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# A CLASTIC PIPE IN THE MIOCENE HORSE SPRING FORMATION OF SOUTHERN NEVADA—IMPLICATIONS FOR SHEAR-ZONE SEISMICITY BETWEEN THE PACIFIC AND NORTH AMERICAN PLATES

**Stephen M. Rowland and Jerry L. King**

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*Stephen M. Rowland stands next to the Lowell Wash clastic pipe—a seismically triggered clastic pipe oriented perpendicular to bedding in the Miocene Horse Spring Formation of southern Nevada. Rod is 1.5 m long, calibrated in dm. Photograph by Gregg Wilkerson.*

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# A Clastic Pipe in the Miocene Horse Spring Formation of Southern Nevada—Implications for Shear-Zone Seismicity Between the Pacific and North American Plates

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## ABSTRACT

We describe and interpret a large, cylindrical, sedimentary structure, 5.1 m long and 1.2 m in diameter exposed in a tributary to Lovell Wash, near Lake Mead in southern Nevada. It occurs within the mid-Miocene Horse Spring Formation. We interpret this structure to be a seismically triggered clastic pipe. Clastic pipes are common and well-studied in the Jurassic of the Colorado Plateau; however, no such structures have previously been recognized in the Miocene of southern Nevada; thus, this is a highly anomalous feature in this region. The Horse Spring consists of fluvial and lacustrine sediments deposited in a basin that formed during Miocene extension of the Basin and Range Province. Abundant $^{40}Ar/^{39}Ar$-dated tuffs in this formation permit us to date the injection of the Lovell Wash clastic pipe at about 13.7 Ma. Paleoliquefaction features and intrastratal folds and faults in the Horse Spring document the occurrence of large earthquakes during its deposition. An earthquake on the nearby Las Vegas Valley shear zone most likely triggered the injection of the Lovell Wash clastic pipe. Motion within this shear zone began roughly 13 Ma, initiating dextral faulting within the nascent Walker Lane–Eastern California shear zone, which now accommodates approximately 20% of the relative motion between the Pacific and North American plates. The Lovell Wash clastic pipe thus represents a harbinger of the development of the Walker Lane–Eastern California shear zone and the divergence of the Pacific and North American plates.

## INTRODUCTION

We describe and interpret a large cylindrical sedimentary structure that is 5.1 m long and 1.2 m in diameter, exposed in a short tributary to Lovell Wash in the Muddy Mountains area of southern Nevada. This structure, which lies within the mid-Miocene Horse Spring Formation, plunges perpendicular to the steeply dipping bedding of that formation (Figure 1).

Lovell Wash is a popular destination for Las Vegas-based hikers and geology field trips (e.g., Rowland, 2025), due to engaging rock exposures, a slot canyon (Anniversary Narrows), the ruins of a 1920s-era borate mine (the Anniversary Mine), stromatolites in the Horse Spring Formation (Hickson et al., 2022), and the puzzling cylindrical structure shown in Figure 1. The purpose of this paper is to describe and interpret this cylindrical structure and place it in the context of extensional tectonics within the Lake Mead region. Methods involved field observations and measurements, microscopic examination of thin sections made from a randomly oriented sample of the structure, and a review of the literature in which similar structures are described and interpreted. This structure is succinctly mentioned

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Figure 1. The Lovell Wash clastic pipe is injected into the Miocene Horse Spring Formation, Muddy Mountains area, southern Nevada. The clastic pipe is perpendicular to bedding. The rod that is 1.5 m long and calibrated in dm.

in the description of Stop 2.2.6 of Hickson et al. (2022), a field guide focused on Miocene and modern microbialites. Those authors interpreted the structure to be the product of seismic shaking, but without further discussion. We are not aware of any other published mention of this pipe.

We interpret this structure to be a seismically triggered injectite. Through the processes of liquefication and fluidization, water-saturated siliciclastic sediment is sometimes injected into adjacent bodies of rock, resulting in distinctive soft-sediment deformation structures called injectites (Hurst et al., 2011; Wheatley et al., 2016; Wheatley and Chan, 2018). These processes can be driven by a variety of mechanisms, including a relatively rapid increase in overburden pressure (e.g., a landslide or submarine slump), diagenetic changes, and seismic shaking (Obermeier et al., 1992, 2005; Munson et al., 1995; Davies et al., 2006; Hurst et al., 2011; Lunina and Gladkov, 2016; Wheatley et al., 2016; Lunina, 2019). In the case of the Lovell Wash pipe, seismic shaking is the only plausible causal mechanism. There are no massive debris-flow strata in the Lovell Wash section that could have caused a rapid increase in overburden pressure. Nor is there reason to suspect a unique diagenetic history in the source bed that could have resulted in a sudden, powerful upward injection of sediment.

