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# Kinematics and timing of the Miocene-Quaternary deformation in Nellis Dunes Recreational Area, Nevada

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# KINEMATICS AND TIMING OF THE MIOCENE-QUATERNARY DEFORMATION IN NELLIS DUNES RECREATIONAL AREA, NEVADA

By

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# ABSTRACT

## Kinematics and Timing of the Miocene-Quaternary Deformation in Nellis Dunes Recreational Area, Nevada

By

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The kinematics and origin of transfer, accommodation and strike-slip zones is of paramount significance in understanding continental extension. The Las Vegas Valley Shear Zone (LVVSZ) is a NW-striking right-lateral fault system in the central Basin and Range province. Despite its prominence among the structures of the region and its role in the regional tectonic development, little is understood about its eastern portion. The inadequately constrained trace of the LVVSZ along its eastern part contributes largely to the ambiguity of the time activity and role of the LVVSZ. The eastern part of LVVSZ lies in Nellis Dunes Recreational Area (NDRA), north of Frenchman Mountain. The area exposes structures, the red sandstone unit, the Muddy Creek Formation, the Las Vegas Formation and the Quaternary deposits. Previous mapping showed different structural configurations in the NDRA and suggested that the area under the NDRA formed as a pull-apart basin between the LVVSZ in the northern part of the area and the Munitions fault that lies to the south and bounds the northern end of the Frenchman Mountain block. However, some structural geometries are inconsistent with the regional pull-apart basin model of Nellis basin. Folds, Thrust Faults and Normal Faults developed in different areas in NDRA. Each part is dominated by distinct compressional and extensional orientations.

In this study, I collected and analyzed more detailed data and suggested a deformation model consistent with the entire fold and fault geometries. Large scale mapping (1:8,000) documented complex structural geometries and kinematics. Structural analysis showed that the area exhibits three different deformations. 1) The NW-striking LVVSZ developed in Miocene-Pliocene in the middle part of the area and stopped moving before the Quaternary. 2) In the Quaternary, a NE- oriented left-lateral accommodation zone developed in the middle part of the area overprinting the LVVSZ deformation. 3) The northern end of the Frenchman Mountain fault curves to the NE forming a left-lateral fault splay in the southern part of NDRA.

**Keywords:** Nellis Dunes, Las Vegas Valley shear zone, Muddy Creek Formation, strike-slip, Frenchman Mountain fault.

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# CHAPTER 1

# INTRODUCTION

Strike-slip zones are critical elements of the kinematic models of continental extension (e.g. Western North America; Wernicke, 1992). They also garner special consideration from the industrial community as they control the distribution of hydrocarbon fields, ground water, and mineral resources within extended terrains (e.g. Ridge Basin, California: Link, 1987). The 120-km-long right-lateral Las Vegas Valley Shear Zone (LVVSZ), southern Nevada, is one of the major strike-slip zones in the central Basin and Range province. The Basin and Range is a major extensional zone in the western United States. However, the location and kinematics of the LVVSZ is poorly documented in some regions particularly along its eastern part (Fig. 1). Many aspects of the temporal distribution and kinematics of extensional and strike-slip faulting in the central Basin and Range province are only poorly constrained, despite decades of structural studies. In particular, the relationship between the major right-lateral LVVSZ and the Quaternary faults remains relatively poorly documented, and thus, controversial. One of the major Quaternary faults in the area is the Frenchman Mountain fault (FMF). It lies east of Las Vegas bounding the western margin of the Frenchman Mountain and Sunrise Mountain Block (Figs. 1A and B). The FMF offsets Quaternary units indicating Quaternary activity, but it also has an older, Miocene, history (Mati et al, 1993; Castor et al., 2000; Duebendorfer et al., 1998). The LVVSZ and the FMF are well-documented as exposed in or projecting into the Nellis Dunes Recreation Area (NDRA), which lies just northeast of Las Vegas, Nevada (Duebendorfer and Black, 1998; Beard et al., 2007; Anderson and

Beard, 2010; McLaurin et al., 2014a, b). The area affords the opportunity to examine the cross-cutting relations among and kinematics of faults and folds in Miocene and younger units and to address the issue of the relationship between the LVVSZ and young normal faults in the region.

Despite the prominence of the LVVSZ among the strike-slip zones of the area, the interpretation of its role in the regional extension of the Central Basin and Range varies. Duebendorfer et al. (1988) suggested that extension took place along a kinematically linked system of normal and strike-slip faults that is responsible for translating material in three dimensions. Duebendorfer and Black (1992), further, described the LVVSZ as a transfer zone that transfers strain between two differentially non-overlapping extended domains. Duebendorfer et al. (1998) made an essential contribution in slightly altering the role of the LVVSZ as a transfer zone that is part of a complex three-dimensional strain field. Faulds and Henry (2008), on the other hand, encompassed the LVVSZ in the Walker Lane. Walker Lane is a right-lateral deformation zone that accommodates about 20-25% of the plate motion (Faulds and Henry, 2008) (Fig. 1A). As part of Walker Lane, deformation along the LVVSZ is part of the component of plate boundary motion that occurs east of the Sierra Nevada rather than part of the extensional deformation in the Central Basin and Range which suggests that the strike-slip motion is the main drive rather than extension.

McLaurin et al. (2014 a, b) brought to light the diversity of structures exposed in and around NDRA, including the LVVSZ. The scale and variety of types of structures exposed necessitates understanding the types and locations of local structures relative to the main strike-slip fault. Strike-slip faults initiate in a system of en-echelon fold and fault segments. With increasing strike-slip movement these fault segments link defining alternating zones of shortening and extension along the strike-slip fault system (Cunningham and Mann, 2007). Typically, five sets of structures form in strike-slip regimes that form in a simple shear domain (Fig. 3): 1) synthetic strike-slip faults (R shears), 2) antithetic strike-slip faults (R’ shears), 3) shortening structures (e.g., folds and thrust faults), 4) extensional structures (e.g., normal faults), and 5) synthetic strike-slip fractures that form at an angle of $-\phi/2$ to the main shear couple (P shears), where $\phi$ is the angle of internal friction (Cloos, 1928; Tchalenko, 1970; Woodcock, 1985; Sylvester, 1988). The geometry of the strike-slip fault or fault zone (e.g. bending or stepping) determines the location and orientation of the associated folds, local domains of extension and shortening, and related fractures and faults (Sylvester, 1988).

The relative orientation and timing of the LVVSZ and the active extension result in controversy about the kinematic compatibility of structures in the region. The LVVSZ had well-documented motion between 8 and 4.5 Ma (Duebendorfer and Black, 1992; dePolo et al., 2006; Forrester, 2009; McLaurin et al., 2014a, b), however, a small number of seismic epicenters were detected along the LVVSZ suggesting that the shear zone is still active (Fig. 2) (Smith et al., 2001; Slemmons et al., 2001; dePolo and dePolo, 2012). The Quaternary extension in the Basin and Range resulted in the development of N to NE-striking normal faults (Zoback et al., 1981; Eaton, 1982; Nakata et al., 1982; Coney and Harms, 1984; Coney, 1987; Wernicke, 1992; Dohrenwend et al., 1991-1992 map series; Hecker, 1993). The orientation of the Quaternary active faults does not agree, nonetheless, with the kinematic model of the right-lateral deformation of LVVSZ, which adds to the discrepancy in the interpretations of deformation in the region.

Along the eastern part of the LVVSZ, three NE-striking faults that have been active through the late Quaternary lie north of NDRA; the Dry Lake fault (DLF), the Arrow Canyon Range fault (ACRF), and the California Wash fault (CWF) (Fig. 1). Similarly, the FMF which has well-documented activity in the late Quaternary lies to the south of NDRA (Dohrenwend et al., 1991; Anderson and O'Connell, 1993) (Fig. 1). The NNE orientation of the Quaternary extensional faults is not consistent with the orientation of the extensional structures formed by the NW right-lateral shearing of the LVVSZ that is supposed to rather be NW according to the kinematic models of right-lateral strike-slip deformation (e.g. Sylvester, 1988) (Fig. 3).

NDRA is one of the least studied areas in southern Nevada. Previous studies of NDRA focused on evaluating the arsenic dust emissions and their adverse health and environmental effects (e.g. Goossens and Buck, 2009; McLaurin et al., 2011; Goossens et al., 2012; Goossens et al., 2015). Regional maps of the Lake Mead area included the eastern part of the LVVSZ however, each map presents a different structural configuration for NDRA. For example, the USGS Lake Mead 30' X 60' Quadrangle geologic map compiled by Beard et al. (2007) suggested the presence of two strands of faults that do not link to the LVVSZ but rather converge and curve to the NE to align with the dominant Quaternary active faults orientation. Beard et al. (2007) showed that LVVSZ does not run through the study area or at least does not cut through the surface. Anderson and Beard (2010) showed that the FMF that bounds the Frenchman Mountain block to the south of NDRA branches northward into two faults. One of these faults continues to the north and terminates against the LVVSZ that runs through northern NDRA and the other curves around the Sunrise Mountain block (Fig. 1). McLaurin et al.

(2014a, b) mapped NDRA in more detail and showed a wide variety of structures of at least three different ages. The ambiguity of surface structural data in NDRA is largely due to the coverage of the area by large sheet of active sand dunes that obscures much of the deformation and the bedrock. Bedrock and structures are exposed in outcrops along the flanks of the sand sheet, along washes, and in the easternmost part of the area. However, most of the structures are small enough that they need more detailed mapping. Regional maps were compiled at a smaller scale than the scale required to map these outcrop-scale structure.

A map compiled by McLaurin et al. (2011) at 1:10,000 scale showed that a complex set of contractional, extensional, and strike-slip structures as well as an angular unconformity developed in the area. The angular unconformity combined with fault offsets of young units suggest that rocks in NDRA experienced more than one deformational event. In this study, I build on the work of McLaurin et al. (2011, 2014a, b) and aim to explain this structural complexity in NDRA in more detail in order to better understand the behavior of the LVVSZ and its interaction with Quaternary deformation along normal faults. Therefore, I 1) mapped part of NDRA at 1:8,000 scale and structurally evaluated the different contractional, extensional and strike-slip structures in terms of their relative timing of movement and age; 2) documented the geometric relationships among and slip sense of these structures, and evaluated their kinematics and kinematic compatibility; 3) demonstrated the relationship between these structures and the NNE-striking Quaternary, active faults; and 4) established whether the LVVSZ is still active in NDRA by finding the age of the youngest motion.  Accordingly, this study provides an example of superposed deformations and displacement transfer along strike-slip deformation zones.

# CHAPTER 2

# GEOLOGIC SETTING

The central Basin and Range exposes two main ages of post-Cretaceous fault sets, Miocene and Pliocene to Quaternary. The LVVSZ, along with the left-lateral Lake Mead fault system, are the principal strike-slip structures within the central Basin and Range. They appear to have been active largely during the Miocene. During the late Pliocene-Quaternary, north- to northeast-striking faults developed east of the Walker Lane through the northern and central Basin and Range, most of which are still active to the present. The Muddy Creek Formation was deposited mostly after the major Miocene deformation except for the younger Pliocene subunits near the Lake Mead area (Bohannon, 1984; Dicke, 1990; Anderson and Barnhard, 1993; Hanson et al., 2005). Hanson et al. (2005) showed syn-tectonic parts of the upper Muddy Creek Formation in the Overton Arm in the Lake Mead area. The depositional age of the Muddy Creek Formation makes it well suited for distinguishing the Miocene-Pliocene structures from the younger Quaternary faults. The Quaternary faults show a reconfiguration of surface structures and tectonic activity in the Basin and Range province. In this section, I will discuss briefly the regional geological context implications for NDRA.

## The Las Vegas Valley Shear Zone

LVVSZ is a ~120 km-long WNW-striking right-lateral shear zone that extends from an orocline near the Spring Mountains in the west to the east of Hamblin Mountain in the east (Fig. 1) (Duebendorfer and Black, 1992; Duebendorfer et al., 1998). It is delineated based on offset Paleozoic strata, offset Mesozoic thrusts and folds, geophysical data, and faults exposed at the surface on the eastern end (Longwell et al., 1965; Longwell, 1974; Duebendorfer and Black, 1992; Sonder et al., 1994; Duebendorfer et al., 1998; Langenheim et al., 2001). The LVVSZ has a total right-lateral displacement of 48 ± 7 km which decreases to the east and cannot be traced east of Hamblin Mountain (Fig. 1) (Longwell, 1960, 1974; Burchfiel 1965; Fleck, 1970; Wernicke et al., 1988; Duebendorfer and Black, 1992).

The activity of the LVVSZ is constrained by the age of the Muddy Creek Formation based on the idea that the Muddy Creek Formation is post-tectonic. Studies suggested that the main deformation along the LVVSZ occurred during the Miocene; between 14 and 5 Ma with a well-documented movement after 13.5 Ma (Duebendorfer and Black, 1992; Sonder et al., 1994; Langenheim et al., 2001; dePolo et al., 2006; Forrester, 2009). However, younger faults have been mapped in some areas (e.g., Slemmons et al., 2001). The 13 Ma-old rocks along the central and eastern LVVSZ in the Sheep Range, Frenchman Mountain, and in the Gale Hills show clockwise oroclinal bending to 070° adjacent to the shear zone manifested in the topographic features and geologic structures around the LVVSZ (Deibert, 1989; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992) (Fig. 1B). Sonder et al. (1998) and Jones et al. (1991) used paleomagnetic studies to demonstrate that this clockwise rotation is consistent with an oroflexure that is also evident in rocks as old as 14 Ma in the Gale Hills (Duebendorfer and Black, 1992). This oroflexure is lapped over by Muddy Creek Formation which is as young as 8.5 Ma in some areas and 4.1 Ma in others (Forrester, 2009). These relations suggest that the main period of movement along the LVVSZ was between 14 and 5 Ma (Duebendorfer and Black, 1992; dePolo et al., 2006; Forrester, 2009). However, Smith et al. (2001);

Slemmons et al. (2001) and dePolo and dePolo (2012) showed some seismic epicenters in the vicinity of the LVVSZ (Fig. 2).

