GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G47162.1

Manuscript received 1 November 2019
Revised manuscript received 2 January 2020
Manuscript accepted 23 January 2020

Climatically driven displacement on the Eglington fault, Las Vegas, Nevada, USA

Kathleen B. Springer and Jeffrey S. Pigati
U.S. Geological Survey, Denver Federal Center, Box 25046, MS 980, Denver, Colorado 80225, USA

ABSTRACT

The Eglington fault is one of several intrabasinal faults in the Las Vegas Valley, Nevada, USA, and is the only one recognized as a source for significant earthquakes. Its broad warp displaces Late Pleistocene spring deposits of the Las Vegas Formation, which record hydrologic fluctuations that occurred in response to millennial- and submillennial-scale climate oscillations throughout the late Quaternary. The sediments allow us to constrain the timing of displacement on the Eglington fault and identify hydrologic changes that are temporally coincident with that event. The fault deforms deposits that represent widespread marshes that filled the valley between ca. 31.7 and 27.6 ka. These marshes desiccated abruptly in response to warming and groundwater lowering during Dansgaard-Oeschger (D-O) events 4 and 3, resulting in the formation of a pervasive, hard carbonate cap by 27.0 ka. Vertical offset by as much as 4.2 m occurred *after* the cap hardened, and most likely after younger marshes desiccated irreversibly due to a sudden depression of the water table during D-O event 2, beginning at 23.3 ka. The timing of displacement is further constrained to *before* 19.5 ka as evidenced by undeformed spring deposits that are inset into the incised topography of the warp. Coulomb stress calculations validate the hypothesis that the substantial groundwater decline during D-O event 2 unclamped the fault through unloading of vertical stress of the water column. The synchroneity of this abrupt hydrologic change and displacement of the Eglington fault suggests that climatically modulated tectonics operated in the Las Vegas Valley during the late Quaternary.

INTRODUCTION

Glacial to interglacial mass changes on the landscape driven by melting glaciers and the regression of pluvial lakes have been shown to increase seismicity on preexisting faulted terrains (Hetzel and Hampel, 2005; Hampel and Hetzel, 2006; Hampel et al., 2007). The load released on the underlying substrate upon removal of both solid and liquid water bodies was sufficient to produce fault displacement at sites throughout the Basin and Range province of North America and elsewhere (Hampel et al., 2007; Lagerbäck and Sundh, 2008). Here, we introduce a Late Pleistocene landscape saturated with water, yet never occupied by glaciers or pluvial lakes, as an analogous setting in which climate may have acted as the mechanism of fault displacement during the last glacial period.

During the Late Pleistocene, springs and desert wetlands covered at least ~1425 km^2 of the extensional basin of the Las Vegas Valley in southern Nevada, USA (Harrill, 1976). Hundreds of meters of sediment held considerable amounts of groundwater as a result of increased effective precipitation, particularly during the peak of the last glaciation (Haynes, 1967; Quade, 1986; Springer et al., 2015, 2018). Centennial-scale warming associated with Dansgaard-Oeschger (D-O) events caused water levels in the valley to drop several times during this period, most notably after groundwater reached its apex during the Last Glacial Maximum (Springer et al., 2015). Warming during D-O event 2, which started at ca. 23.3 ka and lasted several centuries (Andersen et al., 2006), resulted in a sudden and dramatic lowering of the groundwater table throughout the Las Vegas Valley. We hypothesize that this drop released a significant stress load and triggered movement on one of the preexisting intrabasinal faults of the Las Vegas Valley fault system (Bell, 1981; Slemmons, 1998; Page et al., 2005), namely the Eglington fault.

Here, we provide the first firm constraints on the timing of the most recent displacement on the Eglington fault. We also determine the amount of displacement and propose a mechanism that is supported by both the geologic evidence and the timing of climatic and hydrologic changes recorded by the sediments that compose the Las Vegas Formation, a Middle Pleistocene to early Holocene sequence of groundwater-discharge deposits representing springs and desert wetlands that have occupied the valley for at least the past 500 k.y. (Fig. DR1 in the GSA Data Repository[1]; Springer et al., 2018). Resolving the timing, magnitude, and mechanism of displacement on the Eglington fault is essential in refining current seismic hazard estimates in this growing metropolitan area.