There are three general categories of injectites: (1) tabular and wedge-shaped clastic dikes and sills, (2) cylindrical, pillar-shaped clastic pipes that are oriented at a high angle to the bedding within the host rock, and (3) irregular-shaped bodies with no distinct shape (Hurst et al., 2011; Wheatley et al., 2016). We interpret the injectite described and interpreted in this study to be a clastic pipe. Clastic pipes have been most intensively studied in the Colorado Plateau region, where they are abundant in Jurassic deposits (Netoff and Shroba, 2001; Netoff, 2002; Chan et al., 2007, 2019; Wheatley et al., 2016; Wheatley and Chan, 2018; Wheatley et al., 2019). Interest by geologists in clastic pipes, as well as other injectites, has been stimulated in part by their unusual appearance, but also by economic interests: some sandstone pipes in New Mexico have been shown to contain uranium (Schlee, 1963), and injectites of various morphologies sometimes serve as hydrocarbon reservoirs (Hurst and Cartwright, 2007). No clastic pipes have previously been reported in Miocene deposits of southern Nevada, so the discovery of a large pipe in this region captured our interest, leading to this study.

## THE LOVELL WASH CLASTIC PIPE

The Lovell Wash clastic pipe is rooted in a poorly exposed source bed at its lower end and abruptly terminated at its upper end (Figure 2). The exposure (N. 36°13.137', W. 114°42.257'), is just outside the boundary of Lake Mead National Recreation Area (LMNRA), approximately 35 km east of downtown Las Vegas (Figure 3). The site is accessible from Northshore Road in LMNRA, via the Callville Wash North unpaved road and unpaved Anniversary Mine road. A high-clearance vehicle is recommended.

Stratigraphically, this structure occurs near the base of the Lovell Wash Member of the Horse Spring Formation (Figure 4), which is a mixture of fluvial and lacustrine strata (Bohannon, 1984; Hickson et al., 2010, 2022; Lamb et al., 2010). The pipe plunges 43° N., 43 W., perpendicular to the bedding, which dips 47° to the southeast. It is composed of quartz siltstone (Figure 5A). The presence of abundant, radiometrically dated tuffs in the Horse Spring permit us to date the causative earthquake at 13.7 ± 0.2 Ma (Figure 4A).

In thin section, evenly spaced curved lines are seen, which are about 0.5 mm apart (Figure 5B). We interpret these curved lines to be relict flow laminae. The sample from which this thin section was made was not oriented relative to the orientation of the pipe, so we are unable to document the direction of flow through the orientation of the flow laminae. However, because the source bed is at the bottom of the column and the top is abruptly terminated (Figure 2), there is no doubt that the flow direction was stratigraphically upward. The associated strata consist of thinly bedded sandstone, siltstone, and mudstone (Figure 4). Stratigraphically, about 20 m below the interval with the clastic pipe is the top of an about 200-m-thick interval of lacustrine carbonate—the Bitter Ridge Limestone Member of the Horse Spring Formation (Figure 4A). As discussed below, these stratigraphic characteristics likely influenced the seismic response of these sediments to a large earthquake, and the triggering of the injection of the Lovell Wash clastic pipe.

Well-sorted, water-saturated, granular layers of sediment are especially susceptible to liquefaction (Obermeier et al., 2002; Tuttle et al., 2019), and the Lovell Wash clastic pipe exhibits a felicitous combination of such susceptibility factors. The stratigraphic context of the source bed, having been buried beneath several meters of overlying strata, provided the confining pressure that caused the liquefied sediment to burst violently upward as a clastic pipe. Due to a fortuitous confluence of stratigraphy and geomorphology, the Lovell Wash injection pipe is well exposed. However, the source bed of the pipe is not well exposed, so we are unable to document lateral variations and sedimentary structures within that bed.

Figure 6 provides a series of diagrammatic sketches that illustrate our reconstruction of the sequence of events that led to the creation of the Lovell Wash clastic pipe. We infer that a large earthquake occurred on a nearby fault, intensively shaking the grains in a saturated layer of silt. Shifting silt grains reduced the interstitial volume available for pore water, causing an increase in pore-water pressure (cf. Obermeier et al., 2001, 2002). The water-saturated, silty sediment was fluidized and forcefully expelled upward, incorporating fragments of wall rock, and creating the cylinder of quartz siltstone. A ‘sand blow’ is presumed to have formed on the surface, 5.1 m above the top of the source bed; however, erosion presumably planed off the exposed top of the pipe. A succession of new strata was subsequently deposited. The entire section was later tilted 47° to the southeast during Miocene folding, causing the injection pipe to plunge 43° to the northwest.

