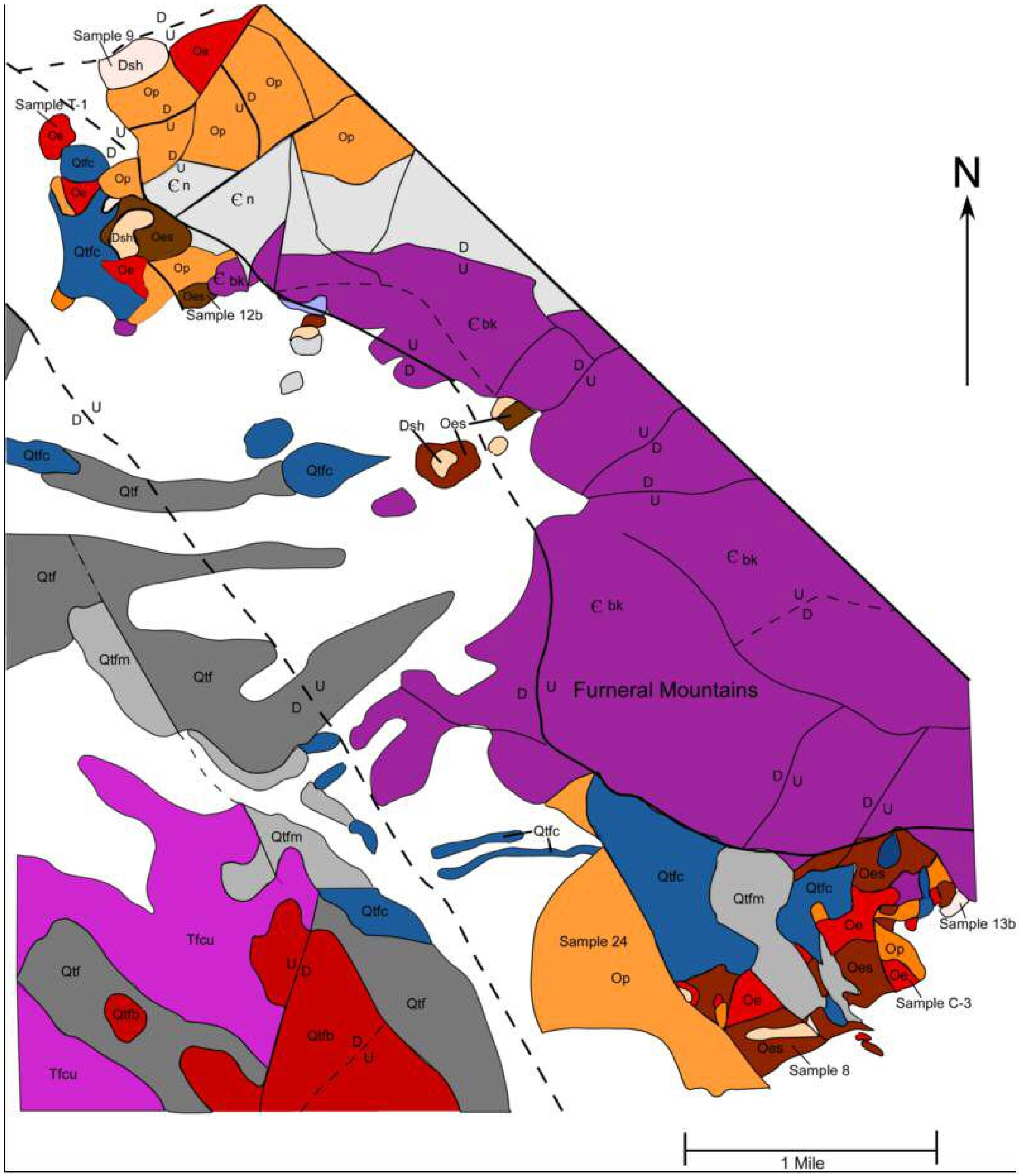


Figure 1.3. Geologic map of the Travertine Point area. The locations of the samples used in this study are indicated on the map.

1.1 Research Objectives

The main purpose of this project is to analyze the conglomeratic rocks of the Travertine Point area in detail and determine their origin. Although they were previously interpreted as landslides, there is a possibility that they are fault breccia formed during the right-lateral movement along the FCFZ. This will produce new data to be used in piecing together the complex Cenozoic tectonic history of the FCFZ.

The results of the analysis carried out during this study will affect two opposing hypotheses concerning the magnitude of displacement along the Furnace Creek Fault zone in general and in the area of the Furnace Creek Wash in particular. If the breccias are found to be fault related then the hypotheses proposed by Serpa and Pravis (1996), Wright et al. (1999), and Cemen et al. (1999) estimating a displacement at or smaller then 50 km is strengthened. The hypotheses proposed by Stewart (1967) and Niemi et al., (2001) of greater then 100 km of displacement will be strengthened if the results of this study show that the breccias are remnants of ancient avalanches.

1.2 Location of Study Area

The thesis area is located along the Furnace Creek Fault zone in the Travertine Point area in the Death Valley region. The study area is located between 36^{o} 22'30"N-36^{o} 27'30"N latitude and 116^{o} 45'00"W- 116^{o} 37'30"W longitude near the California-Nevada state line. Furnace Creek Wash is on the eastern border of Death Valley National Park and the Amargosa Desert. It can be located on the Echo Canyon Quadrangle, California (Fig. 1.2, 1.3).

1.3 Method of Study

The following tasks were accomplished in this project:

1) Mapped in greater detail than McAllister (1970) an area of about 10 square miles around the Travertine Point area within the Furnace Creek Wash.
2) Collected about 30 hand sample sized rocks from all exposed formations in the area. From these samples, 20 were prepared into thin-sections. Petrographic analysis was then conducted to establish clast shape and size. Two of the thin-sections were analyzed using the OSU JEOL 733 the electron microprobe to determine the chemical composition of the matrix and compare it with that of the clasts.
3) Measured a stratigraphic section of a conglomerate/mudstone sequence within the Travertine Point area.
4) Constructed 4 true to scale, structural cross-sections within the Furnace Creek Wash area.

This data in this study will be used to test current hypothesis concerning the magnitude of displacement along the Furnace Creek Fault zone. The new data will also create more control points along the fault zone which will allow the fault to be mapped in more detail through the Travertine Point area. Three cross-sections trending perpendicular to the fault zone will display the subsurface within the fault zone to depths around 6000' and will suggests that the Paleozoic rocks are brecciated at that depth as they are on the surface.

1.4 Previous Investigations

The geologic history along the FCFZ includes initial fault movement, the magnitude of lateral displacement along the fault, and the amount of crustal extension resulting from fault movement. Although the magnitude of fault displacement along the FCFZ is disputed, the timing of the initial fault movement is solidly established. Cemen et al.,(1985) first proposed that fault movement began about 14 Ma, shortly before the first basal units of the Artist Drive Formation were deposited. Wright et al.,(1999) and Cemen et al. (1999) have since modified this estimate by increasing it to 17 Ma. Niemi et al. (2001) renamed the Artist Drive Formation to the Eagle Mountain Formation. They suggest that the Eagle Mountain Formation represents "the onset of rapid extension in the region ca. 15 Ma", which alludes to a time period prior to 15 Ma for initial fault movement to begin.

To calculate an accurate time range for the inception of movement along the FCFZ, a combined understanding of the volcanic and sedimentary strata within two formations, Amargosa Valley and the younger Bat Mountain, is required. These two formations were in place prior to the development of the Furnace Creek Basin. Radiometric dates from tuff layers provide absolute upper and lower limits to the age range while the sedimentary strata within these formations reveal the sequential details of the events in between.

Two significant tuff beds exist within the Amargosa Valley Formation have been radiometrically dated using the K/Ar method. The older exists within a playa deposit overlying the basal conglomerate and is ~25 Ma and the younger tuff comes from the upper member and is ~20 Ma (Cemen et al., 1985, 1999). Age for the younger boundary comes from a tuff layer close to the base of the Artiest Drive Formation (Eagle Mountain Formation from Neime et al.) and is ~14 Ma based on a K/Ar biotite age (Cemen et al., 1985 and Wright et al., 1999). Since the base of Artist Drive Formation represents the initiation of the basin sedimentation, it can be estimated that fault movement pre-dates its development. Based on the radiometrically-dated tuffs alone, the inception of fault movement can be loosely fitted into a 25 Ma-14 Ma range. From there the sedimentary strata of the formations fill in the details of the geologic story. Each formation contains a conglomerate member marker bed.

The Amargosa Valley conglomerate underlies the 25 Ma playa deposit which Cemen et al.,(1999) estimates to be ~26Ma. It contains numerous clues for a deposition that pre-dates fault movement, including clasts derived from a homogenous source which came mainly from the formation that immediately underlies it. This eliminates the possibility of source migration associated with fault movement. The clasts also reveal little to no attenuation or fracturing which accompanies fault-movement. It has been concluded that the lower conglomerate of the Amargosa Valley is a product of a paleotopographic high that pre-dates movement along the Furnace Creek Fault (Cemen et al., 1999).

The Bat Mountain conglomerate is not in the stratigraphic vicinity of any tuff layer to give it an absolute age, but the deformational evidence within the unit strongly points towards a conglomerate that post-dates fault movement. Its clasts are derived from a wide variety of sources implying source migration along a fault (Cemen et al., 1999). Based upon the diverse clasts within the conglomerate, the original source was strata between late Proterozoic through late Paleozoic that was estimated to be about 7 km thick. The preserved alluvial fan is much too small to accommodate an erosional load of that magnitude. This coupled with the inverse stratigraphy of the clasts (Cemen et al., 1985; Cemen and Wright, 1990), presents strong evidence that the source area was severly attenuated, implying that a transtensional event was already fully underway (Cemen et al., 1999, Wright et al., 1999).