THE EGLINGTON FAULT

The Eglington fault is a blind normal fault at depth with no brittle surface deformation observed along its 11 km length. Displacement was propagated to the surface as a broad warp with convex west curvature, deforming the sediments of the Las Vegas Formation with reported vertical offset of 10–30 m (Haynes, 1967; Bell, 1981; Ramelli et al., 2011). Although largely obscured by urbanization, the trace of the fault is still exposed in its northeasternmost segment, near its terminus, where this study took place (Fig. 1).

The Eglington fault is likely related to a preexisting structure at depth, given that its surface expression coincides with a gravity ridge bounding two gravity lows (Plume, 1989; Langenheim et al., 2001, 2005). In addition, seismic reflection

---

[1] GSA Data Repository item 2020170, additional details on methods, and other supporting information, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org. Downloadable files of the data presented in the Data Repository can be found at https://doi.org/10.5066/P9URNORV

CITATION: Springer, K.B., and Pigati, J.S., 2020, Climatically driven displacement on the Eglington fault, Las Vegas, Nevada, USA: Geology, v. 48, p. 574–578, https://doi.org/10.1130/G47162.1

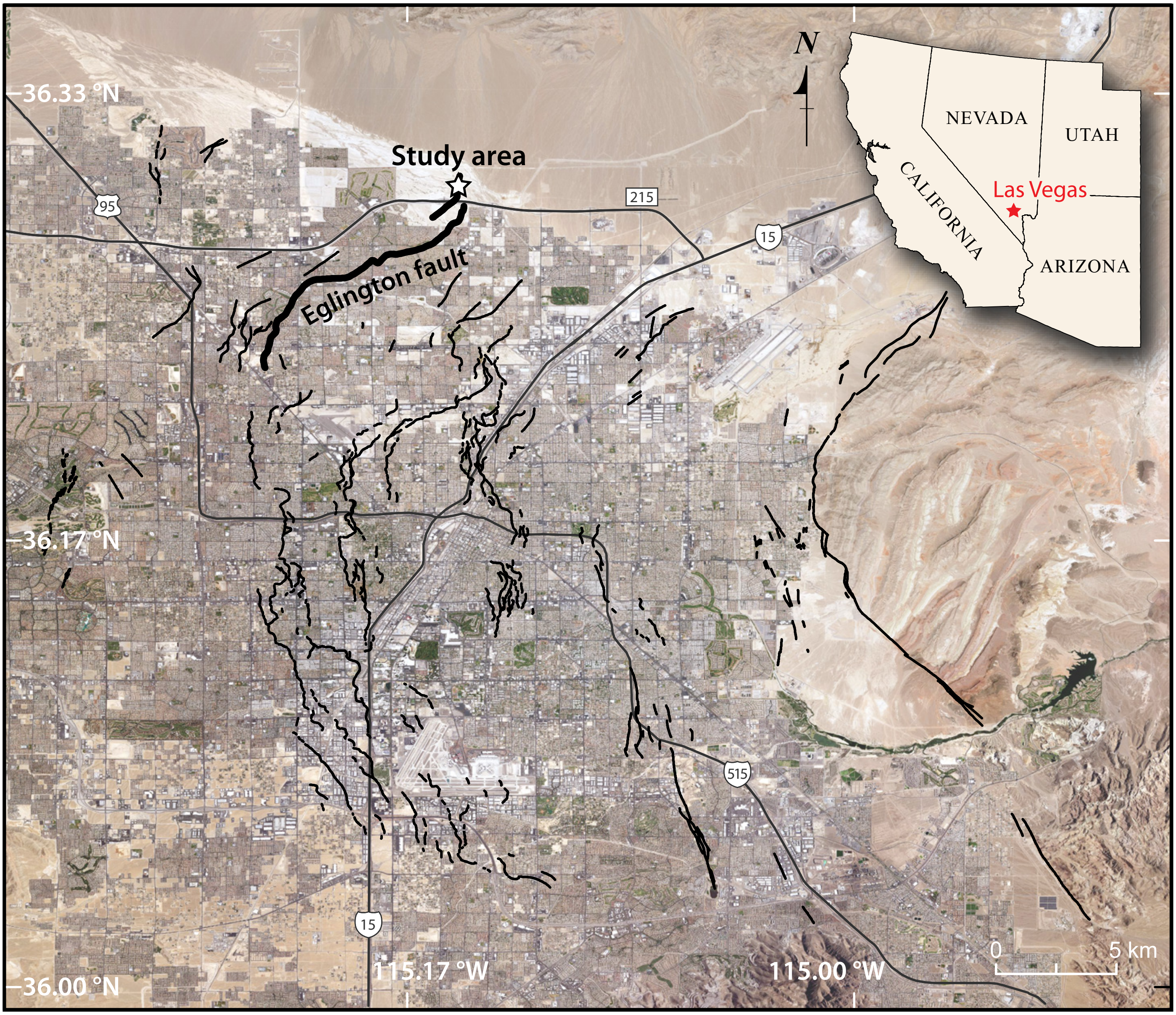

Figure 1. Landsat image of Las Vegas Valley, Nevada, USA, from 2017 CE with locations of all known Quaternary faults from the U.S. Geological Survey (USGS) Quaternary fault and fold database (https://www.usgs.gov/natural-hazards/earthquake-hazards/hazards/faults/, accessed 05 August 2019). Landsat image is courtesy of USGS Earth Resources Observation and Science Center (https://www.usgs.gov/centers/eros). Inset: Location of Las Vegas Valley in southern Nevada (red star).

data show that it overlies large extensional basement offsets (~200 m) buried beneath ~2 km of Cenozoic basin-fill alluvium (Langenheim et al., 1998).