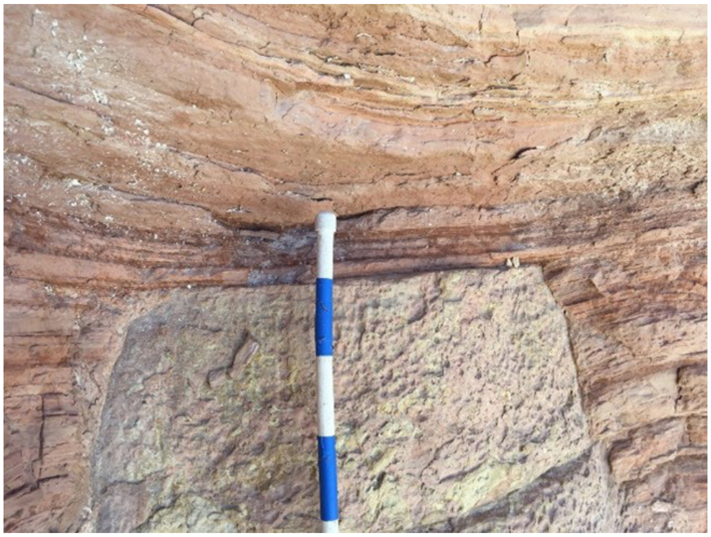

Figure 2. Top margin of the clastic pipe, showing its flat termination, parallel to bedding. Units of calibrated rod are dm.

## TECTONIC CONTEXT

There is abundant evidence that the Horse Spring Formation was deposited during a time of active seismicity. The southern Nevada region experienced large-scale westward extension in the range of 300% to 400% during the Miocene Epoch (Wernicke et al., 1988). Between about 17 and 10 Ma, the Frenchman Mountain/Rainbow Gardens/Sunrise Mountain structural block, which lies on the east side of Las Vegas Valley (Figure 3), was translated about 60 km westward, from its pre-extension position near Gold Butte, and tilted about 50° to the east. This movement occurred on a system of kinematically coupled detachment faults, left-lateral strike-slip faults (Lake Mead fault system), and the right-lateral Las Vegas Valley shear zone (Anderson, 1973; Bohannon, 1979; Nelson and Jones, 1987; Duebendorfer et al., 1989; Duebendorfer and Wallin, 1991; Duebendorfer and Black, 1992; Duebendorfer and Simpson, 1994; Sonder et al., 1994; Fryxell and Duebendorfer, 2005; Lamb et al., 2010, 2015, 2022; Anderson, 2012; Rowland, 2022). The Las Vegas Valley shear zone is the longest fault system in this region (Figure 3). As noted above, it is a major right-lateral, strike-slip fault zone that exceeds 100 km in length (Longwell, 1974; Wernicke et al., 1982; Langenheim et al., 2001; Faulds and Henry, 2008). The resulting morphologically complex basin that formed between the western edge of the Colorado Plateau and the Frenchman Mountain/Rainbow Gardens/Sunrise Mountain block (Figure 3) was filled with fluvial and lacustrine deposits of the Miocene Horse Spring Formation (Bohannon, 1984; Hickson et al., 2010; Lamb et al., 2010; 2022), which ranges in age from approximately 11.8 to 16.5 Ma in the Lovell Wash area (Figure 4A). Modern Lake Mead partially occupies this same basin today.

The conspicuous role of faulting in the development of the Horse Spring basin has long been recognized (e.g., Anderson, 1973; Castor, 1993; Cakir et al., 1998; Anderson, 2012; Lamb et al., 2022). At least three horizons within the Horse Spring Formation (identified in Figure 4) contain seismically generated features: (1) intrastratal folding and faulting in the informally named Anniversary Mine limestone, within the Lovell Wash Member (Figure 4B), (2) the Lovell Wash clastic pipe (Figure 4C), and (3) dish and pillar structures in the Thumb Member (Figure 4D). Abundant tuff beds provide high-resolution $^{40}Ar/^{39}Ar$ dating within this formation (Hickson et al., 2010; Lamb et al., 2015). Revised age calculation standards for $^{40}Ar/^{39}Ar$ dating will probably cause these ages to change slightly (Z.W. Anderson, Utah Geological Survey, personal communication, 2023).

