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I, Nicholas Ferry, hereby submit this original work as part of the requirements for the degree of Master of Science in Geology.

It is entitled:

**Role of a Rigid Bedrock Substrate on Emplacement of the Blue Diamond
Landslide, Basin and Range Province, Eastern Spring Mountains, Southern
Nevada**

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Role of a Rigid Bedrock Substrate on Emplacement of the Blue Diamond Landslide, Basin and Range Province, Eastern Spring Mountains, Southern Nevada

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by

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Abstract

Rock avalanches are high velocity mass movements of fragmented rock that experience unusually long runouts. Emplacement of rock avalanches have been studied for over a century, yielding many explanations for their enhanced mobility. Whereas most of these hypotheses address intrinsic mechanisms, few have addressed the influence of runout path substrate material. This study investigates the role of a rigid bedrock substrate in the emplacement of the Blue Diamond landslide deposit.

To better understand the role of the runout path material, facies analyses were conducted at exposed remnants of the landslide breccia. Observed sedimentary fabrics and internal morphologies were identified and mapped following standard facies models for large-rock avalanche deposits. The presence of basal fabrics and morphologies rules out a frictionless emplacement because they represent prolonged interactions at the rock avalanche – substrate interface. This suggests that the rock avalanche endured significant basal shear resistance during motion; however, conservative H/L estimates indicate a low to moderate basal resistance was experienced.

Aided by outcrop mapping, clast count data from 120 stations across the deposit shed light on intrinsic mechanisms that occurred in the slide mass. Correlations between matrix and carbonate count frequencies show that areas with more matrix experience substantial amounts of fragmentation and comminution. It is likely that basal shear stresses were transmitted upward through the rock mass during emplacement which is seen in the vertical transition from matrix-

rich to matrix-poor breccia facies. Observations of proportional breakage and enhanced mobility may best be explained by the process of dynamic fragmentation.

Uncertainties surrounding the originally interpreted genesis and distribution of the landslide deposit led to an alternate emplacement hypothesis. I propose that the landslide breccia was derived from slightly north of the previously suggested source area and slid into the Blue Diamond Hill site where it was deposited onto Moenkopi Formation. Afterward and over some time, the underlying Moenkopi Formation experienced gravity gliding as it slid from the Blue Diamond Hill site to its current position in the Blue Diamond area, taking the landslide breccia with it. However, more field observations are needed to validate this secondary emplacement hypothesis.

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Table of Contents

Abstract	ii
Copyright	iv
Acknowledgements	v
List of Figures	vii
List of Tables	viii
List of Appendices	ix
1. Introduction	1
2. Geologic Setting	7
3. Methods	25
4. Results	31
5. Discussion	48
6. Conclusions	60
7. References	62
8. Appendix A	70
9. Appendix B	104

List of Figures

Figure 1: Map of known mega-landslide deposits in the Basin and Range Province	3
Figure 2: Map of southern Nevada and study location in Blue Diamond area, Nevada	6
Figure 3: Map of Sevier thrusts in the Spring Mountains	9
Figure 4: Stratigraphic units exposed in the Blue Diamond area and adjacent Spring Mountains	18
Figure 5: Map of exposed remnants and original distribution of Blue Diamond landslide	20
Figure 6: Deposit exposures at proximal, medial and distal zones	21
Figure 7: Main clast types of the Blue Diamond landslide breccia	23
Figure 8: Bar charts depicting clast distributions throughout the Blue Diamond landslide breccia	31
Figure 9: Scatter plot of carbonate vs matrix frequencies	32
Figure 10: Schematic of idealized morphology of large rock avalanche deposits	38
Figure 11: Proximal zone sedimentary fabrics and deposit morphologies	40
Figure 12: Medial zone sedimentary fabrics and deposit morphologies	42
Figure 13: Distal zone sedimentary fabrics and deposit morphologies	44
Figure 14: XRF sample locations and their chemical compositions	47
Figure 15: Maps of several Blue Diamond landslide hypotheses	58
Figure 16: Conceptual model of emplacement of Blue Diamond landslide	59

List of Tables

Table 1: Numerical example of the statistical ranking method.....	29
Table 2: Total clast count data.....	32
Table 3: Errors associated with clast counting	34
Table 4: Clast distribution ranking table	37
Table 5: XRF composition ranking table	37
Table 6: Basal mixed zone matrix XRF compositional data	46

List of Appendices

Appendix A: Clast Count Data and Locations	70
Appendix B: Samples, Facies, and XRF Data	104

Introduction

Landslides are common in regions of high relief and occur in many different environments. Although they tend to be initiated by destabilizing tectonic events, slope failure can occur as climatic and geologic conditions change over time (Keefer, 1994). Landsliding processes and deposits play a fundamental role in delineating the geomorphic and geologic change of an impacted area (Nicoletti and Sorriso-Valvo, 1991; Nichols et al., 2006). Understanding the interaction between the rock avalanche body and runout path material can aid us in interpreting the mechanisms controlling large rock avalanche emplacement (Aaron and McDougall, 2019).

Mega-landslides (herein defined as covering more than 1 km²) have both fast and slow emplacement mechanisms (Beratan, 1998), called large rock avalanches and gravity slides, respectively. Large rock avalanches are one of the most destructive types of landslides (Siebert, 1984; Yarnold and Lombard, 1989). Despite being poorly understood, catastrophic and gravity driven landslide deposits have been recognized in the field (Burchfiel, 1966; Friedmann, 1997). Catastrophic landslides are thought to have been rapidly emplaced because they display a set of distinguishable features that portray pervasive internal brecciation. Gravity driven landslides are thought to occur over a significant period of time because they lack the pervasive internal brecciation observed in rapidly emplaced landslides (Beratan, 1996; Davis and Friedmann, 2005).

Mega-landslide deposits reside on the surface and in the subsurface throughout the Basin and Range province of the western United States (e.g., Longwell, 1951; Shreve, 1968; Miller and John, 1988; Castleton et al. 2016) (Figure 1). Many of these deposits are classified as rock

avalanche breccias, which are sedimentary breccias that form through mass wasting events caused by catastrophic slope failure. Rock avalanches are known to travel up to 100 m/s during their emplacement process, carrying more than 100 m³ of heavily fragmented debris up to 20 km from their source area in a matter of seconds (Harrison and Falcon, 1937; Pierson and Costa, 1987; Hewitt et al., 2008; Dufresne et al., 2016). A key characteristic of rock avalanches are their long runout distances relative to their mass and height of drop (Heim, 1882; Howard, 1973; Hsü and Voight, 1978; Melosh, 1987; Legros, 2002). Whereas the mechanisms behind these long runouts are not well understood, the relationship between the height of drop and runout length influence their mobility and morphology (Yarnold and Lombard, 1989; Friedman, 1997; Shea and van Wyk de Vries, 2008; Dufresne et al., 2009).

Several models have been developed to explain the excessive mobility of large rock avalanches. Most of the models address internal mechanisms that occur during emplacement. The intrinsic models include: air cushion mobility (Shreve, 1968), frictional heating (Erismann, 1979; Goren and Aharonov, 2007; Hu et al., 2019), acoustic fluidization (Melosh, 1979; Johnson et al., 2016), and dynamic fragmentation (Davies et al., 1999; Davies and McSaveney, 2009). One model that accounts for external factors suggests that substrate interactions play a role in the mobility of large rock avalanches (Hungr and Evans, 2004; McDougall and Hungr, 2005; Schneider et al., 1999; Pollet et al., 2005; Dufresne et al., 2010; Whittall et al., 2017; Aaron and McDougall, 2019).

Figure 1. Some of the known mega-landslide deposits in the Basin and Range and the degree of their study (courtesy of Dr. Daniel Sturmer). The Blue Diamond mega-landslide (subject of this study) is pointed out on the map.

The dynamics of rock avalanche emplacement influence the deposit characteristics and any hazard to people. Due to their long runout distances they pose a potential hazard to areas significantly far (10's of km) from the source area (Goren and Aharonov, 2007; Hungr et al., 2014). The extreme internal brecciation they experience results in exceptional porosity and permeability, giving them potential to be excellent fluid reservoirs following burial (French and

Schalla, 1998; Moore and Herbertson). Because they can be laterally constrained, large rock avalanches can be used as a tool for reconstructing the tectonic history of a basin (Topping, 1993). However, the flow dynamics during emplacement are poorly understood (Shreve, 1968; Erismann, 1979; Melosh, 1979; Davies et al., 1999; Aaron and McDougall, 2019). The distribution of sedimentary fabrics and morphologies in heterolithic rock avalanches provide a window into flow dynamics within the deposit.

One such deposit that can be used to understand the emplacement dynamics of large rock avalanches is the Blue Diamond landslide, southern Nevada. Remnants of the deposit are exposed along the foothills of the Spring Mountains in the Blue Diamond area (figure 2b) in the westernmost part of the Las Vegas Valley, southern Nevada (Figure 2a). This deposit is a heterogeneous large rock avalanche megabreccia that consists primarily of Paleozoic carbonate clasts with minimal amounts of Mesozoic siliciclastic clasts that tend to be concentrated in the basal portion of the deposit (Page et al., 1998). Some sections of the deposit have lenses of clasts composed of one rock type surrounded by breccia of a different rock type (Page et al., 1998). Additionally, Page et al. (1998) noted that in some cases these lenses are offset by shear planes within the slide.

In this study I used multiple techniques to interpret the mechanisms that control the mobility and comminution processes of the Blue Diamond heterogeneous large rock avalanche deposit. Compositions and textures of the megabreccia deposit were described and used to determine lateral zonation and interpret emplacement mechanisms. Statistical analyses were applied to clast count data to quantify the changes of clast proportions with increasing transport distance, enabling establishment of a paleotransport direction and a better constraint to the

degree of comminution. These data were aided by XRF analysis of selected samples from the basal matrix material. Together, these data provide an insight into the mechanisms behind the mobility and emplacement of the Blue Diamond landslide.

Figure 2. a) Index map of southern Nevada showing location of figure 2b (Image modified from USGS National Map Database); b) Location of the Blue Diamond mega-landslide and its proximity to Las Vegas, Nevada.

Geologic Setting

Spring Mountain Tectonism

Sevier Orogeny

The Sevier orogeny is characterized by formation of stacked thin-skinned thrust plates and associated folds that form the substrate and source area for the Blue Diamond landslide. Deformation was initiated by a combination of contractional plate-convergence and conductive heating of the crust by eastward Farallon slab subduction that resulted in nearly 140 kilometers of shortening (Armstrong, 1968; Fleck, 1970; Allmendinger and Jordan, 1981). Cretaceous subduction from the west caused crustal thickening and broad uplift resulting in up to 3km of elevation in the Sevier orogenic hinterland (e.g., Decelles, 2004; Decelles and Coogan, 2006; Busby and Putirka, 2009). Tectonic reconstructions indicate that central Nevada may have been a high elevation orogenic plateau commonly called the Nevadaplano (Coney and Harms, 1984; Ernst, 2009; Snell et al., 2014). As the Pacific-Farallon Ridge converged with the North American plate, the Farallon slab rolled back and the configuration of the plate boundary changed, resulting in late Cenozoic east-west extension that progressively collapsed the orogenic belt (e.g., Atwater, 1970; Wernicke et al., 1982, 1988; Atwater and Stock, 1998; Snell et al., 2014; Best et al., 2016; Cassel et al., 2018). The Sevier orogeny is characterized by east-vergent frontal fold and thrust belt structures that consists of low-angle décollement thrust faults that offset regional strata (Armstrong, 1968; Heller et al., 1986).

Sevier Thrusts in the Spring Mountains

Several Sevier frontal thrust faults and plates compose the Spring Mountains (Figure 3). The Spring Mountains are located on the west side of Las Vegas Valley. The Spring Mountains are dominated by three major north- to northeast-striking thrust faults that represent multiple periods of thrusting. The westernmost and structurally highest thrust fault in the stack is the Wheeler Pass thrust, which juxtaposes Neo-Proterozoic and Lower Cambrian rocks on overturned beds of the Permian Bird Spring Formation (Figure 3) (Fleck, 1970; Page et al., 2005). The Lee Canyon thrust cuts through the central part of the Spring Mountains, placing Cambrian Bonanza King Formation atop Permian Bird Spring Formation (Figure 3) (Fleck, 1970; Burchfiel et al., 1974). Perhaps the best exposed thrust faults in the region, the Keystone and Contact/Red Spring/Wilson Cliffs thrust(s) traverse the entire length of the Spring Mountains and place Cambrian Bonanza King Formation atop Jurassic Aztec Sandstone (Figure 3 and 4) (Axen, 1980; Burchfiel et al., 1997; Page et al, 2005). The easternmost and structurally lowest thrust fault in the stack is the Bird Spring thrust, which runs subparallel to the Keystone thrust where it places Paleozoic rocks atop Mesozoic rocks (Figure 3) (Hewitt, 1931, 1956; Page et al., 2005). As a result of Mesozoic thrusting, the rocks in the Spring Mountains experienced 36 – 75 km of regional shortening (Burchfiel et al., 1974).

Explanation

▲—▲ Thrust fault	■ Macks Canyon and Lee Canyon thrust plates
— Normal fault	■ Keystone, Red Spring, and Deer Creek thrust plates
■ Quaternary-Cenozoic rocks, undivided	■ Bird Spring thrust plate, semi-autochthonous rocks, and Frenchman Mtn
■ Wheeler Pass and Gass Peak thrust plates	■ Red Spring blocks
■ Sheep and Las Vegas Ranges	■ Las Vegas Valley shear zone

Figure 3. Map showing Sevier thrusts in the Spring Mountains and other major structures in the Las Vegas Valley area (modified from Page et al., 2005).

The Keystone, Contact/Red Spring/Wilson Cliffs, and Bird Spring thrusts are the structurally lowest thrusts in the Spring Mountains and appear in the Blue Diamond area (Hewitt, 1931; 1956; Carr, 1983; Page et al., 2005). The Bird Spring thrust crops out in the foothills of the eastern Spring Mountains (Figure 3). It extends nearly 30 km northward from the Bird Spring Range through the Blue Diamond area and terminates north of the La Madre fault (Figure 3). The upper plate places Permian redbeds above the Triassic Virgin Limestone and Moenkopi Formation in the lower plate (Page et al., 2005). The next structurally higher thrust(s) are the

Contact/Red Spring/Wilson Cliffs thrust faults and place Upper Paleozoic rocks over Jurassic Aztec Sandstone. These thrusts formed as one fault but are cut and offset by the La Madre and similar faults (Burchfiel et al., 1997). Structurally above them lies the Keystone thrust, which occurs along the entire eastern face of the Spring Mountains (Figure 3). The Keystone thrust juxtaposes Cambrian Bonanza King Formation atop Upper Paleozoic rocks or Jurassic Aztec Sandstone (Burchfiel et al., 1974; Axen, 1984, 1985).