There is a lack of consensus as to the mechanism and timing of displacement of the Eglington fault, and few studies have addressed its paleoseismic history (e.g., dePolo et al., 2013). The 2014 update of the U.S. Geological Survey (USGS) national seismic hazard model classifies it as a late Quaternary fault of tectonic origin with a slip rate estimate of 0.16 mm/yr, and identifies it as the only fault within the Las Vegas Valley fault system that is considered a seismic source of earthquakes (M >6), contributing significantly to the probabilistic ground-motion hazard for the Las Vegas Valley (Petersen et al., 2014; Haller et al., 2015). The Eglington fault displacement history has also been attributed to aseismic processes, including climatically driven dewatering and subsequent differential hydrocompaction of fine-grained sediments at the interface with coarse-grained alluvial fan deposits (Maxey and Jameson, 1948; Mifflin, 1998). While differential compaction can occur in these settings and has been documented with respect to historical subsidence related to groundwater withdrawal in the Las Vegas Valley (Bell, 1981), the spatial distribution of the Las Vegas Formation sediments along the Eglington fault does not support this hypothesis (Amelung et al., 1999).

AMOUNT OF DISPLACEMENT

Widespread marshes that occupied the Las Vegas Valley during the last full glacial period are represented by bed D_2 of the Las Vegas Formation—a unit that is discernibly warped by the Eglington fault in our study area. Bed D_2 is the most geographically extensive unit within the formation, dates to between ca. 31.7 and 27.6 ka, and typically consists of 1–2 m of white to gray silts with interbedded black mats and a prominent, thick (~1 m), hard groundwater (i.e., non-pedogenic) carbonate cap at the top (Springer et al., 2015, 2018) (Fig. DR1).

To determine the amount of offset of bed D_2, we used both lidar data and a high-precision Trimble GPS system to measure the position