Dish and pillar structures can form without seismic shaking (Lowe and LoPicolo, 1974; Mills, 1983); however, in this case the deformation is so pronounced that seismic shaking is almost certainly the causative agent. Tests for distinguishing seismic from non-seismic soft-sediment structures include (1) whether the structure formed suddenly, and (2) whether the features occur in a tectonic setting in which seismicity is a plausible explanation (Wheeler, 2002). There is little question that the deformation occurred abruptly, and this region was tectonically very active in the mid-Miocene, when these sediments were deposited.

The intrastratal folding and faulting in the Anniversary Mine Limestone (N. 35°12.973', W. 114°42.376') (Figure 4B), originally reported by Castor (1993), also support the inference of recurring seismicity. These features are confined to discrete stratigraphic intervals, and the combination of brittle and ductile deformation

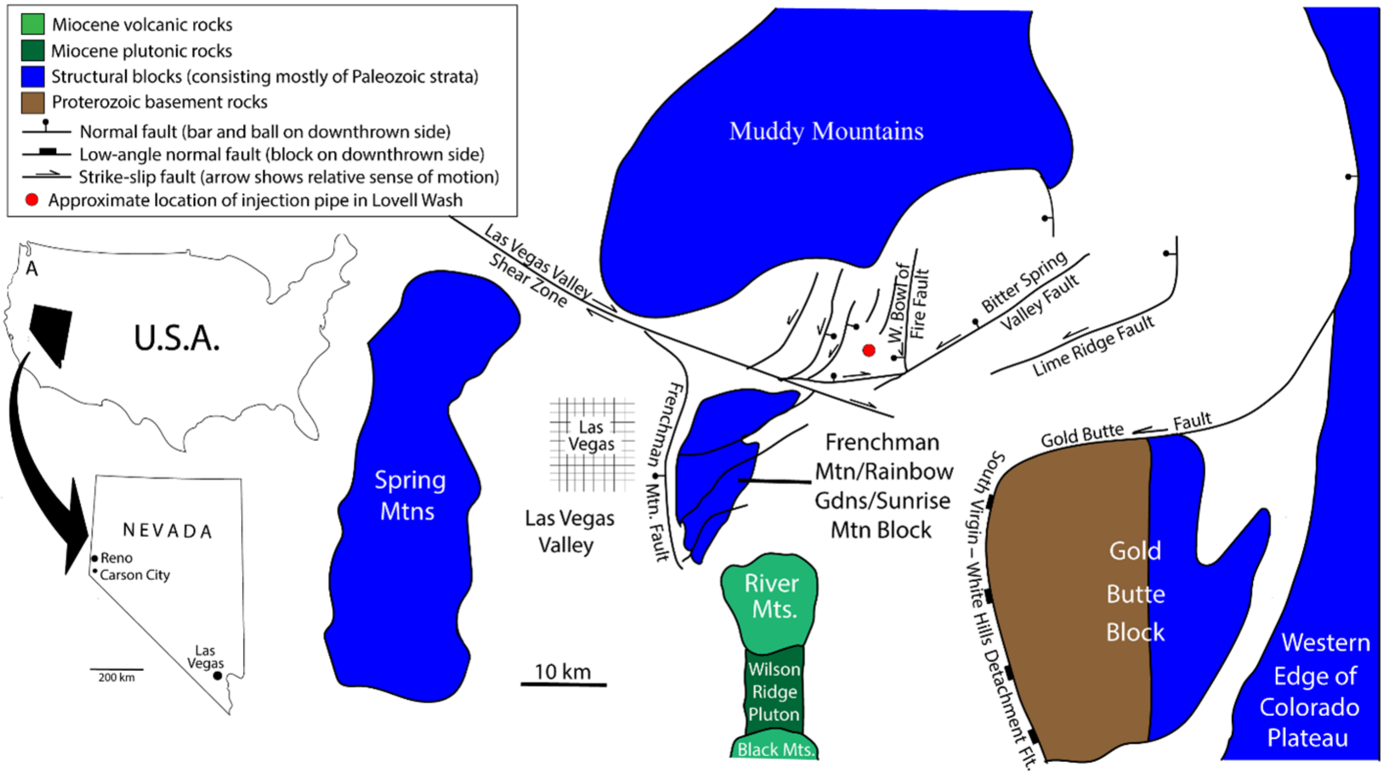

Figure 3. Index map and generalized geologic map showing faults that were active during deposition of the lower half of the Lovell Wash Member of the Horse Spring Formation. The Las Vegas Valley shear zone extends northwestward, beyond the length shown. Modified from Anderson (2012, Figure 4.6).

indicates that the sediments were only partially lithified. The conspicuous evidence of shear strain, along with the fact that these features are contained within a narrow stratum, leads us to conclude that they were seismically induced by ground shaking.