Complex structural relationships among the Keystone, Contact, Red Spring, and Wilson Cliffs thrusts have led to controversy surrounding which fault is the lowest of the major thrusts in the eastern Spring Mountains. Longwell (1926) originally interpreted the Red Spring thrust as the structurally lowest thrust of the range, overridden by the younger Keystone thrust. However, Longwell (1960) later proposed that the Red Spring plates were fragmented blocks derived from the front of the Keystone plate that were overridden by the eastward thrusting Keystone plate. The Keystone and Red Spring thrusts remain controversial with many workers having developed structural models from Longwell's interpretations (Davis, 1973; Burchfiel et al., 1974, 1997; Axen, 1985; Matthews, 1988; Fleck and Carr, 1990).

Near Mountain Springs Pass, the Keystone thrust is cut by the northwest-striking, high-angle Cottonwood fault which forms the southern boundary of the Wilson Cliffs (Figure 3). Faulting resulted in the Keystone thrust being displaced 60 m down-to-the-southwest, which offset Paleozoic rocks in the downthrown block against the Jurassic Aztec Sandstone in the upthrown block (Figure 4) (Davis, 1973). Whereas the Cottonwood Fault is thought to have been active before the emplacement of the Keystone thrust in the Late Cretaceous, deformation of

the thrust suggests that it was active during and/or following emplacement of the Keystone thrust plate (Axen, 1985; Page et al., 1998).

Basin and Range Development

The Basin and Range is a physiographic province that formed beginning in the middle Miocene and is characterized by a series of north and north-west striking parallel valleys and ranges that extend from the Wasatch Range of Utah to the Sierra Nevada (e.g., Dickinson, 2002, 2013). Stresses responsible for the initiation of Basin and Range extension are likely consequences of Late Cretaceous to early Cenozoic tectonism and can be attributed to the configurations between the North American, Pacific, and Farallon tectonic plates, Farallon slab rollback and the slab window (Atwater, 1970; Dickinson and Snyder, 1979; Zoback et al., 1981; Coney, 1987; Parsons, 1995; Liu and Shen, 1998; Best et al., 2016). Extension is thought to have started around 18 Ma, in the central Basin and Range, near the study area, and continues to the present day (Stewart, 1971; Wernicke et al., 1988; Bidgoli et al., 2015). The magnitude of extension in the province is quite large with some proposing that it may have doubled its width due to the possibility that the normal faults that bound the ranges may flatten out with depth (Hamilton and Myers, 1966).

Las Vegas Valley Shear Zone

The Las Vegas Valley Shear Zone (LVVSZ) is a northwest-striking, right-lateral strike-slip fault zone that makes up part of the Las Vegas domain of the Walker Lane shear zone. It can be traced for nearly 150 km across most of southern Nevada where it is responsible for nearly 60 km of right-lateral displacement in the Las Vegas Valley (Longwell, 1960, 1974; Burchfiel, 1965, Faulds and Henry, 2008). The shear zone is bounded by east- to northeast-striking left-lateral fault belts at both ends (Burchfiel, 1965, Albers, 1967, Stewart et al., 1968). Many of the larger mountain ranges and other topographic features adjacent to the shear zone show clockwise rotation of up to 100° (Sonder et al., 1994; Faulds and Henry, 2008). Most of the activity along the LVVSZ is thought to have occurred between ~13 to 6 Ma with strain rates of <1.33 mm/yr and is based on stratigraphic and structural relations in the valley (Deibert, 1989; Castor et al., 2000; Faulds and Henry, 2008). Because offset decreases at the eastern and western ends of the LVVSZ, it has been proposed that a transverse structure was the main driver of the regional extension that is responsible for the genesis of two pull-apart basins beneath the Las Vegas Valley (Fleck, 1970; Guth, 1981; Ron et al., 1986; Rowley, 1998; Campagna and Aydin, 1994; Page et al., 2005). Workers interpret the basin to be up to 4 km deep with Cenozoic sediments filling the space (Langenheim et al., 1998, 2001; Page et al., 2005).

Significant Stratigraphic Units of the Blue Diamond Landslide

This study uses the stratigraphic hierarchy synthesized by Hewitt (1931, 1956) and Page and others (2005) from sedimentary sections exposed in the Las Vegas, Goodsprings, and Ivanpah

Quadrangles, respectively. Due to significant thrusting, stratigraphic units in the area can be subdivided into two groups; the footwall (Bird Spring Thrust plate) and hangingwall (Keystone Thrust plate) (Page et al., 2005) (Figure 4). This section summarizes the stratigraphic units within the thrust plates in the Blue Diamond area (Page et al., 1998).

Bird Spring Thrust Plate

Aztec Sandstone, Ja (Jurassic)

The Aztec Sandstone is Jurassic in age with a maximum exposed thickness of 650 m at Sandstone Bluffs in the east-central Spring Mountains, where it forms prominent tan to pale red cliffs (Hewett, 1931, 1956; Page et al., 2005). The formation is a quartzose sandstone consisting of well-sorted, subrounded grains of quartz and hematite, held together by calcite cement. Hewett (1956) interpreted the deposit to have been eolian sands based on stratification, uniform texture, and thickness of cross-bed sets. Aztec Sandstone is exposed throughout the eastern Spring Mountains where the top of the unit is truncated by the Keystone or Contact/Red Spring/Wilson Cliffs thrust fault.

Chinle Formation, JTrc (Late Triassic)

The Chinle Formation is Late Triassic in age and is approximately 280 – 300 m thick in the Las Vegas Quadrangle (Hewett, 1931, 1956; Page et al., 2005). The formation is dominated by thinly bedded red to yellowish-brown siltstone and sandstone with olive green to red shales that make up the lower contact of the formation. Significant exposures of the Chinle Formation are

found in the Rose Tank area where the upper redbeds gradually transition into large scale cross beds of the Aztec Sandstone.

Shinarump Conglomerate Member, TRcs (Late Triassic)

The Shinarump Conglomerate is a 10 – 30 m thick basal member of the Chinle Formation that is Late Triassic in age (Hewett, 1931, 1956; Page et al., 2005). It contains coarse grained sand with 1 m thick lenses of well-rounded pebbles. Pebble clasts are predominantly made up of reddish-brown to yellowish-brown chert held in a dark-brown sandy matrix. Exposures are very poor with the most prominent outcrop appearing between the Sandstone Bluffs and Red Rock Canyon National Conservation Area.

Moenkopi Formation, TRm (Early to Middle Triassic)

The Moenkopi Formation is Early to Middle Triassic in age with a combined thickness of 585 m in the Blue Diamond area (Hewett, 1931, 1956; Page et al., 2005). The formation consists of three distinct members; from top to bottom they are the upper redbed member, the tan colored, cherty Virgin Limestone Member, and the Timpoweap Conglomerate Member. Outcrops of the formation occur sporadically on the eastern slope of the Spring Mountains and nearby ridges.

Kaibab and Toroweap Formations, Pkt (Early Permian)

The combined Kaibab and Toroweap Formations are Early Permian in age and, in combination are approximately 250 - 300 m thick in the Blue Diamond area in the eastern Spring Mountains (Hewett, 1931, 1956; Page et al., 2005). Page et al. (1998) described the formations

as a gray fossiliferous limestone with brown chert layers and nodules along with pronounced beds of gypsum. The best exposures are located in the Blue Diamond area where the formations make up most of Blue Diamond Hill and cap the entire Bird Spring Range.

Permian Redbeds, Pr (Permian)

The Permian Redbeds are Early Permian and approximately 300 m thick in the Blue Diamond area (Page et al., 2005). The formation consists of red to white crossbedded sandstone with interbedded siltstone and shale. Outcrops are exposed in the low hills of the Spring Mountains in the Blue Diamond area.

Bird Spring Formation, PPMb (Permian, Pennsylvanian, and Mississippian)

The Bird Spring Formation, undivided is Late Mississippian to Early Permian in age with an estimated thickness of 750 m in the Blue Diamond area (Longwell and Dunbar, 1936; Page et al., 1998, 2005). The formation appears in both thrust plates with Page et al. (1998) describing the autochthon as brownish-gray limestone, sandy limestone, dolostone and some areas of brown sandstone and shale with up to 50 percent being composed of chert.

Keystone Thrust Plate

Monte Cristo Group, Mm (Mississippian)

The Monte Cristo Group is early to middle Mississippian in age with a maximum thickness of 300 m in the eastern Spring Mountains (Hewett, 1931, 1956; Page et al., 2005). The unit is divided the unit into four members, from top to bottom; Yellowpine Limestone, Bullion

Limestone, Anchor Limestone, and Dawn Limestone. Yellowpine Limestone is a dark-gray to light-olive-gray, medium crystalline limestone with sparse nodules of gray to brown chert. Buillion Limestone is a light-gray, encrinitic wackestone to grainstone. Anchor Limestone is a gray to light-olive-gray fine-to-medium grained limestone. It contains beds of chert that are dark-gray and weathers moderate-orange to light-brown. Dawn Limestone is the basal member that is a dark-gray, thinly-bedded, bioclastic, oolitic limestone.

Sultan Limestone, MDu (Mississippian and Devonian)

The Sultan Limestone is Middle Devonian to early Mississippian in age with a maximum thickness of 200 m in the eastern Spring Mountains (Hewett, 1931, 1956; Page et al., 2005). Sultan Limestone is the equivalent of the Guilmette Formation farther north and is made up of three members. The Crystal Pass Member is a light-gray micritic limestone. The Valentine and Ironside Members are made up of cycles of thin-bedded, dark-gray limestone and thick-bedded, light-gray dolostone.

Mountain Springs Formation, DOm (Devonian and Ordovician)

The Mountain Springs Formation is Late Ordovician to Middle Devonian in age with a maximum thickness of 295 m (Gans, 1974; Page et al., 2005). The lowest unit is made up of sequences of dark to light-gray coarse dolomite with white chert nodules. The upper unit consists light to dark-gray, thin-bedded dolomite with calcite filled vugs and chert nodules. The formation is only exposed in the eastern Spring Mountains in the Keystone thrust plate.

Nopah Formation, Cn (Cambrian)

The Nopah Formation is Late Cambrian in age with a maximum thickness of 345 m in the eastern Spring Mountains (Hewett, 1956; Page et al., 2005). Nopah Formation is a dark and light-gray, medium-crystalline and thin to thick-bedded dolostone with discontinuous layers and yellowish-brown chert nodules. The base is defined by the Dunderburg Shale Member which is a silty limestone and olive-green shale with trilobite fragments common.

Bonanza King Formation, Cbk (Cambrian)

The Bonanza King Formation is Middle to Late Cambrian in age with a maximum thickness of 445 m in the eastern Spring Mountains (Page et al., 2005). Bonanza King Formation is the equivalent of the lower Goodsprings Dolomite and consists of the Banded Mountain and Papoose Lake Members (Hewett, 1931; Gans, 1974). Banded Mountain Member is a light to dark-gray, fine to medium-crystalline dolostone and limestone. Alternating light and dark-gray colors provided the member with its distinctive banded appearance. Papoose Lake Member is a dark-gray dolostone with distinctive grayish-orange burrow mottles and sparse limestone and silty dolostone beds.

Figure 4. Units offset by the Keystone thrust in the Spring Mountains adjacent to the Blue Diamond area (modified from Page et al., 1998).

Blue Diamond Landslide Megabreccia

Landslide Distribution

The Blue Diamond landslide megabreccia has been previously mapped and described by Page et al. (1998) and briefly revisited by Page et al. (2005). Page et al. (1998) interpret the ancestral landslide deposit encompassing all megabreccia outcrops, which covers an area at least 10 km long and 5 km wide about 15 km west of Las Vegas, Nevada (Figure 5). From these data they estimated the original distribution of the landslide to have covered an area of nearly 25 km², making it one of the largest megabreccia deposits in the region. The location of the proposed source area relative to the current position of the deposit requires 10 km runout distance (Page et al., 1998, 2005). Topographic controls likely influenced landslide distribution, whereby deposition was confined to the Blue Diamond area by the Blue Diamond Hill and Bird Spring Range, respectively (Page et al., 1998).

Today, exposed remains of the deposit cap some of the foothills of the eastern Spring Mountains near Blue Diamond, Nevada (Figure 5). The northernmost exposure is located atop Blue Diamond Hill where it caps two small buttes on the hill's dip slope. Southernmost exposures of the deposit are restricted to north of the Bird Spring Range, capping larger buttes. Its easternmost exposure extends into the Cottonwood Valley where it rests at local stream level (Page et al., 1998). The bulk of the deposit remains cap most of the 4 km long, northwest-southeast trending, Blue Diamond ridge where it forms walls of breccia up to 60 m thick (Figure 6). Page et al. (1998) hypothesize that the ridge fills a poorly defined synclinal sag with the limbs being the southwest dipping Blue Diamond Hill and west-northwest dipping Bird Spring Range.

Other than secondary landslides off the western end of the long deposit, the authors suggest that the local topography has not changed much since landsliding occurred (Page et al., 1998).

Figure 5. Map showing the current exposed remnants of the Blue Diamond landslide and the original distribution and source area of the landslide as proposed by Page et al., (1998) (modified from Page et al., 1998).

Figure 6. Deposit outcrops along the Blue Diamond Ridge: a) proximal (red) and medial (green); b) distal (yellow); c, d) proximal at Hill 4358' location; and e) proximal (red), medial (green) and distal (yellow) along the 4 km long Blue Diamond Ridge and Blue Diamond Hill looking north from Hill 4358'.

Description of Deposit

Page et al. (1998) describe the landslide deposit as a chaotically mixed, poorly sorted, subangular to subrounded limestone, dolomite, and dolomitic quartzite breccia in a comminuted matrix of the same material. They estimate the average clast size to be about 1 m in diameter with some clasts as large as 20 m in diameter. Clasts are comprised mainly of Devonian Sultan Limestone and the lower Mississippian Monte Cristo Group with fewer than 10% of the clasts being made up of Jurassic Aztec Sandstone and Triassic Moenkopi Formation (Figure 7) (Page et al., 1998). The deposit sits unconformably atop Mesozoic strata with an undulating contact and a basal mixed zone consisting of landslide breccia and material from the underlying Triassic Moenkopi Formation.