An anticlinal warp within the Amargosa Valley Formation reveals two important clues. First, that it was pre-Bat Mountain in that it effected only the Amargosa Valley Formation. Secondly, within the Amargosa Valley, erosion was focused on the crest of the anticline, affecting only the upper member (Cemen et al., 1999). This suggests a local instead of regional deformational event. Moreover, the folds trend more westerly putting them at an oblique angle to the main fault zone, classifying them as en-echelon folds. If this is the correct interpretation, then the compressional event could represent the precursor to movement along the fault zone (Cemen et al., 1999). Since the upper member contains a tuff layer ~20 Ma (Cemen and Wright, 1990), the age range for initial fault movement is reduced to somewhere between ~20 Ma and ~14 Ma (Cemen et al., 1999 and Wright et al, 1999).

Above the upper member lies a limestone unit that is an independent layer between the Amargosa Valley and the Bat Mountain formations. It was once termed the Algal Limestone (Cemen et al., 1985, Wright et al., 1990) but has now been formally named the Kelly's Well formation (Cemen et al., 1999). Because of its large size, it has been interpreted to be a large lake existing in a time of tectonic repose (Cemen et al., 1999). Although the Kelly's Well contains no tuff layer to indicate an absolute age, it is estimated to be ~18 Ma, which leaves adequate time for the previous tectonic uplift to subside. Based on the volume of limestone, the tectonic repose lasted approximately one million years (Cemen et al., 1999).

About 17 Ma, the stage of tectonic repose was abruptly ended by the events that developed the Bat Mountain formation. As previously mentioned, the Bat Mountain conglomerate was the first stratigraphic evidence of Furnace Creek Fault movement, but evidence shows that the extensional event was well underway by then. Therefore, it has been estimated that the extensional event began around 17 Ma, which allows enough time for the source of the Bat Mountain conglomerate to be attenuated (Cemen et al., 1999). Around 16 Ma, the Bat Mountain conglomerate was deposited along the northeast side of a dynamic fault zone (Cemen et al., 1999 and Wright et al., 1999).

Chapter Two

Rock Units

The study area is located at the Travertine Point area of the Funeral Mountains along the Furnace Creek Fault Zone. This area contains rock units ranging in age from Cambrian to Quaternary that are well exposed. However, this study is mostly concerned with the Cenozoic structural development of the study area. Therefore, only the Cenozoic stratigraphic units will be discussed detail in this chapter while the pre-Cenozoic rock units will only be discussed briefly. The ages and thicknesses of the following formations are from Cemen et al., (1985) and were measured from units exposed in the southeastern and central parts of the Funeral Mountains. Figure 2.1 is a pre-Cenozoic stratigraphic column for the Death Valley region taken from Hunt and Mabey, (1966) and Cemen and Wright, (1990).

2.1 Pre-Cenozoic Rock Units

2.1.1 Proterozoic to Paleozoic rocks

The oldest formation in the Death Valley region is the Johnnie Formation, which is about 1.8 billon years old. It is bout 1000 ft thick and is mainly shale interbedded with dolomite with quartzite at the base (Hunt and Mabey, 1966). Directly above the Johnnie Formation is the Stirling Quartzite which is about 4800 ft thick. The youngest Pre-Cambrian formation is the Wood Canyon formation and it was measured to be about 4000 ft thick.

2.1.2 Cambrian

The early Cambrian begins with the Zabriskie Quartzite. It is a massive quartzite measured to be about 800 ft thick. The Carrara Formation overlies the Zabriskie and is about 1600 ft thick. The unit represents an early to middle Cambrian transition form clastic beds, which are mainly shale and silt, to the overlying carbonates composed of mostly limestone and dolomite. This transition is evidenced by the alterations of shaly and silty layers with layers of limestone throughout the formation.

	Age			Formation	Lithology	Thickness
Phanerozoic	Paleozoic	Mis.	L	Perdido Formation	limestone	500'
Phanerozoic	Paleozoic	Mis.	E	Tin Mountain Limestone	limestone	300'
Phanerozoic	Paleozoic	Devo.	L, M	Lost Burro Formation	limestone, quartzite, and sandstone beds	500'
Phanerozoic	Paleozoic	Devo. / Sil.	E	Hidden Valley Dolomite	thick-bedded, light in color, fine grained dolomite	1400'
Phanerozoic	Paleozoic	Ordo.	L	Ely Springs Dolomite	massive black dolomite	500'
Phanerozoic	Paleozoic	Ordo.	M	Eureka Quartzite	massive quartzite	400'
Phanerozoic	Paleozoic	Ordo.	M, E	Pogonip Group	dolomite w/ limestone at base, shale in middle ,dolomite at top	2200'
Phanerozoic	Paleozoic	Cambrian	Late	Nopah Formation	shale member base dolomite member top	700'
Phanerozoic	Paleozoic	Cambrian	Late, Middle	Bonanza King Formation	thick bedded arid massive dolomite	3600'
Phanerozoic	Paleozoic	Cambrian	Middle, Early	Carrara Formation	shaly and silty, and limestone members	
Phanerozoic	Paleozoic	Cambrian	Early	Zabriskie Quartzite	quartzite mostly massive arid	800'
Proterozoic				Wood Canyon Formation	bottom unit quartzite then shale, top unit dolomite	4000'
Proterozoic				Stirling Quartzite	well-bedded quartzite some shale	4800'
Proterozoic				Johnnie Formation	Mostly shale base interbedded dolomite and quartzite	1000'

Figure 2.1. Stratigraphic column represents the Cenozoic Rock Units for the Death Valley region (After Hunt and Mabey, 1966 and Cemen and Wright, 1990)

The Bonanza King Formation is middle to late Cambrian in age and is the thickest of all the Paleozoic formations at 3600 ft. It is a dark grey to black, massive limestone. It is overlain by the Nopah Formation, which is a massive dolomite formation about 700 ft thick.

2.1.3 Ordovician

The Ordovician begins with the 2200 ft Pogonip group. The Pogonip is a light gray dolomite with an abundance of gastropods. It has a limestone at the base which contains brachiopods and a shale unit in the middle (Hunt and Mabey, 1966). Directly above the Pogonip group is Eureka Quartzite. It is a 400 ft thick massive quartzite that is middle Ordovician in age. The late Ordovician is represented by the Ely Springs, which is a 500 ft thick black massive dolomite that contains brachiopods and corals (Hunt and Mabey,1966).

2.1.4 Upper Paleozoic

Lying just above Ely Springs is the Hidden Valley Dolomite. It represents the Silurian and early Devonian. It is about 1400 ft thick and is a light gray colored dolomite. It also contains crinoid stems (Hunt and Mabey,1966). The middle and late Devonian is represented by the Lost Burro formation. It is about 500 ft thick and has limestone, quartzite, and sandstone members and contains brachiopods in each member (Hunt and Mabey,1966).

2.2 Cenozoic Rock Units

The study area comprises a segment of the Furnace Creek Wash adjacent to the southwestern side of the Southern and Central Funeral Mountains. The Northeast side of the fault-zone contains Cambrian-Devonian age sedimentary rocks that have been heavily brecciated. Lying unconformablely over these tilted breccias is a conglomerate to mudstone sequence that has been dated to be Quaternary in age. On the southwest side of the fault-zone are basalts and conglomerates of the Funeral Formation within the Furnace Creek Basin. To show the stratigraphy of the study area, a stratigraphic column (Fig. 2.2) has been constructed which includes the conglomerate/mudstone sequence with its unconformable contact with the lower Paleozoic sedimentary rocks.

During this study the conglomerate to mudstone sequence was measured in the Travertine Point area (Fig. 2.2). The combined thickness of the sequence is 885 ft and is oriented with an attitude of N40E, 20 SE. The sequence lies unconformably over the brecciated Paleozoic basement. Although no igneous beds were observed in the mudstone, clasts from the lower Paleozoic rocks comprise the conglomerate and the sequence has been dated as the same age as the Funeral Formation. Evidence for this age is that the sequence is on the same stratigraphic level as the Funeral basalts and conglomerate to the southwest. A facies change is observed as the Funeral conglomerates and basalts to the southwest interfinger with the conglomerate to mudstone sequence to the northeast.

2.2.1Conglomerate

At the base of the measured section, the conglomerate is red to white, calcite cemented, massively bedded. Its clasts are gravel-sized, poorly-sorted, moderate to well rounded, and are derived from the Paleozoic Hidden Valley Dolomite, Ely Springs Dolomite, and Pogonip Formation (Fig. 2.3). Eighty feet up the section, the cement is completely calcite. The clasts are predominately Hidden Valley and Ely Springs dolomites (Fig. 2.4). There is a substantial increase in calcite mud 280 ft up the section (Fig. 2.5). It is a matrix supported conglomerate and the clasts are from the Pogonip, Ely

Springs, and Hidden Valley. The transition into mudstone begins 370 ft up the section and the contact is 10 ft up from there (Fig. 2.6).

2.2.2 Mudstone

The mudstone was measured to be 505 ft thick (Fig 2.13). It is a laminated micrite claystone according to Folk's Classification (Fig. 2.8). About 140 ft from the contact with the lower conglomerate is a conglomerate band about 6 in thick. Its clasts are poorly sorted and are derived from the Ely Springs Dolomite (Fig. 2.7). The remainder of the section is mudstone.

2.2.3 Interpretation

The conglomerate to mudstone sequence is interpreted as a southeasterly flowing fluvial system that began with relatively high energy represented by 380 feet of the conglomerate unit at its base which grades into 505 feet of laminated mudstone. The contact between the two units is conformable based on the transition from conglomerate to mudstone. Several lines of evidence within the conglomerate lead to a fluvial interpretation. The clasts are not brecciated showing that they came from another source other than the basement rocks beneath. The clasts, which are also moderate to well rounded and of variable composition (Fig. 2.4) are surrounded by a calcitic mud matrix showing a relatively long transport distance.