The large size of the Lovell Wash clastic pipe indicates that it was triggered by a relatively high-magnitude event that involved lengthy ground shaking. Earthquakes with a moment magnitude (Mw) of 7.5 or greater occur only on reverse, strike-slip, or oblique-slip faults, rather than normal faults. Earthquakes on continental normal faults have smaller maximum moment magnitudes, rarely exceeding 7.0 Mw (Muldashev et al., 2022), apparently due to the weakness of the lithosphere in extension. In contrast, it is not uncommon for long strike-slip faults to have magnitudes of about 8 Mw (Neely and Stein, 2021). Furthermore, earthquakes with magnitudes of 7.5 Mw or above occur only on strike-slip faults with rupture lengths of 100 km or greater (Wells and Coppersmith, 1994). The left-lateral Lake Mead fault system (Figure 3), although it was active in the mid-Miocene, is too short to be a strong candidate to have produced an earthquake large enough to trigger the injection of the Lovell Wash clastic pipe.

The severity of earthquake shaking and seismically induced liquefaction is greatest near the fault rupture surface; attenuation with distance from this surface approximates a logarithmic function (Youd and Perkins, 1987). Thus, the causative fault of the Lovell Wash clastic pipe must have been in the vicinity of the liquefaction structure. Anderson (2012) and Lamb et al. (2022) have conducted detailed analyses of the structural history of the basin in which the upper part of the Horse Spring Formation was deposited. In the region of the Lovell syncline, where the Lovell Wash clastic pipe occurs, the Las Vegas Valley shear zone is the only strike-slip fault that is long enough to plausibly generate an earthquake strong enough to trigger an injection pipe