Guth (1981), Wernicke et al. (1982), and Duebendorfer and Black (1992) suggested that the LVVSZ is a transfer structure that transfers strain between differentially extended terrains that are rooted in deep regional-scale detachments. Differential extension is shown on both the eastern and western margins of LVVSZ. In the western region, the shear zone separates a highly extended region north of the shear zone and the unextended Spring Mountains south of the shear zone (Burchfiel et al., 1974; Duebendorfer and Black, 1992; Langenheim et al., 2001). The Sheep Range detachment system north of the LVVSZ accommodates a total extension of about 40 km along the western part of the LVVSZ (Guth, 1981; Guth, 1990; Duebendorfer and Black, 1992). To the east, the highly extended Boulder Basin is separated from the less extended Muddy Mountains (Duebendorfer and Black, 1992). The Saddle Island detachment, a low-angle normal fault, accommodated this extension within Boulder Basin by 20 km of movement (Weber and Smith, 1987; Duebendorfer and Black, 1992). Movement along the Saddle Island detachment and the LVVSZ between 13 and 8.5 Ma produced Boulder Basin; a major extensional basin (Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992). In the central region of the LVVSZ, Las Vegas Valley is bounded on the north by the LVVSZ (Longwell, 1960; Campagna and Levandowski, 1991; Duebendorfer and Black, 1992).

## The Quaternary Faults

Late Cenozoic extension resulted in the formation of spaced basins and ranges in the Basin and Range province (Hamilton and Mayers, 1966; Davis and Burchfiel, 1973;

Chamberlin, 1983; Miller et al., 1983; Platt, 1986; Jayko et al., 1987; Wernicke, 1992; Sonder and Jones, 1999). In the central Basin and Range, the middle to late Miocene extension was overprinted by a late-stage moderate crustal extension that was expressed by north and northeast-striking normal faults (Zoback et al., 1981; Eaton, 1982; Nakata et al., 1982; Coney and Harms, 1984; Coney, 1987; Wernicke, 1992; Dohrenwend et al., 1991-1992 map series; Hecker, 1993) (Fig. 1). In some locations, older faults were reactivated. The younger faults are typically arranged into domians separated by accommodation and/or strike-slip zones (Stewart, 1998; Thenhaus and Bernhard, 1998). Some of these faults are still active today (Dohrenwend et al., 1991; Swadley, 1995; dePolo, 1998). Activity is recorded by many seismic epicenters and Quaternary fault scarps in the region (Dohrenwend et al., 1991; Anderson and O'Connell, 1993; Smith et al., 2001; Slemmons et al., 2001; dePolo et al., 2006; dePolo and dePolo, 2012).

Within Nevada, Quaternary fault scarps are clustered into four zones separated by three accommodation zones that act as rupture barriers between the extensional domains (Stewart, 1980; Thenhaus and Barnhard, 1998) (Fig. 1B). NDRA lies in the southernmost Quaternary fault belt and represents a locality where the LVVSZ interfaces with the younger Quaternary deformation. Three main Quaternary faults lie north of NDRA (Fig. 1); the Dry Lake, Arrow Canyon Range, and California Wash faults (Castor et al., 2000; Beard et al., 2007). Directly south of NDRA, the FMF is the main Quaternary fault present in the area (Anderson and O'Connel, 1993; Matti et al., 1993; Castor et al., 2000). The Dry Lake, Arrow Canyon Range, and California Wash faults are all west-dipping faults (Schell, 1981; Anderson and O'Connel, 1993; Bohannon, 1983; dePolo, 1998; Dohrenwend et al., 1991; Pearthree et al., 1983; Swadley, 1995). The FMF, in the south, dips toward the west as well (Anderson and O’Connel, 1993, Campanga and Aydin, 1994). Also in the south, but west of the FMF, a zone of east-dipping faults, the Las Vegas Valley fault system, is exposed (Fig. 2) (dePolo et al., 2006).

## Muddy Creek Formation

The Muddy Creek Formation is one of the main stratigraphic units exposed along the eastern part of LVVSZ. It is the most widespread Cenozoic formations in the Lake Mead area (Metcalf, 1982; Williams, 1996; Forrester, 2009; Muntean, 2012; Hilgen et al. 2012; Walker et al. 2013; Dickenson et al., 2014; McLaurin et al., 2014a, b)). It extends from its type locality north of Glendale, Nevada to the valleys of the Muddy and Virgin rivers and California Wash (Beard et al., 2007; Forrester, 2009; Dickinson et al., 2014) (Fig.1B). The base of the Muddy Creek Formation is exposed only along the borders of the valleys and its true thickness is not exactly known (Bohannon, 1984).

Deposition of the Muddy Creek Formation took place in unconnected basins where deposition continued longer in some basins depends on tectonic activity, sediment influx, and climate. In the Mesquite Basin (Fig. 1B), deposition of the Muddy Creek Formation started about 9 Ma and the youngest basalts yielded a K-Ar age of 4.1 ± 0.2 Ma (Woodburne and Swisher, 1995; Williams, 1996; Dickinson et al., 2014). The top tuff of the Muddy Creek Formation in the Virgin River depression is as young as 3 Ma in age (Dickinson et al., 2014). In any case, deposition lasted until Pliocene and did not continue into the Quaternary in any of the Muddy Creek depositional basins.

The Muddy Creek Formation consists mainly of fluvial and lacustrine deposits interbedded with tuffs and basalts in some basins (Billingsley, 1995; Williams, 1996;

Williams et al., 1997; Forrester, 2009; Muntean, 2012). Bohannon (1984) subdivided the Muddy Creek Formation into two main parts; an upper silty part and a gypsiferous lower part. It is composed mainly of pink sandstones, siltstones and claystones in the upper part (Bohannon, 1984; Beard et al., 2007). Gypsum, gypsiferous sandstone and siltstone, and arenaceous gypsum are common in the lower part (Bohannon, 1984; Beard et al., 2007). Both parts range in grain size from sand to mud (Muntean, 2012). Conglomerate is also present at the basin margins but is less common than both of the other facies (Muntean, 2012; Bohannon, 1984). All three facies occur around Boulder Basin, Frenchman Mountain and Las Vegas Valley, but with poorly understood distribution (Bohannon, 1984; Muntean, 2012). The maximum thickness is not exactly known but may be more than 700 m (Bohannon et al., 1993; Beard et al., 2007).

Detailed stratigraphic study of the Muddy Creek Formation in NDRA was carried out by McLaurin et al. (2011), McLaurin et al. (2012) and McLaurin et al. (2014). In NDRA the Muddy Creek formation is composed of interbedded clastics, carbonates and tuff (McLaurin et al. 2014). Older subunits commonly crop out in the south of NDRA and stratigraphy gets younger from south to north.

# CHAPTER 3

# METHODS

NDRA was mapped at 1:8,000 scale using standard geologic mapping techniques (Fig.4). QuickBird, ASTER 1B, and USGS 7.5' topographic maps for the Apex quadrangle were used delineate locations of units and structures, and to aid in identifying structures, rock units, and determine the relative age of the most recent deformation. To perform the structural analysis, including testing kinematic compatibility, stereographs and rose diagrams were constructed and used to compare structural orientations in different domains. Rose diagrams were used for faults where fault strikes could be well constrained, but dips could not. Stereographs were drawn using Allmendinger's Stereonet 9 program (Allmendinger et al., 2014). Cross sections along with stereographs were used to define the strain fields and analyze the operating stresses during the deformational phase(s), specifically the orientation of regional and local stresses as well as direction and age of motion on faults. Kinematic compatibility tests were used to analyze whether faults and folds could have formed synchronously in the NDRA and to determine to which phase of regional deformation affected an area.

# CHAPTER 4

# STRATIGRAPHY

Detailed stratigraphic studies in NDRA were carried out by McLaurin et al. (2011), McLaurin et al. (2012), McLaurin et al. (2014a, b) and Goossens et al. (2015). They established the stratigraphy within the Muddy Creek Formation using grain size, lithology and sedimentary structures. In this study I follow their stratigraphic classification and ages for the Muddy Creek Formation with some suggestions.

Four main stratigraphic units crop out in NDRA; the Red Sandstone unit, the Muddy Creek Formation, the Las Vegas Formation, and the Quaternary deposits (Figs. 4 and 5, Plate 1). Bohannon (1988) described the Red Sandstone as red sandstones, conglomerates, siltstones and claystones interbeds. In NDRA, the Red Sandstone is represented by a red conglomerate unite (Nc) that is exposed in the easternmost part of the mapped part. Muddy Creek Formation is composed of 6 subunits (Goossens et al., 2015). From older to younger, Muddy Creek Formation starts with interbedded red siltstone and claystone (Nrst). The Nrst is mainly exposed in the southern and northernmost parts of NDRA. The thickness of the Nrst unit is 7 meters measured in the central part of the study area.

The Nrst is overlain by a limestone unit; White Limestone”a” (Nwla). The Nwla is exposed over large portions of the area. Locally, a 1 meter-thick white to light grey tuff lies between the Nwla and the Nrst. A tuff with a similar stratigraphic position was identified in the northern part of Frenchman Mountain by Castor et al. (2000) and Castor and Faulds (2001) that dated to 5.59 Ma and most likely is correlative the tuff of Wolverine Creek.

The Nwla is overlain by a clastic sequence that starts from older to younger with two successive claystone units; Nwcs and Nbcs. The sequence ends with two successive sandstone units; Nys and Nrs. The Nwcs is mainly exposed in the eastern part of the area. In some parts, the color of the Nwcs changes from white to yellow due to the contamination with arsenic (McLaurin, 2014). This unit is overlain by another brown claystone layer (Nbcs) that is also exposed in the eastern part of the area. The two claystones are intercalated with some coarser siltstone layers.

The yellow sandstone, Nys, overlies the Nbcs directly. The Nys was exposed due to the main thrust in the central southern part of the area. According to Mclaurin et al. (2011, 2012), Mclaurin et al. (2014a, b), and Goossens et al. (2015), the unit is composed mainly of medium dark yellowish orange and light brown sand. McLaurin et al. (2011) showed that the Nys is overlain by red sandstone facies (Nrs) that consists of cross-bedded sandstone and siltstone. However, the Nrs is not exposed in the mapped area.

A white limestone facies (Nwlb) overlies the Nys in the central and the northwestern parts of the mapped area. The Nwlb facies lies conformably on the Nys and is composed of coarsely crystalline limestone with common Paleozoic pebbles. The stratigraphic position of the Nwlb is ambiguous. Mclaurin et al. (2012), Mclaurin et al. (2012a), and Goossens et al. (2015) described the Nwlb as potentially correlative to the Las Vegas Formation which unconformably overlies the Muddy Creek Formation. Williams (1996), nonetheless, mapped three similar petrocalcic horizons in the Mesquite Quadrangle: Trk, the young Tertiary calcrete; Tik, the intermediate age calcrete, and ToK, the older Tertiary calcrete. The Trk and the Tik are composed mainly of angular to rounded cobbles and both are younger than and unconformably overlie the Muddy Creek Formation. In contrast, the Tok is composed mainly of smaller clasts that are no bigger than small pebbles and was deposited by an incision that started at 5 Ma (Williams, 1996). Longwell (1965) described the Las Vegas Formation as light-colored, shallow lake silts and clays while Haynes (1967) showed carbonate caprock overlying the lake deposits in Tule Springs that had a radiocarbon age of 18,000 to 11,600 $^{14}$C yr B.P. (Quade et al., 1998; McLaurin et al., 2011).

The close composition of the Nwlb in NDRA to the ToK of Williams et al. (1996) and the absence of the unconformity detected in the mapped part between the Nwlb and the underlying Nys suggests that the Nwlb is most probably the uppermost petrocalcic horizon of the Muddy Creek Formation, However more detailed stratigraphic correlation between the Nellis Basin and the main sedimentary basins of the Muddy Creek Formation and the Las Vegas Formation is needed to solve the uncertainty of the stratigraphic position of the Nwlb

In McLaurin et al (2011), a gypsiferous sandstone layer (Ngs) that is stratigraphically equivalent to the Nwlb overlies the Nys in some localities. The Ngs is commonly composed of three fining upward cycles starting with very coarse sand and occasional conglomerate to very fine sand on the top of each cycle. Some medium sandstone lenses occur within the gypsiferous sand unit. The Ngs crops out only in the northernmost part of NDRA and does not crop out in the mapped area in this study.

The Quaternary-Recent deposits cover a large part of the area. They are commonly composed of active washes (Qa), older alluvial deposits (Qoa), sand dunes (Qd), and desert pavement (Qoap). Qoa are composed of reworked Paleozoic carbonate clasts imbedded in sand and silt. Qa is mainly deposited in active drainage channels. It is composed of unconsolidated gravel, sand and silt.