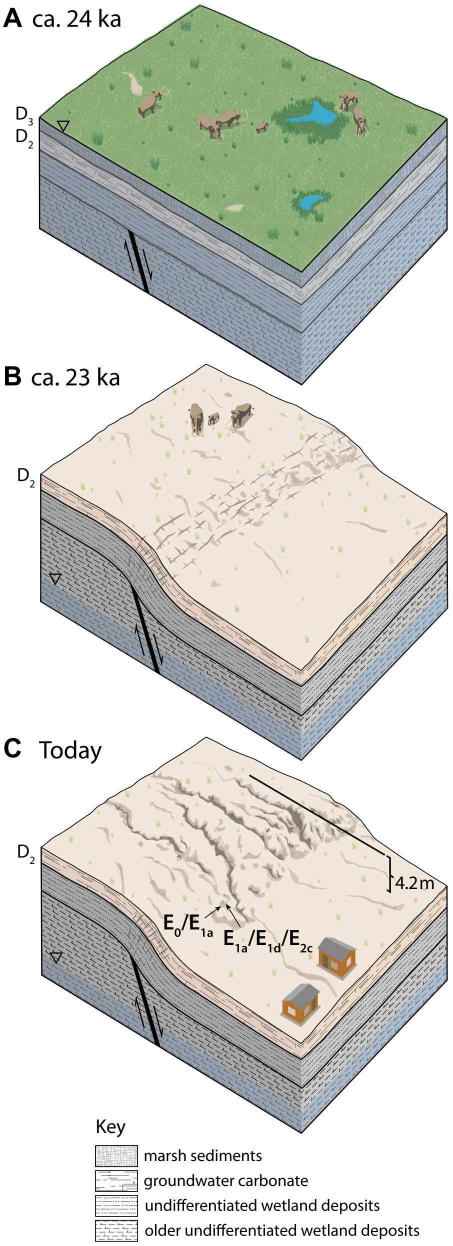

Figure 2. Conceptualized conditions at ground surface in the Las Vegas Valley study area (Nevada, USA), pertinent stratigraphic units of Las Vegas Formation, and position of water table (shown in blue and marked by inverted triangle) and Eglington fault. (A) At ca. 24 ka, water tables in Las Vegas Valley reached their maximum height, extensive marshes provided water source for megafauna, bed D_3 sediments had been deposited on top of hard carbonate cap of bed D_2, and there was no deformation on Eglington fault. (B) Between ca. 23.3 and 23.0 ka, water tables dropped between 10 and 33 m, which triggered displacement on fault, deforming bed D_2. This irreversible drop in water table led to erosion throughout the valley, and sediments of bed D_3 were largely stripped, exposing warped carbonate cap of bed D_2. (C) Today, water tables are low, bed D_3 has been completely eroded, and bed D_2 is broken up and heavily dissected. Within warp, D_2 cap is offset vertically by as much as ~4.2 m, and undeformed sediments of beds E_0, E_{1a}, E_{1d}, and E_{2c} are inset 2–4 m into incised topography of bed D_2.