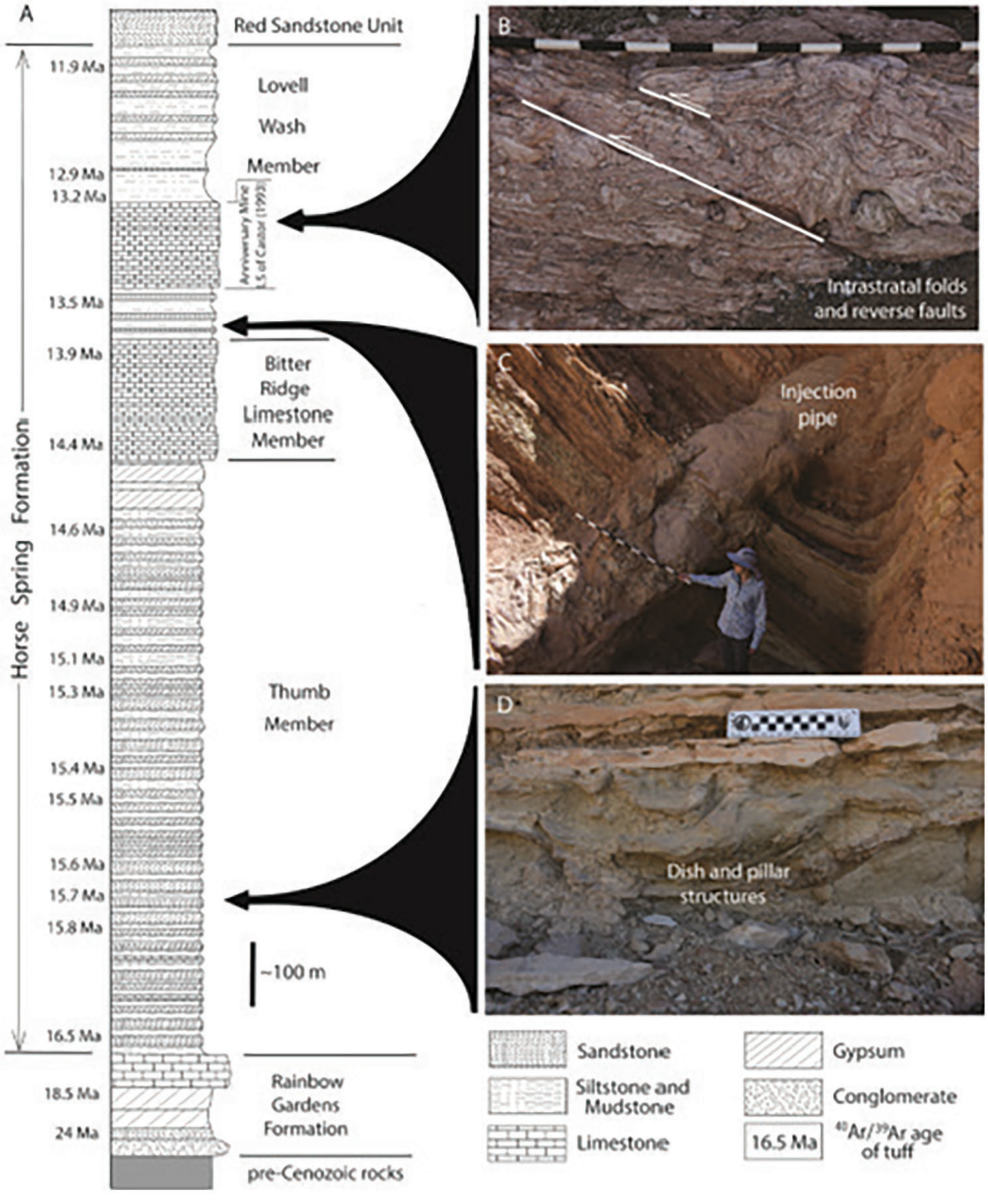

Figure 4. (A) Generalized stratigraphic column and weathering profile of the Horse Spring Formation and directly overlying and underlying units in the east Gale Hills region, east of Las Vegas. Modified from Hickson et al. (2010), Anderson (2012), and Lamb et al. (2015). $^{40}$Ar/$^{39}$Ar ages, which come from thin tuff horizons, are representative of dates reported by Lamb et al., (2015). (B) Intrastratal folds and reverse faults, interpreted to be of seismic origin, exposed in Lovell Wash, about 0.4 km south of the injection pipe. Scale units are dm. (C) Lovell Wash pipe. Staff is 1.5 m long, divided into dm. (D) Dish and pillar structures, interpreted to be of seismic origin, exposed in Bitter Spring Valley (Echo Wash drainage), about 10 km northeast of Lovell Wash.