Although the mudstone shows no cross bedding to directly estimate the direction of flow, the direction is derived firstly from the geologic map of the region (Plate 1). Qtfc and Qtfm are remnant fluvial deposits dispersed throughout the research area and are trending in a southeasterly fashion. The direction of flow is confirmed by Cemen et al., (1999), who interpreted the upper three members of the Amargosa Valley Formation “as recording a south to southeasterly progradation of a fluvial facies over a lacustrine facies”.

Because no volcanic layers were found in the mudstone, the fluvial system could only be placed in a relative sequence of events. Its stratigraphic position along with the lack of brecciation within the sequence shows that the fluvial system began after the brecciation of the Paleozoic sedimentary rocks. The sequence lies unconformably over the brecciated Paleozoic rocks. Figures 2.9 and 2.10 show Ely Springs and Eureka Quartzite inclusions within the mudstone. Clasts within the conglomerate are Cambrian to Devonian in age basement rocks. Normal faulting in the area has continued after the deposition of the fluvial unit. Figure 2.11 shows normal fault displacement through the conglomerate to mudstone sequence.

In the Travertine Point area, the southwest side of the fault zone is occupied by the Funeral basalts and conglomerates. The basalt adjacent to the fault zone and just west of the breccias has an attitude of N55^{o}W, 20^{o}-30^{o} SW (Fig.2.12). The geologic map (Plate 1) reveals that this is the northeast limb of a northwesterly trending syncline. The southeast limb dips roughly 20^{o} -30^{o} NE. Brecciated fragments of the Cambrian Bonanza King and Ordovician Pogonip limestone were observed within the basalt. Based on these observations it is assumed that these fragments were transported by basalt flows during the Funeral Formation and that the brecciated Paleozoic rocks rest depositionally beneath the basalt. Since this is the same stratigraphic sequence observed with the fluvial system, it is correlated with the Funeral Formation.

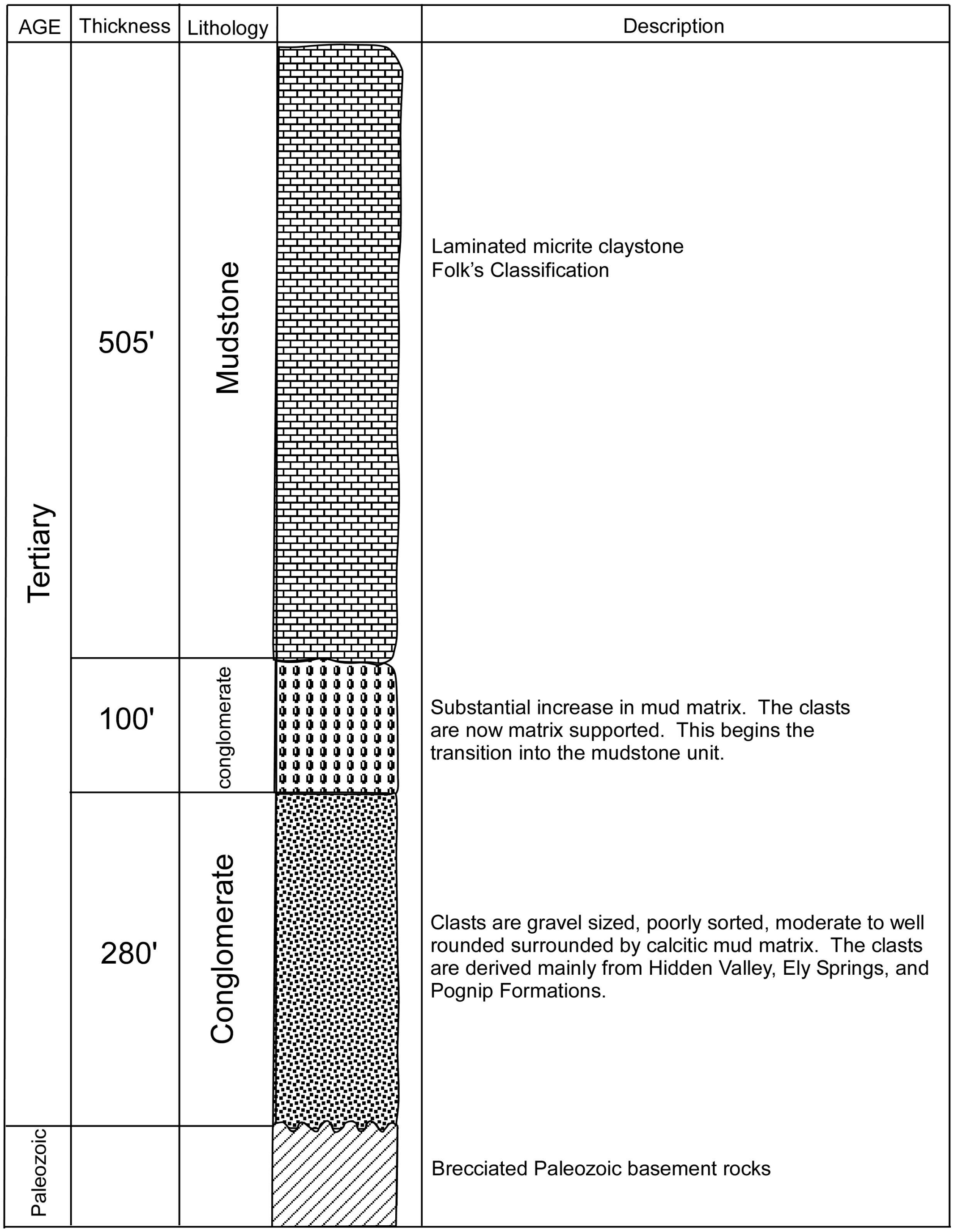


Figure 2.2. Stratigraphic column of conglomerate to mudstone fluvial system in the Travertine Point area. The system rests unconformably on the brecciated sedimentary rocks.

Figure 2.3. Conglomerate at the base of the sequence. Cement is reddish to white. The clasts are mainly dolomite, quartzite, and limestone all from undeformed Paleozoic basement rocks. It is poorly sorted with rounded clasts.

Figure 2.4. Pictures of conglomerate member of the fluvial system in thin section and outcrop. This sample was collected 80 feet up the section from the base. It is mainly composed of Ely Springs and Hidden Valley Dolomite and Eureka Quartzite.

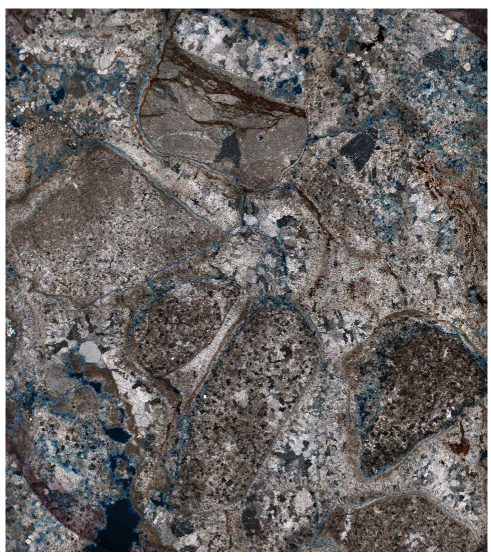


Figure 2.5. Picture of outcrop and thin section of the fluvial system 280 feet up the section. This point shows a substantial increase in mud content which increases up section toward the mudstone contact. The clasts are moderate to well-rounded.

Figure 2.6. Picture of the contact between conglomerate and mudstone members of the fluvial system 380 feet up the sequence. The transition zone began about twenty feet below this point.

Figure 2.7. Picture of conglomerate unit within the mudstone member of fluvial system measured about 510 feet up the column.

Figure 2.8. Picture of mudstone member of the fluvial system in outcrop and thin section. This sample was taken about 30 feet up from the contact with the conglomerate which is about 410 feet up the column. Based on the content of mud, it is classified as a laminated micrite according to Folk's classification.

Figure 2.9. Picture of Eureka Quartzite in contact with the fluvial mudstone. The mudstone contains quartzite inclusions showing an unconformable contact.

Figure 2.10. Picture of Ely Springs Dolomite in contact with the Fluvial mudstone. The mudstone contains dolomite inclusions showing an unconformable contact.

Figure 2.11. Normal fault displacement through the conglomerate/mudstone sequence. This is evidence for correlating the sequence to the Funeral Formation in age.

Figure 2.12. Funeral Formation basalt tilting to the southwest adjacent to the southwest side of the fault zone. This the northeast limb of a northwesterly trending syncline.

Figure 2.13. Picture of the mudstone unit of the fluvial system tilting to the southeast.

Chapter Three

Petrographic analysis

During this study, several rocks were petrographic analyzed to test the origin of the breccias found in the study area. If they were faulted insitu then they must show evidence for cataclasis and cataclastic flow. A breccia is defined as "a coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or a fine-grained matrix", (Jackson and Bates, 1984). Davis and Reynolds (1996) outline two characteristics of breccias formed by cataclastic flow: they display 1) "pervasive cracks and generally sharp, angular grains and fragments", and 2)"look remarkably similar at all scales of observation from the scale of outcrop down to a scale of electron microscopy".

For this project, 30 hand samples were collected along the fault zone adjacent to the Funeral Mountains and 20 were made into thinsections. After they were examined with a petrographic microscope, 9 were chosen as representation of the micostructures of the entire region. The goal of this analysis was to look for evidence of cataclastic flow and sense of shear. An attempt was made to show the "remarkable similarities of all scales from outcrop level down to microscopic" (Davis and Reynolds, 1996). If this is established, in addition to pervasive fracturing displayed at the outcrop scale, the breccias would qualify as fault breccia.