Figure 7. Main clast types entrained in the Blue Diamond landslide: a) Moenkopi Fm type clast; b) Aztec Sandstone type clast; c) carbonate type clast

Origin of the Deposit

Page et al. (1998) determined that the landslide originated directly west of the deposit in the upper Spring Mountains. Although it is difficult to determine a precise location due to the erosion of topography over time, they interpreted the source area to be the hanging wall of the Keystone thrust because it is the nearest upslope location with exposed Devonian and Mississippian carbonates that make up the deposit (Figure 4). The age of the Blue Diamond Landslide is poorly constrained with deposition thought to have occurred between the emplacement of the Keystone Thrust in the Late Cretaceous and early Quaternary time (Page et al., 1998). They interpret that landsliding occurred in the Late Cenozoic due to the deposit being encased by early Quaternary to Late Cenozoic alluvium, and from age relations of other landslides in the area. With this information, Page et al. (1998) suggest that the Blue Diamond landslide was likely induced by overthrusting of the Keystone thrust fault, resulting in gravitational collapse in response to high relief during the development of the Basin and Range. Additionally, Page et al. (1998) think that landslide emplacement occurred as a catastrophic rock-avalanche that slid during high velocity transportation. This interpretation is based on the west-dipping slip surfaces of two deposit caps that appear on the Blue Diamond Hill and the occurrence of jigsaw and crackle brecciation (Figure 5).

Methods

Clast Counting

Clast counting is a method used to quantify the proportions of one or more clast types within a target population of clasts. To perform clast counts, a sample population must be randomly heterogeneous, and the sample must be drawn at random so that each sample has an equal and independent chance at being selected (Howard, 1993). Statistical validity is achieved by establishing formal procedures in order to randomly select the precise point to be counted on the outcrop and the clasts to be counted at that location. Since parts of the target population are concealed or inaccessible, not all locations on an outcrop have an equal chance at being selected, therefore, a truly random sample cannot be achieved (Howard, 1993).

Clast counts were conducted throughout the Blue Diamond Mega-landslide breccia in order to better characterize the longitudinal, lateral, and vertical changes in proportions of various clasts. Initial field reconnaissance was conducted to determine outcrop accessibility and to identify the clast types to be counted within the deposit. Sampling sites were selected following methods described by Petersen and Calvin (1965). First, a coordinate system was used to establish an origin point on a geological map of the study area. Using the origin point as a reference, random distances were selected, and their corresponding points were used as the location where the sample would be taken. Once these locations were established, two 1x1 m quadrants were randomly selected using a table of random numbers. Counts were then carried out in as many fixed stratigraphic intervals as accessibility allowed. Point counting techniques commonly used for thin section analysis were used for clast counting procedures in the field.

Statistical Analysis

Counting Errors

In order to better understand each clast's contribution, means and percentages were calculated for the total count and counts in each lateral zone. Counting errors were calculated for the total count and those in each lateral zone. Errors emerge from the misidentification of clasts of a certain characteristic within a population of breccia clasts. Probable error associated with counting was calculated as follows:

$$CE = \pm t \sqrt{p(1-p)/n}, \quad [1]$$

where CE = counting error about the mean; t is the tabulated value of Student's t-distribution for $n - 1$ degrees of freedom and confidence level $\alpha/2$; p is the proportion of an individual component; and n being the total number of clasts in the target population (Natrella, 1966; Howard, 1993).

Sampling errors occur when statistical characteristics of a population are estimated from a sample of that population. This error is a function of the precise point of sampling and homogeneity. Sampling errors were calculated as follows:

$$SE = t(S/\sqrt{n}), \quad [2]$$

where SE = sampling error of the mean; t is the tabulated value of Student's t-distribution for $n - 1$ degrees of freedom and 0.05 level; S is the standard deviation associated with the number of counts n (Natrella, 1966; Howard, 1993).

Total probable error is the result of the analytical and sampling errors associated with clast counting procedures. The counting error can be used in place of the analytical error as long as the error associated with clast identification is negligible. Total probable errors were calculated as follows:

$$TE = \sqrt{(e_1)^2 + (e_2)^2}, \quad [3]$$

where TE = the total probable error; and e_1 and e_2 are the sampling and analytical errors (Natrella, 1966; Howard, 1993).

The Ranking Method

Ranking methods were conducted to compare clast distributions and the distribution of basal mixed zone chemical compositions within each lateral zone. Ranking is used to compare the distributions of an entity whose absolute frequencies are not known. This method ranks each component according to their relative abundancies. For example, the first rank is given to the component with the highest frequency, the second rank is given to the component with the next highest frequency and so on (Cheeney, 1983; Marsal and Merriam, 1987; Davis, 2002).

Since more than two distributions were compared, the *Coefficient of Concordance*, W , was used. In this method, multiple distributions (m) that represent different geological profiles are compared. First, the numbers:

$$M = m(k + 1)/2, \text{ and} \quad [4]$$

$$A = m^2(k^3 - k)/12 \quad [5]$$

are calculated. Then classes (k) of each distribution are ranked according to their relative frequencies and the sum of the ranking of each component is taken. The difference between the sums and M are then calculated and squared and summed (S). Then the *Coefficient of Concordance* is calculated where

$$W = S/A. \quad [6]$$

If W is equal to one, then all distributions coincide; however, if W is equal to zero, then all ranks are randomly distributed. To test the significance of W ,

$$W^* = (S - 1)/(A + 2), \text{ and} \quad [7]$$

$$F_0 = (m - 1)W^*/(1 - W^*) \quad [8]$$

are then computed. The Snedecor F -test is then applied by comparing F_0 to the tabulated F -value from Snedecor's F -table for the degrees of freedom

$$v - column = (k - 1) - (2/m), \text{ and} \quad [9]$$

$$v - row = (m - 1) * v - column. \quad [10]$$

If F_0 is larger than the tabulated value then W is significant (Cheeney, 1983; Marsal and Merriam, 1987; Davis, 2002). A numerical example is provided below in Table 1.

Table 1. Numerical example of the comparison of $m=3$ rank sequences.						
Class	I	II	III	IV	V	VI
1 st Distribution	6	3	4	1	2	5
2 nd Distribution	1	3	6	4	2	5
3 rd Distribution	6	2	1	4	5	3
Sums	13	8	11	9	9	13
M	10.5	10.5	10.5	10.5	10.5	10.5
Differences	2.5	-2.5	0.5	-1.5	-1.5	2.5
Squares	6.25	6.25	0.25	2.25	2.25	6.25
Sum of Squares	S=23.5					
W	W^*	v -column	v -row	F_0	F	Significant
0.15	0.14	4.3	8.7	0.33	4.2	No
Snedecor's F-Table: 5% level. $A = 157.5$, $k=6$.						

Facies and Sample Analysis

Sedimentary facies and deposit morphologies were mapped after Yarnold and Lombard's (1989) facies model and described using standard sedimentological procedures at twelve locations within the deposit. Facies analysis can help us determine the lateral zonation from proximal, medial, and distal while inferring the transportation mechanisms. Additionally, careful mapping of the basal contact facies should elucidate the paleoslope and source-area directions during the time of their emplacement (Yarnold and Lombard, 1989).

Twenty-one samples that cover a range of lithologies in the deposit were collected in the field and analyzed in the Basins Lab at the University of Cincinnati. Each sample was carefully described using standard sedimentological procedures. The description process included sedimentological descriptors of lithology, color, particle size, primary and penecontemporaneous sedimentary structures, facies designations, and contact descriptions.

X-Ray Fluorescence Analysis

Eight samples from the basal contact area and one sample each from the Aztec Sandstone and Moenkopi Formation were analyzed for chemical composition by wavelength-dispersive X-ray fluorescence. Samples were crushed and turned into a silty powder by a ball mill. Following standard loss-on-ignition procedures each powdered sample was dehydrated and cooked to burn off any carbonate in them. Samples were then fused into glass beads using the Katanax Fluxer. This was followed by x-ray fluorescence analysis using a Rigaku Supermini 200 to determine the elemental composition of each selected sample.

Results

Clast Counting

Based on the compositional descriptions by Page et al. (1998) and observations in this study, we differentiated six clast groupings: (1) carbonates, (2) matrix, (3) Aztec Sandstone, (4) Moenkopi Formation, (5) chert, and (6) calcite. The total counting results and those for each lateral zone of the Blue Diamond landslide deposit are presented in Figure 8 and Tables 2 and 3. The results and locations of the total individual count sets are available in Appendix A. Counting procedures yielded 120 count stations throughout the deposit with a total of 10,800 observations.

Figure 8. Total clast distribution and clast distributions at each accumulation zone.

Total Deposit Counts

The total clast distributions are as follows: carbonate (5,193 counts, 48.1%), matrix (4,836 counts, 44.8%), chert (382 counts, 3.5%), calcite (192 counts, 1.8%), Aztec Sandstone (149 counts, 1.4%), and Moenkopi Formation (48 counts, 0.4%) (Table 2). Total carbonate and matrix frequencies from each count set were compared and plotted and shows a strong negative correlation between the carbonates and matrix (Figure 9).

Figure 9. Scatter plot showing the correlation between total carbonate counts versus total matrix counts throughout the deposit.

Table 2. Total clast count data (n=10,800) for Blue Diamond Landslide Breccia with separate clast count data (n=3420, 3780, 3600) for proximal, medial, and distal lateral zones of deposit.								
Clast Type	Total		Proximal		Medial		Distal	
	n	%	n	%	n	%	n	%
Carbonates	5193	48.1	1489	43.5	2034	53.8	1670	46.4
Matrix	4836	44.8	1669	48.8	1522	40.3	1645	45.7
Chert	382	3.5	192	5.6	57	1.5	133	3.7
Calcite	192	1.8	18	0.5	45	1.2	129	3.6
Aztec	149	1.4	34	1.0	92	2.4	23	0.6
Moenkopi	48	0.4	18	0.5	30	0.8	0	0.0
N	10800	—	3420	—	3780	—	3600	—
K	120	—	38	—	42	—	40	—
Symbols: %, clast contribution percentage; N, total individual counts; K, total counting stations.								

Statistical Analysis

Counting Errors

Counting errors were calculated at the 0.05 confidence level for the total counts and each zone. At the 0.05 confidence level with $n = \infty$ for all target populations, the tabulated t-value of 1.65 was applied to the counting error equation. For example, out of 3,420 counts in the proximal zone, 1,489 were carbonates. The counting error associated with the proportion of carbonate clasts (0.44) is

$$CE = \pm t \sqrt{p(1-p)/n} = 1.65 \sqrt{0.44(1-0.44)/3420} = 0.014. \quad [1]$$

From this, we can state with 95% confidence the percentage of carbonate clasts in the proximal zone is $43.5 \pm 1.4\%$. This calculation was applied to all count data and is displayed in Tables 2 and 3.

Sampling errors were calculated at the 0.05 confidence level for the same locations. Since the sampling error depends on count sets, rather than total counts, the n-value for each location was different. At the 0.05 confidence level the tabulated t-value's for $n = 120, 38, 42,$ and 40 were applied to the counting error equation for each zone's target population. Count sets are $n = 38$ in the proximal zone. The tabulated t-value for $n = 38$ count sets at the 0.05 confidence level is $t = 1.69$. Standard deviation for proximal zone carbonate count frequencies was $S = 18.9$. The sampling error associated with the standard error of the mean is

$$SE = t \left(\frac{S}{\sqrt{n}} \right) = 1.69(18.9/\sqrt{38}) = 5.2 \quad [2]$$

From this, we can state with 95% confidence that the true population of carbonate clasts in the proximal zone is $45.3 \pm 5.19\%$. Results from the sampling error calculation are displayed in Table 3.

Once the counting and sampling errors are established the total probable error can be estimated. Since the error associated with clast identification was negligible, the counting error was used in place of analytical error. Using e_1 as the counting error and e_2 as the sampling error, the total probable error associated with proximal zone carbonate counts can be calculated. The total probable error associated with proximal carbonate clast counts is

$$TE = \sqrt{(e_1)^2 + (e_2)^2} = \sqrt{(1.4)^2 + (5.2)^2} = 5.4 \quad [3]$$

From this, we can state that with 95% confidence the total probable error of proximal zone carbonate clast counts is $\pm 5.4\%$. Total probable error results are displayed in Table 3.

Table 3. Errors associated with clast counting. All values are percentages.																
Clast Type	Total				Proximal				Medial				Distal			
	X	CE ¹	SE ²	TE	X	CE ¹	SE ³	TE	X	CE ¹	SE ³	TE	X	CE ¹	SE ⁴	TE
Carbonates	43.3	0.8	2.8	3.0	39.2	1.4	5.2	5.4	48.5	1.3	3.9	4.1	41.8	1.4	5.1	5.3
Matrix	40.3	0.8	2.5	2.6	43.9	1.1	4.6	4.7	36.2	1.3	3.2	3.5	41.1	1.4	4.5	4.7
Chert	3.2	0.3	1.0	1.0	5.1	0.6	1.8	1.9	1.4	0.3	0.7	0.8	3.3	0.5	1.8	1.9
Calcite	1.6	0.2	0.9	0.9	0.5	0.2	1.6	1.6	1.1	0.3	0.8	0.9	3.2	0.5	1.6	1.7
Aztec	1.2	0.2	0.5	0.6	0.9	0.3	1.0	1.0	2.2	0.4	1.2	1.3	0.6	0.2	0.9	0.9
Moenkopi	0.4	0.1	0.2	0.2	0.5	0.2	0.4	0.5	0.7	0.2	0.5	0.6	0.0	0.0	0.4	0.4
n	1080	—	—	—	3420	—	—	—	3780	—	—	—	3600	—	—	—
k	120	—	—	—	38	—	—	—	42	—	—	—	40	—	—	—
Symbols: X, mean; CE, counting error; SE, sampling error; TE, total error; n, total count at each zone; k, total counting stations. ¹ t=1.65, ² t=1.66, ³ t=1.69, ⁴ t=1.68																

The Ranking Method

The ranking method was used to compare the clast distributions of each zone. Since three distributions ($m = 3$) were simultaneously compared, the coefficient of concordance was

applied. Each distribution consisted of $k = 6$ classes and were ranked based upon their relative frequency. First, the numbers

$$M = m(k + 1)/2 = 3(6 + 1)/2 = 10.5, \text{ and} \quad [4]$$

$$A = m^2(k^3 - k)/12 = 3^2(6^3 - 6)/12 = 157.5 \quad [5]$$

were calculated. The rank of each of each class was summed and the difference was taken by subtracting M from its value. The differences were then squared and the squares were summed, where $S = 129.5$. All previous values were then used to compute the coefficient of concordance,

$$W = S/A = 129.5/157.5 = 0.82. \quad [6]$$

If $W = 1$, then all distributions coincide. If $W = 0$, then all ranks are randomly distributed. To test the significance of our value,

$$W^* = (S - 1)/(A + 2) = (129.5 - 1)/(157.5 + 2) = 0.81, \text{ and} \quad [7]$$

$$F_0 = (m - 1)W^*/(1 - W^*) = 0.81(3 - 1)/(1 - 0.81) = 8.3 \quad [8]$$

were calculated. Snedecor's F -test was applied by comparing F_0 to the tabulated value at the 5% level: $F = 4.2$. Since F_0 is larger than the tabulated F -value, we can state with 95% confidence that W is significant. Therefore, there is a strong concordant relationship between the distribution of clast types throughout the deposit. Results are displayed in Table 4 below.