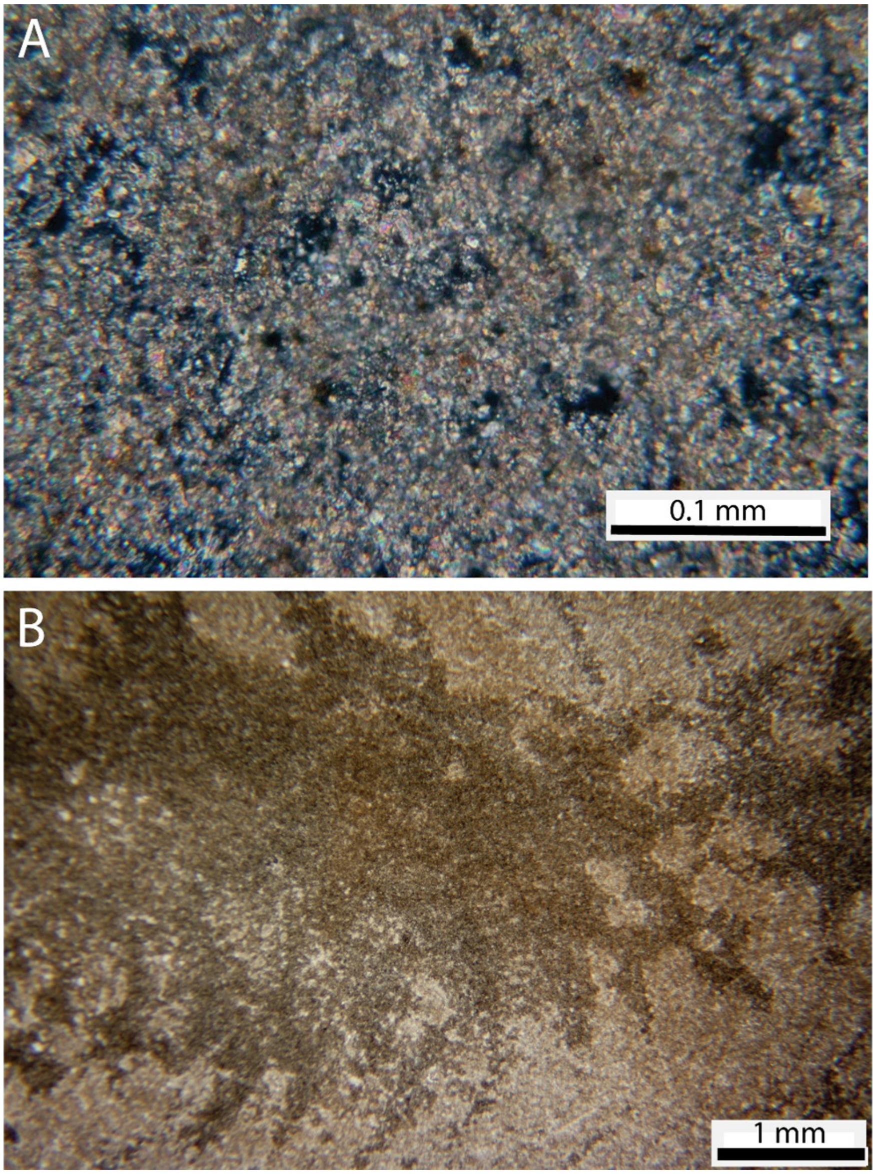

Figure 5. Thin section photomicrographs of a sample of the Lovell Wash clastic pipe; plane-polarized light. (A) High-magnification image showing silt grains. (B) Lower magnification image showing curved laminae interpreted to be relict flow laminae.

as large as the Lovell Wash clastic pipe (Dee et al., 2024); it also occurs within a few km of the pipe (Figure 3). We conclude, therefore, that it is highly probable that seismicity within the Las Vegas Valley shear zone triggered this liquefaction event.

Empirical data indicate that a strike-slip fault of about 100 km—comparable to the Las Vegas Valley shear zone— would be capable of generating an earthquake in the magnitude 7.5 to 7.8 range (e.g., Wells and Coppersmith, 1994). An earthquake in this magnitude range would be expected to produce a peak ground acceleration (PGA) of about 0.2 g at a distance of 20 km at a site with an average shear-wave velocity in the top 30 m (Vs30) of 760 meters/second (m/s) (Boore et al., 2014). A PGA value of 0.2 g above the minimum PGA threshold of 0.1 to 0.15 g is considered to be required to cause liquefaction in susceptible sediments (de Magistris et al., 2013). A Vs30 value of 760 m/s corresponds to the boundary between National Earthquake Hazard Reduction Program (NEHRP) Site Classes B (rock) and C (very dense soil or soft rock) (Petersen et al., 2023). The soft, saturated sediments at the location of the Lovell Wash clastic pipe would have had much lower shear-wave velocities, resulting in higher PGAs than 0.2 g for

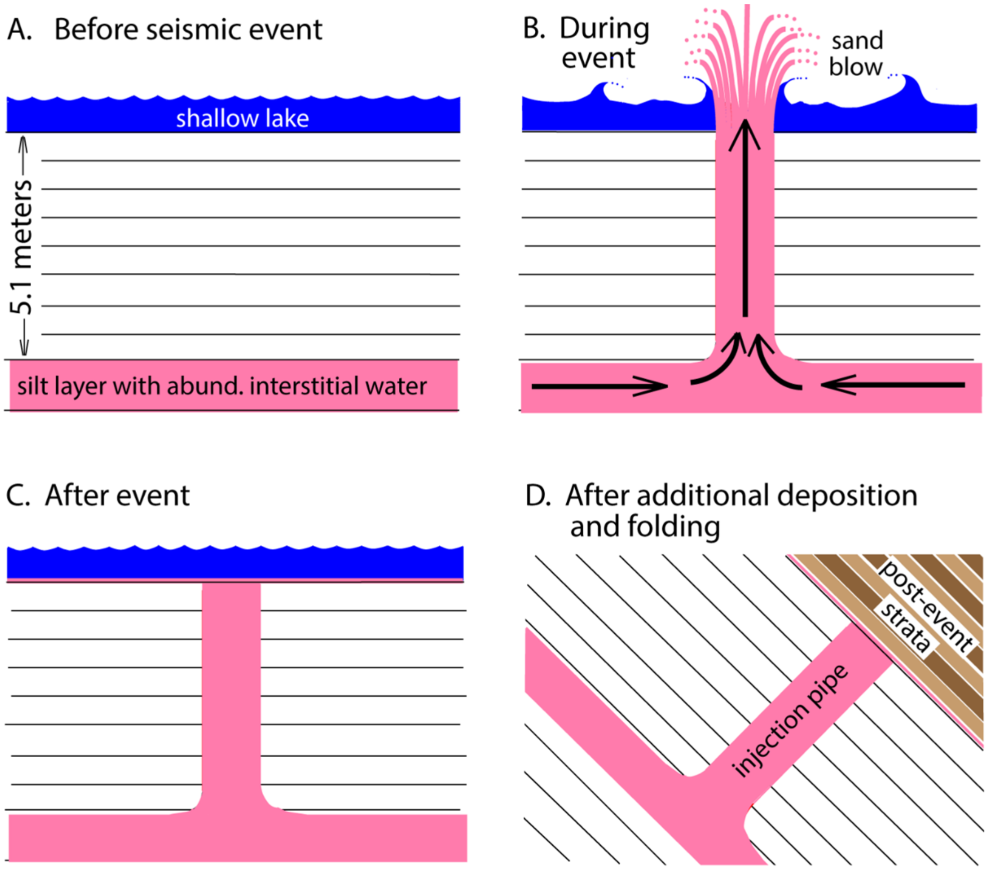

Figure 6. Schematic 4-stage model for the development of the Lovell Wash clastic pipe.

a magnitude 7.5 to 7.8 earthquake at a distance of 20 km.