The rock types included in this study are limestones from the Bonanza King and Poganip Formations, dolomite from the Hidden Valley and Ely Springs Formations, and quartzite from Eureka, all of which have been brecciated at outcrop and hand specimen scale.

Fig. 3.1 is a picture of one Devonian age Hidden Valley Dolomite referred to as sample 8. This sample was collected at the southeastern end of the study area at 36° 20’30”N and 116° 39’30”W. The sample shows the remarkable similarities of the grain size and shape at three different levels of microscopy: outcrop, handsample, and thinsection. At all three scales, the clasts are sharp, angular grains of dolomite surrounded by a dolomitic matrix composed of similar but smaller angular grains.

Fig. 3.2 shows a handsample of Hidden Valley Dolomite referred to as sample 13b from the southeastern part of the study area at 36° 22’30”N and the 116° 39’30”W. Fig. 3.3 shows sample 9, which was collected in the northwestern part of the study area at 36° 23’30”N and 116° 40’00”W. This rock has angular grains of dolomite surrounded by matrix composed of ground up dolomite grains at both handsample and thinsection scale.

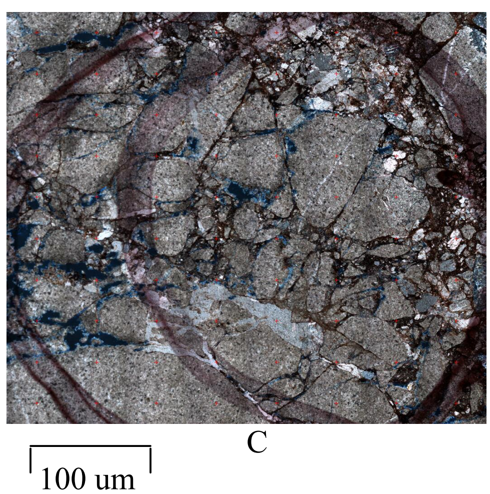
Fig. 3.4 shows the Eureka Quartzite in handsample and thinsection scales collected at 36° 23’30”N and the 116° 40’00”W toward the northwestern part of the study area. The rock contains angular quartzite clasts surrounded by matix composed of smaller ground up, angular quartzite clasts. Fig. 3.5 shows a picture of Eureka Quartzite in handsample and thinsection scale from sample C-3 collected from the southeastern end of the study area at 36° 21’30”N and 16° 39’30”W. Observations of this sample show sharp, angular quartzite clasts surrounded by matrix composed of smaller ground up quartzite fragments.

Fig. 3.6 shows a picture of sample 24 in thinsection from a sample of the Pogonip limestone collected at 36° 23’30”N and 116° 39’30”W in the southeastern end of the study area. A handsample picture is not provided as no characteristic features are seen at that scale. The main objective of showing this sample is to display the sharp angular limestone clasts surrounded by calcite crystals that formed within the pore space. Because limestone is more likely to deform ductilely within a shear zone instead of brittley as in quartzite, it may experience fluid-related softening during cataclastic flow and grains that may normally resist deformation dissolve resulting in pore space. As fluid flow within the shear zone continues, minerals such as calcite tend to form within the pore space (Davis and Reyonlds, 1996).

Fig. 3.7 is a thin-section scale picture of Ely Springs Dolomite, sample 12b, which was collected at 36° 23’30”N and116° 40’00”W at the northwestern end of the study area. Within the boxed area, is a small fracture displaying right-lateral shear which is consistent with the shear movement along the Furnace Creek fault zone. Because the breccias in this area were so broken up, no bedding plane was visible and therefore the specimens were not collected as oriented samples with the specific intention of finding a sense of shear.

A

B



C

Figure 3.1. Three different scales of Hidden Valley Dolomite showing sharp angular grains and they are strikingly similar at all three scales. A) Outcrop scale showing pervasive cracks and sharp angular fragments. B) Hand sample scale showing sharp angular clasts of dolomite surrounded by dolmitic matrix. C) Thin section scale showing sharp angular clasts surrounded by dolomitic matrix.

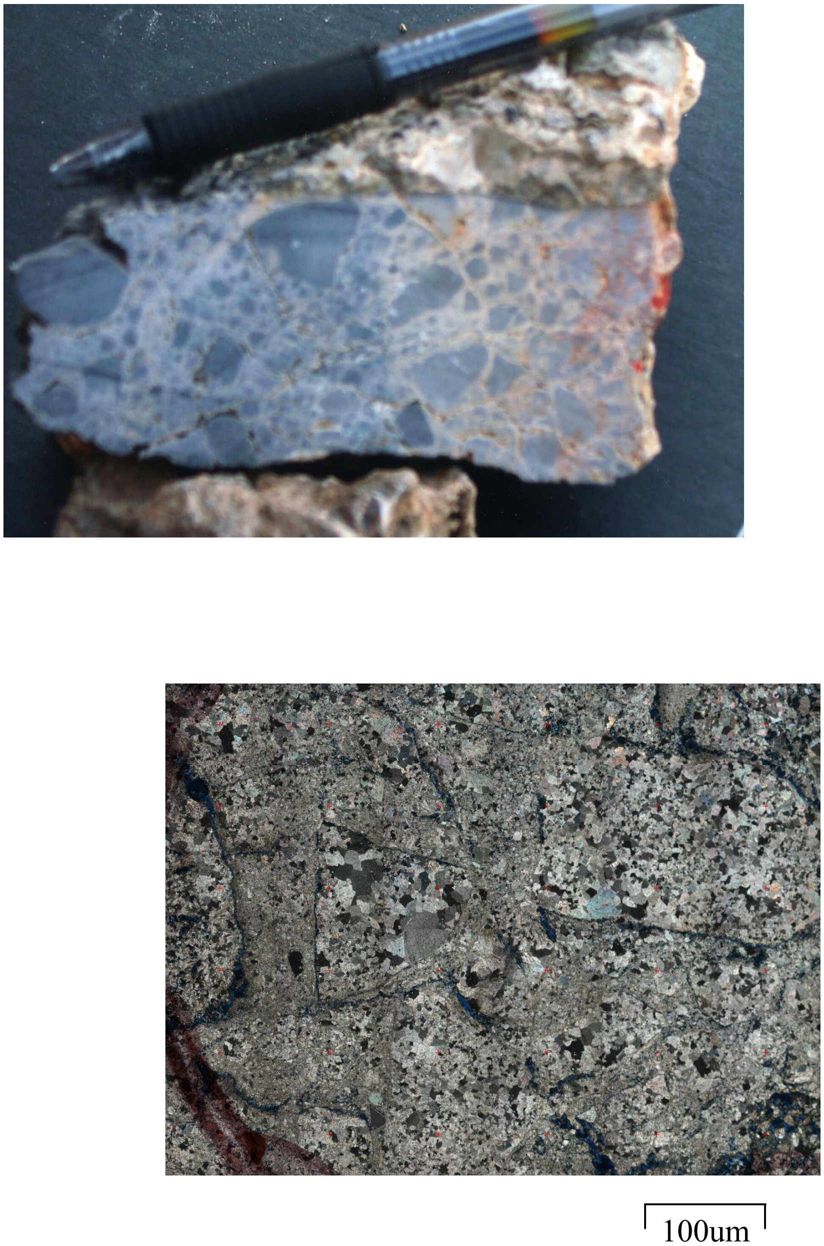


Figure 3.2. A picture of Hidden Valley Dolomite in handsample and thin section scales. This sample was collected along the fault zone toward the southeastern part of the study area (Fig.1.3). The two scales are strikingly similar in displaying sharp, angular dolomite fragments surrounded by dolomitic matrix.

100um

Figure 3.3. Picture of Hidden Valley Dolomite in handsample and thin section scales. This sample was collected along the fault zone toward the northwestern end of the study area (Fig.1.3). The clasts and matrix of the handsample are dolomite. The thin section shows dolomite clasts surrounded by a matrix composed of very fine, ground fragments of dolomite