The ranking method was then applied to another three-sample distribution ($m = 3$) of $k = 18$ classes in order to compare the chemical composition of the basal mixed zone at each section of the deposit. Following the same procedure as the clast distributions, the numbers

$$M = m(k + 1)/2 = 3(18 + 1)/2 = 28.5, \text{ and} \quad [4]$$

$$A = m^2(k^3 - k)/12 = 3^2(18^3 - 18)/12 = 4360.5 \quad [5]$$

were calculated. Then the coefficient of concordance was calculated at

$$W = S/A = 4024.5/4360.5 = 0.89. \quad [6]$$

To test the significance of the coefficient,

$$W^* = (S - 1)/(A + 2) = (4024.5 - 1)/(4360.5 + 2) = 0.88, \text{ and} \quad [7]$$

$$F_0 = (m - 1)W^*/(1 - W^*) = 0.92(3 - 1)/(1 - 0.88) = 23.7 \quad [8]$$

were calculated. Snedecor's F -test was applied by comparing F_0 to the tabulated value at the 5% level: $F = 2.2$. Since F_0 is larger than the tabulated F -value, we can state with 95% confidence that W is significant. Therefore, there is a strong concordant relationship between the compositional distribution throughout the deposit. Results are displayed in Table 5 below.

Table 4. Ranking of clast frequency distribution.

Clast Type	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi
Proximal	2	1	3	5	4	5
Medial	1	2	4	5	3	6
Distal	1	2	3	4	5	6
Sums	4	5	10	14	12	17
<i>M</i>	10.5	10.5	10.5	10.5	10.5	10.5
Differences	-6.5	-5.5	-0.5	3.5	1.5	6.5
Squares	42.3	30.3	0.3	12.3	2.3	42.3
<i>Sum of Squares</i>	S=129.5					
<i>W</i>	<i>W</i> *	<i>v-column</i>	<i>v-row</i>	<i>F</i> ₀	<i>F</i>	<i>Significant</i>
0.82	0.81	4.3	8.7	8.3	4.2	Yes
Snedecor's F-Table: 5% level. A = 157.5, k=6.						

Table 5. Ranking of relative frequency distribution of the chemical composition of basal mixed zone.

Table 5. Ranking of relative frequency distribution of the chemical composition of basal mixed zone.																			
Sample	Na2O	MgO	Al2O3	SiO2	P2O5	S	K2O	CaO	TiO2	V	MnO	Fe2O3	Zn	As	Sr	Zr	Ba	Cl	
D2S1	9	2	4	3	10	13	5	1	7	16	11	6	15	14	12	17	8	17	
D2S5	7	2	4	3	10	14	5	1	9	17	11	6	13	15	12	16	8	18	
D2S6	16	2	4	3	8	12	5	1	9	10	16	6	14	13	11	15	7	16	
Sums	32	6	12	9	28	39	15	3	25	43	38	18	42	42	35	48	23	51	
M	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	28.5	
Difference	3.5	-22.5	-16.5	-19.5	-0.5	10.5	-13.5	-25.5	-3.5	14.5	9.5	-10.5	13.5	13.5	6.5	19.5	-5.5	22.5	
Squares	12.25	506.25	272.25	380.25	0.25	110.25	182.25	650.25	12.25	210.25	90.25	110.25	182.25	182.25	42.25	380.25	30.25	506.25	
Sums of Squares	3860.5																		
W		W*	v-column				v-row				F0	F				Significant			
0.89		0.88	16.3				32.7				15.3	2.2				Yes			
Snedecor's F-Table: 5% level. A = 4360.5, k=18.																			

Sedimentology

Facies were mapped and analyzed according to the dry climate large rock avalanches facies models developed by Yarnold and Lombard (1989). Their model includes, from top to bottom, a coarse breccia sheet, a matrix-poor zone, a disrupted zone, and a discontinuous basal mixed zone (Figure 10a). The breccia sheet consists of a vertical facies succession of matrix-rich breccia, jigsaw breccia, and crackle breccia (Figure 10b). The Blue Diamond landslide breccia exhibits this general facies succession throughout each portion of the deposit.

Figure 10. a) Idealized morphology of dry-climate rock-avalanche deposits showing characteristic features at each accumulation zone; (S) substrate; (MZ) mixed zone; and (BS) breccia sheet (modified from Yarnold and Lombard, 1989). b) Large rock-avalanche breccia sheet lithofacies in proper stacking order (modified from Woodcock and Mort, 2008).

Proximal Features

The mixed zone is a discontinuous layer of silty conglomerate that is typically about 1 m thick and makes up the basal portion of the deposit. It is characterized by a pink matrix composed of silty and sandy material that supports entrained angular clasts (Figure 11e). Most of the clasts

are derived from the overlying carbonate breccia sheet with occasional Aztec Sandstone clasts and very few substrate clasts (Moenkopi Formation). The contact between the deposit and the substrate is undulatory with relief of less than one meter. Well exposed contacts occasionally exhibit a shear-slip surface with fault gouge up to 30 cm thick resting on the upper redbeds of the Moenkopi Formation (Figure 11d). Entrained clasts range from 0.5 cm to 25 cm in maximum dimension and tend to be subangular to angular in roundness. In some areas, clastic dikes derived from the mixed zone protrude up to 1 m into the disrupted zone of the overlying breccia sheet (Figure 11c).

The proximal breccia sheet thickness varies throughout the deposit where it ranges from 5 – 20 m thick. The basal portion of the breccia sheet contains a 3 – 7 m thick disrupted zone which is dominated by the matrix-rich facies (Figure 11b). Clasts consist of highly rotated fragments of pale green carbonates that range from a few centimeters to several meters in diameter and tend to be irregularly spaced. The matrix is made up of poorly sorted yellowish gray dolomitic silty sand. Locally, matrix material makes up larger portions of the breccia block volume than the fragments. In most areas, disrupted zone clasts are draped and sometimes powdered with an orange-pink silty material likely sourced from the mixed zone. The material is poorly cemented and the thickness ranges from a few cm to 25 cm.

The lower interval of the breccia sheet typically grades into an 8 – 15 m thick matrix-poor zone. The lower portion of the zone consists of carbonate clasts that display the jigsaw breccia facies; however, it is relatively thin in the proximal area of the deposit and quickly transitions into the upper portion of the breccia sheet. The breccia cap is dominated by competent, dark gray carbonate megablocks featuring the crackle breccia facies (Figure 11a). Vuggy texture appears

on nearly every exposed megablock surface. The carapace has ridged topography with moderately developed east-west-trending ridges.

Figure 11. Textural features of the proximal zone. a) crackle breccia facies, b) matrix-rich facies of the disrupted zone, c) clastic dike derived from mixed zone penetrating disrupted zone, d) shear slip surface, e) mixed zone with entrained clasts.

Medial Features

The matrix material in the mixed zone is similar to that of the proximal area; however, it appears more frequently and transitions from pink to light orange-pink in color. In the proximal end of the zone, a mixed zone with a sharp undulatory basal contact and a consistent thickness of 1 m is common (Figure 12c). From both observations and clast counts, the medial area experiences a significant increase of Mesozoic clasts (Table 2). Whereas the entrained carbonate clasts continue to be angular the entrained siliciclastic clasts appear more rounded than in the proximal mixed zone.

With a maximum thickness of 60 m, the breccia sheet of the medial zone is the thickest of the entire deposit. The disrupted zone ranges from a few meters up to 15 m thick and is characterized by an abundance of matrix dominated clasts of the matrix-rich facies. Most of the clasts are derived from the rock avalanche debris, but large entrained boulders of Aztec Sandstone and chert occur more frequently than in the proximal zone (Figure 12b, d). Large lenses of fractured clasts of Aztec Sandstone appear throughout the zone (Figure 12d).

The breccia sheet is missing the lower portion of the matrix-poor zone and proceeds directly to the upper crackle breccia facies zone (Figure 12a). Much like the cap in the proximal zone, the medial zone breccia cap is made up entirely of competent breccia megablocks that are gray in color. Most of the megablocks are semi-continuous with some of them being offset next to or on top of disrupted zone or mixed zone facies. The carapace has ridged topography with well-developed east-west-trending ridges.

Figure 12. Textural features of the medial zone. a) crackle breccia facies atop matrix-rich facies, b) 6 m block of Aztec Sandstone, c) undulatory mixed zone, d) 7 m thick disrupted zone with significantly more entrained Aztec Sandstone clasts than proximal or distal zones.

Distal Features

Outcrops of the basal mixed zone are rare in the distal portion of the deposit. In places where the base of the landslide deposit is exposed, thin layers of gouge (5 – 15 cm) separate the sheet from the substrate (Figure 13b). The gouge material is heavily comminuted, consisting of a fabric of very fine-grained platy material that rests subparallel to the substrate. Where the mixed zone is present, it appears as a discontinuous lens of light brown matrix with entrained angular

clasts of carbonates and a few rounded clasts of Aztec Sandstone up to 10 cm in diameter. In some places it has an undulatory contact with the substrate (Figure 13c).

The distal breccia sheet is up to 30 m thick. The disrupted zone is well-developed with an abundance of matrix-rich breccia. Clasts in this zone range from pebble to cobble in size with some clasts displaying the jigsaw breccia facies (Figure 13d). In some areas, clastic dikes sourced from the mixed zone protrude several meters into the breccia. Laterally extensive comminuted slip surfaces that are subparallel to the base of the lobe occur in the disrupted zone (Figure 13d).

The matrix-poor portion of the breccia sheet consists of a thin zone of jigsaw breccia facies and is mostly dominated by crackle breccia facies. Megablocks of crackle breccia make up most of the upper portion of the zone. The carbonate megablocks range in color from light gray at the base of the matrix-poor zone to dark gray at the cap of the breccia sheet. Locally, some exposed crackle breccia facies blocks exhibit a polished surface texture (Figure 13a). The carapace has a ridged topography with a moderately-developed east-west-trending ridge.

Figure 13. Textural features of the distal zone. a) polished crackle breccia facies, b) fault gouge resting unconformably on disturbed basal substrate, c) undulatory mixed zone with entrained clasts, d) disrupted zone with entrained jigsaw breccia clasts and slip surface.

Longitudinal Trends

The mixed zone seems to be a discontinuous layer beneath the entire deposit. Its occurrence increases from proximal to medial but is rarely found in the distal portion. From proximal to medial, the mixed zone most commonly appears as a meter-thick undulatory layer, whereas it reaches up to 0.5 m in the distal zone. Comminuted slip surfaces appear proximally and distally but disappear in the medial zone. Disrupted zone matrix-rich breccia is found throughout the deposit and is abundant and well-developed in the medial zone. Outcrops of the

disrupted zone are moderately developed in the proximal and distal zones. Matrix material makes up a larger volume of breccia blocks in the medial portion whereas disrupted zone blocks are clast heavy proximally and distally. This trend can be described as a general outward thinning of the disrupted zone. Carbonate clast sizes increase distally and tend to be very angular whereas siliciclastic clasts are rounded and increase in size into the medial portion then dramatically decrease in size distally. Large (>10 m) boulders of Aztec Sandstone clasts are common in the medial zone as well as a general increase in clast size. The total thickness of the landslide debris was observed to have an outward thinning pattern from the medial portion.

Vertical Trends

The breccia sheet grades upward from matrix-rich to matrix-poor with a general upward decrease in the volume of matrix. Jigsaw breccia facies of the upper portion of the breccia sheet are poorly developed with the fabric grading from matrix-rich breccia immediately into the crackle breccia facies. The breccia sheet shows a downward increase in the amount of shearing. This is interpreted from an increase of fragments and matrix in the disrupted zone that were derived from the larger megablocks in the matrix-poor zone. Pervasive shearing can also be seen in the mixed zone. The silty particles of the matrix and general lack of large clasts show a high degree of comminution. Homogeneity and a lack of structure also suggest that the mixed zone underwent thorough intermixing. There is an upward increase in the maximum particle size from 16 μm to 25 cm in the basal mixed zone of the deposit and is associated with the vertical fabric trend.

X-Ray Fluorescence Analysis

The comparison of chemical compositions of eight matrix samples from the mixed zone with two parent samples suggests that the Aztec Sandstone and Moenkopi Formation are not the primary source of the basal mixed zone matrix (Figure 14b). The most abundant chemical compounds are MgO and CaO, suggesting that the matrix was formed through pervasive comminution of the carbonate clasts (Table 6). Because some of the carbonate source units are abundant with chert, it is difficult to determine the extent of Aztec Sandstone and Moenkopi Formation contributions within the mixed zone matrix. However, if the matrix is representative of the clast distributions, then it is likely that Aztec Sandstone and Moenkopi Formation contributed little to the matrix.

Table 6. Chemical composition data for several mixed zone samples and parent samples (Aztec and Moenkopi).