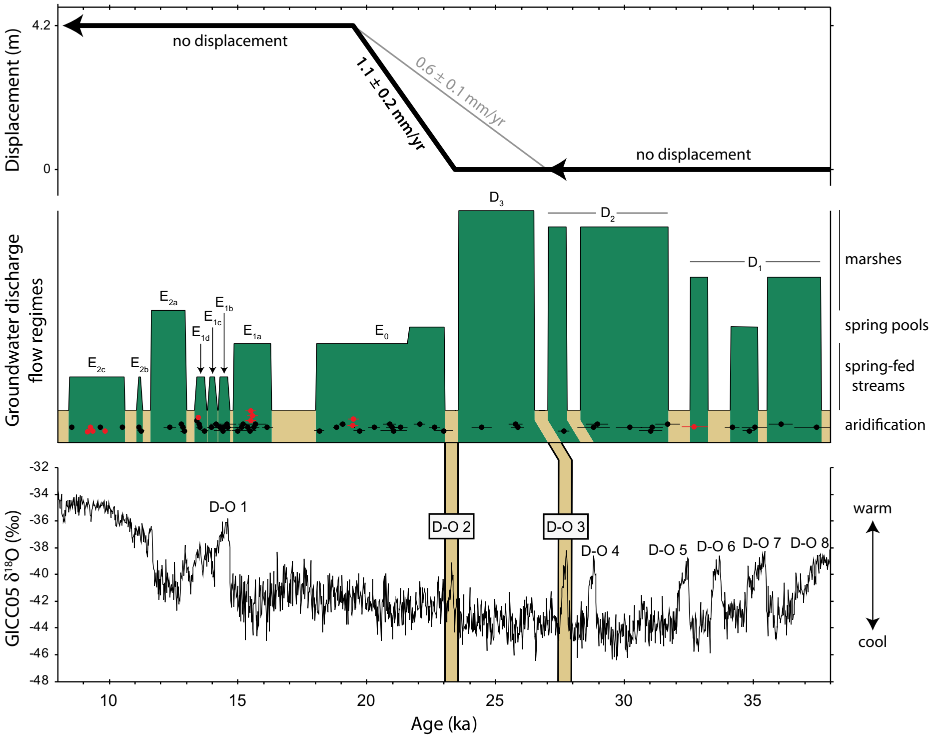

Figure 3. Displacement on the Eglington fault (Nevada, USA) compared to hydrologic records of the Las Vegas Formation and timing of climatic fluctuations interpreted from oxygen isotope ($\delta^{18}O$) data from Greenland ice cores. Top panel: Timing and rate of fault displacement, including our preferred scenario that displacement occurred in response to significant drop in water table and concomitant unloading of vertical stress during and post– Dansgaard-Oeschger (D-O) event 2 and deposition of bed E_0 between 23.3 and 19.5 ka (thick dark line). Alternatively, displacement between 27.0 (post–D-O event 3) and 19.5 ka is also shown (thin gray line). Middle panel: Discrete discharge events shown in green, and intervening aridification shown in tan (after Springer et al., 2015, 2018). Identifiers above green bars refer to beds of the Las Vegas Formation. Black filled circles are calibrated radiocarbon ages with uncertainties presented at 2σ (95%) confidence level that were published previously (Springer et al., 2015, 2018); red filled circles denote ages reported here for the first time (Table DR5 [see footnote 1]). Groundwater discharge flow regimes represented by Las Vegas Formation sediments. Bottom panel: $\delta^{18}O$ data from Greenland ice core records using GICC05 chronology (Andersen et al., 2006).

and elevation of the carbonate cap on both the up- and downthrown sides of the fault. We found that this bed is offset vertically by as much as 4.2 m (Fig. DR2).

TIMING OF DISPLACEMENT

The Las Vegas Formation sequence provides a detailed and nearly complete record of dynamic hydrologic changes for the past ~40 k.y., including cycles of wetland expansion and contraction that correlate tightly with abrupt warming during D-O events as well as other millennial and submillennial climatic oscillations (Springer et al., 2015, 2018). The congruence of the Las Vegas Formation deposition with Northern Hemispheric climatic events allows us to constrain the timing of surface deformation and inferred displacement of the Eglington fault on these time scales.

The fault deforms the deposits of bed D_2, including the hard carbonate cap at the top of the unit. This extensive cap represents a sequence of events during the last full glacial period in which carbonate-rich silts and clays were deposited in marshes and wet meadows starting at ca. 31.7 ka, followed by rapid depression of the water table, desiccation of the wetlands, and case hardening under warm, dry conditions associated with D-O events 4 and 3 that center at ca. 28.8 and 27.7 ka, respectively (Andersen et al., 2006) (Figs. 2–3). Based on the age of bed D_2 and assuming a duration of 500 yr for each of these D-O events (Andersen et al., 2006), desiccation of the wetland and concomitant hardening of the carbonate cap at the top of bed D_2 were complete by ca. 27.0 ka. Displacement along the Eglington fault must have occurred after the cap hardened, post–27.0 ka.

Shortly after this time, the water table in the Las Vegas Valley rose again, and groundwater levels reached their maximum height (at or near the surface), creating widespread marshes represented by bed D_3, between ca. 25.8 and 24.5 ka (Springer et al., 2015, 2018). Along the valley axis, bed D_3 has largely been stripped, but its extensive marginal facies is preserved in the western parts of the valley overlying bed D_2. Based on its distribution and stratigraphic position elsewhere, bed D_3 was certainly present in the Eglington area, but has been eroded away (Fig. 2).

Dramatic lowering of the water table throughout the valley occurred later, coincident with D-O event 2, beginning at ca. 23.3 ka, marking the final collapse of the last full-glacial marshes that dominated the landscape. Extensive erosion, commonly several meters or more, occurred at this time. Importantly, D-O event 2 also marks the timing of a fundamental change in the hydrology of the valley, as groundwater discharge flow regimes shifted from marshes and wet meadows to point-source discharge through faults resulting in spring-fed streams and minor spring pools. This pattern began at 23.0 ka and prevailed through the rest of the Pleistocene and into the early Holocene (Springer et al., 2015, 2018).

Near the Eglington fault, the reinitiation of spring discharge at 23.0 ka is recorded by deposits of bed E_0 (Fig. 3). Soft-sediment deformation is observed in this unit dating to ca. 19.7 ka, possibly as a result of ground motion (Fig. DR3). The fault acted as a conduit for rising groundwater, and flat-lying, undeformed sediments of bed E_0 (19.5–19.4 ka) are inset 2–4 m into the deformed and subsequently incised topography of bed D_2 (Fig. 2). Additional undeformed spring-discharge units, including beds E_{1a} (ca. 15.5 ka) and E_{1d} (13.5–13.4 ka), are also inset into bed D_2 within the warp. Finally, bed E_{2c}, an early Holocene spring-fed fluvial system with extensive tufa formation that dates to 10.6–8.5 ka, drapes unbroken over the warp (Figs. DR4–DR5). Together, these inset units show that incision of the warp, and hence displacement, must have occurred prior to 19.5 ka, and there is no evidence that the fault has been active since that time (Fig. 3).