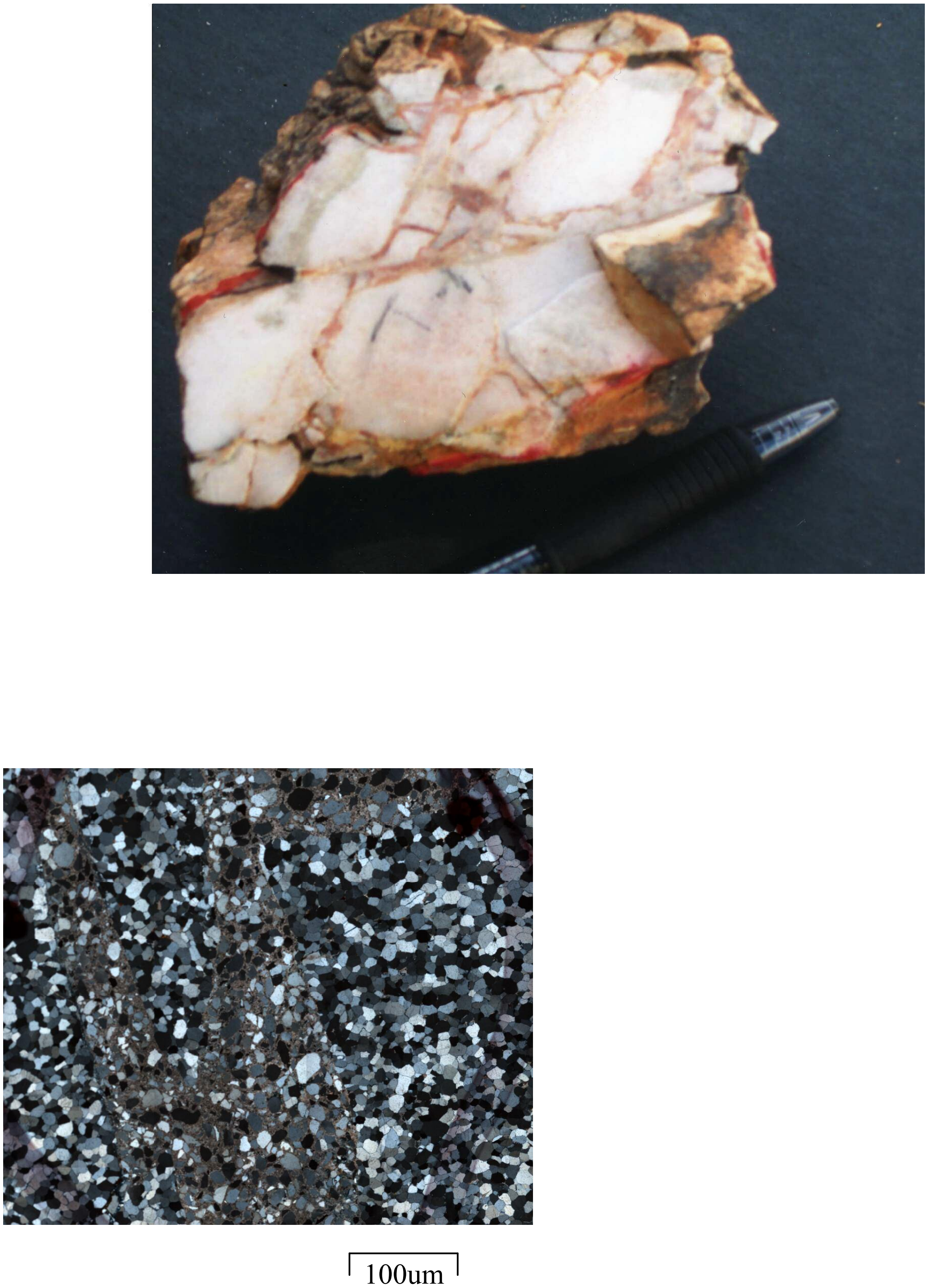
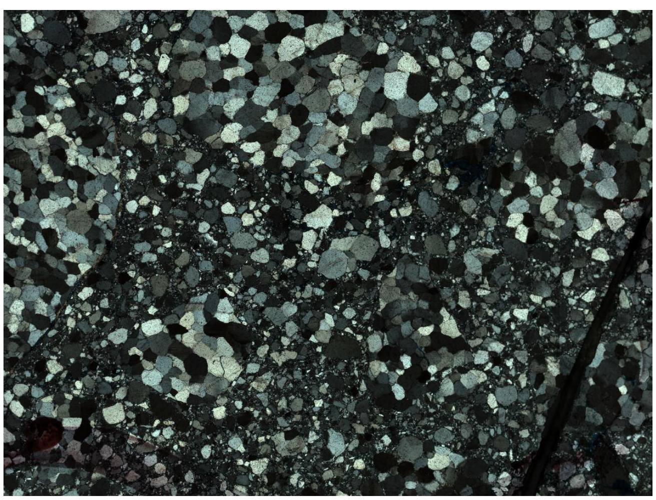


Figure 3.4. Picture of Eureka Quartzite in handsample and thin section scales. This sample was collected along the fault zone toward the northwestern end of the study area (Fig.1.3). The handsample shows quartz clasts surrounded by quartz matrix. The thin section shows quartz clasts surrounded by matrix composed of ground up fragments of quartz.



100 um

Figure 3.5. Picture of Eureka Quartzite thin section scale. This sample was collected along the fault zone in the southeastern part of the study area (Fig.1.3). The picture shows sharp, angular quartz fragments surrounded by matrix composed of ground up quartz grains.

100um

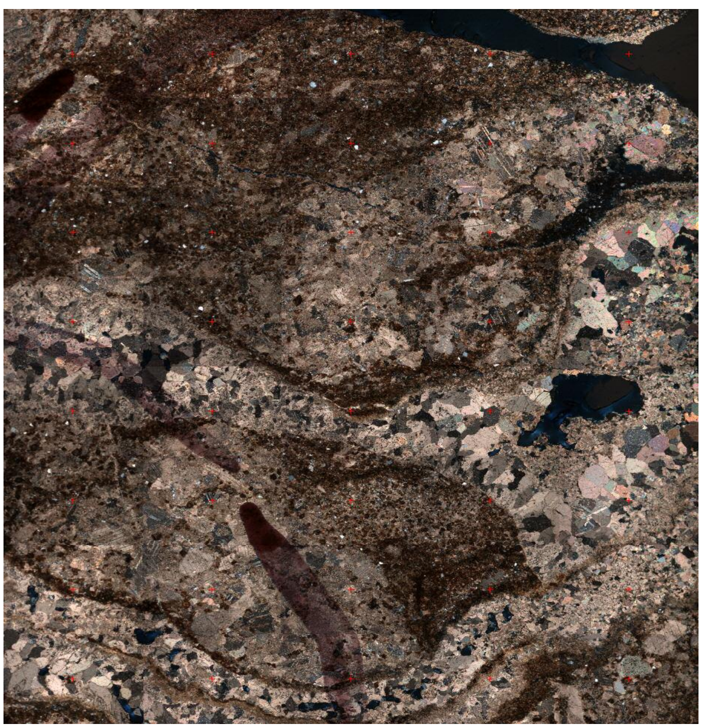


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Figure 3.6. Picture of Pogonip limestone at thin section scale. This sample was collected along the fault zone in the southeastern part of the study area. This sample shows calcite crystals that formed within the pore space. This is often a product of cataclastic flow.

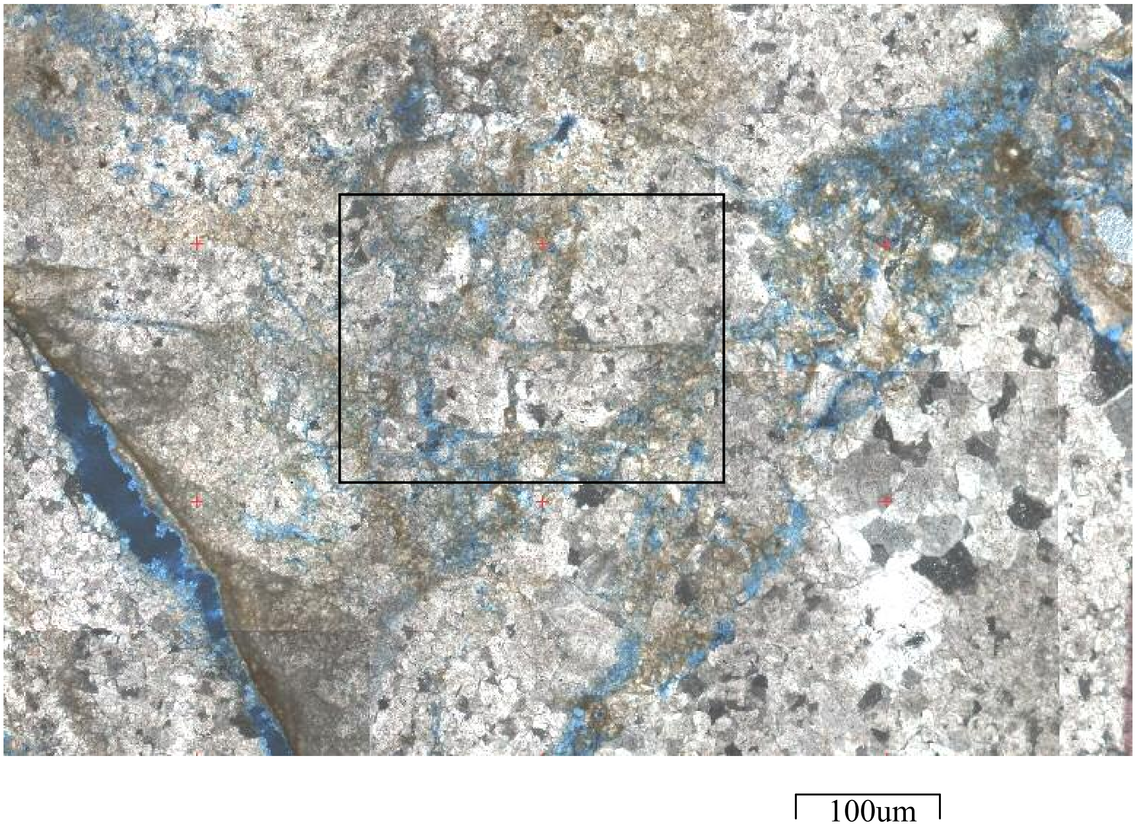


Figure 3.7. Picture of Ely Springs Dolomite at thin section scale of about 600 micrometers. This sample was collected along the fault zone at the northwestern part of the study area. Within the box is a small fracture that has been offset by right-lateral shear which matches the right-lateral movement along the Furnace Creek Fault zone

Chapter Four

Microprobe Analysis

To strengthen the hypothesis that the breccias along the fault zone in the Travertine Point area are fault-related, two rocks were analyzed using the OSU JEOL Electron Microprobe. As stated in Chapter 3, breccias formed by cataclastic flow along a fault zone show remarkable similarities of texture and fragment angularity at all levels of microscopy. The objective of this chapter is to show the consistency of fault-related characteristics at an even smaller scale. This chapter presents the results obtained with the microprobe on two thinsection samples of the brecciated Paleozoic sedimentary rocks along the Furnace Creek fault zone. The first is a sample of Ordovician age Eureka Quartzite. It was collected at 36^0 23'30"N and 116^0 40'00"W in the northwestern part of the study area (Fig. 1.3). The other is a sample of Devonian age Hidden Valley Dolomite which is referred to as sample 8. It was collected in the southeastern part of the study area at 36^0 21'30"N and 116^0 39'30"W (Fig.1.3). The goal of these analyses is to qualitatively compare the chemical compositions of different clasts within the samples and to compare the compositions of the surrounding matrix to that of the clasts.