Qoa is paved by reworked clasts at some localities forming desert pavement. Desert pavements were mapped by Beard et al. (2007) as part of the Qoa. In this study desert pavements are mapped separately as Qoap. Qoap is commonly composed of closely packed, interlocking angular and subrounded pebbles.

Qd cover a large portion of the mapped area (Fig. 6, Plate 1). It is composed of inactive and active friable sand sheet. Some parts of the Qd are stabilized by vegetation and/or rock fragment.

# CHAPTER 5

# STRUCTURE

The Muddy Creek Formation is extensively deformed in NDRA. Structures are mostly exposed along washes and in small outcrops. Most of the folds crests are eroded. Fold orientations have been determined using stereographs of bedding measured on the exposed fold limbs. Twenty-one faults were mapped (Fig. 6). Most of the mapped faults do not have scarps on the surface. Hence, faults were identified by their offset type in outcrop and cross sections. Offset could be identified along many of them using stratigraphic separation.

McLaurin et al. (2011) showed two distinct structural domains, each is dominated by a distinct set of structures. Their maps shows that the southern part of NDRA is dominated by northeast-southwest striking Pliocene-Quaternary normal to oblique-slip faults and west-northwest trending folds, while the northern part is mainly dominated by north-northeast-striking normal faults. The new mapping at a more detailed scale showed more structures that aided in identifying distinct structural orientation domains (Fig.4).

Structures in the central part of the mapped part of NDRA, which were mapped in detail, agreed well with the map of McLaurin et al. (2011). More structures with different orientations were mapped in the northwestern and southern parts of the study area Appendix B). The northwestern part is dominated by NE-trending folds (Fig. 6; Plate 1). Structural cross-sections revealed NE-striking faults in the middle part of the NDRA (Plate 2), Contrastingly, NW to WNW-striking normal faults were mapped in the west and northwest of study area (Fig. 6, Plate 1). Left-lateral strike-slip faults dominate the southern part of the study area north of the Frenchman Mountain block.

Accordingly, I divided the area into three structural domains, A, B, and C, based on the dominant bed strike direction, which is controlled by the strikes and trends of structures (Fig. 7). Domain A lies in the northwestern corner of NDRA. Folds and thrust faults in domain A are generally NE-oriented, whereas normal faults generally strike NW. Domain B lies to the southeast of domain A and occupies the largest part of NDRA. Domain B mostly contains NW-trending folds, a NW-striking thrust fault and a few NE-striking normal faults. Domain C lies in the farthest southeast. Left-lateral strike-slip faults are the main structures Domain C.

## Domain A

Domain A contains folds, normal faults and a thrust fault that only cut through the Muddy Creek Formation (Fig. 8A; Plates 1 and 2). The contractional structures (i.e. folds and thrusts) are generally oriented NE (Fig 6B). Extensional normal faults generally strike NW-SE.

Eight alternating anticlines and synclines lie in domain A. The western part of domain A is occupied by three gently plunging folds (ag, ak, and aj on Fig. 8; Plate 1). Two gently plunging synclines are separated by an anticline. Folds aj and ak plunge and trend 1.5°/076° and 0.9°/082°, respectively (Table 1). Their axial planes are inclined 76° and 82° S. Syncline ag plunges and trends 1.5°/260°. Its axial plane is dips 81° SE.

A NE-striking thrust lies in the western part of domain A (Thrust G on Fig. 8A; Plate 1). Thrust G is exposed in a small outcrop cut by motorcycles on the top of a small hill, to the south of fold ag (Fig. 8A, Plate 1). The fault strikes N34°E and dips 30°SE.

Four minor normal faults (E, F, H, and I) are exposed in the center of the domain (Fig. 8; Plate 1). These faults are covered by the Qoa and are only exposed in a large wash. Faults E and F lie southeast of fault D. The two minor faults form a graben in the Nwla with only 0.5 m throw. Faults H and I lie in the south of the wash. Both faults dip 47 º NE with 1.5 m throw of the Nrst.

The eastern part of domain A is dominated by four alternating gently plunging, ENE-oriented anticlines and synclines (b, c, d, and c) with an 80-m wavelength (Fig. 8A; Table 1; Plate 1).

## Domain B

Domain B is mostly covered by Quaternary deposits (Fig. 9A; Plates 1 and 2). Muddy Creek Formation crops out in the eastern part and along washes in the middle and western parts. The Muddy Creek Formation is highly deformed in domain B. However, most of the deformation is obscured under the vast sand dunes covering the area. A major NE-striking normal fault (Fault O) brings Nwla of the Muddy Creek Formation to the surface on the eastern side and that more resistant lithology allowed more deformation to be mapped in the eastern part domain B. Structures crop out along washes in the middle part of this domain.

Beds, generally, strike NW in domain B (Fig. 9B). The Muddy Creek Formation in the domain is largely folded. A few major and minor faults were mapped as well (Figs. 4 and

7A; Plate 1). Folds are generally oriented NW and are clustered along a NW-trending zone in the middle part of domain B except for anticline z, A gently plunging anticline lies in the eastern part of domain B and crops out along Gypsum Wash, which is oriented NE. Fourteen alternating plunging anticlines and synclines were mapped in the middle part of domain B. Two NW-trending folds (m and n) developed in the hanging wall of Fault Q, a NE-striking fault that lies in the south of the domain B. Syncline m plunges and trends 1.5°/312° whereas anticline n plunges and trends 2.5°/085°. Four NW-SE-oriented, gently plunging folds (ai, ah, ae, and ad) were mapped in the westernmost part of domain B (Fig. 9A; Plate 1). Folds ai and ah plunge and trend SE, whereas folds ad and ae plunge and trend NW.

Nine faults that range in age between Miocene and Quaternary were mapped in domain B. Some faults separate the Muddy Creek Formation and the Quaternary deposits; others separate different subunits of the Muddy Creek Formation that are older than the Nwla. Faults in domain B have two distinctive orientations. Younger Quaternary faults strike NE-SW, whereas older faults strike NW-SE and NE-SW.

Six faults lie in the eastern part of domain B. Fault N, a major normal fault, runs NE-SW, along Gypsum Wash, and separates Quaternary units in the hanging wall block from the Nwla, Nrs and Nc in the footwall. The fault dips due SW with an estimated throw of 58-90 m (Table 4).

Three parallel faults (J, K, and L) that strike NW and dip NE lie in the footwall of fault N, while one NE-stiking fault (fault M) lies to the south of and terminates against fault L and separates the Nc from the Nrst (Fig. 9A; Plate 1). Faults J and K cut through the Muddy Creek Nwla. These two faults are parallel with a 21º NE dip.

Two more faults (Q and P) were mapped in the middle part of domain B (Fig. 9; Plates 1 and 2). Fault Q ia a normal fault that dips to SW with an estimated throw of 10-15 m. It juxtaposes the Nrst and Nwla on its footwall and the Nwla on its hanging-wall. Fault P is a NW-striking thrust fault that brought the Nrst up to the surface over the Nys. Fault P is composed of two segments. The western segment strikes 330º, whereas the eastern segment strikes 275º.

## Domain C

Domain C lies to the southeast of domain B (Fig. 7). Small parts of domain C are covered by Quaternary deposits, while the Muddy Creek Formation crops out over much of the area (Fig. 10A; Plate 1). Domain C is mostly deformed by left-lateral strike-slip faults, nonetheless a few normal faults and minor folds were mapped. Seven folds (p, q, r, s, t, u, and v) cluster around a left-lateral strike-slip fault (fault R) in the northern part of domain C. Folds p, q, and r lie to the north of fault R and plunge 20° to 26° NE and folds s, t, and u lie to the south and plunge 22° to 34° SW. Fold v lies east of fault R. the axial trace of fold v curves NE at its eastern tip. All seven folds plunge away from the fault. Two small domes (w and y) and a NE-oriented doubly-plunging anticline (anticline x) lie to the east of fault R. The limbs of the anticline become more gently-dipping from south to north. To the south, the northwestern limb dips 25°NW while the southeastern limb dips 15°SE and to the north both limbs dip 3º.

Six left-lateral strike-slip faults (T, U, V, W, X, and Y) that strike nearly E-W were mapped in domain C. The six faults cut the Nwcs creating a domino-like structure in map view. Short normal faults lie between the left-lateral strike-slip faults separating the Nwcs from the adjacent Nbcs. The strike-slip faults gather and link into one strike-slip fault (Fault Z) to the west while they die out toward the east. The Nwcs is bounded by another strike-slip fault (Fault S) on the north that runs between two steeply dipping, NW-striking normal faults.

# CHAPTER 6

# DISCUSSION

Previous research suggested that the basin under the NDRA formed as a pull-apart basin between the LVVSZ in the northern part of NDRA and the Munitions fault that lies to the south and bounds the northern end of the Frenchman Mountain block (c.f., Fig. 11A) (e.g. Castor et al., 2000). However, some structural geometries are inconsistent with the regional pull-apart basin model of Nellis basin. Pull-apart basins usually result in the development of transverse normal faults that have oblique strikes to the main shearing direction (Katzman et al., 1995; Smit et al., 2008). However, NDRA is mainly dominated by folds along with a smaller number of thrusts and normal faults. Moreover, structures have different orientations at different locations implying the development of various deformations. McLaurin et al. (2014) suggested the development of a restraining bend along the LVVSZ that runs NW-SE through the middle part of NDRA. This restraining bend resulted in the formation of a zone of tight folds with fold axes parallel to the strike of LVVSZ. In their interpretation, the formation of N- to NE-striking normal to oblique-slip faults can have two origins. They suggested that the N- to NE-striking faults may have formed by left-lateral deformation related to the Lake Mead Fault System (LMFS). LMFS is a left-lateral deformation zone that lies 20 km southeast of the NDRA (Fig. 1). Another interpretation is that these faults are related to the N- to NE-striking Pliocene-Quaternary faults that lie north and south of NDRA (McLaurin et al. 2014).

Large scale mapping (1:8,000) revealed three structural domains in which each shows different kinematics and timing of deformation. The presence of different fault ages in domains A, B, and C as well as the local angular unconformity in domain A implies more than one deformational event. Structural analysis and comparisons to theoretical structural deformation models suggested an interaction between three distinct deformations. In this section I discuss the kinematics of deformation in each structural domain and their relation to the surrounding geological context.

## Las Vegas Valley Shear Zone

Regional studies of southern Nevada showed that the LVVSZ extends from north of the Spring Mountains in the west to east of Hamblin Mountain in the east (Fig. 1) (e.g., Duebendorfer and Black, 1992; Duebendorfer et al., 1998; Faulds and Henry, 2008). Nonetheless, smaller scale maps were not capable of documenting the trace LVVSZ in NDRA. Hence, special attention to NDRA was needed in order document the geometry of the shear zone there.

The LVVSZ is formed by WNW-striking right-lateral strike-slip displacement (Duebendorfer and Black, 1992; Sonder et al., 1994; Langenheim et al., 2001). Shortening and extensional structures associated with strike-slip deformation develop at 45° to the main shear couple and perpendicular to each other (Ramsay 1967; Tchalenko, 1970; Lowell, 1972; Courtillot et al., 1974; Mandl and others, 1977; Krantz, 1994; Cunningham and Mann, 2013) (Fig. 3). Later, structures may rotate up to 19° in proportion with the amount of shearing and as they approach the principal deformation zone they get dragged to align with the main shearing direction (Sylvester, 1988). Consequently, shortening structures associated with the WNW-striking right-lateral strike-slip deformation of the LVVSZ essentially strike in the NE to ENE direction, while extensional structures essentially strike in the NW to NNW direction.

In domain A, folds trend ENE and a thrust fault strikes NE (Fig. 8A; Plate 1). Appropriately, normal faults in domain A generally strike NW, ~90° to the folds and thrusts. Close to the middle part of domain A, normal faults strike NNW and toward the south of the domain normal faults strike more to the NW. Folds are clustered in the middle of domain A. This relative orientation of extensional and contractional structures in domain A as well as the change in fault strikes away from the middle of domain A imply the presence of a WNW-striking right-lateral displacement in the middle according to the kinematic models of the right-lateral strike-slip deformation (e.g. Sylvester, 1988) (Figs. 3 and 8A; Plate 1). However, no strike-slip faults were found on the surface implying that the shear zone developed through the subsurface but did not cut through the surface. The trace of the LVVSZ was delineated using the relative orientation of the compressional and extensional structures to the principal deformation zone. Structures close to the principal deformation zone (i.e. the main strike-slip fault) tend to rotate and reorient themselves to the main shearing direction. Therefore, the trace of the LVVSZ would cut through the middle of domain A (Fig. , Plate 1).

The trace of the LVVSZ was poorly defined in previous regional maps. McLaurin et al. (2014) suggested that the LVVSZ runs through the middle part of NDRA which is equivalent to domain A of this study. Accordingly, my trace of the LVVSZ agrees with the trace defined by McLaurin et al. (2014) for the eastern part of NDRA.

Structures in domain A were all mapped in the Muddy Creek Formation, but did not cut through either the Las Vegas Formation or the Quaternary deposits, and so, formed a local angular unconformity between the Muddy Creek Formation and the Quaternary deposits. That implies that the LVVSZ developed in the northwestern part of NDRA and stopped moving before the Quaternary.