Bed D_2 and the multiple, undeformed inset units of the Las Vegas Formation provide robust constraints on the timing of displacement, and also allow us to calculate maximum slip rates during the Late Pleistocene. The geologic evidence suggests that up to 4.2 m of vertical offset occurred *after* 27.0 ka, and most likely after 23.3 ka, but *before* 19.5 ka. A slip rate of 0.6 ± 0.1 mm/yr is the most conservative estimate if deformation took place between 27.0 and 19.5 ka. Our preferred scenario, however, is that all of the displacement occurred during and after D-O event 2, between 23.3 and 19.5 ka, resulting in a slip rate of 1.1 ± 0.2 mm/yr (Fig. DR6).

CLIMATE CHANGE AS A MECHANISM OF FAULT DISPLACEMENT

The abrupt transition to warm conditions during D-O events at the end of the last full glacial period, particularly during D-O event 2, occurred within decades to centuries. In the Las Vegas Valley, dramatic lowering of groundwater levels occurred in temporal synchroneity with these warming events, which removed a significant load over a preexisting fault structure in a short amount of time. We estimate that the minimum and maximum amounts of groundwater drawdown during the warming of D-O event 2 were 10 and 33 m, respectively, which means that the mass released was 7.11 × 10^{12} to 2.35 × 10^{13} kg, equivalent to removal of a ~5–16-m-deep water body across the entire Las Vegas Valley (Fig. DR7). We hypothesize that this triggered movement on the Eglington fault through unloading of vertical stress, akin to induced seismicity related to the removal of glacial ice or pluvial lakes elsewhere in the Great Basin.

Was the vertical load released by the rapid drop in water-table levels during D-O event 2 enough to unclamp the Eglington fault? What are the hydrogeologic parameters that would allow this to occur in the Las Vegas Valley? If the removal of the water mass is the only consideration, then a reduction in pore-fluid pressure would more than counter the effects of the diminished normal stress and the fault would not slip. In the Las Vegas Valley, however, there is a confining layer between the near-surface aquifer and the Eglington fault (Maxey and Jameson, 1948; Plume, 1989), so the pore pressure on the fault remained constant, regardless of variations in surface hydrology. With that established, we evaluated Coulomb stress changes over a wide range of dip angles (40°–70°), coefficient of friction values (0.1–0.7), and water-table drop estimates (10–33 m). The results show that the sudden vertical load change caused by groundwater withdrawal promotes Coulomb failure on the Eglington fault for all dip angles when coefficient of friction values exceed 0.55. When coefficient of friction values are between 0.45 and 0.55, the results are variable and are dependent on the dip angle. Displacement is inhibited for all dip angles when coefficient of friction values are less than 0.45 (Fig. 4; Table DR8 in the Data Repository).

All of the available evidence, including the climatic and hydrologic history of the Las Vegas Valley recorded in the Las Vegas Formation sequence, suggests that climatically modulated tectonics is responsible for the most recent displacement on the Eglington fault. Geologic evidence constrains the timing of displacement to between 27.0 and 19.5 ka, but it likely occurred