Two thinsections were cleaned and coated with a thin layer of conductive carbon. Both samples were imaged using backscattered electrons (BSE) (Fig. 4.1 and 4.2). In this process a high-energy electron beam impacts a specimen. Electrons that are deflected off the nucleus of atoms in the sample are referred to as backscattered electrons (Reed, 1996). The microprobe operated using 15 nA beam and 15 KV accelerating potential. The samples were qualitatively analyzed using an Energy Dispersion Spectrometer (EDS) (Fig. 4.3-4.6). The objective of this analysis is to display the qualitative concentration of a particular element based on the number of X-rays produced when impacted by the electron beam. The dolomite sample was X-ray element mapped in magnesium and calcium (Fig. 4.7 and 4.8).

4.1 Quartzite Analysis

The BSE image of the quartzite sample (Fig. 4.1) shows dark gray regions representing clasts, a light gray region representing the cement, and the black representing pore space. According to Jackson and Bates, (1984), cement is "chemically precipitated mineral material that occurs in the spaces among the grains of a sedimentary rock" while matrix is "the finer-grained material enclosing the larger grains in a sedimentary rock". The region in between the clasts is referred to as cement because the material fills the entire space between the quartz crystals and the parallel orientation of the micro-striations within the lighter material. This shows evidence of chemical precipitation of mineral material due possibly to fluid flow within the fault zone. The chemical analysis in Figure 4.3 represents both the cement and clasts, which shows large silicon and oxygen peaks and a small calcium peak. The lighter color of the cement could be explained by a trace element that escaped detection by the EDS. The image produced in Figure 4.1 shows sharp angular quartzite clasts separated by quartzite cement with little porosity. These results show that the clasts are entirely quartzite and the cement is composed of quartz with an unknown trace element, possibly iron or calcium. The homogeneous chemical composition of all the clasts and a similar composition of the cement are consistent with the observations of the mesoscopic and microscopic scales in the previous chapter.

4.2 Dolomite Analysis

The BSE image produced for the dolomite sample (Fig. 4.2) shows larger amount of pore space compared to the quartzite sample. This image shows three distinct colors with each color representing a certain distances from the pore space. The black represents the pore space, while the dark represents an area rich in magnesium and the light areas represent regions rich in calcium. Three EDS were produced. The first represents the light region adjacent to a pore and the other two are positioned further away.

Fig. 4.4 represents the area adjacent to the pore within the light region of the sample. This area displays a large calcium peak relative to magnesium. Fig. 4.5 shows an area that is within the light region but further away from the pore space. In this area, oxygen is the largest peak, whereas the calcium and magnesium are about equal heights.

Figure 4.6 displays the area of the dark region on the dolomite sample. In this area the oxygen peak is dominant followed by the magnesium peak. Calcium shows the smallest peak. This relationship between composition and position relative to the pore space is a strong indication that the calcium content decreases moving away from the pore space.

Two X-ray element maps of calcium and magnesium were produced on the dolomite sample (Fig. 4.7 and 4.8). The higher concentration of calcium is adjacent to the pore space with decreasing concentration further toward the center of the grain, confirming what the EDS displayed. The higher concentration of magnesium is dispersed throughout the interior of the grain. Its concentration decreases closer to the pore space where the calcium concentration increases. This image is also in accordance with the EDS produced on this sample.

4.3 Results

The analysis of the quartzite sample showed clasts of one composition and a cement that was slightly different, in the BSE images. If these breccias formed by landslides, then it would be expected to contain clasts of all five rock types in the study area. A foreign cement would be expected to be present instead of one that is similar to the clasts.

The ductile characteristic of dolomite explains the presence of the porosity found in the dolomite samples. A rock that has been deformed by ductile deformation in a shear zone may experience fluid-related softening. This can occur when fluid-flow such as in cataclastic flow, dissolve grains that would normally resist deformation resulting in pore space. Calcite has been known to form within the porosity as a product of continual fluid flow within the shear zone (Davis and Reyonlds, 1996). In this case the calcium-rich region surrounding the pore space with the magnesium concentration increasing in direct proportion to the distance from the porosity is interpreted as a product of cataclastic flow within a fault-zone.

Although the results found in this analysis cannot alone prove a fault-related origin for the Travertine Point breccias, they do show that the texture, composition, and angularity of the rock fragments are consistent at all levels of microscopy, which is a characteristic of breccias produced by cataclastic flow.

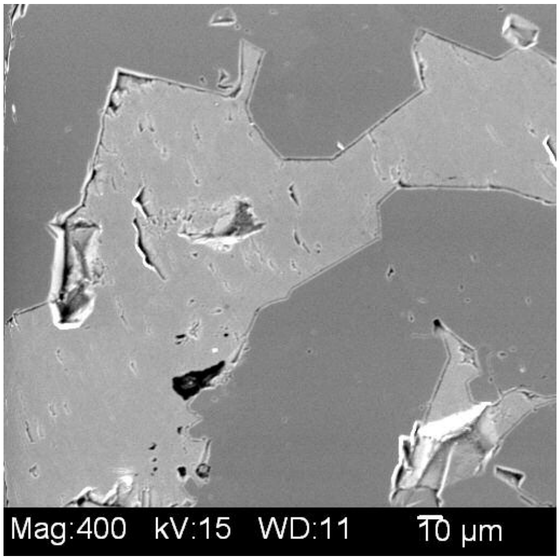
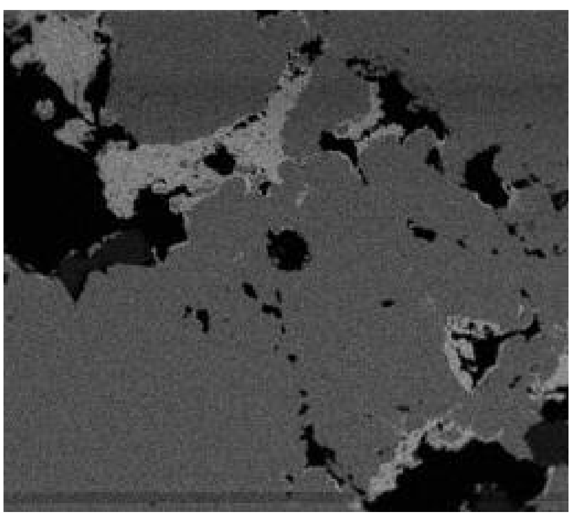


Figure 4.1. Backscattered electron image produced for Eureka Quartzite (sample T-1). The image shows the dark gray area as quartz clasts, the lighter gray quartz cement, and the black cracked areas in the center are pore spaces.



10 um

Figure 4.2. Backscattered electron image produced for Hidden Valley Dolomite (sample 8). This image shows a larger area of pore space than the quartzite sample. The black area represents pore space, the dark area represents an area rich in magnesium, and the light area represents an area rich in calcium.

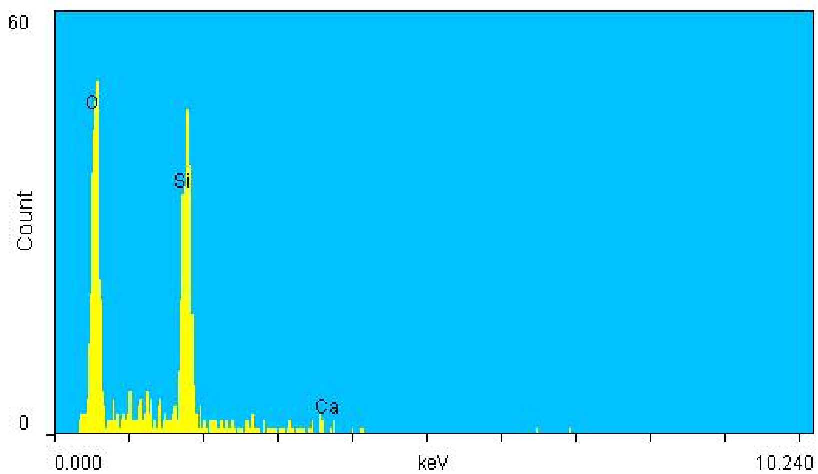


Figure 4.3. EDS showing the chemical analysis of clasts within a sample of Eureka Quartzite.

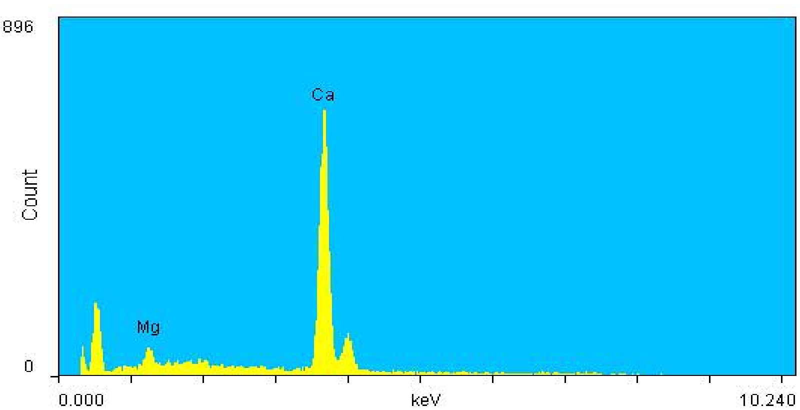


Figure 4.4. EDS showing the chemical analysis of a sample of Hidden Valley Dolomite. The area the tested was adjacent to the pore space showing a high concentration of calcium and a low concentration of magnesium.