The LVVSZ has well-documented activity between 14 Ma and 4.5 Ma. (Duebendorfer and Black, 1992; Forrester, 2009). Smith et al. (2001), Slemmons et al. (2001), and dePolo and dePolo (2012) showed seismic epicenters in the vicinity of the LVVSZ suggesting that the shear zone is still active. However, if the LVVSZ is currently active, its right-lateral displacement should be kinematically compatible with the current NW extension of the central Basin and Range. The active extension in the central Basin and Range formed NE to NNE-striking normal faults that, given their spatial distribution near NDRA, would be likely to form left-lateral strike-slip zones to accommodate the differential strain between them, given the strike direction of the Quaternary faults (Fig. 1B) and the kinematic models of strike-slip deformation. In NDRA all faults that have well-constrained Quaternary activity, according to their cross-cutting relationship with the Quaternary deposits, are NE-striking which is not compatible with the LVVSZ deformation. Normal faults that are kinematically compatible with the WNW-striking LVVSZ would reasonably strike NNW (c.f., Fig. 3B). Accordingly, the LVVSZ was only active before and during the Muddy Creek Formation time and stopped moving before the Quaternary deposition when a new deformation took over. Given the relatively large spacing of seismograph stations in the region, which makes the uncertainty on the epicentral locations relatively large, it is possible that the earthquakes are not associated with the LVVSZ, but with other faults and that the LVVSZ is no longer active.

In the eastern part of Domain B, three NW-striking normal faults (J, K, and L on Fig. 9) cut the Muddy Creek Formation (Fig. 9A; Plate 1). The four faults terminate against a

NE-striking Quaternary fault (N). This termination implies that the LVVSZ also developed through the eastern part of NDRA and was later overprinted by a younger Quaternary deformation that developed in the center of the map area obscuring the right-lateral shearing-related structures.

## Left-Lateral Accommodation Zone

The configuration of the shortening and extensional structures in domain B suggest that the most of the domain deformed by simple left-lateral shearing according to the left-lateral shear models (e.g. Sylvester, 1988; Katzman et al., 1995; Smit et al., 2008) (Figs. 3 and 9; Plate 1). Folds and thrust faults generally trending NW dominate a narrow belt that runs NE-SW through the domain. The folds occur in a left-stepping en-echelon arrangement. In left-lateral strike-slip deformation folds usually form in a left-stepping en-echelon arrangement in a narrow zone or belt over or close to the principal deformation zone (Sylvester, 1988). Five NE-striking normal faults in domain B cut through the Quaternary deposits. The relative location and orientation of compressional and extensional structures of domain B imply that they were formed as secondary structures to an ENE- to a local E-W-striking left-lateral displacement zone. This Quaternary left-lateral accommodation zone was not recognized and documented in previous, less detailed, studies.

NE-striking Quaternary, active faults in the Basin and Range are distributed in belts that are separated by transverse accommodation zones (Fig. 1A) (Hamilton and Myers, 1966; Davis and Burchfiel, 1973; Chamberlin, 1983; Miller et al., 1983; Platt, 1986; Jayko et al., 1987; Wernicke, 1992; Sonder and Jones, 1999). The accommodation zones are characterized by a low density of Quaternary normal faults and more strike-slip deformation (Stewart, 1998; Thenhaus and Barnhard, 1998). Three main NNE-striking Quaternary faults lie north of NDRA: the Dry Lake, Arrow Canyon Range, and California Wash faults (Fig. 1B) (Castor et al., 2000; Beard et al., 2007). To the south of NDRA, the FMF is the main Quaternary fault present in the area (Anderson and O'Connel, 1993; Campanga and Aydin, 1994; Castor et al., 2000). The three faults north of NDRA accommodate a different amount and locus of extension than accommodated on the FMF south of NDRA (Anderson and O'Connel, 1993; Campanga and Aydin, 1994). Consequently, the relative location and motion along the Quaternary fault set in the north and FMF in the south require the development of a synthetic ENE-trending accommodation zone to form between them in order to transfer and accommodate this differential extensional.

The southern sections of the Dry Lake, Arrow Canyon Range, and California Wash faults curve toward the southwest (Fig. 1B), whereas the FMF curves to the northeast at its northern section acquiring a left-lateral sense or component of displacement (Figs. 1B and 10B). That implies that the faults are being dragged and rotated or curved during propagation to align with an active left-lateral displacement in NDRA.

The structural configuration in domain B, the orientation of the Quaternary faults, and geodetic data (e.g., Kreemer et al., 2012) suggest a currently active ENE-trending left-lateral displacement in the middle part of the map area. The Late Cenozoic extension that was responsible for the development of LVVSZ was overprinted by a late-stage moderate crustal extension that was expressed by north and northeast-striking normal faults (Zoback et al., 1981; Eaton, 1982; Nakata et al., 1982; Coney and Harms, 1984; Coney, 1987; Wernicke, 1992; Dohrenwend et al., 1991-1992 map series; Hecker, 1993). The late-stage crustal extension resulted in the development of the current left-lateral deformation in NDRA overprinting the LVVSZ deformation that ceased activity before the Quaternary (Fig. 11).

## Frenchman Mountain Fault

The FMF lies to the south of NDRA bounding the west side of the Frenchman Mountain and Sunrise Mountain blocks (Fig. 1C). At its center, the FMF strikes N-S and dips west (Fig. 10B) (Longwell et al., 1965; dePolo, 1988; Dohrenwend et al., 1991; Anderson and O'Connel, 1993; Campanga and Aydin, 1994; Castor et al., 2000). The FMF experienced multiple displacements with reported offsets of 6.6 and 8.9 km and it is marked by scarps in Quaternary deposits (Matti et al., 1993; dePolo, 1988; Rittase, 2007). The southern segment of the FMF strikes northwest (Anderson and O'Connell, 1993; Campanga and Aydin, 1994). Castor et al. (2000) suggested that the southern segment of the FMF may exhibit a right-lateral strike-slip movement as it becomes parallel to LVVSZ.

The northern segment of the FMF is composed of discontinuous short scarps formed in Quaternary deposits (Castor et al., 2000). During the Quaternary, the northern section developed during multiple episodes and curved toward the east around the Frenchman Mountain block near Nellis Air Force Base reorienting the fault strike to the ENE (Fig 1B and 10B) (Campanga and Aydin, 1994). The ENE-striking segment acquired a sinistral-normal sense of displacement (Anderson and Beard, 2010).

The location of the northern termination of the FMF previously was not resolved, but the new data presented here sheds light on it. Most of the northern FMF trace is obscured by the Quaternary sediments. Castor et al. (2000) and Beard et al. (2007) suggested that the

FMF may link to the north with the LVVSZ. Anderson and Beard (2010), on the other hand, showed that the FMF curves northward around the Sunrise Mountain block. These two options can be distinguished by the configuration at the fault tip. Like other fault types, strike-slip faults usually terminate in one of three ways (Fig. 11B) (Davis and Burchfiel, 19773; Sylvester, 1988; Jackson et al., 1995; Swanson, 2005; Joussineau et al., 2007; Mouslopoulou et al., 2007): 1) free-tip termination: the strike-slip fault normally dies out in the rock (Fig. 10C1), 2) fault intersection: the strike-slip fault may intersect with a normal, reverse, or another strike-slip fault that usually takes over the displacement (Fig. 10C2), or 3) horsetail splay: the strike-slip movement gets distributed over several strike-slip splay branches of the main strike-slip fault (Fig. 11B3). Linkage with the LVVSZ would result in a fault intersection whereas curving around the Sunrise Mountain block could result in either a free-tip termination or a horsetail splay.

Domain C is dominated by a set of left-lateral strike-slip faults (Fig. 10A). The faults mainly strike E-W at their eastern tips. Towards the west the faults curve to the southwest and gather in one single fault that strikes parallel to and aligns with the northern segment of the FMF(Fig. 11A). This relationship signifies that the northern segment of the FMF splays in domain C forming a horsetail splay through which the displacement is distributed. The faults offset the brown siltstone subunit of the Muddy Creek Formation and die out in the Quaternary deposits.

The northernmost fault of the FMF horsetail splay cuts through the Nwla (Fig. 10A). To the north of this fault lie three folds that plunge to the northeast (p. q, and r on Fig. 10A). To the south, three folds that plunge to the southwest are exposed (s, t, and u on Fig. 10A). In the map view, the fault splays appear to be cutting through a pre-existing fold set that was once oriented northeast (Fig. 10B). The fold set was composed of two double-plunging anticlines with an intervening doubly plunging syncline. The northeast oriented doubly-plunging fold set was most likely formed by the older right-lateral strike-slip deformation of the LVVSZ, then, later, the folds were cut and displaced by the northernmost FMF horsetail splay (Fig. 10B).

Hence, The NW-striking LVVSZ developed in Miocene-Pliocene in the middle part of the area and stopped moving before the Quaternary (Fig. 12 and 13). In the Quaternary, a NE- oriented left-lateral accommodation zone developed in the middle part of the area overprinting the LVVSZ deformation. The northern end of the Frenchman Mountain fault curves to the NE forming a left-lateral fault splay in the southern part of NDRA.

The previously inadequately constrained trace of the LVVSZ along its eastern part contributed largely to the ambiguity of the time of activity and role of the LVVSZ. NDRA is one of the areas where the trace of the LVVSZ is not well-constrained. Previous mapping showed different structural configuration in the NDRA. The structural configuration and traces of the LVVSZ, presented here, agree with the NDRA part in the geologic map of Lake Mead Quadrangle compiled by Beard et al. (2007). The trace of the LVVSZ in the present map generally agrees with the deformation zone of the LVVSZ presented by McLaurin et al. (2014) for the northwestern and eastern parts of the mapped part of NDRA. However, this map presents a NE-left-lateral deformation that develops through the middle part of NDRA overprinting the LVVSZ deformation.

## Future work

The controversy of the activity of the LVVSZ and its role in the regional extension of the Basin and Range Province requires more detailed studies in previously studied areas and paying more attention to less-studied parts. Determination of the exact age of activity of the LVVSZ depends largely on the age of the youngest deposits through which it cuts. The Muddy Creek Formation has relatively different ages in different basins. Accordingly, The age of the tuff units in the Muddy Creek Formation in NDRA is critical in better bracketing the age of deposition of the Muddy Creek Formation in NDRA.

The scarcity of seismic stations in southern Nevada makes the determination of the exact location of the seismic epicenter in the vicinity of the LVVSZ ambiguous. Hence installing more stations in the region will help better understand the seismicity of the area and mitigating any potential Quaternary earthquake hazards.

Stratigraphic correlation for the Muddy Creek Formation and the Las Vegas Formation with their type depositional basins will be of a paramount importance in better describing the stratigraphy of the youngest deposits in NDRA.

# CHAPTER 7

# CONCLUSIONS

The controversy of the activity of the LVVSZ and its role in the regional extension of the Basin and Range Province requires more detailed studies in areas previously mapped and examination of less-studied regions. The eastern part of the LVVSZ is a remarkable area along the LVVSZ because it provides an example of cross-cutting deformations that is a key in understanding the relationship between the LVVSZ and the Quaternary deformation. Detailed mapping at 1:8000 scale helped incorporate more structures into the kinematic analysis and documented the structural overprint.

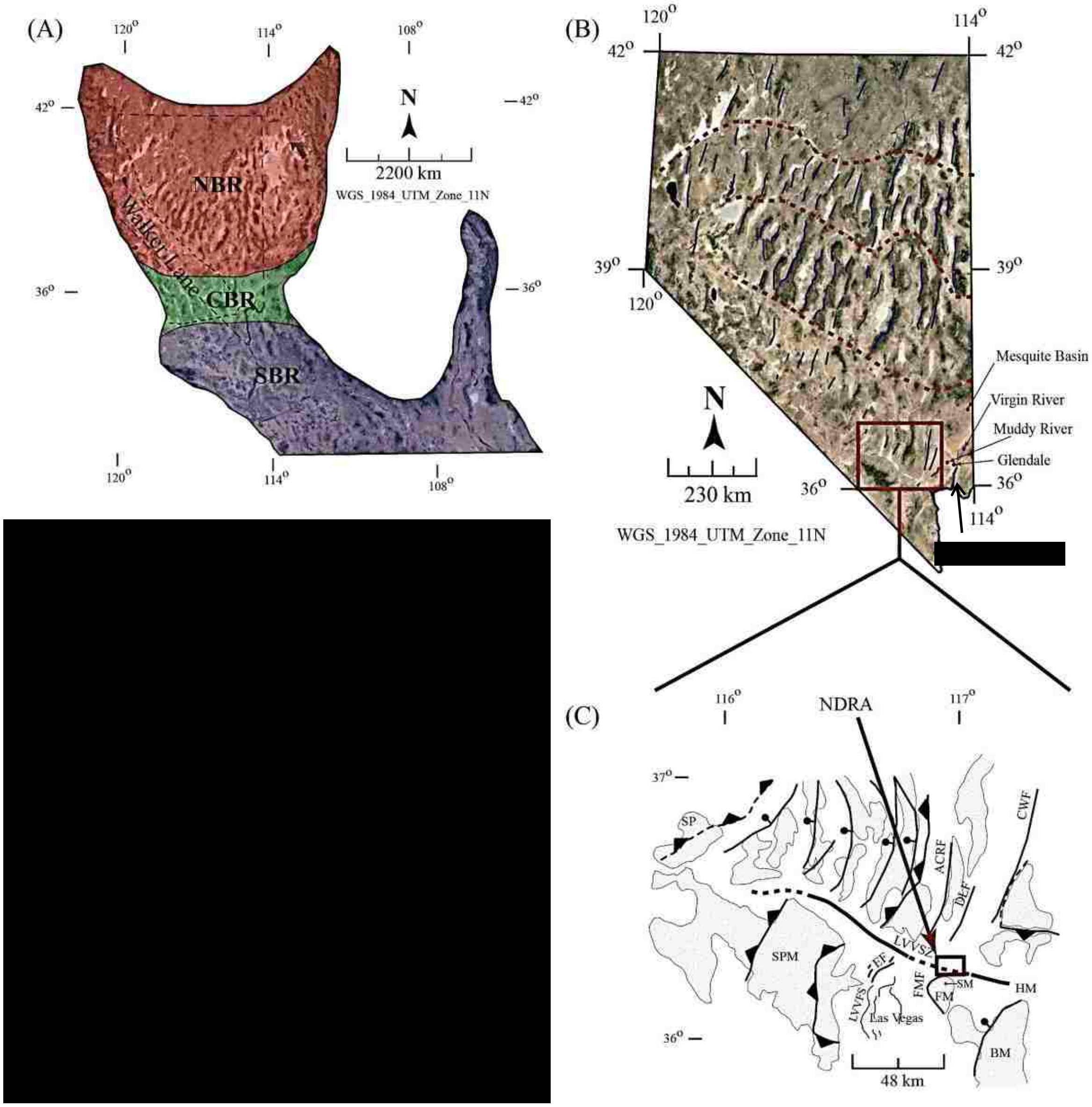
The structures in NDRA presented three distinct deformations each with different kinematics and relatively different timing (Fig. 13). After deposition of the Muddy Creek Formation, the NW-striking right-lateral LVVSZ deformed the area resulting in the formation of NE-oriented contractional structures and WNW- to NW-striking extensional structures. Some of these NW-striking normal faults cut the Nwlb. Therefore, the timing of the LVVSZ deformation is constrained by the age of the Nwlb which lies either at the top of or on top of the Muddy Creek Formation. The LVVSZ-related deformation does not appear to impact any units younger than Nwlb, and so, appears to be inactive.