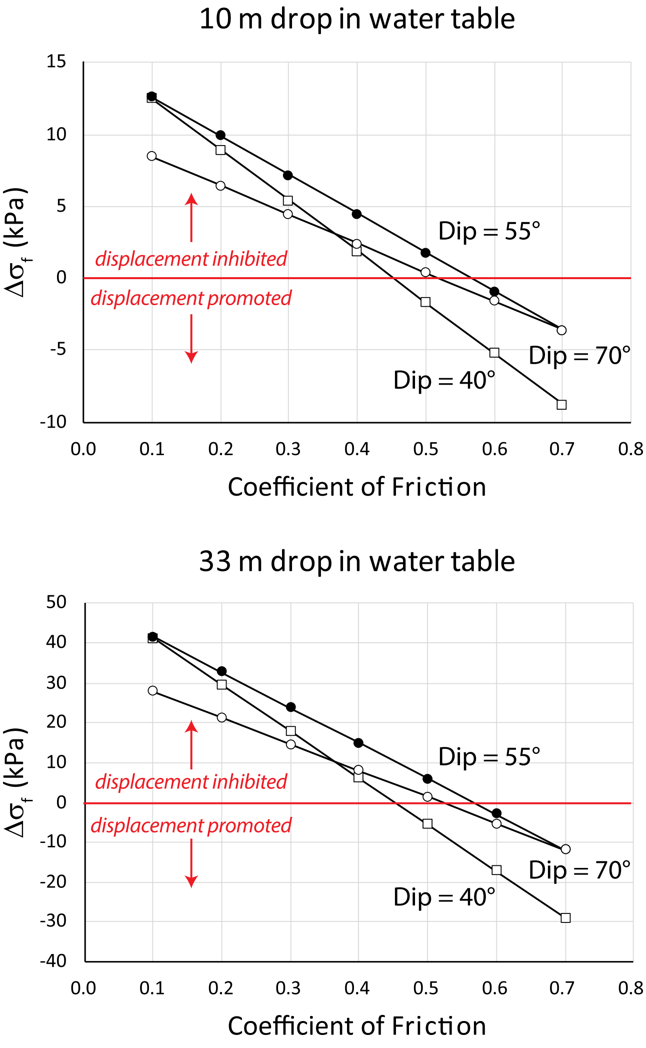

Figure 4. Summary of Coulomb stress changes ($\Delta\sigma_f$) for the Eglington fault (Nevada, USA) over a wide range of dip angles (40°–70°), coefficient of friction values (0.1–0.7), and water-table drop estimates (10 m, upper panel; 33 m, lower panel). Changes in Coulomb stress fields were sufficient in both magnitude and direction to promote displacement for all dip angles when coefficient of friction values exceed 0.55.

coincident with a substantial and irreversible drop in groundwater levels in a relatively narrow window of time during and after the abrupt warming of D-O event 2, between 23.3 and 19.5 ka, in one or more earthquake events. Coulomb stress-change calculations support the hypothesis that this sudden release of the groundwater load activated the fault, causing it to slip and deform the deposits of the Las Vegas Formation by as much as ~4.2 m vertically. There is no evidence of displacement on the Eglington fault subsequent to 19.5 ka. With respect to the future seismic potential of the Eglington fault, the data and observations presented here should be incorporated in updates of the USGS national seismic hazard model for the Las Vegas Valley.

ACKNOWLEDGMENTS

We thank the U.S. National Park Service staff of Tule Springs Fossil Beds National Monument for facilitating our work under permit TUSK-2015-2019 SCI-001 (K.B. Springer, Principal Investigator). We thank Dan Muhs, Rich Briggs, Ryan Gold, Will Levandowski, Seth Dee, Janet Slate, and an anonymous reviewer for providing constructive reviews of this manuscript. We also thank Randy Schumann, Paco van Sistine, and Jeremy Havens for assistance with the figures. This project was funded in part by the U.S. Geological Survey Climate and Land Use Change Research and Development Program through the Paleohydrology of Desert Wetlands project. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES CITED

Amelung, F., Galloway, D.L., Bell, J.W., Zebker, H.A., and Laczniak, R.J., 1999, Sensing the ups and down of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation: Geology, v. 27, p. 483–486, https://doi.org/10.1130/0091-7613(1999)027<0483:STUADO>2.3.CO;2.

Andersen, K.K., et al., 2006, The Greenland Ice Core Chronology 2005, 15–42 ka. Part 1: Constructing the time scale: Quaternary Science Reviews, v. 25, p. 3246–3257, https://doi.org/10.1016/j.quascirev.2006.08.002.

Bell, J.W., 1981, Subsidence in Las Vegas Valley: Nevada Bureau of Mines and Geology Bulletin 95, 84 p.

Haller, K.M., Moschetti, M.P., Mueller, C.S., Rezaeian, S., Petersen, M.D., and Zeng, Y., 2015, Seismic hazard in the Intermountain West: Earthquake Spectra, v. 31, p. S149–S176, https://doi.org/10.1193/103114EQS173 M.

Hampel, A., and Hetzel, R., 2006, Response of normal faults to glacial-interglacial fluctuations of ice and water masses on Earth's surface: Journal of Geophysical Research, v. 111, B06406, https://doi.org/10.1029/2005JB004124.

Hampel, A., Hetzel, R., and Densmore, A.L., 2007, Postglacial slip rate increase on the Teton normal fault, northern Basin and Range Province, caused by melting of the Yellowstone ice cap and deglaciation of the Teton Range?: Geology, v. 35, p. 1107–1110, https://doi.org/10.1130/G24093A.1.

Harrill, J.R., 1976, Pumping and ground-water storage depletion in Las Vegas Valley, Nevada, 1955–1974: Nevada Department of Conservation and Natural Resources Water Resources Bulletin 44, 70 p.