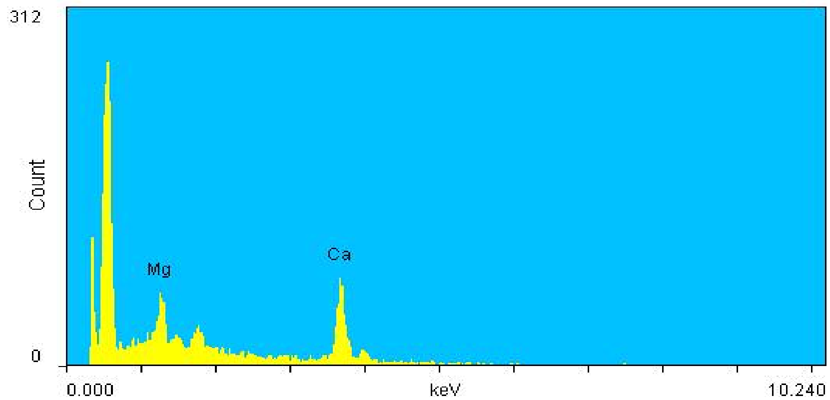


Figure 4.5. EDS showing the chemical composition of a sample of Hidden Valley Dolomite. The area tested was toward the center of the grain showing about equal concentrations of magnesium and calcium.

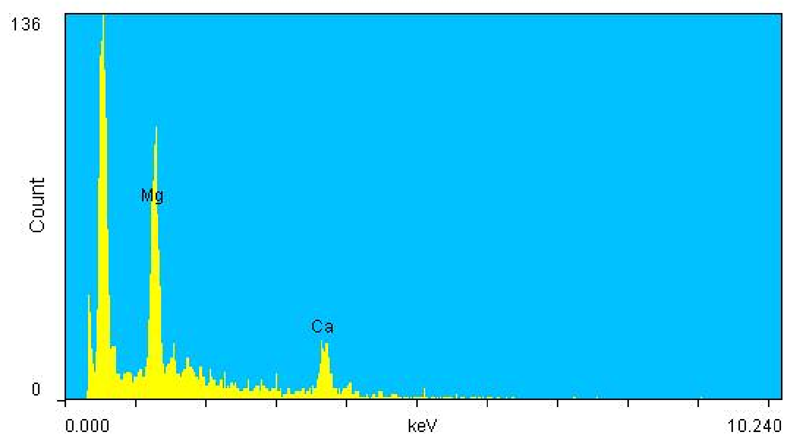


Figure 4.6. EDS showing the chemical composition of a sample Hidden Valley Dolomite. The area tested was further away from the pore space that in figure 4.5. This area shows a considerable higher concentration of magnesium than the EDS taken closer to the pore space.

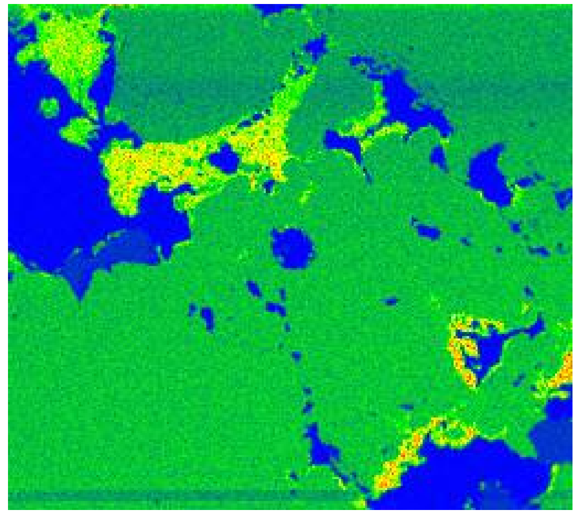


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Figure 4.7. X-ray element map of a sample of Hidden Valley dolomite taken for calcium. The image shows a high concentration of brighter colors around the pore space (blue areas).

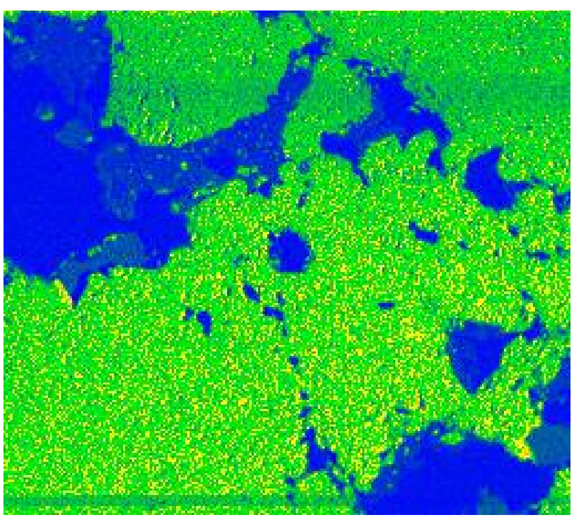

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Figure 4.8. X-ray magnesium map of the same Hidden Valley dolomite. The image shows a high concentration of brighter colors dispersed throughout the grain (green areas)

Chapter Five

Structural Geology

The structure of the FCFZ is characterized by right-lateral strike-slip movement combined by vertical displacement produced by the extensional component. Although both sides of the fault experienced extension as fault movement transpired, the southwest side experienced a higher magnitude of extension and thus being downthrown to form the Furnace Creek Basin (Cemen et al., 1985).

5.1 Displacement Along the Furnace Creek Fault Zone

The magnitude and timing of extension in the Death Valley region can be measured directly by the amount of displacement along strike-slip faults in the region. The debate over the magnitude of displacement along the Death Valley-Furnace Creek Fault zones emerged in the late sixties with the “large displacement” verses the “small displacement interpretations. Steward (1967) estimated as much as 50 miles of displacement in Central Death Valley with the open ended possibility of more. Lines of evidence for this reasoning included displaced isopach and facies lines in formations in the following ages: Precambrian, Cambrian, Devonian, Silurian, and Mississippian. Stewart (1967) and Stewart et al.(1968) also estimated in the Northern Death Valley area, north of the confluence of the Death Valley and Furnace Creek fault zones, that displacement is about 50 miles. This estimation is based on offset facies in the lower

Cambrian Zabriskie Quartzite. McKee (1968) agreed with this estimate on the basis of displaced granitic rocks in the White Mountains area and Precambrian and lower Paleozoic facies in the Death Valley region. Wright and Troxel (1967) also correlated several linear features that cross both the Death Valley and Furnace Creek fault zones, which indicated little to no displacement. These features include Precambrian paleogeologic contacts, a belt of talc mineralization, and an algal dolomite unit. According to their observations "right-lateral, strike-slip movement of 10 or more miles on the Death Valley fault zone, if restored would anomalously juxtapose the clastic wedge with a terrane in the Panamint Range where the 'algal' dolomite is preserved".

Wright and Troxel (1970) maintained their earlier maximum limit of 10 miles of displacement along the Furnace Creek fault zone, but added more evidence to support their estimate. First, the isopach difference claimed by Stewart (1967) to be fault-related, could actually be attributed to westward stratigraphic thinning since the data points used in their interpretation were widely spaced. Second, the evenly spaced and straight isopachous contours constructed by Stewart (1967) would require an extremely stable depositional environment. Wright and Troxel (1970) observed that the formations beneath the mapped area display clues for crustal instability thus creating a fairly unstable depositional environment for the younger formations.

The most substantial observation Wright and Troxel (1970) added was the presence of larger northwest extension on the southwest side of the Furnace Creek fault zone. Lines of evidence for this interpretation include the abundance of northwest trending normal faults, magma bodies on the southwest side of the fault zone, and the presence of Furnace Creek Basin deposits all of which are missing in the Grapevine and Funeral Mountains on the northeast side.

Differential extension on opposite sides of the fault helped reconcile seemingly conflicting data in that it lead to developing the interpretation of progressive displacement of zero displacement at the southeastern end to around 50 km north of the northern end of Death Valley (Cemen et al.1985). The amount of northern displacement was derived from McKee (1968) who based it on the existence of a pluton that is Jurassic in age and is found on both sides of the fault with an offset distance of about 50 km. This interpretation allows 10 km of displacement within the Furnace Creek Wash area (Cemen et al.1985), based on the existence of Paleozoic sedimentary rocks found on both sides of the fault. When these rocks are restored to juxtaposition with the differential extension considered, the required distance is no more then 10 km (Cemen et al.1985).

Stewart (1983) modified the earlier "large displacement" interpretation by comparing the different mountain ranges in the area. This hypothesis states that Proterozoic to Mesozoic rocks of the Panamint Range were once overlying the Proterozoic strata of the Black Mountains and were detached and transported 80 km to the northwest driven by the combined right lateral displacement along the Furnace Creek fault zone and left-lateral displacement along the Garlock fault zone (Fig.1.2).

As a major piece of evidence for this hypothesis is a 10km-thick section of Precambrian and Paleozoic strata. This strata is exposed in the Panamint Range, Funeral Mountains, Resting Springs Range, and Nopah Range, while it remains suspiciously absent in the Black Mountains. Stewart (1983) maintains that this strata is missing as a result of tectonic transport and not erosion since appropriately thick sedimentary debris produced by an erosional event of that magnitude have not been found. He also finds problematic that this strata was eroded in the Black Mountains area but preserved in the remaining mountain ranges. Cemen et al. (1985), however, proposed that the late Proterozoic to late Paleozoic strata was transported by sedimentary processes to the northeast and were deposited as several conglomerates of the Bat Mountain area, especially the large conglomerate member of the Bat Mountain Formation.

Cemen et al. (1999) and Wright et al. (1999) provided more evidence for the small displacement hypothesis as they explained tectonostratigraphic evolution of the sedimentary rocks in the southeastern Funeral Mountains and the Furnace Creek Basin, respectively.