An earthquake rupturing the entire length of the Las Vegas Valley shear zone would have generated strong ground motion for a significant duration. Assuming a typical rupture velocity for strike-slip earthquakes of 2.5 km/s (Chounet et al., 2018), and a rupture length of 100 km, a unilateral rupture initiating at one end of the fault would have taken 40 seconds to propagate the length of the fault, all the while releasing seismic energy, causing the ground to shake, and possibly inducing liquefaction. A bi-lateral rupture initiating in the middle of the fault would have ruptured for a shorter duration but released seismic energy from both rupture fronts simultaneously.

The Lovell Wash clastic pipe formed in low-seismic-velocity, fluvial sediments—the basal strata of the Lovell Wash Member of the Horse Spring Formation (Figure 4). However, these fine-grained siliciclastic deposits overlie (a few meters below) carbonate-dominated, higher seismic velocity, lacustrine deposits of the Bitter Ridge Limestone Member. The seismic impedance contrast between the deeper carbonate and shallower siliciclastic strata would have amplified the seismic waves and trapped seismic energy, resulting in reverberations and resonance at the natural period of vibration of the sediment column (e.g., Gunn, 2018). Consequently, a magnitude 7.5 to 7.8 earthquake in the Las Vegas Valley shear zone likely would have generated ground motions for tens of seconds that exceeded the threshold for liquefaction at the location of the Lovell Wash injection structure.

## IMPLICATIONS FOR EARLY SHEAR-ZONE SEISMICITY BETWEEN THE PACIFIC AND NORTH AMERICAN PLATES

The Lovell Wash clastic pipe, along with other evidence of large earthquakes that occurred during deposition of the Horse Spring Formation, contributes to an emerging story of mid-Miocene plate-boundary

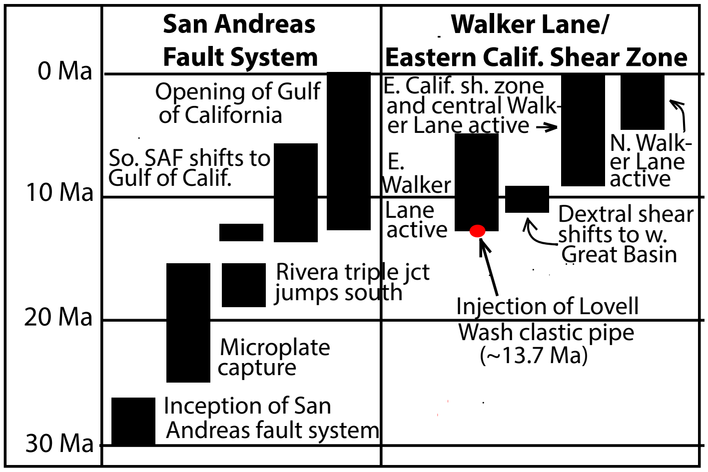

Figure 7. Location and age of the Lovell Wash clastic pipe in the context of the development of the San Andreas fault system and the Walker Lane-Eastern California shear zone. Modified from Faulds and Henry (2008).

dynamics and the creation of the Walker Lane-Eastern California shear zone (Figure 7). The Walker Lane is a system of dextral faults—including the Las Vegas Valley shear zone—in the western Great Basin; it is a northern extension of the Eastern California shear zone. Together, these dominantly dextral fault systems accommodate about 20% of the relative plate motion between the Pacific and North American plates, and they transfer this interplate motion east of the Sierra Nevada block (Thatcher et al., 1999; Dixon et al., 2000; Kreemer and Hammond, 2007; Faulds and Henry, 2008). The north 60° west-trending Las Vegas Valley shear zone is parallel to the San Andreas fault system; it developed inboard—east of the Sierra Nevada—of where the San Andreas and associated faults first became organized into a through-going system (Faulds and Henry, 2008). Thus, the seismic events that triggered the Lovell Wash clastic pipe represent the early stage of major plate-boundary events between the Pacific and North American plates.

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