Haynes, C.V., Jr., 1967, Quaternary geology of the Tule Springs area, Clark County, Nevada, *in* Wormington, H.M., and Ellis, D., eds., Pleistocene Studies in Southern Nevada: Nevada State Museum of Anthropological Paper 13, p. 1–104.

Hetzel, R., and Hampel, A., 2005, Slip rate variations on normal faults during glacial-interglacial changes in surface loads: Nature, v. 435, p. 81–84, https://doi.org/10.1038/nature03562.

Lagerbäck, R., and Sundh, M., 2008, Early Holocene faulting and paleoseismicity in northern Sweden: Geological Survey of Sweden Research Paper C-836, 80 p.

Langenheim, V.E., Grow, J., Miller, J.J., Davidson, J.D., and Robison, E., 1998, Thickness of Cenozoic deposits and location and geometry of the Las Vegas Valley shear zone, Nevada, based on gravity, seismic reflection, and aeromagnetic data: U.S. Geological Survey Open-File Report 98-576, 32 p., https://doi.org/10.3133/ofr98576.

Langenheim, V.E., Grow, J.A., Jachens, R.C., Dixon, G.L., and Miller, J.J., 2001, Geophysical constraints on the location and geometry of the Las Vegas shear zone, Nevada: Tectonics, v. 20, p. 189–209, https://doi.org/10.1029/1999TC001159.

Langenheim, V.E., Blakely, R.J., Page, W.R., Lundstrom, S.C., Dixon, G.L., and Jachens, R.C., 2005, Geophysical framework of the Las Vegas 30′ × 60′ quadrangle, *in* Page, W.R., et al., Geologic and geophysical maps of the Las Vegas 30′ × 60′ quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, p. 45–55.

Maxey, G.B., and Jameson, C.H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Spring Valleys, Clark and Nye Counties, Nevada: State of Nevada Office of the State Engineer Water Resources Bulletin 5, 121 p.

Mifflin, M.D., 1998, Observations on the origin of Las Vegas Valley compaction scarps, *in* dePolo, C.M., ed., Proceedings of a conference on seismic hazards in the Las Vegas region: Nevada Bureau of Mines and Geology Open-File Report 98-6, p. 1–44.

Page, W.R., et al., 2005, Geologic and geophysical maps of the Las Vegas 30′ × 60′ quadrangle, Clark and Nye Counties, Nevada, and Inyo County, California: U.S. Geological Survey Scientific Investigations Map 2814, scale 1:100,000, https://doi.org/10.3133/sim2814.

Petersen, M.D., Zeng, Y., Haller, K.M., McCaffrey, R., Hammond, W.H., Bird, P., Moschetti, M., Shen, Z., Bormann, J., and Thatcher, W., 2014, Geodesy- and geology-based slip-rate models for the western United States (excluding California) national seismic hazard maps: U.S. Geological Survey Open-File Report 2013-1293, 80 p., https://doi.org/10.3133/ofr20131293.

Plume, R.W., 1989, Ground-water conditions in Las Vegas Valley, Clark County, Nevada: Part 1, Hydrogeologic framework: U.S. Geological Survey Water-Supply Paper 2320-A, 15 p., https://doi.org/10.3133/wsp2320A.

Quade, J., 1986, Late Quaternary environmental changes in the upper Las Vegas Valley, Nevada: Quaternary Research, v. 26, p. 340–357, https://doi.org/10.1016/0033-5894(86)90094-3.

Ramelli, A.R., Page, W.R., Manker, C.R., and Springer, K.B., 2011, Geologic map of the Gass Peak SW quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 175, scale 1:24,000.

Slemmons, D.B., 1998, Seismotectonic setting for the Las Vegas basin, *in* dePolo, C.M., ed., Seismic hazards in the Las Vegas region: Nevada Bureau of Mines and Geology Open-File Report 98-6, p. 70.

Springer, K.B., Manker, C.R., and Pigati, J.S., 2015, Dynamic response of desert wetlands to abrupt climate change: Proceedings of the National Academy of Sciences of the United States of America, v. 112, p. 14,522–14,526, https://doi.org/10.1073/pnas.1513352112.

Springer, K.B., Pigati, J.S., Manker, C.R., and Mahan, S.A., 2018, The Las Vegas Formation: U.S. Geological Survey Professional Paper 1839, 62 p., https://doi.org/10.3133/pp1839.

Printed in USA