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	S	K2O	CaO	TiO2	V	MnO	Fe2O3	Zn	As	Sr	Zr	Ba	Cl	LOI	Total
D2S1	0.13	22.33	1.36	6.66	0.07	0.01	0.48	27.26	0.27	0.00	0.03	0.32	0.00	0.00	0.02	0.00	0.14	0.00	40.88	100.0
D2S5	0.16	11.05	6.30	10.71	0.08	0.01	2.13	31.29	0.11	0.00	0.03	1.81	0.01	0.01	0.02	0.00	0.13	0.00	36.11	100.0
D2S6	0.00	20.68	2.07	8.65	0.11	0.02	0.66	27.76	0.05	0.02	0.00	0.59	0.01	0.01	0.02	0.00	0.11	0.00	39.18	99.9
D3S1	0.26	9.57	1.59	6.26	0.14	0.11	0.52	41.75	0.06	0.00	0.02	0.52	0.01	0.00	0.01	0.00	0.21	0.03	38.74	99.8
D4S5	0.05	0.46	1.54	13.23	0.14	0.03	0.61	50.29	0.01	0.00	0.00	0.40	0.01	0.01	0.01	0.00	0.10	0.00	33.07	99.9
D5S1	0.07	14.54	1.39	7.07	0.09	0.03	0.51	35.72	0.03	0.01	0.02	0.38	0.01	0.00	0.00	0.01	0.09	0.03	39.94	99.9
D7S1	0.15	19.78	1.52	12.87	0.10	0.05	0.48	25.45	0.04	0.06	0.02	0.43	0.01	0.00	0.01	0.01	0.21	0.00	38.68	99.9
D7S2	0.30	19.67	1.72	12.96	0.08	0.04	0.46	25.45	0.07	0.01	0.03	0.51	0.01	0.01	0.01	0.00	0.17	0.04	38.42	99.9
Aztec	0.01	0.58	2.64	90.53	0.06	0.02	0.78	4.54	0.00	0.02	0.00	0.50	0.01	0.01	0.00	0.01	0.11	0.11	—	99.9
Moenkopi	2.84	1.92	9.86	67.69	0.19	0.03	2.38	11.59	0.58	0.00	0.11	2.43	0.01	0.01	0.02	0.02	0.23	0.00	—	99.9

Figure 14. a) Location of basal mixed zone matrix samples chosen for XRF analysis. b) Compositions of selected basal mixed zone samples and Aztec Sandstone and Moenkopi Formation parent samples.

Discussion

The Blue Diamond landslide experienced rapid emplacement over a rigid bedrock substratum forming a set of distinct features common to large rock avalanche deposits. Distribution of sedimentary fabrics and deposit morphologies rule out a frictionless emplacement. A downward increase in the percentage of matrix suggests that the slide block endured a rapid upward diminishing penetrative shear that was concentrated at the base of the landslide during motion. As rotational and overburden stresses were applied to the landslide, local stress concentrations began to exceed the compressive strength of the material, resulting in pervasive fragmentation, clast dispersion and enhanced mobility. Whereas many proposed transportation mechanisms are proposed for large rock avalanches, our observations suggest that the emplacement of the Blue Diamond landslide was strongly controlled by interactions with the runout path substrate.

Runout path substrate plays a critical role in the mobility of large rock avalanches, yet it is poorly understood. Many studies on the topic have tended to focus on large rock avalanches and the role of saturated runout path material (Legros, 2002; Hungr and Evans, 2004; Dufresne et al., 2010, 2016). Unfortunately, the study of saturated substrates only addresses rock avalanche mobility under certain conditions. The mechanics resulting from interactions between large rock avalanches and bedrock substrates remain unclear. The discussion below concentrates on the interaction between a large rock avalanche and rigid bedrock substrate.

Analysis of observed sedimentary fabrics and morphologies within the Blue Diamond landslide breccia allow for a detailed reconstruction of its emplacement. These characteristic

features are key to understanding the relationship between rock avalanche mobility and bedrock substrate of the run-out path. A combination of mature and immature textures within the landslide breccia are best explained by multiple mechanisms acting on the rock mass during transportation.

Basal Friction and Motion

Sedimentary fabrics within the landslide breccia are interpreted to have been developed through frictional interactions at the rock avalanche – substrate interface during emplacement. The existence of a basal mixed zone and fault gouge indicate repeated encounters between the landslide base and substrate (Friedmann, 1997). A rapid transition from disrupted zone fabric to matrix-poor fabric implies that the landslide endured intense shear concentrations at the rock avalanche – substrate interface that diminished upward during runout and may explain the relative absence of the jigsaw breccia facies. Furthermore, unfractured calcite veins within crackle breccia clasts confirm that the fabrics were formed contemporaneously with transportation (Schneider et al., 1999). Together, these fabrics eliminate a frictionless emplacement as they are evidence of basal resistance that likely influenced its mobility.

A study by Aaron and McDougall (2019) carried out the back analysis of 45 rock avalanche case histories to understand the effect of runout path material on rock avalanche mobility. Their results show that regardless of volume, rock avalanches that encountered bedrock substrate endured high basal shear resistance ($\mu = 0.35 - 0.45$) during emplacement. However, their results are not consistent with our findings, as conservative H/L estimates indicate the Blue Diamond

landslide experienced a low to moderate resistance ($\mu \sim 0.08 - 0.2$) to motion, which is shown by landslide breccia outcrops atop the west dipping Blue Diamond Hill. Additionally, all evidence indicates that emplacement occurred on a rigid bedrock substrate and should have resulted in limited mobility.

A possible explanation for reduced friction may reflect the extent of rock avalanche – substrate interaction and the development of the mixed zone. Yarnold and Lombard (1989) examined six different large rock avalanche deposits in the southern Basin and Range province to develop a facies model for landslide breccias formed in dry climates. They interpreted the discontinuous mixed zone to be a result of the recurring interactions between the irregular base of the rock avalanche and asperities on the runout path during emplacement. As rock avalanches encounter asperities, substrate material is sheared and entrained into the deposit where it mixes with material from the rock mass and locally accumulates on the underside of the deposit, forming the mixed zone (Yarnold and Lombard, 1989). As such, the low apparent friction encountered by the Blue Diamond landslide, especially the outcrops on Blue Diamond Hill, may represent reduced surface area contact at the rock avalanche – substrate interface which explains the low basal resistance and enhanced mobility experienced by the landslide breccia. Whereas this scenario is plausible, intrinsic mechanisms may also have been at work.

Dynamic Fragmentation and Mobility

As the Blue Diamond landslide deposit exists as an intensely brecciated mass of carbonate and siliciclastic clasts, it is likely that the fragmentation process had some influence on the

mobility and distribution of the deposit. Consequently, zonal changes in clast proportions throughout the landslide breccia document the degree of fragmentation and comminution during emplacement. A strong negative correlation between matrix and carbonate frequencies shows that their occurrences are directly related to one another. This indicates that areas with more observed matrix experienced substantial amounts of proportional breakage during emplacement.

These observations, along with those mentioned in the previous section, can best be explained by the process of dynamic fragmentation developed by Davies et al. (1999). In brief, compressive and shear stresses create elastic strain energy in clasts, which causes high velocity fragmentation and is released as kinetic energy within the rock avalanche body. Fragmentation causes an instantaneous increase of internal pressure in translating rock masses, reducing the intergranular stress in the shear layer. As a result, the overall frictional resistance in the shear layer is reduced, leading to increased distal mobility and reduced proximal mobility (Davies et al., 1999; Davies and McSaveney, 2009).

The question remains as to how this process affected the mobility of the Blue Diamond landslide. Many field (Dunning, 2006; Locat et al., 2006) and laboratory (Manzella and Labouise, 2009; Imre et al., 2010) studies have focused on rock fragmentation during runout; however, they fail to link the two. Bowman et al. (2012) demonstrated the relationship between the degree of fragmentation and runout length but did not address the role of substrate interaction. A study by Dufresne (2012) linked these parameters with runout path materials by conducting granular flow simulations over multiple types of substrates. They found that model runs that overrode a rough base (similar to rigid bedrock) saw proximal ends halting earlier with distal ends

experiencing longer runouts, confirming the conclusions of Davies et al. (1999) on dynamic fragmentation. These results explain the mobility of the Blue Diamond landslide and how dynamic fragmentation influenced runout while also allowing us to gain insight on local topographic conditions during failure.

Role of Topography

The Blue Diamond landslide was a highly mobile large rock avalanche that was likely influenced by local topography. It has been interpreted that many rock avalanches were initiated through gravitational collapse in response to high relief created during the development of the Basin and Range Province (Burchfiel et al., 1974). During motion, the translating mass was limited to the Blue Diamond area by confining topography at the distal end of the runout path. Whereas much is not known about local paleotopography, these parameters play a significant role in understanding the mobility of the Blue Diamond landslide.

The Blue Diamond landslide is thought to have been sourced from a headwall in the Keystone thrust plate; however, it is unclear as to how far the upper plate extended and to what height it reached at the time of failure. Understanding these factors would allow for a proper reconstruction of emplacement as it would provide more precise height and length values when calculating Heim's ratio. Page et al. (1998) hypothesize that the upper plate of the Keystone thrust once extended well over the Aztec Sandstone of the Wilson Cliffs and stood much higher than at the present day. This reduction of runout length and an increased drop height between 2.5 and 3 km would align with estimated friction coefficients of Aaron and McDougall (2019).

However, estimates of the extent of the Keystone thrust are limited and there are few known rock avalanches that experienced drop heights greater than 2 km (Friedmann, 1997).

Assuming the proposed original distribution is correct (Figure 5) (Page et al., 1998), mobility of the rock avalanche was almost certainly controlled by local topography. As it appears, the rock avalanche was confined to the Blue Diamond area by the Bird Spring Range to the south and Blue Diamond Hill to the north. These obstacles likely altered the runout course and may have been solely responsible for ceasing runout altogether as they are high energy dissipative geomorphic controls (Nicoletti and Sorriso-Valvo, 1991; Pollet et al., 2002). Shea and van Wyk de Vries (2008) replicated deposit geometries of 13 known rock avalanches through analogue modeling. They were able to characterize the effect of oblique deflection. They found that the obstructed side produced its own tongue shaped geometry and traveled farther than the unobstructed side. Their models produced similar geometries to that of the proposed original distribution of the Blue Diamond landslide, as the portion obstructed by Blue Diamond Hill created a separate tongue from the main body of the deposit and has a farther runout distance (Page et al., 1998).

Distribution of the Blue Diamond Landslide Deposit

Remnants of the Blue Diamond landslide deposit are scattered throughout the foothills of eastern flank of the Spring Mountains in the Blue Diamond area. Most of the landslide breccia caps the 4 km long northwest – southeast trending Blue Diamond Ridge. Southwesternmost exposures appear north of the Bird Spring Range along the Cottonwood Valley where they cap

large buttes. Perhaps the most intriguing exposures are two outcrops of breccia, which cap small buttes on the dip slope of the southwest dipping Blue Diamond Hill.

Page et al. (1998) think the landslide breccia was sourced from the eastern Spring Mountains in the upper plate of the Keystone thrust about 5 km west of the proximal end of the deposit (Figure 15a). They propose that landsliding was initiated by gravitational collapse of the thrust plate in the late Cenozoic. Based on their field observations, they project the original distribution of the deposit to have covered an area of nearly 25 km² (Figure 15a). This projection encompasses all exposed landslide breccia outcrops in the Blue Diamond area which indicates a runout distance of nearly 10 km (Page et al., 1998).

The Page et al. (1998) interpretation aligns with evidence presented herein; however, their original landslide distribution raises many questions. Whereas the logic behind their proposed source area is reasonable, their suggested distribution appears too large for the source area to accommodate. Using the proposed source and landslide areas and estimated thicknesses from Page et al. (1998), the proposed source area and landslide distribution have yielded volumes of 0.7 km³ and 1.5 km³, respectively. At the same time, deposit geometry and runout distances match the results of many studies mentioned above. Timing of emplacement also raises many questions regarding genesis as the Late Cenozoic was an active time of landsliding in the southern Basin and Range (Longwell, 1951). Many landslide breccias interpreted to be of the same age are exposed throughout the Spring Mountains and in adjacent areas (Burchfiel, 1975; Axen, 1985). Blue Diamond landslide breccia outcrops at Hill 4358' even rest atop other tabular landslide deposits (Page et al., 1998). The presence of many contemporaneously emplaced landslide breccias and deep-seated scarps along the Keystone thrust plate of the Spring Mountains

suggests that the Blue Diamond landslide breccia may be a product of multiple landslide episodes (Figure 15b).

The uncertainties regarding the genesis of the Blue Diamond landslide have led to the development of an alternative emplacement hypothesis. I propose that the Blue Diamond landslide may have originated slightly north of the previously proposed source area and was deposited on Blue Diamond Hill as a catastrophic rock avalanche (Figure 15c). Then over some time, the underlying Moenkopi Formation underwent gravity gliding as it slowly crept from Blue Diamond Hill into the Blue Diamond area, bringing the landslide breccia with it (Figure 15d). This hypothesis accounts for about 8.5 km of initial runout from the Spring Mountains and nearly 270 m of vertical displacement from Blue Diamond Hill to its current position.

If the Blue Diamond landslide breccia has been displaced from Blue Diamond Hill, then evidence for a rootless detachment should be present in the area. Normal faults are mapped and run parallel to the proposed glide block (Page et al., 2005). Adjacent to these normal faults exist triangular facets on the dip slope of Blue Diamond Hill which are indicative of normal faulting (Hamblin, 1976; Wallace, 1978). Their low angle may reflect the dip of the glide plane of the proposed glide block; however, some insist that triangular facet geometries are strongly controlled by rock composition and incised channel spacing (Ellis et al., 1999). Gravity gliding could also explain the two isolated outcrops that cap Blue Diamond Hill and why Moenkopi Formation only exists underneath exposed landslide breccia.

Several years after Page et al. (1998) investigated the Blue Diamond landslide, Page et al. (2005) identified a 30 km² gravity glide deposit of Kaibab and Toroweap Formations in the Red

Rock Wash area (Figure 2). They interpreted the glide block to have been sourced from the northeastern section of Blue Diamond Hill where it was initiated by faulting on the La Madre normal fault. The existence of this glide block supports our alternate emplacement hypothesis as it is proof that Blue Diamond Hill is suitable for gravity gliding to occur. If this is true, it potentially refutes Page et al. (1998) interpretation of a broad synclinal sag immediately under Blue Diamond Ridge. The axis is inferred by the attitudes of the surrounding Blue Diamond Hill and Bird Spring Range; however, the syncline is poorly defined and may actually reflect accommodation from overburden during emplacement of our proposed glide block.

Whereas this emplacement method may be plausible, additional facies mapping and clast counts will be needed at the Blue Diamond Hill outcrops and the proposed Moenkopi Formation glide block. Unfortunately, a glide block basal contact is likely buried by colluvium and is yet to be assessed to test this proposed emplacement hypothesis.