During the Quaternary and after the LVVSZ, an ENE-oriented left-lateral displacement formed in the central part of the map area and overprinted the LVVSZ deformation. This left-lateral deformation is now documented and evidenced by NW-oriented compressional structures and NE-striking normal faults. The left-lateral displacement probably accommodated differences in the amount and loci of extension between the NE-striking Quaternary faults to the north and south of NDRA (i.e., CWF, DLF, ACRF, and FMF, respectively).

Also during the Quaternary, a series of left-lateral fault splays cut through the southern part of the area. These faults join southward and form a horsetail splay at the northern tip of the FMF. These northward splays terminate in the southern NDRA and overprinted the LVVSZ deformation, which also shows that the LVVSZ is an older deformation in the area.

The scarcity of seismograph stations in southern Nevada adds challenges to attributing the seismic epicenters to the LVVSZ or other faults in the region. Therefore, the presence of seismicity along the LVVSZ is ambiguous. As in NDRA, the LVVSZ may be overprinted by younger deformation in other areas. Consequently, I encourage more detailed studies of the LVVSZ and its interaction with the Quaternary deformation in other parts along the LVVSZ.

# FIGURES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114°
108°
42°
42°
36°
36°
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NBR
Walker Lane
CBR
SBR
120°
114°
108°
(B)
120°
114°
42°
42°
39°
39°
120°
Mesquite Basin
Virgin River
Muddy River
Glendale
N
230 km
36°
36°
114°
WGS_1984_UTM_Zone_11N
(C)
116°
NDRA
117°
37°
SP
ACRF
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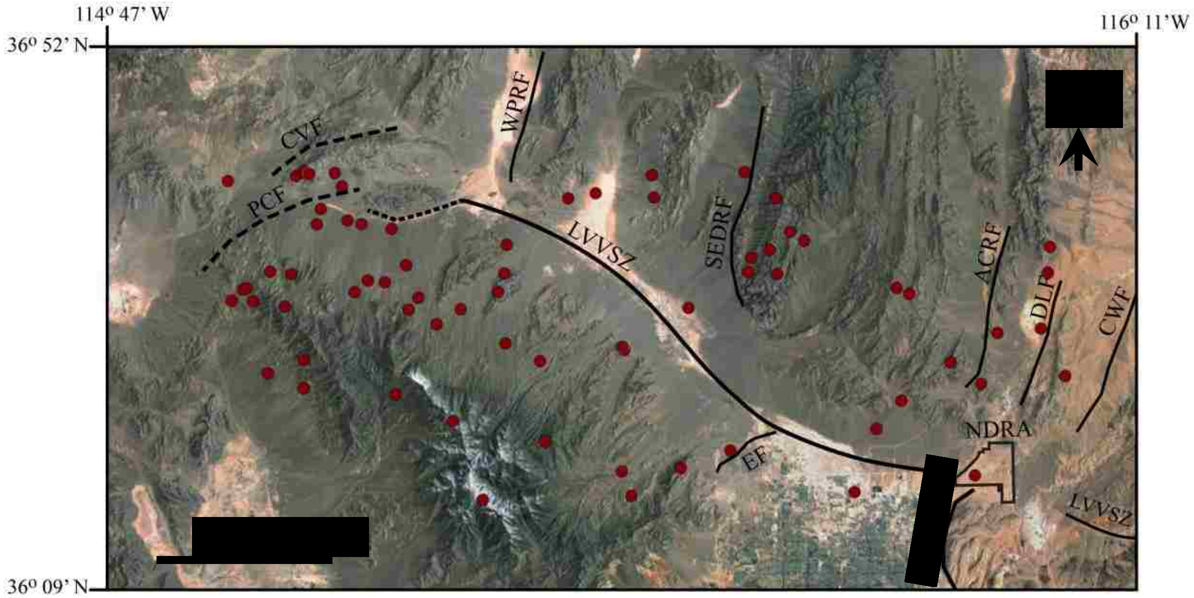
Las Vegas
36°
BM
48 km



[redacted] [redacted] [redacted]

Figure 2. Seismic epicenters in the vicinity of the LVVSZ. Seismic epicenters were recorded in the vicinity of the LVVSZ suggesting that it may be active. The locations of epicenters for earthquakes of M (0.3-3.9) are shown by the red dots. Earthquake data were acquired from the USGS Hazard Program website. The spacing of seismograph stations in the area is relatively large and the uncertainties on the locations of the epicenters are correspondingly large. ACRF = Arrow canyon range Fault; CVF = Crossgrain Valley Fault; CWF = California Wash Fault; DLF = Dry Lake Fault; EF = Eglington Fault; FMF = Frenchman Mountain Fault; PCF = Peace Camp Faults; SEDRF = Sheep-East Desert Ranges fault; WPRF = West Pintwater Range Fault;. Quaternary Faults are compiled from the USGS Interactive fault Map.

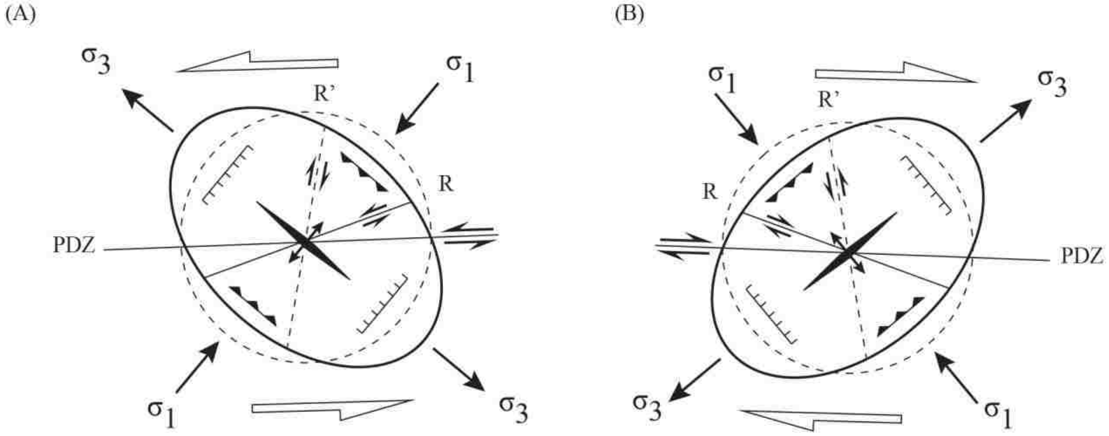


Figure 3. Strain ellipsoids of strike-slip deformation. These strain ellipsoids show the locations of extensional and contractional structures relative to the principal deformation zone in simple shear. (A) Sinistral shearing. (B) Dextral shearing. $\sigma_1$ = Maximum stress; $\sigma_3$ = Minimum stress; R = synthetic fractures; R' = antithetic fractures; PDZ = principal deformation zone. Modified from Sylvester (1988).

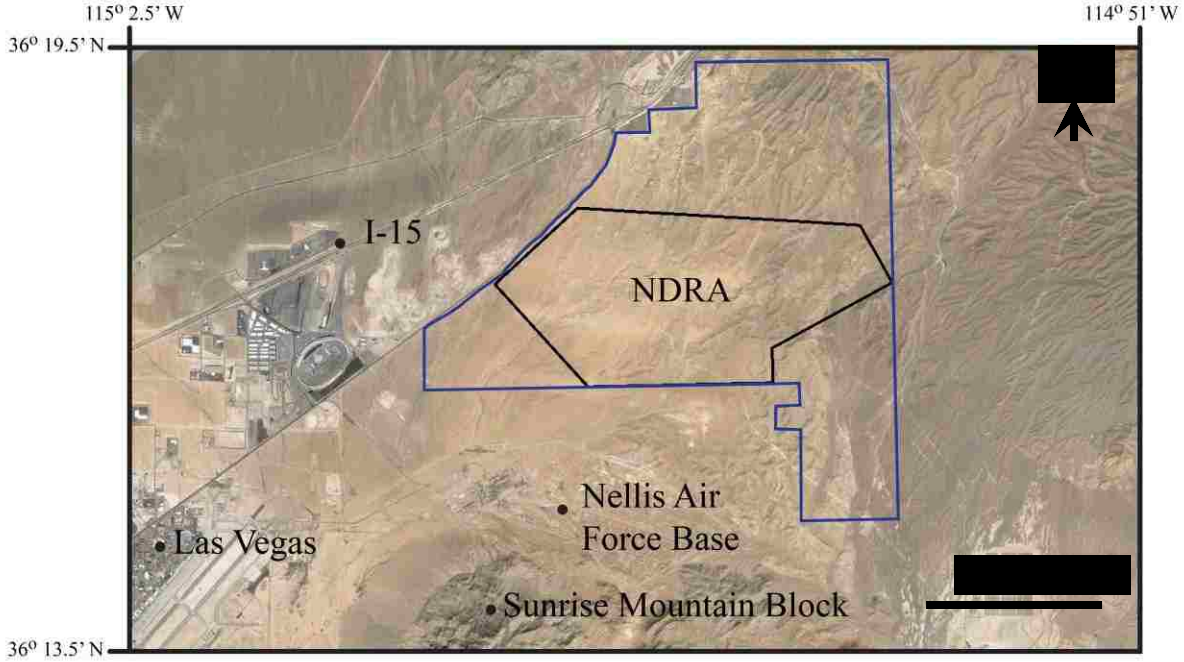


Figure 4. Location of the mapped part of NDRA. The NDRA boundary is represented by blue polygon. Location of the mapped part of NDRA is shown by the black polygon.The mapped part lies northeast of Las Vegas, north of Frenchman Mountain and the Sunrise Mountain Block. I-15 passes northwest of NDRA. To the south, the area is bounded by Nellis Air Force Base, and is bounded to the north by latitude 36° 17' 38.60".