Neimi et al. (2001) modified the “large displacement” hypothesis to over 100 km of northwest translation of mountain blocks. The main evidence presented by Niemi et al., (2001) is the apparent proximal depositional source of Eagle Mountain and Resting Springs Range being the Hunter Mountain Batholith about 104 km to the northwest. Based on compositional analysis of conglomerates at the Eagle Mountain and Resting Springs, they claim that the conglomerates were deposited proximal to Hunter Mountain and transported 104 km to the northwest as a result of strike-slip faulting and extension. The analysis of the conglomerates also shows a fairly homogenous composition implying a lack of dilution by other sources and that transport by sedimentary processes was less than 20 km. The conglomerates also were found to contain tephra clasts that were 40Ar/39Ar dated ~11.6Ma and older. Cemen et al. (1999) and Wright et al.(1999) however have proposed that southwest transport of the Hunter Mountain Batholith fragments along the Furnace Creek Wash is due to the presence of a fluvial system which is the dominant sediment environment in the Artist Drive Formation from 14 Ma to 6 Ma.

Cemen and Baucke (2005) have established piercing points on the southwestern and northeastern sides of the Furnace Creek fault zone. On the northeast side is the Clery Thrust located in the southern Funeral Mountains. It brings Cambrian Bonanza King Formation over Ordovician Eureka Quartzite and Ely Springs Dolomite. A similar fault contact has been observed on the southwest side of the fault zone near Desolation Canyon. These two areas are separated by 30+/- 5 km and are considered to be a continuous fault structure that has been offset by right-lateral displacement along the Furnace Creek fault zone. Establishing the Travertine Point breccias as fault-related strengthens this hypothesis by allowing the fault zone to be solidly mapped through the area, thus making it easier to connect these two points.

5.2 Geometry of the Furnace Creek Fault Zone

Plate 2 shows a cross section along the up thrown northeastern side of the fault zone along A-A’ (Plate 1). There is a relative lack of basin deposits on the northeastern side of the fault. A small amount of Furnace Creek mudstone is exposed in the middle of the cross section and on the geologic map just to the southwest there exists small remnants of the upper sedimentary member of the Artist Drive Formation. The lack of Funeral aged deposits shows evidence that the northeast side was a structural high during the last stages of basin sedimentation.

On the same side, remnants of folds from a Mesozoic compressional event were preserved. On the northwest end of the cross section, Cambrian formations such as the

Nopah, Bonanza King, and Carrara are dipping about 20^o NW. Moving to the southeast shows these same formations along with Ordovician Pogonip dipping about 20^o SE. This dip direction remains until the southeast side of the basin deposits, where the Ordovician and Cambrian formations are dipping about 10^o NW. The dips change again at the southeast end of the cross section as the beds dip about 35^o SE. The alternating dip directions show signs of a preserved anticline/syncline series which is a remnant of the Schwaub Peak thrust and compressional feature formed during the Late Creteceous Sevier Orogeny. The Mesozoic compressional anticline/syncline pair was cross cut by Cenozoic high angle listric normal faults that trend in a northeasterly direction and dip to the northwest and southeast. This shows evidence that the northeast side was extended but the lack of basin sedimentation along with the compressional structures remaining in tack shows that it was extended less than the southwest side.

The structure map (Plate 1) of the southeast portion of the Furnace Creek Wash was produced for the purpose of placing the study area in a larger context. The map is a combination of three separate mapping projects. McAllister (1970) provided data for the geology of the Furnace Creek Basin on the southwest side of the fault zone and the Funeral Mountains to the northeast. The research area was re-mapped in greater detail in this study.

Chapters 3 and 4 have shown that the Paleozoic rocks between the basin and the Funeral Mountains are consistent with fault brecciation. The fault breccia origin of these rocks allows more control in mapping the Furnace Creek Fault Zone through this area since McAllister traced the fault zone southwest along the Furnace Creek Wash down to the present research area but went no further. Interpreting the rocks as fault breccia also allows more control to estimate the condition of the Paleozoic rocks along the fault zone at depths greater than 6000 feet below the surface.

5.2.1 Mapping the fault zone

The rocks within the northeast boundary of the fault zone are heavily brecciated while the ones while the ones outside the fault zone do not display much brecciation. Tracing the southwestern boundary of the fault zone was difficult due to the heavy extension that side of the fault experienced. Mapping the area in greater detail allowed more faults to be mapped, all of which trend northwest parallel to the fault zone. When the map of the study area was inserted next to the previous map, the newly mapped faults were found to be subparallel to the previously mapped faults of the Furnace Creek fault zone.

As alluvium cover increased to the southeast fault detection becomes more obscure. At the southeast end of the research area, control for tracing the fault zone relies on clues hidden in the Funeral basalt. Because the basalt is a basin constituent, the fault must trace to the north of a patch of basalt about a square mile just south of the research area. Folds within the basalt are also valuable clues to fault detection. Folds through out the basin have been classified by Wright and Troxel (1984) as extensional folds parallel to fault movement. This is a confirmation of McAllister's map (1970) of the basin which shows folds through out the basin parallel to fault movement. Using this as a guide, the fault zone boundary was placed roughly perpendicular to the northwest trending syncline within the basalt on the southwest side of the fault zone.

5.2.2 Subsurface along the fault zone

The remaining three cross sections are on the basin side of the Furnace Creek fault zone (Plates 3-5) and place the brecciated Paleozoic sedimentary rocks in their structural context. Listric normal faults trending northwest and dipping about 60^{o} -70^{o} SW and NE cut through the Paleozoic rocks. All of the basin units are present through the Pleistocene Funeral Formation. The Bonanza King Formation is placed unconformably below the Artist Drive Formation. Wright et al. (1999) also observed this contact both at the surface and in the underground workings at the Billie borate mine. They noted that the Paleozoic sedimentary rocks from the Cambrian Bonanza King through the Cambrian Wood Canyon were heavily brecciated at the surface as well as the subsurface based on both vertical and horizontal drilling within the mine. Based on that evidence, the cross sections show the Paleozoic rocks along the fault zone heavily brecciated both at the surface and underground. This implies they were brecciated as a result of fault movement, which petrographic analysis has confirmed in chapters 3 and 4.

Plates 3 and 4 are cross sections along B-B’ and C-C’ respectively trending northeast through the southern and northern ends of the study area. Therefore they cut through the brecciated basement rocks at the surface. Because these rocks are now considered within the fault zone, it can be hypothesized that the Paleozoic basement rocks are also brecciated at depths greater than 6000’ below the surface.

Plate 5 is a cross section along D-D’ trending northeast. It is northeast of the study area and cuts through the fault zone in a region covered with alluvium. An exposure of a unit of the Furnace Creek Formation at the southwestern boundary of the fault zone allowed control of where the stratigraphy began. As a result the unconformity between the oldest Artist Drive unit and the Bonanza King Formation was projected at about 7000 feet below the surface. The basement rocks are hypothesized to be brecciated since they lie within the fault zone.

Chapter Six

Conclusions

The purpose of this thesis is to produce a detailed study of the Travertine Point area along the Furnace Creek fault zone, which can be used to piece together the geologic history of the region and help solidify the amount of displacement along the fault zone The conclusions of this study consist of the following:

1. Analysis of the conglomerate to mudstone sequence found in the study area and measured in this study, shows evidence of a fluvial system flowing from an unbrecciated source to the faulted area. This is evidenced by clasts that are moderate to well rounded, from heterogeneous sources surrounded by a foreign calcite matrix. The system initiated as high energy and gradually transitioned into relatively lower energy. Since the sequence is cross cut by fault displacement, the fluvial system must have been active for much of the fault movement.

2. Petrographic analysis of the Travertine Point breccias reveals that they were produced by cataclastic flow as fault breccia along the Furnace Creek fault zone characterized by right-lateral shear. This is based on several lines of evidence. One is the sharp, angular clasts surrounded by matrix composed of even smaller crushed grains of the same composition. Another is the remarkable similarities at all scales of observation which includes the measured angles of the rock fragments. Other lines of evidence such as calcite veins within the pore space, and the right-lateral sense of shear at the thin section level strongly support this interpretation.

3. Electron microprobe analysis of the quartzite breccias shows that the clasts and cement are of similar chemical composition and confirmed that the areas around the pore space in the dolomite was more calcium-rich than the intra-grain area which proved to be more magnesium-rich. This again supports the interpretation of cataclastic flow along a fault-zone and fault breccia classification for the Paleozoic breccias.

4. If 100 km of displacement along the fault is possible than these basement rocks should not be juxtaposed on both sides of the fault. The presence of the fluvial system within the study area strengthens the idea that transport of sediment greater than 20 km from the source is not unlikely. All evidence in this study strengthens the hypothesis estimating a displacement at or smaller than 50 km along the Furnace Creek Wash.

5. The cross section on the northeast side of the fault-zone reveals a pre-extension anticline/syncline pair that has been preserved despite being cross cut by Cenozoic extension. This indirectly shows more evidence that the northeastern side of the fault experienced extension of less magnitude than the southwestern side. The remaining cross sections show the Paleozoic Bonanza King lying unconformably beneath the oldest basinal deposit. It along with the subsequent basement rocks have been brecciated along the fault zone.

6. The brecciated Paleozoic rocks being a product of fault movement allows more control in tracing the Furnace Creek Fault Zone in much greater detail through the research area.

6.1 Future Studies

Future studies of this region should include similar analysis of the Paleozoic rocks exposed to the northwest of the study area along the fault zone to see if consistent results can be obtained. The Red Amphitheater to the northeast of the study area needs to be reconsidered in light of what was revealed in this study.

The interpretation of the Travertine Point breccias being fault-related would be strengthened if electron microprobe analyses could be conducted on the Bat Mountain landslides to the southeast of the Travertine Point area. This would display a contrast of landslide breccia to that of fault breccia at the microscopic level.

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