A Model for Emplacement

Derived from the upper plate of the Keystone thrust, the rock avalanche likely vacated its source area at high velocity as a coherent slab of carbonate rock (Figure 16). As it exited its source area, it overrode the sandstone bluffs of the Wilson Cliffs, entraining significant amounts of Aztec Sandstone before it reached the run-out path. During runout, the rock avalanche experienced relatively high basal shear resistance as it encountered its rigid bedrock substrate resulting in the formation and distribution of its sedimentary fabrics and internal morphologies. Compressive and shear stresses initiated the dynamic fragmentation process, which caused the rock avalanche

to endure a reduced basal resistance allowing for enhanced mobility. Dynamic fragmentation influenced rock avalanche mobility resulting in the proximal end experiencing moderate basal resistance ($\mu \sim 0.35$) and the distal end encountering little resistance to motion ($\mu \sim 0.1$). Local topography altered the runout path course and restricted the rock avalanche to the Blue Diamond area where it is currently exposed.

Application to Basin and Range Large-Scale Landslides

Observations and interpretations presented herein have important implications for understanding large-scale landslides within the Basin and Range province. Caution should be taken when interpreting the emplacement of individual deposits as the mechanisms that govern the mobility of rock avalanches that override rigid bedrock substrates will be different than those that encounter alluvium. Furthermore, detailed mapping of the distribution of sedimentary fabrics and deposit morphologies is necessary to fully understand emplacement dynamics. The Blue Diamond landslide can be used as an analog for other dry-climate, large rock avalanches emplaced across rigid bedrock substrates. However, emplacement mechanisms can be complex and the model presented here should not be universally applied to all large-scale landslides in the Basin and Range province.

Explanation

Surficial Deposits	Source area for gravity glide hypothesis
Keystone Thrust: Plate Cambrian through Permian rocks	Projected Blue Diamond landslide distribution for gravity glide hypothesis
Bird Spring: Plate Permian through Jurassic rocks	Projected source areas and Blue Diamond landslide deposit contributor landslides for multiple landslide hypothesis
Exposed remnants of the Blue Diamond landslide	Gravity glide block
Original extent of Blue Diamond landslide and source area as proposed by Page et al. (1998)	
	Thrust Fault

Figure 15. Map view of a) Page et al. (1998) interpretation of source area and original deposit extent; b) multiple landslide model; c) model of farther north source area and catastrophic deposition onto Blue Diamond Hill; d) subsequent gravity gliding and fragmentation on gypsum-bearing substrate to present configuration (modified from Page et al., 1998).

Figure 16. Conceptual model of the emplacement of the Blue Diamond landslide deposit and its internal development as it traveled from its source along a rigid bedrock runout path until its deposition. Not to scale.

Conclusions

The Blue Diamond landslide breccia was emplaced at high velocity as it slid over a rigid bedrock substratum. Distributions of sedimentary fabrics and deposit morphologies rule out a frictionless emplacement as they are evidence for repeated interaction at the rock avalanche – substrate interface. This interaction should have reduced the runout distance of the rock avalanche but estimates of Heim's ratio suggest that the Blue Diamond landslide experienced low to moderate resistance to motion. Intrinsic mechanisms working within the translating mass likely explain the enhanced mobility encountered by the rock avalanche. Compressional and shear stresses induced the dynamic fragmentation process during motion which resulted in a reduction of frictional resistance at the rock avalanche – substrate interface causing a longer observed runout distance for the Blue Diamond landslide. This runout was likely halted by confining topography of the distal Blue Diamond Hill and Bird Spring Range.

Based on uncertainties surrounding the proposed original distribution of the Blue Diamond landslide deposit by Page et al. (1998), I present an alternative emplacement. I propose that the Blue Diamond landslide originated as a catastrophic rock avalanche that was derived slightly north of its previously suggested source area. During runout, the rock avalanche directly encountered Blue Diamond Hill where it ran upslope, eventually being deposited upon Moenkopi Formation on the hill. Underlying Moenkopi Formation and landslide breccia then experienced gravity gliding as it was transported from Blue Diamond Hill to its current position in the Blue Diamond area. Future studies are needed to validate this hypothesis and should include field

investigations of the glide block detachment and footwall surfaces; knickpoint analysis on Blue Diamond Hill; and clast counts of the Blue Diamond Hill outcrops.

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Appendix A

Clast Count Data and Locations

Clast Count Results and Locations

Count #	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total	Longitude	Latitude
CC 1	36	54	0	0	0	0	90	36°0'40.56"N	115°26'24.84"W
CC 2	54	32	4	0	0	0	90	36°0'40.68"N	115°26'24.66"W
CC3	51	39	0	0	0	0	90	36°0'41.52"N	115°26'27.72"W
CC 4	52	38	0	0	0	0	90	36°0'41.58"N	115°26'16.08"W
CC 5	61	29	0	0	0	0	90	36°0'41.10"N	115°26'15.66"W
CC 6	61	26	3	0	0	0	90	36°0'40.74"N	115°26'14.70"W
CC 7	40	50	0	0	0	0	90	36°0'43.02"N	115°26'21.96"W
CC 8	27	55	4	0	4	0	90	36°0'49.03"N	115°26'15.18"W
CC 9	36	46	2	0	6	0	90	36°0'38.82"N	115°26'12.18"W
CC 10	14	57	0	0	19	0	90	36°0'38.70"N	115°26'10.50"W
CC 11	5	73	0	0	12	0	90	36°1'58.26"N	115°24'5.64"W
CC 12	26	60	0	0	4	0	90	36°1'58.26"N	115°24'5.52"W
CC 13	30	53	0	0	7	0	90	36°1'59.40"N	115°24'7.62"W
CC 14	70	17	3	0	0	0	90	36°1'59.52"N	115°24'7.26"W
CC 15	16	74	0	0	0	0	90	36° 2'4.02"N	115°24'9.30"W
CC 16	27	63	0	0	0	0	90	36° 2'4.02"N	115°24'9.42"W
CC 17	36	29	0	25	0	0	90	36° 2'7.44"N	115°24'13.56"W
CC 18	22	46	0	22	0	0	90	36° 2'7.38"N	115°24'13.56"W
CC 19	8	76	6	0	0	0	90	36° 2'6.66"N	115°24'18.72"W
CC 20	28	62	0	0	0	0	90	36° 2'6.66"N	115°24'18.78"W
CC 21	0	42	0	48	0	0	90	36° 2'8.10"N	115°24'20.76"W
CC 22	12	53	23	2	0	0	90	36° 2'8.10"N	115°24'20.76"W
CC 23	21	63	0	6	0	0	90	36°2'18.18"N	115°24'28.14"W
CC 24	59	31	0	0	0	0	90	36°2'18.00"N	115°24'27.96"W
CC 25	29	48	7	6	0	0	90	36°2'18.24"N	115°24'23.94"W
CC 26	39	37	14	0	0	0	90	36°2'18.36"N	115°24'24.36"W
CC 27	23	64	3	0	0	0	90	36°2'16.74"N	115°24'13.02"W
CC 28	55	28	5	2	0	0	90	36°2'16.86"N	115°24'13.14"W
CC 29	23	67	0	0	0	0	90	36°2'13.32"N	115°24'4.08"W
CC 30	20	35	35	0	0	0	90	36°2'13.62"N	115°24'4.20"W
CC 31	38	45	5	2	0	0	90	36° 2'8.16"N	115°24'1.50"W
CC 32	64	26	0	0	0	0	90	36° 2'8.46"N	115°24'1.20"W
CC 33	30	56	4	0	0	0	90	36°2'23.16"N	115°24'55.26"W
CC 34	51	35	4	0	0	0	90	36°2'23.04"N	115°24'55.38"W
CC 35	46	36	6	2	0	0	90	36°2'23.22"N	115°24'55.44"W
CC 36	50	29	9	0	0	2	90	36°2'23.53"N	115°24'56.74"W
CC 37	14	54	3	19	0	0	90	36°2'23.44"N	115°24'56.05"W
CC 38	29	40	0	0	19	2	90	36°2'26.16"N	115°25'0.06"W
CC 39	53	37	0	0	0	0	90	36°2'42.06"N	115°25'1.86"W
CC 40	67	23	0	0	0	0	90	36°2'41.76"N	115°25'1.50"W
CC 41	55	35	0	0	0	0	90	36°2'42.48"N	115°25'2.16"W
CC 42	71	19	0	0	0	0	90	36°2'42.12"N	115°25'1.86"W
CC 43	64	26	0	0	0	0	90	36°2'43.14"N	115°25'2.52"W
CC 44	90	0	0	0	0	0	90	36°2'42.90"N	115°25'1.68"W
CC 45	35	55	0	0	0	0	90	36°2'44.28"N	115°25'3.12"W
CC 46	51	39	0	0	0	0	90	36°2'44.16"N	115°25'3.06"W
CC 47	63	24	3	0	0	0	90	36°2'44.40"N	115°25'3.72"W
CC 48	61	29	0	0	0	0	90	36°2'44.28"N	115°25'3.54"W
CC 49	55	35	0	0	0	0	90	36°2'40.08"N	115°24'58.02"W
CC 50	38	52	0	0	0	0	90	36°2'39.96"N	115°24'57.96"W
CC 51	50	38	2	0	0	0	90	36°2'38.52"N	115°24'55.68"W
CC 52	47	43	0	0	0	0	90	36°2'38.52"N	115°24'55.68"W
CC 53	27	58	0	3	2	0	90	36°2'35.64"N	115°25'22.86"W

CC 54	36	52	0	0	2	0	90	36°2'35.76"N	115°25'22.68"W
CC 55	46	43	0	1	0	0	90	36°2'35.16"N	115°25'23.88"W
CC 56	52	33	0	0	4	1	90	36°2'35.28"N	115°25'23.64"W
CC 57	47	35	0	4	4	0	90	36°2'33.24"N	115°25'23.40"W
CC 58	60	27	0	0	3	0	90	36°2'33.12"N	115°25'23.40"W
CC 59	34	46	0	4	6	0	90	36°2'31.02"N	115°25'24.60"W
CC 60	51	23	0	0	15	1	90	36°2'31.02"N	115°25'24.48"W
CC 61	70	20	0	0	0	0	90	36°2'31.32"N	115°25'28.20"W
CC 62	73	17	0	0	0	0	90	36°2'31.38"N	115°25'28.26"W
CC 63	54	36	0	0	0	0	90	36°2'31.08"N	115°25'34.08"W
CC 64	55	35	0	0	0	0	90	36°2'31.20"N	115°25'34.26"W
CC 65	37	39	0	0	14	0	90	36°2'33.00"N	115°25'41.76"W
CC 66	29	40	0	0	11	10	90	36°2'33.00"N	115°25'41.70"W
CC 67	49	28	13	0	0	0	90	36°2'34.62"N	115°25'43.56"W
CC 68	51	34	0	0	5	0	90	36°2'34.62"N	115°25'43.86"W
CC 69	33	40	3	6	0	8	90	36°2'35.52"N	115°25'49.08"W
CC 70	45	37	4	0	0	4	90	36°2'35.40"N	115°25'48.96"W
CC 71	46	36	2	6	0	0	90	36°2'31.92"N	115°25'39.84"W
CC 72	53	35	2	0	0	0	90	36°2'32.10"N	115°25'40.14"W
CC 73	20	65	0	0	5	0	90	36°2'31.92"N	115°25'36.60"W
CC 74	46	38	2	0	2	2	90	36°2'31.98"N	115°25'36.78"W
CC 75	20	70	0	0	0	0	90	36°2'56.94"N	115°25'52.02"W
CC 76	44	41	0	0	0	5	90	36°2'57.00"N	115°25'52.02"W
CC 77	28	57	0	0	0	5	90	36°2'54.54"N	115°25'55.32"W
CC 78	38	49	0	0	3	0	90	36°2'54.54"N	115°25'55.38"W
CC 79	45	45	0	0	0	0	90	36°2'53.64"N	115°25'58.92"W
CC 80	52	38	0	0	0	0	90	36°2'53.82"N	115°25'59.04"W
CC 81	19	64	7	0	0	0	90	36°2'57.30"N	115°25'59.52"W
CC 82	53	0	37	0	0	0	90	36°2'57.24"N	115°25'59.40"W
CC 83	62	28	0	0	0	0	90	36°2'50.64"N	115°26'2.76"W
CC 84	38	52	0	0	0	0	90	36°2'50.40"N	115°26'2.64"W
CC 85	65	18	7	0	0	0	90	36°2'49.26"N	115°26'3.06"W
CC 86	45	36	9	0	0	0	90	36°2'49.08"N	115°26'3.12"W
CC 87	18	50	22	0	0	0	90	36°2'49.02"N	115°26'5.28"W
CC 88	29	44	17	0	0	0	90	36°2'48.96"N	115°26'5.28"W
CC 89	24	66	0	0	0	0	90	36°2'49.20"N	115°26'7.14"W
CC 90	46	44	0	0	0	0	90	36°2'49.26"N	115°26'7.26"W
CC 91	44	40	0	6	0	0	90	36°2'51.24"N	115°26'8.58"W
CC 92	79	0	11	0	0	0	90	36°2'51.78"N	115°26'10.38"W
CC 93	44	46	0	0	0	0	90	36°2'50.10"N	115°26'6.00"W
CC 94	36	43	8	0	0	3	90	36°2'50.28"N	115°26'4.38"W
CC 95	50	36	4	0	0	0	90	36°2'46.14"N	115°25'59.04"W
CC 96	53	37	0	0	0	0	90	36°2'46.38"N	115°25'58.44"W
CC 97	24	50	16	0	0	0	90	36°2'46.26"N	115°25'57.18"W
CC 98	12	61	17	0	0	0	90	36°2'45.90"N	115°25'56.34"W
CC 99	11	61	18	0	0	0	90	36°2'44.16"N	115°25'54.96"W
CC 100	20	64	6	0	0	0	90	36°2'43.38"N	115°25'53.52"W
CC 101	41	44	0	0	0	5	90	36°2'36.54"N	115°25'54.18"W
CC 102	17	59	0	12	2	0	90	36°2'34.62"N	115°25'53.10"W
CC 103	39	51	0	0	0	0	90	36°2'14.58"N	115°24'32.46"W
CC 104	71	12	7	0	0	0	90	36°2'14.52"N	115°24'31.68"W
CC 105	22	64	4	0	0	0	90	36°2'13.44"N	115°24'24.90"W
CC 106	69	21	0	0	0	0	90	36°2'13.14"N	115°24'24.66"W
CC 107	26	64	0	0	0	0	90	36°2'11.64"N	115°24'39.66"W
CC 108	87	3	0	0	0	0	90	36°2'10.86"N	115°24'41.46"W
CC 109	37	53	0	0	0	0	90	36°2'8.52"N	115°24'42.78"W