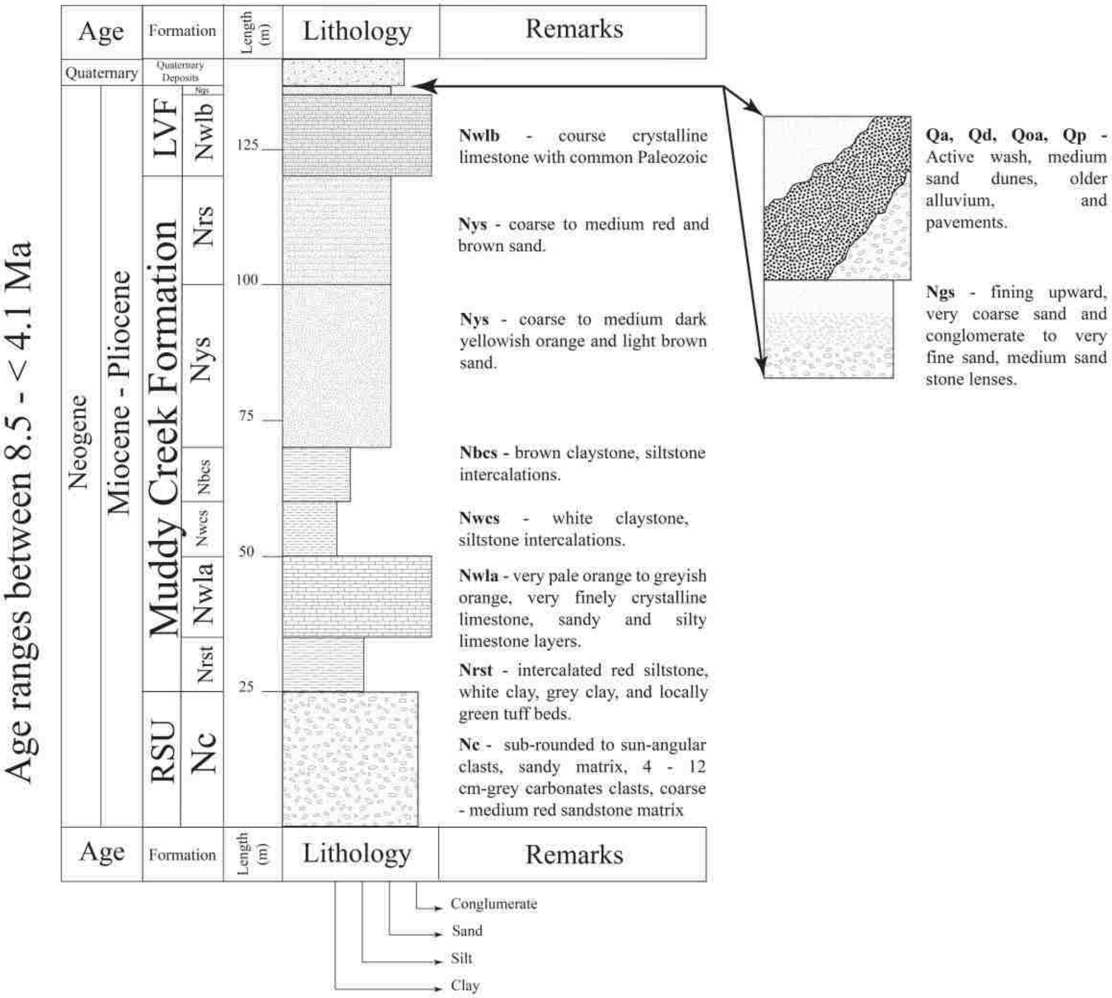
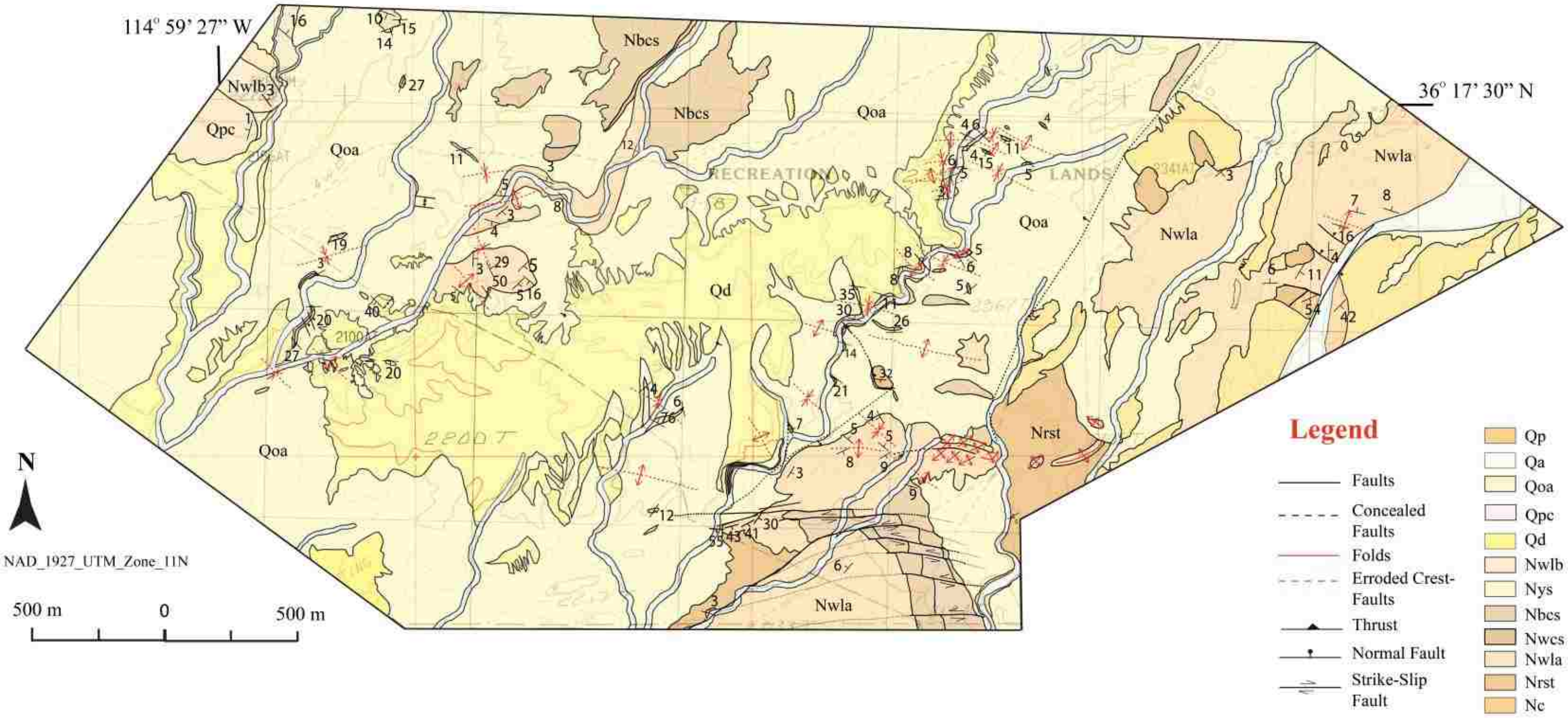
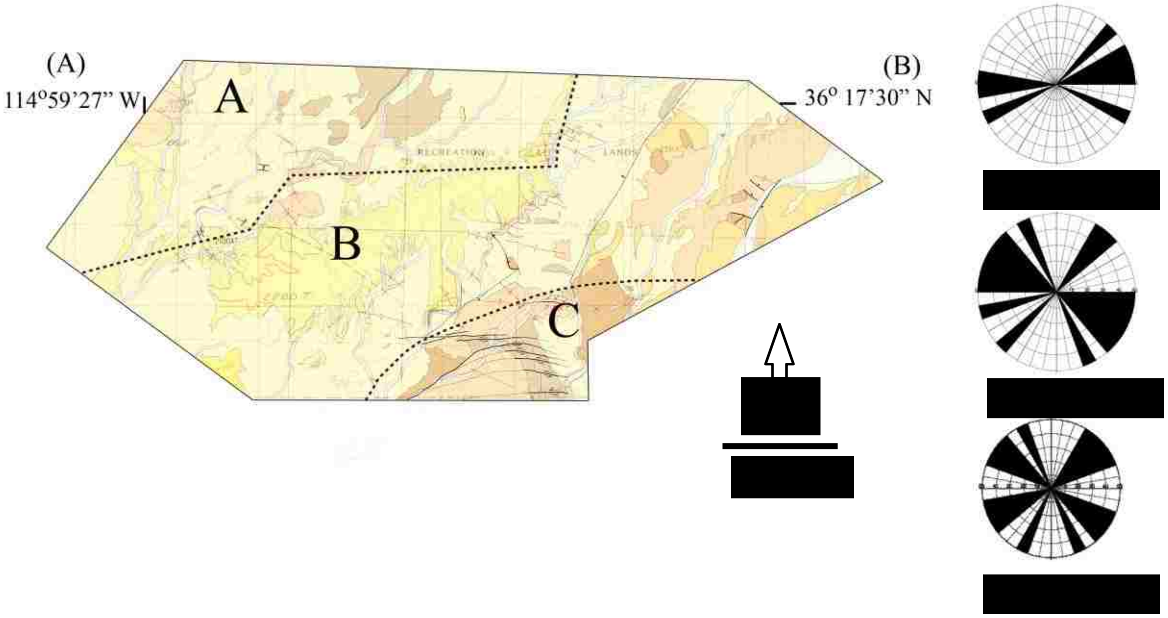


Figure 5. Stratigraphy of NDRA. The Red Sandstone unite, the Muddy Creek Formation, the Las vegas Formation and the Quaternary deposits are the main surface stratigraphic units in NDRA. The stratigraphic section is after Bohannon (1984), Beard et al. (2007), McLaurin et al. (2011), McLaurin et al. (2012), McLaurin et al. (2014a, b), and Goossens et al. (2015). Age range refers to the possible age range of the Muddy Creek Formation compiled from all the depositional basins of the formation according to Williams (1996), Castor et al. (2000), Castor and Faulds (2001), Forrester (2009), Muntean (2012), and Dickinson et al. (2014).


114° 59' 27" W
36° 17' 30" N
Nwlb
Qpc
Qoa
Nbcs
Qd
RECREATION
LANDS
Nwla
Nrst
N
NAD_1927_UTM_Zone_11N
500 m
0
500 m
Legend
Faults
Concealed Faults
Folds
Erroded Crest-Faults
Thrust
Normal Fault
Strike-Slip Fault
Qp
Qa
Qoa
Qpc
Qd
Nwlb
Nys
Nbcs
Nwcs
Nwla
Nrst
Nc

[redacted]



[redacted]

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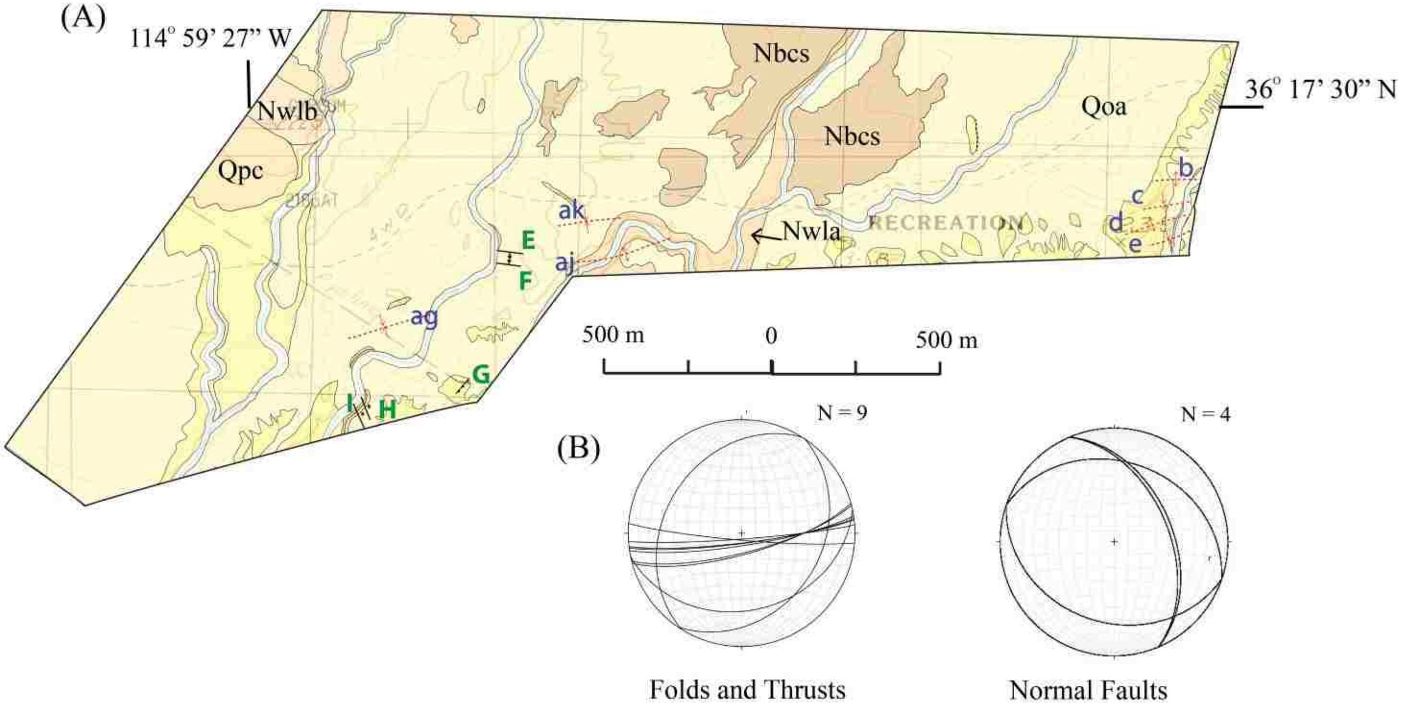
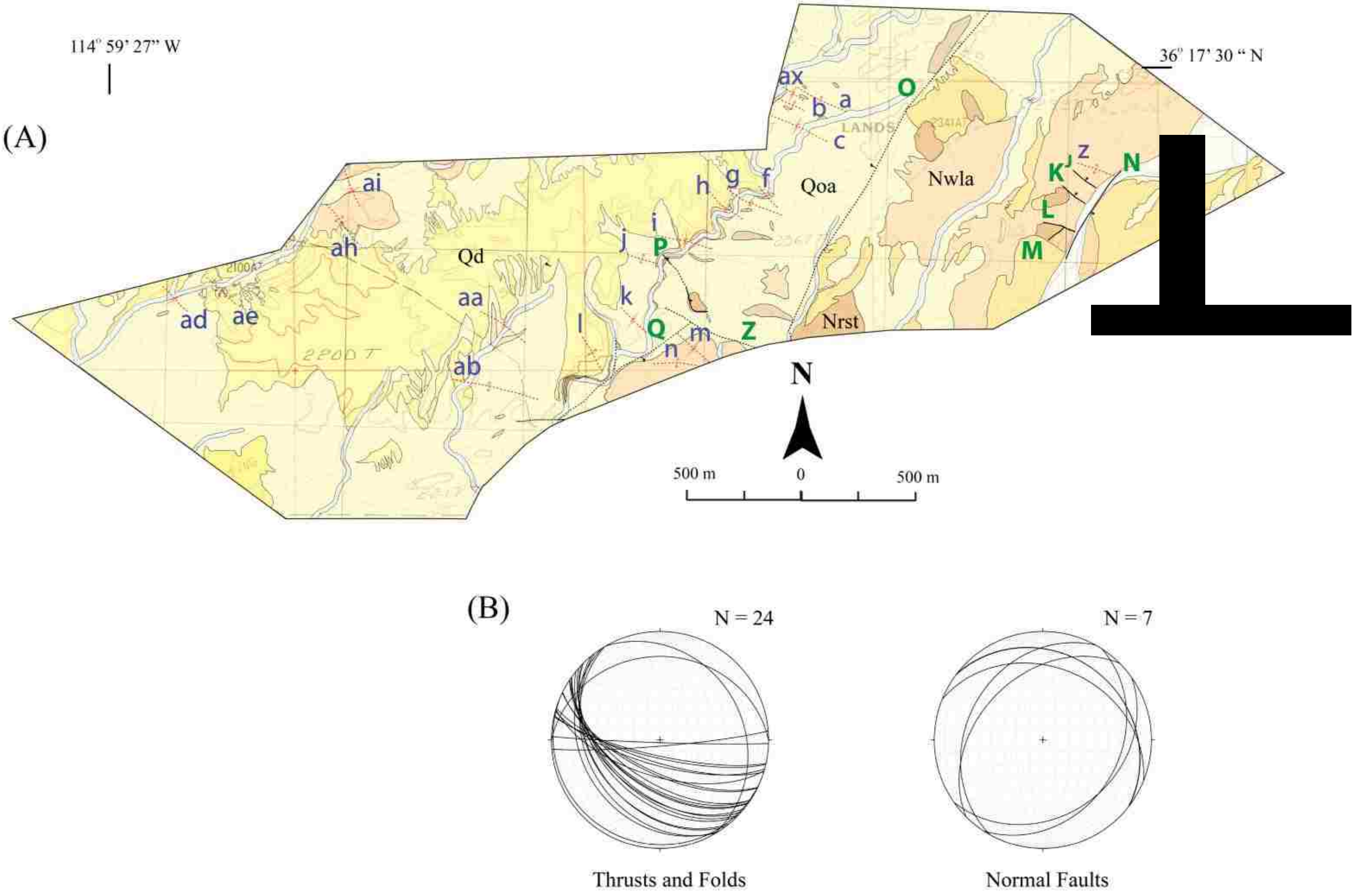
Figure 7. Structural domains. Three structural domains, A, B, and C, were defined based on the dominant strike of beds. (A) shows the structural domains. Domains are defined according to bed strikes. (B) shows rose diagrams of the dominant bed strikes in each domain.



Folds and Thrusts

Normal Faults

[redacted]



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Thrusts and Folds

Normal Faults

[redacted]

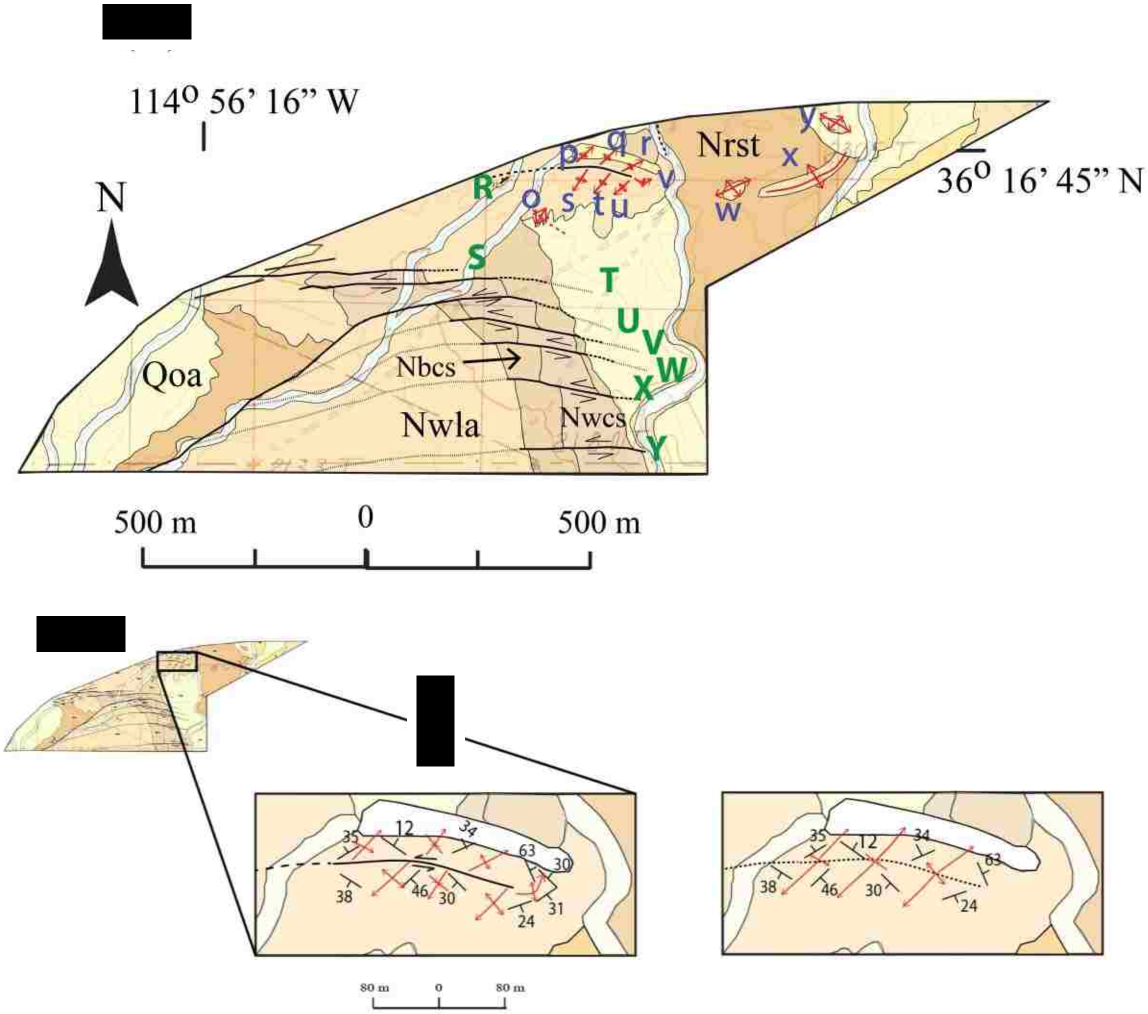
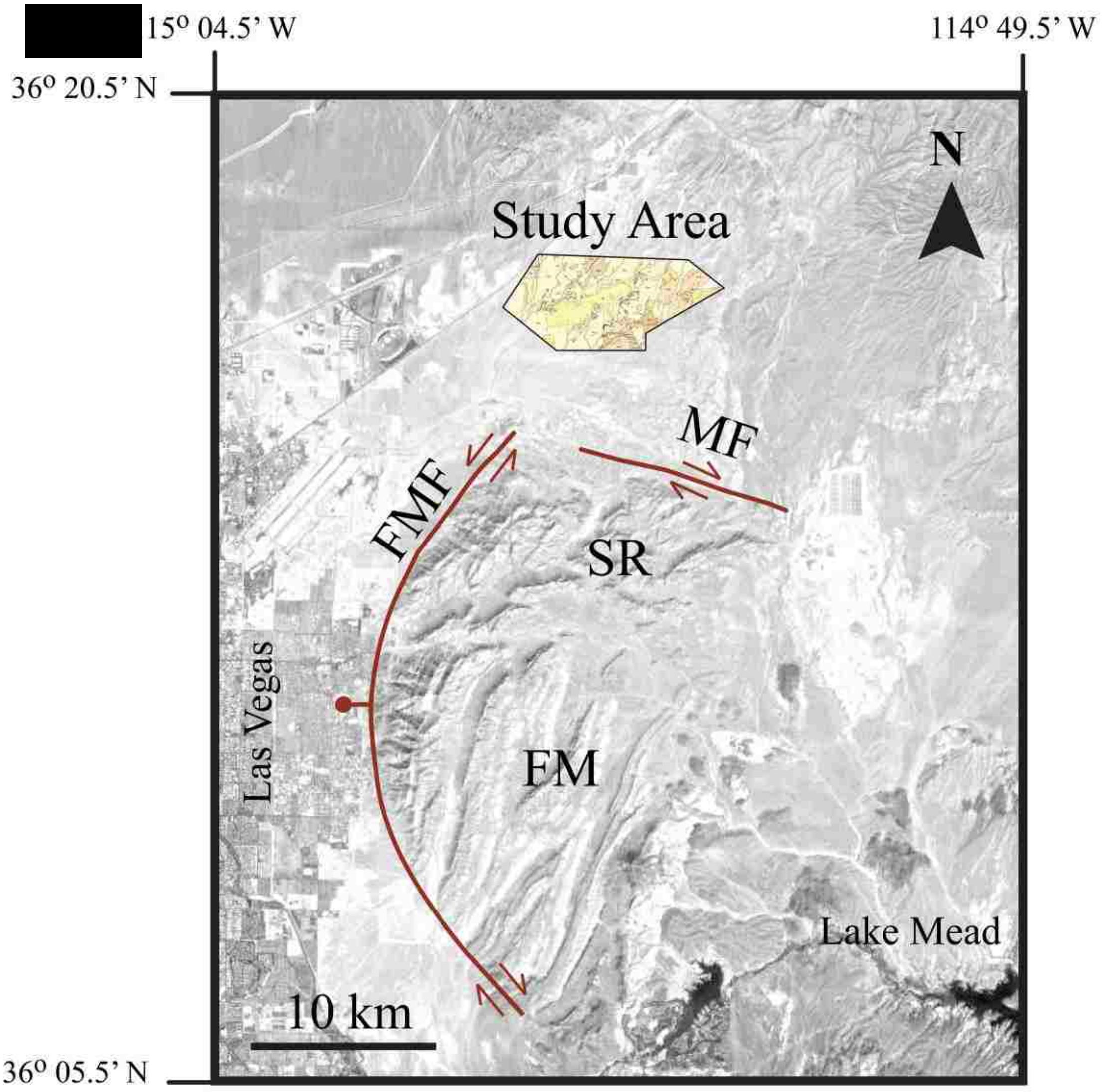


Figure 10. Domain C. (A) Geological map of domain C. (B) Restoration of folds p, q, r, s, t, u, and v. the resoration of the motion along Fault R showed that the folds were three doubly-plunging anticlines that were later cut by one of the FMF splay strands.

[redacted]



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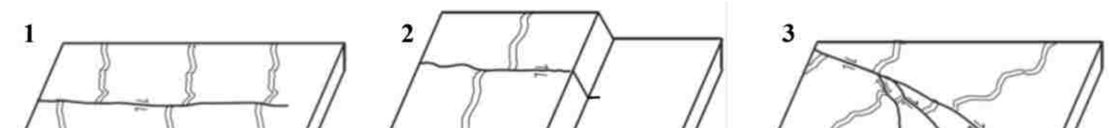
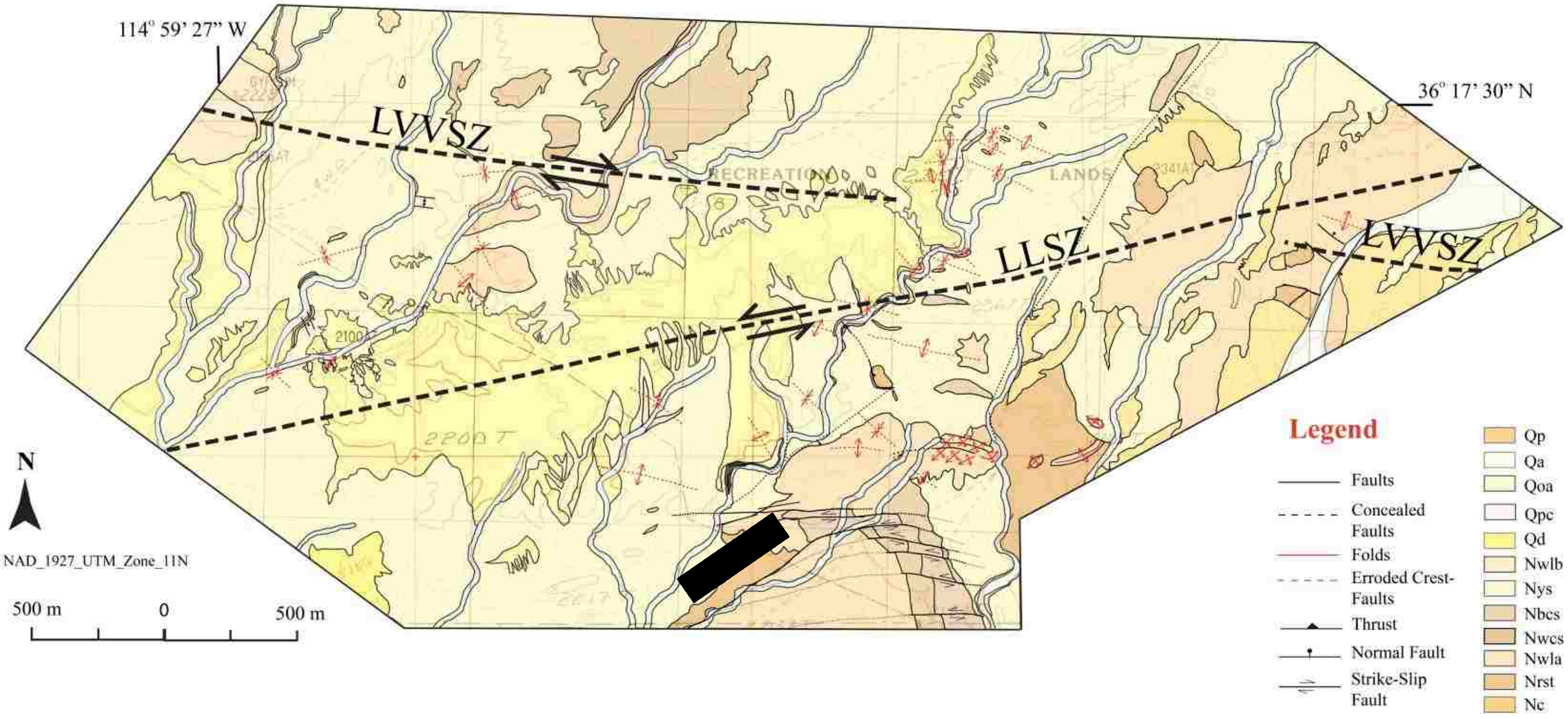