CC 110	46	34	0	10	0	0	90	36° 2'7.74"N	115°24'42.30"W
CC 111	60	30	0	0	0	0	90	36° 2'6.78"N	115°24'41.28"W
CC 112	49	37	2	2	0	0	90	36° 2'6.18"N	115°24'41.28"W
CC 113	88	0	2	0	0	0	90	36° 2'6.36"N	115°24'40.68"W
CC 114	49	35	2	4	0	0	90	36° 2'7.44"N	115°24'37.26"W
CC 115	69	21	0	0	0	0	90	36° 2'7.50"N	115°24'33.60"W
CC 116	80	10	0	0	0	0	90	36° 2'7.20"N	115°24'32.16"W
CC 117	63	27	0	0	0	0	90	36° 2'7.56"N	115°24'37.26"W
CC 118	72	18	0	0	0	0	90	36° 2'8.70"N	115°24'39.06"W
CC 119	34	41	15	0	0	0	90	36° 2'7.26"N	115°24'36.18"W
CC 120	58	32	0	0	0	0	90	36° 2'6.12"N	115°24'42.36"W

Pie Chart Key

Carbonates

Matrix

Chert

Calcite

Aztec Sandstone

Moenkopi Fm

Total Count Sets: 120

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi Total
n	5193	4836	382	192	149	48
Mean	43.275	40.3	3.183333	1.6	1.241667	0.4
Contribution (%)	48.1	44.8	3.54	1.78	1.38	0.444
Count Sets	120	120	120	120	120	120
CI (%)	2.85765896	2.505112	0.98183	0.871442	0.534308	0.222531

Proximal Clast Counts: CC 1 – 10, CC 75 – 102

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi Total
n	1489	1669	192	18	34	3420
Mean	39.1842105	43.92105	5.052632	0.473684	0.894737	0.473684
Contribution (%)	43.5	48.8	5.61	0.526	0.994	0.526
Count Sets	38	38	38	38	38	38
CI (%)	4.45699331	4.256955	2.205031	0.57727	0.876792	0.382982

Proximal Counts: CC 1 – 5

Lithology	Carbonates	Matrix	Chert	Caliche	Artec	Moenkapi	Total
CC 1	14	57	0	0	19	0	90
Contribution (%)	15.6	63.3	0.00	0.00	21.11	0.000	100.0
CC 2	54	32	4	0	0	0	90
Contribution (%)	60.0	35.6	4.44	0.00	0.00	0.000	100.0
CC 3	51	39	0	0	0	0	90
Contribution (%)	56.7	43.3	0.00	0.00	0.00	0.000	100.0
CC 4	52	38	0	0	0	0	90
Contribution (%)	57.8	42.2	0.00	0.00	0.00	0.000	100.0
CC 5	61	29	0	0	0	0	90
Contribution (%)	67.8	32.2	0.00	0.00	0.00	0.000	100.0

Proximal Counts: CC 6 – 10

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 6	61	26	3	0	0	0	90
Contribution (%)	67.8	28.9	3.33	0.00	0.00	0.000	100.0
CC 7	40	50	0	0	0	0	90
Contribution (%)	44.4	55.6	0.00	0.00	0.00	0.000	100.0
CC 8	27	55	4	0	4	0	90
Contribution (%)	30.0	61.1	4.44	0.00	4.44	0.000	100.0
CC 9	36	46	2	0	6	0	90
Contribution (%)	40.0	51.1	2.22	0.00	6.67	0.000	100.0
CC 10	14	57	0	0	19	0	90
Contribution (%)	15.6	63.3	0.00	0.00	21.11	0.000	100.0

Proximal Counts: CC 75 – 79

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 75	20	70	0	0	0	0	90
Contribution (%)	22.2	77.8	0.00	0.00	0.00	0.000	100.0
CC 76	44	41	0	0	0	5	90
Contribution (%)	48.9	45.6	0.00	0.00	0.00	5.556	100.0
CC 77	28	57	0	0	0	5	90
Contribution (%)	31.1	63.3	0.00	0.00	0.00	5.556	100.0
CC 78	38	49	0	0	3	0	90
Contribution (%)	42.2	54.4	0.00	0.00	3.33	0.000	100.0
CC 79	45	45	0	0	0	0	90
Contribution (%)	50.0	50.0	0.00	0.00	0.00	0.000	100.0

Proximal Counts: CC 80 – 84

Lithology	Carbonates	Matrix	Chert	Caliche	Aztec	Meenkopi	Total
CC 80	52	38	0	0	0	0	90
Contribution (%)	57.8	42.2	0.00	0.00	0.00	0.000	100.0
CC 81	19	64	7	0	0	0	90
Contribution (%)	21.1	71.1	7.78	0.00	0.00	0.000	100.0
CC 82	53	0	37	0	0	0	90
Contribution (%)	58.9	0.0	41.11	0.00	0.00	0.000	100.0
CC 83	62	28	0	0	0	0	90
Contribution (%)	68.9	31.1	0.00	0.00	0.00	0.000	100.0
CC 84	38	52	0	0	0	0	90
Contribution (%)	42.2	57.8	0.00	0.00	0.00	0.000	100.0

Proximal Counts: CC 85 – 89

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 85	65	18	7	0	0	0	90
Contribution (%)	72.2	20.0	7.78	0.00	0.00	0.000	100.0
CC 86	45	36	9	0	0	0	90
Contribution (%)	50.0	40.0	10.00	0.00	0.00	0.000	100.0
CC 87	18	50	22	0	0	0	90
Contribution (%)	20.0	55.6	24.44	0.00	0.00	0.000	100.0
CC 88	29	44	17	0	0	0	90
Contribution (%)	32.2	48.9	18.89	0.00	0.00	0.000	100.0
CC 89	24	66	0	0	0	0	90
Contribution (%)	26.7	73.3	0.00	0.00	0.00	0.000	100.0

Proximal Counts: CC 90 – 94

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 90	46	44	0	0	0	0	90
Contribution (%)	51.1	48.9	0.00	0.00	0.00	0.000	100.0
CC 91	44	40	0	6	0	0	90
Contribution (%)	48.9	44.4	0.00	6.67	0.00	0.000	100.0
CC 92	79	0	11	0	0	0	90
Contribution (%)	87.8	0.0	12.22	0.00	0.00	0.000	100.0
CC 93	44	46	0	0	0	0	90
Contribution (%)	48.9	51.1	0.00	0.00	0.00	0.000	100.0
CC 94	36	43	8	0	0	3	90
Contribution (%)	40.0	47.8	8.89	0.00	0.00	3.333	100.0

Proximal Counts: CC 95 – 99

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 95	50	36	4	0	0	0	90
Contribution (%)	55.6	40.0	4.44	0.00	0.00	0.000	100.0
CC 96	53	37	0	0	0	0	90
Contribution (%)	58.9	41.1	0.00	0.00	0.00	0.000	100.0
CC 97	24	50	16	0	0	0	90
Contribution (%)	26.7	55.6	17.78	0.00	0.00	0.000	100.0
CC 98	12	61	17	0	0	0	90
Contribution (%)	13.3	67.8	18.89	0.00	0.00	0.000	100.0
CC 99	11	61	18	0	0	0	90
Contribution (%)	12.2	67.8	20.00	0.00	0.00	0.000	100.0

Proximal Counts: CC 100 – 102

Lithology	Carbonates	Matrix	Chert	Calclite	Aztec	Meenkopi	Total
CC 100	20	64	6	0	0	0	90
Contribution (%)	22.2	71.1	6.67	0.00	0.00	0.000	100.0
CC 101	41	44	0	0	0	5	90
Contribution (%)	45.6	48.9	0.00	0.00	0.00	5.556	100.0
CC 102	17	59	0	12	2	0	90

Medial Clast Counts: CC 33 – 74

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi Total
n	2034	1522	57	45	92	3780
Mean	48.4285714	36.2381	1.357143	1.071429	2.190476	0.714286
Contribution (%)	53.8095238	40.26455	1.507937	1.190476	2.433862	0.793651
Count Sets	42	42	42	42	42	42
CI (%)	3.83160559	3.146555	0.689538	0.826774	1.154832	0.523288

Medial Counts: CC 33 – 37

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi	Total
CC 33	30	56	4	0	0	0	90
Contribution (%)	33.3	62.2	4.44	0.00	0.00	0.000	100.0
CC 34	51	35	4	0	0	0	90
Contribution (%)	56.7	38.9	4.44	0.00	0.00	0.000	100.0
CC 35	46	36	6	2	0	0	90
Contribution (%)	51.1	40.0	6.67	2.22	0.00	0.000	100.0
CC 36	50	29	9	0	0	2	90
Contribution (%)	55.6	32.2	10.00	0.00	0.00	2.222	100.0
CC 37	14	54	3	19	0	0	90
Contribution (%)	15.6	60.0	3.33	21.11	0.00	0.000	100.0

Medial Counts: CC 38 – 42

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Meenkopi	Total
CC 38	29	40	0	0	19	2	90
Contribution (%)	32.2	44.4	0.00	0.00	21.11	2.222	100.0
CC 39	53	37	0	0	0	0	90
Contribution (%)	58.9	41.1	0.00	0.00	0.00	0.000	100.0
CC 40	67	23	0	0	0	0	90
Contribution (%)	74.4	25.6	0.00	0.00	0.00	0.000	100.0
CC 41	55	35	0	0	0	0	90
Contribution (%)	61.1	38.9	0.00	0.00	0.00	0.000	100.0
CC 42	71	19	0	0	0	0	90
Contribution (%)	75.9	21.1	0.00	0.00	0.00	0.000	100.0

Medial Counts: CC 43 – 47

Lithology	Carbonates	Matrix	Chert	Caliche	Aztec	Meenkopi	Total
CC 43	64	26	0	0	0	0	90
Contribution (%)	71.1	28.9	0.00	0.00	0.00	0.000	100.0
CC 44	90	0	0	0	0	0	90
Contribution (%)	100.0	0.0	0.00	0.00	0.00	0.000	100.0
CC 45	35	55	0	0	0	0	90
Contribution (%)	38.9	61.1	0.00	0.00	0.00	0.000	100.0
CC 46	51	39	0	0	0	0	90
Contribution (%)	56.7	43.3	0.00	0.00	0.00	0.000	100.0
CC 47	63	24	3	0	0	0	90
Contribution (%)	70.0	26.7	3.33	0.00	0.00	0.000	100.0

Medial Counts: CC 48 – 52

Lithology	Carbonates	Matrix	Chert	Caliche	Aztec	Meenkopi	Total
CC 48	61	29	0	0	0	0	90
Contribution (%)	67.8	32.2	0.00	0.00	0.00	0.000	100.0
CC 49	55	35	0	0	0	0	90
Contribution (%)	61.1	38.9	0.00	0.00	0.00	0.000	100.0
CC 50	38	52	0	0	0	0	90
Contribution (%)	42.2	57.8	0.00	0.00	0.00	0.000	100.0
CC 51	50	38	2	0	0	0	90
Contribution (%)	55.6	42.2	2.22	0.00	0.00	0.000	100.0
CC 52	47	43	0	0	0	0	90
Contribution (%)	52.2	47.8	0.00	0.00	0.00	0.000	100.0

Medial Counts: CC 53 – 57

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Menkopi	Total
CC 53	27	56	0	3	2	0	90
Contribution (%)	30.0	64.4	0.00	3.33	2.22	0.000	100.0
CC 54	36	52	0	0	2	0	90
Contribution (%)	40.0	57.8	0.00	0.00	2.22	0.000	100.0
CC 55	46	43	0	1	0	0	90
Contribution (%)	51.1	47.8	0.00	1.11	0.00	0.000	100.0
CC 56	52	33	0	0	4	1	90
Contribution (%)	57.8	36.7	0.00	0.00	4.44	1.111	100.0
CC 57	47	35	0	4	4	0	90
Contribution (%)	52.2	38.9	0.00	4.44	4.44	0.000	100.0

Medial Counts: CC 58 – 62

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Menkopi	Total
CC 58	60	27	0	0	3	0	90
Contribution (%)	66.7	30.0	0.00	0.00	3.33	0.000	100.0
CC 59	34	46	0	4	6	0	90
Contribution (%)	37.8	51.1	0.00	4.44	6.67	0.000	100.0
CC 60	51	23	0	0	15	1	90
Contribution (%)	56.7	25.6	0.00	0.00	16.67	1.111	100.0
CC 61	70	20	0	0	0	0	90
Contribution (%)	77.8	22.2	0.00	0.00	0.000	0.000	100.0
CC 62	73	17	0	0	0	0	90
Contribution (%)	81.1	18.9	0.00	0.00	0.000	0.000	100.0

Medial Counts: CC 63 – 67

Lithology	Carbonates	Matrix	Chert	Caliche	Aztec	Menkopi	Total
CC 63	54	36	0	0	0	0	90
Contribution (%)	60.0	40.0	0.00	0.00	0.00	0.000	100.0
CC 64	55	35	0	0	0	0	90
Contribution (%)	61.1	38.9	0.00	0.00	0.00	0.000	100.0
CC 65	37	39	0	0	14	0	90
Contribution (%)	41.1	43.3	0.00	0.00	15.56	0.000	100.0
CC 66	29	40	0	0	11	10	90
Contribution (%)	32.2	44.4	0.00	0.00	12.22	11.111	100.0
CC 67	49	28	13	0	0	0	90
Contribution (%)	54.4	31.1	14.44	0.00	0.00	0.000	100.0

Medial Counts: CC 68 – 72

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Menkopi	Total
CC 68	51	34	0	0	5	0	90
Contribution (%)	56.7	37.8	0.00	0.00	5.56	0.000	100.0
CC 69	33	40	3	6	0	8	90
Contribution (%)	36.7	44.4	3.33	6.67	0.00	8.889	100.0
CC 70	45	37	4	0	0	4	90
Contribution (%)	50.0	41.1	4.44	0.00	0.00	4.444	100.0
CC 71	46	36	2	6	0	0	90
Contribution (%)	51.1	40.0	2.22	6.67	0.00	0.000	100.0
CC 72	53	35	2	0	0	0	90
Contribution (%)	58.9	38.9	2.22	0.00	0.00	0.000	100.0