Figure 11. Fault terminations. (A) Geological map of Frenchman Mountain. FM = Frenchman Mountain Block; FMF = Frenchman Mountain Fault; MF = Munitions Fault; NDRA = Nellis Dunes Recreational Area; SR = Sunrise Mountain Block. (B) Fault terminations; (B1) free-tip fault termination; (B2) termination against another fault; (B3) horsetail splay.



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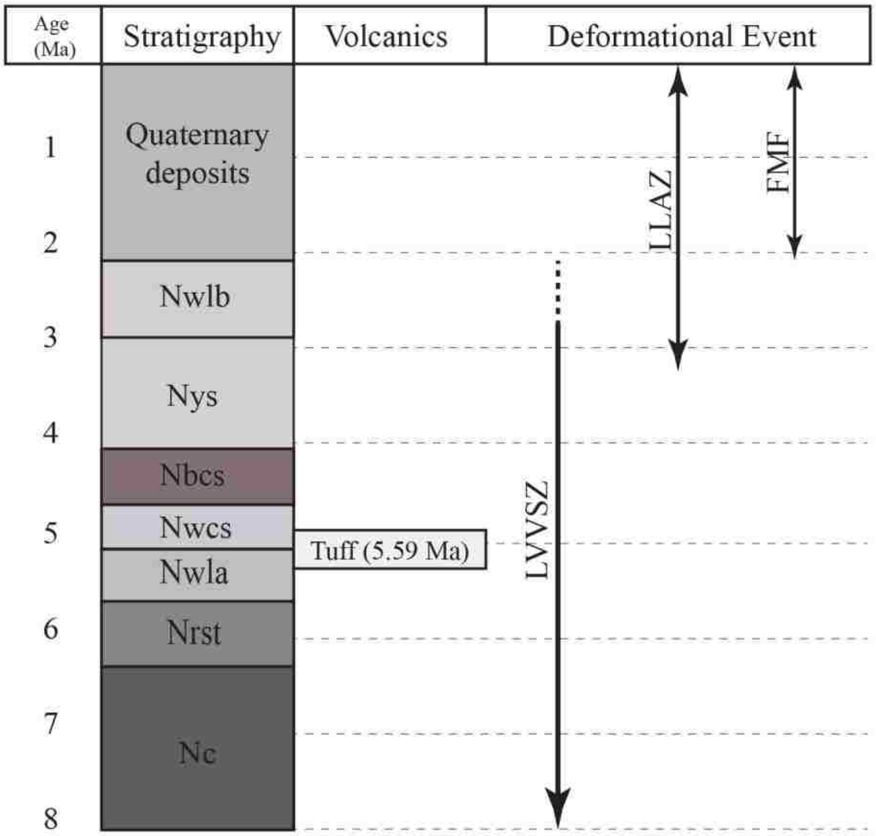

Figure 13. Time sequence of deformation in NDRA. Time sequence of deformation in NDRA is based on which units are involved in each of the three different deformations . The tuff date is from Castor et al. (2000) and Castor and Faulds (2001) The age of the Nwlb is tentative (see Discussion).

# TABLES

Table 1. Fold measurements in domain A.

| Fold* | Axial Trace | | Axial Plane | | Interlimb Angle | Classification | Type |
|---|---|---|---|---|---|---|---|
| | Trend | Plunge | Strike | Dip | | | |
| b W | 098.7 | 1 | 098.6 | 81.3 S | 172.2 | Gentle | Anticline |
| c W | 265.8 | 0.1 | 085.8 | 85.8 S | 170 | Gentle | Syncline |
| d | 076 | 0.7 | 075.8 | 76 S | 169.1 | Gentle | Anticline |
| e | 074.8 | 0.6 | 074.6 | 74.8 S | 172.1 | Gentle | Syncline |
| aj | 076.1 | 1.5 | 075.7 | 76.1 S | 172.6 | Gentle | Anticline |
| ak | 082.6 | 0.9 | 82.5 | 82.6 S | 164.1 | Gentle | Syncline |
| ag | 0260.6 | 1.5 | 80.8 | 80.6 S | 158.5 | Gentle | Syncline |

*Refer to domain A map (Fig. 8A) for fold locations.

Table 2. Fault measurements in domain A.

| Fault* | Strike | Dip | Type | Throw (m) | Hanging Wall | Footwall |
|---|---|---|---|---|---|---|
| E | 109 | SW | Normal | 0.5 | Nwla | Nwla |
| F | 109 | NE | Normal | 0.5 | Nwla | Nwla |
| G | 34 | 30 SE | Thrust | 4 - 6 | Nwla | Nwla |
| H | 157 | 47 NE | Normal | 1 | Nrst | Nrst |
| I | 157 | 47 NE | Normal | 1 | Nrst | Nrst |

*Refer to domain A map (Fig. 8A) for fault locations.

Table 3. Fold measurements in domain B.

| Fold* | Axial Trace | | Axial Plane | | Interlimb Angle | Classification | Type |
|---|---|---|---|---|---|---|---|
| | Trend | Plunge | Strike | Dip | | | |
| a | 120.2 | 0.5 | 112.9 | 04.1 S | 166.2 | Gentle | Anticline |
| ax | 126.4 | 0.9 | 125.7 | 53.6 | 159.1 | Gentle | Syncline |
| b E | 125.7 | 1 | 125 | 54.4 S | 159.5 | Gentle | Anticline |
| c E | 295.2 | 2.1 | 116.2 | 64.8 S | 169.1 | Gentle | Syncline |
| f | 321.8 | 0.9 | 142.9 | 38.2 W | 169.1 | Gentle | Anticline |
| g | 289.8 | 4.4 | 111.4 | 70.3 S | 173.7 | Gentle | Syncline |
| h | 315 | 0 | 135 | 45 S | 162 | Gentle | Anticline |
| i | 103.6 | 2.5 | 103.6 | 76.4 S | 115.2 | Gentle | Syncline |
| j | 281.9 | 2.5 | 102.4 | 78.1 S | 154.5 | Gentle | Anticline |
| k | 131.9 | 3 | 129.2 | 48.1 S | 152.9 | Gentle | Syncline |
| l | 327.4 | 1.2 | 149.3 | 32.7 W | 170.4 | Gentle | Anticline |
| m | 312.2 | 1.5 | 133.6 | 47.8 S | 171.5 | Gentle | Syncline |
| n | 85.4 | 2.5 | 085.2 | 85.4 S | 168 | Gentle | Anticline |
| aa | 102 | 3.3 | 101.3 | 78 S | 172.7 | Gentle | Syncline |
| ab | 109.6 | 11.6 | 105.5 | 70.9 S | 101.3 | Open | Anticline |
| ad | 301.2 | 3.9 | 123.6 | 58.8 S | 161.3 | Gentle | Syncline |
| ae | 310.4 | 1.3 | 131.5 | 49.6 S | 155.2 | Gentle | Anticline |
| af | 092 | 4.5 | 091.8 | 88 S | 97.8 | Open | Syncline |
| ah | 142.1 | 1.1 | 140.8 | 37.9 W | 125.1 | Gentle | Anticline |
| ai | 152.3 | 2.6 | 147.4 | 27.8 W | 148.1 | Gentle | Syncline |
| ay | 284.7 | 3.3 | 106.5 | 62.4 S | 122.3 | Open | Anticline |
| z | 286.9 | 0.6 | 107.1 | 73.1 S | 157 | Gentle | Anticline |

*Refer to domain B map (Fig. 9A) for fold locations.

Table 4. Fault measurements in domain B.

| Fault* | Strike | Dip | Type | Throw (m) | Hanging Wall | Footwall |
|---|---|---|---|---|---|---|
| J | 128 | 21 NE | Normal | 6 | Nwla | Nwla |
| K | 127 | 21 NE | Normal | 6 | Nwla | Nwla/Nrst |
| L | 112 | 33°NE | Normal | 8 - 15 | Nwla | Nrst/Nc |
| M | 045 | 40 NW | Normal | 7 - 10 | Nrst | Nc |
| N | 033 | SE | Normal | 58 - 90 | Qoa/Qp | Nwla |
| O | 029 | NW | Normal | 66 - 105 | Qoa | Nwla/Nrst |
| P (W) | 150 | 24 NE | Thrust | 7 - 10 | Nrst | Nys |
| P (E) | 090 | 24 N | Thrust | 7 - 10 | Nrst | Nys |
| Q | 055 | SE | Normal | 10 - 15 | Nwla | Nwla |

*Refer to domain B map (Fig. 9A) for fault locations.

# Appendices

## Appendix A

### Plates

Plate 1. Geologic map of Nellis Dunes Recreational Area.
(Please find Plate 1 in the attachment entitled Geologic Map of Nellis Dunes Recreational Area)

Plate 2. Geologic cross-sections of Nellis Dunes Recreational Area.

(Please find Plate 2 in the attachment entitled Geologic Cross-sections of Nellis Dunes Recreational Area)

# Appendix B
# Photographs

Photo 1. The picture shows an outcrop of the Nwla, Nwcs, and Nbcs in Domain A. The Nwla is overlain by the Nwcs and Nbcs.

Photo 2. The color of the Nwcs changes from white to yellow in some parts due to the contamination with arsenic.

Photo 3. Limestone “b” (Nwlb). The picture shows void-filling calcite that is common in Nwlb.

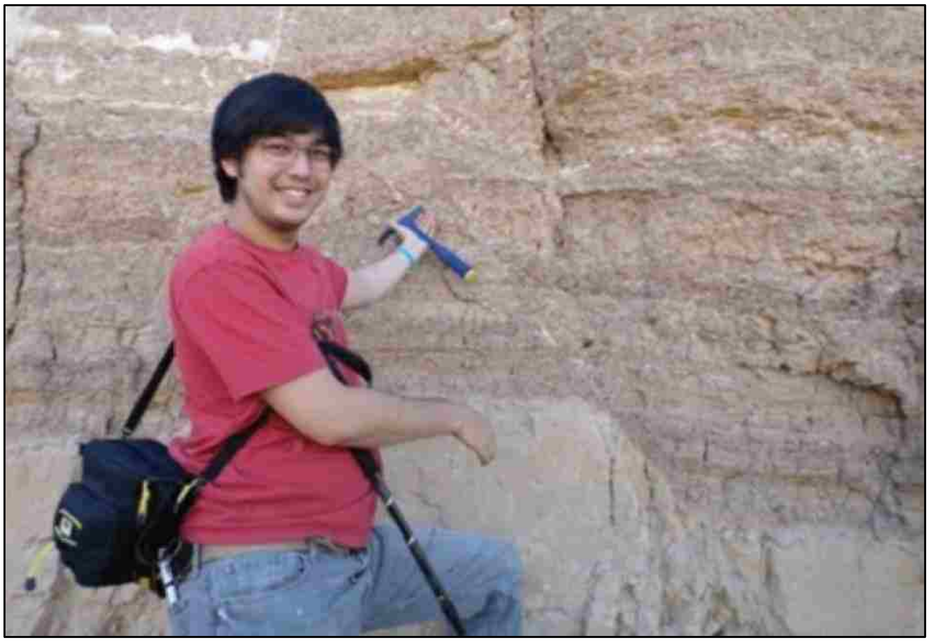

Photo 4. NW-stiking normal faults developed in Northern NDRA.

Photo 5. The LVVSZ stopped moving before the Quaternary forming a local unconformity in Domain A.

Photo 6. NE- striking thrust fault (Fault G) developed in the southern part of Domain A.

Photo 7. NE-oriented plunging folds folds deveoped in domain C by LVVSZ deformation in the Miocene-Pliocene.

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