Medial Counts: CC 73 – 74

Lithology	Carbonates	Matrix	Chert	Caliche	Aztec	Monkopi	Total
CC 73	20	65	0	0	5	0	90
Contribution (%)	22.2	72.2	0.00	0.00	5.56	0.000	100.0
CC 74	46	38	2	0	2	2	90
Contribution (%)	51.1	42.2	2.22	0.00	2.22	2.222	100.0

Distal Clast Counts: CC 11 – 32, 103 – 120

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Moenkopi
n	1670	1645	133	129	23	0
Mean	41.75	41.125	3.325	3.225	0.575	0
Contribution (%)	46.388889	45.69444	3.694444	3.583333	0.638889	0
Count Sets	40	40	40	40	40	40
CI (%)	6.11654388	5.296214	1.854154	2.367836	0.585584	0

Distal Counts: CC 11 – 15

Lithology	Carbonates	Matrix	Chert	Calcite	Aritec	Meenkopi	Total
CC 11		5	73	0	0	12	90
Contribution (%)	5.6	81.1	0.00	0.00	13.33	0.000	100.0
CC 12		26	60	0	0	4	90
Contribution (%)	28.9	66.7	0.00	0.00	4.44	0.000	100.0
CC 13		30	53	0	0	7	90
Contribution (%)	33.3	58.9	0.00	0.00	7.78	0.000	100.0
CC 14		70	17	3	0	0	90
Contribution (%)	77.8	18.9	3.33	0.00	0.00	0.000	100.0
CC 15		16	74	0	0	0	90
Contribution (%)	17.8	82.2	0.00	0.00	0.00	0.000	100.0

Distal Counts: CC 16 – 20

Lithology	Carbonates	Matrix	Chert	Calcite	Artec	Meentkopi	Total
CC 16	27	63	0	0	0	0	90
Contribution (%)	30.0	70.0	0.00	0.00	0.00	0.000	100.0
CC 17	36	29	0	25	0	0	90
Contribution (%)	40.0	32.2	0.00	27.78	0.00	0.000	100.0
CC 18	22	46	0	22	0	0	90
Contribution (%)	24.4	51.1	0.00	24.44	0.00	0.000	100.0
CC 19	8	76	6	0	0	0	90
Contribution (%)	8.9	84.4	6.67	0.00	0.00	0.000	100.0
CC 20	28	62	0	0	0	0	90
Contribution (%)	31.1	68.9	0.00	0.00	0.00	0.000	100.0

Distal Counts: CC 21 – 25

Lithology	Carbonates	Matrix	Chert	Calcite	Artec	Meenkopi	Total
CC 21	0	42	0	48	0	0	90
Contribution (%)	0.0	46.7	0.00	53.33	0.00	0.000	100.0
CC 22	12	53	23	2	0	0	90
Contribution (%)	13.3	58.9	25.56	2.22	0.00	0.000	100.0
CC 23	21	63	0	6	0	0	90
Contribution (%)	23.3	70.0	0.00	6.67	0.00	0.000	100.0
CC 24	59	31	0	0	0	0	90
Contribution (%)	65.6	34.4	0.00	0.00	0.00	0.000	100.0
CC 25	29	48	7	6	0	0	90
Contribution (%)	32.2	53.3	7.78	6.67	0.00	0.000	100.0

Distal Counts: CC 26 – 30

Lithology	Carbonates	Matrix	Chert	Calcite	Artec	Meentkopi	Total
CC 26	39	37	14	0	0	0	90
Contribution (%)	43.3	41.1	15.56	0.00	0.00	0.000	100.0
CC 27	23	64	3	0	0	0	90
Contribution (%)	25.6	71.1	3.33	0.00	0.00	0.000	100.0
CC 28	55	28	5	2	0	0	90
Contribution (%)	61.1	31.1	5.56	2.22	0.00	0.000	100.0
CC 29	23	67	0	0	0	0	90
Contribution (%)	25.6	74.4	0.00	0.00	0.00	0.000	100.0
CC 30	20	35	35	0	0	0	90
Contribution (%)	22.2	38.9	38.89	0.00	0.00	0.000	100.0

Distal Counts: CC 31 – CC 32, 103 – 105

Lithology	Carbonates	Matrix	Chert	Calcite	Aritec	Meentkopi	Total
CC 31	38	45	5	2	0	0	90
Contribution (%)	42.2	50.0	5.56	2.22	0.00	0.000	100.0
CC 32	64	26	0	0	0	0	90
Contribution (%)	71.1	28.9	0.00	0.00	0.00	0.000	100.0
CC 103	39	51	0	0	0	0	90
Contribution (%)	43.3	56.7	0.00	0.00	0.00	0.000	100.0
CC 104	71	12	7	0	0	0	90
Contribution (%)	78.9	13.3	7.78	0.00	0.00	0.000	100.0
CC 105	22	64	4	0	0	0	90
Contribution (%)	24.4	71.1	4.44	0.00	0.00	0.000	100.0

Distal Counts: CC 106 – 110

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Menkopi	Total
CC 106	69	21	0	0	0	0	90
Contribution (%)	76.7	23.3	0.00	0.00	0.00	0.00	100.0
CC 107	26	64	0	0	0	0	90
Contribution (%)	28.9	71.1	0.00	0.00	0.00	0.00	100.0
CC 108	87	3	0	0	0	0	90
Contribution (%)	96.7	3.3	0.00	0.00	0.00	0.00	100.0
CC 109	37	53	0	0	0	0	90
Contribution (%)	41.1	58.9	0.00	0.00	0.00	0.00	100.0
CC 110	46	34	0	10	0	0	90
Contribution (%)	51.1	37.8	0.00	11.11	0.00	0.00	100.0

Distal Counts: CC 111 – 115

Lithology	Carbonates	Matrix	Chert	Calcite	Artec	Menkopi	Total
CC 111	60	30	0	0	0	0	90
Contribution (%)	66.7	33.3	0.00	0.00	0.00	0.00	100.0
CC 112	49	37	2	2	0	0	90
Contribution (%)	54.4	41.1	2.22	2.22	0.00	0.000	100.0
CC 113	88	0	2	0	0	0	90
Contribution (%)	97.8	0.0	2.22	0.00	0.00	0.000	100.0
CC 114	49	35	2	4	0	0	90
Contribution (%)	54.4	38.9	2.22	4.44	0.00	0.000	100.0
CC 115	69	21	0	0	0	0	90
Contribution (%)	76.7	23.3	0.00	0.00	0.00	0.000	100.0

Distal Counts: CC 115 – 120

Lithology	Carbonates	Matrix	Chert	Calcite	Aztec	Menkopi	Total
CC 116	80	10	0	0	0	0	90
Contribution (%)	88.9	11.1	0.00	0.00	0.00	0.00	100.0
CC 117	63	27	0	0	0	0	90
Contribution (%)	70.0	30.0	0.00	0.00	0.00	0.00	100.0
CC 118	72	18	0	0	0	0	90
Contribution (%)	80.0	20.0	0.00	0.00	0.00	0.00	100.0
CC 119	34	41	15	0	0	0	90
Contribution (%)	37.8	45.6	16.67	0.00	0.00	0.00	100.0
CC 120	58	32	0	0	0	0	90
Contribution (%)	64.4	35.6	0.00	0.00	0.00	0.00	100.0

Appendix B

Samples, Facies, and XRF Data

Samples

Samples	Latitude	Longitude	Notes
D2S1	36° 2'56.94"N	115°25'51.60"W	Clastic Dike
D2S2	36° 2'57.00"N	115°25'51.60"W	Slide Surface
D2S3	36° 2'57.00"N	115°25'51.66"W	Carbonate clast; above D2S2
D2S4	36° 2'57.00"N	115°25'51.66"W	Carbonate; above D2S3
D2S5	36° 2'57.00"N	115°25'51.66"W	Clastic Dike; float
D2S6	36° 2'56.94"N	115°25'51.66"W	Clastic Dike; altered
D3S1	36° 0'40.56"N	115°26'10.08"W	Slide Surface
D3S2	36° 0'40.56"N	115°26'10.08"W	Stratigraphically above D3S1
D3S3	36° 0'40.74"N	115°26'9.48"W	Stratigraphically above D3S2
D4S1	36° 0'40.80"N	115°26'24.60"W	Slide Surface
D4S2	36° 0'40.74"N	115°26'24.60"W	Stratigraphically above D4S1
D4S3	36° 0'40.32"N	115°26'25.38"W	Slide Surface from F01
D4S4	36° 0'40.32"N	115°26'25.38"W	Stratigraphically above D4S3
D4S5	36° 0'38.70"N	115°26'12.24"W	Taken from F02
D4S6	36° 0'39.18"N	115°26'10.02"W	Fracture Aztec in matrix
D5S1	36° 1'58.32"N	115°24'5.58"W	Slide Surface
D5S2	36° 1'59.52"N	115°24'7.38"W	Carbonate Breccia
D5S3	36° 2'7.38"N	115°24'13.62"W	Calcite?
D5S4	36° 2'7.38"N	115°24'13.62"W	Chert clast; above D5S3
D6S1	36° 2'23.04"N	115°24'55.44"W	Slide surface w/ jigsaw breccia
D6S2	36° 2'8.10"N	115°24'16.50"W	Slide surface
D6S3	36° 2'8.10"N	115°24'16.50"W	Slide surface
D6S4	36° 2'41.76"N	115°25'1.56"W	Chunk of carbonate boulder
D6S5	36° 2'41.76"N	115°25'1.50"W	matrix-rich clast-supported breccia
D7S1	36° 2'35.28"N	115°25'23.70"W	Slide surface
D7S2	36° 2'33.00"N	115°25'41.88"W	Slide surface
D8S1	36° 2'53.82"N	115°25'59.58"W	Slide surface

Facies Observations

Observation	Latitude	Longitude	Notes
F01	36°0'49.03"N	115°26'13.74"W	Moderately developed disrupted zone (3 m) atop a discontinuous, pinkish-white basal mixed zone (0.5m).
F02	36°0'38.70"N	115°26'12.24"W	Well-developed disrupted zone (10 m) atop orangish-pink basal mixed zone (1.5m) w/ entrained carbonate breccia boulder.
F03	36°0'38.70"N	115°26'10.56"W	Moderately developed disrupted zone (5 m) atop a discontinuous, pink basal mixed zone (0.5m) w/ entrained Aztec clasts.
F04	36° 2'8.10"N	115°24'16.50"W	Poorly developed jigsaw breccia facies grading into well-developed crackle breccia facies w/ some polished surfaces.
F05	36°2'26.13"N	115°25'0.05"W	Matrix rich breccia facies (3 m) w/ entrained jigsaw breccia clasts. Shear slip surface is present within matrix rich breccia.
F06	36°2'41.76"N	115°25'1.50"W	Matrix rich breccia facies poorly grading into crackle breccia facies. No jigsaw breccia is present.
F07	36°2'43.68"N	115°25'1.92"W	Highly fractured matrix rich breccia facies grading into larger clasts of same facies (4 m) atop undulatory seam of grayish-pink basal mixed zone.
F08	36°2'35.40"N	115°25'23.76"W	Well-developed disrupted zone (7 m) w/ large entrained Aztec clasts, some feature jigsaw brecciation. Grades into matrix rich breccia facies.
F09	36°2'33.12"N	115°25'41.88"W	Matrix rich breccia facies (5 m) atop highly undulatory pinkish-white basal mixed zone w/ a lot of entrained Aztec clasts.
F10	36°2'57.36"N	115°25'52.02"W	Matrix poor breccia facies (5 m) atop a moderately developed disrupted zone. Pink clastic dikes derived from basal mixed zone are present.
F11	36°1'58.26"N	115°24'5.52"W	Matrix rich breccia facies (5 m) atop an undulatory orangish-pink basal mixed zone (1 m) w/ well rounded entrained Aztec clasts.
F12	36°2'23.04"N	115°24'55.50"W	Well-developed disrupted zone (3 m) atop Moenkopi Fm substrate. Between the two is a 1 m long band of fault gouge.
F13	36°2'31.50"N	115°25'24.30"W	Large Aztec boulders (up to 15 m) present in float and disrupted zone of breccia outcrops.

XRF Data

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	S	K2O	CaO	TiO2	V	MnO
D2S1	0.133	22.327	1.363	6.659	0.074	0.007	0.478	27.259	0.270	0.001	0.030
D2S5	0.157	11.052	6.298	10.714	0.076	0.012	2.132	31.288	0.111	0.002	0.029
D2S6	0.000	20.679	2.074	8.651	0.110	0.016	0.662	27.758	0.054	0.021	0.000
D3S1	0.256	9.572	1.587	6.258	0.144	0.115	0.522	41.746	0.058	0.000	0.018
D4S5	0.053	0.458	1.536	13.227	0.139	0.030	0.608	50.293	0.006	0.000	0.000
D5S1	0.069	14.545	1.390	7.067	0.088	0.027	0.511	35.716	0.032	0.008	0.017
D7S1	0.145	19.776	1.525	12.866	0.096	0.048	0.477	25.454	0.045	0.058	0.015
D7S2	0.303	19.675	1.718	12.957	0.075	0.037	0.455	25.448	0.067	0.007	0.028
Aztec	0.011	0.582	2.636	90.530	0.060	0.016	0.783	4.543	0.002	0.022	0.000
Moenkopi	2.838	1.925	9.861	67.691	0.189	0.029	2.376	11.593	0.584	0.005	0.112

Fe2O3	Zn	As	Sr	Zr	Ba	Cl	Total
0.320	0.001	0.003	0.019	0.000	0.142	0.000	99.968
1.810	0.013	0.006	0.017	0.002	0.132	0.000	99.957
0.587	0.005	0.010	0.017	0.005	0.111	0.000	99.937
0.522	0.006	0.000	0.013	0.003	0.207	0.031	99.799
0.398	0.005	0.005	0.013	0.003	0.096	0.000	99.937
0.382	0.011	0.003	0.003	0.005	0.091	0.030	99.936
0.426	0.010	0.002	0.011	0.007	0.214	0.000	99.851
0.509	0.006	0.005	0.009	0.000	0.166	0.037	99.916
0.504	0.008	0.012	0.004	0.012	0.105	0.106	99.936
2.435	0.007	0.006	0.018	0.017	0.231	0.000	99.914