Geochemical Evolution of Eocene Lakes in the Nevada Hinterland of the North American Cordillera

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Abstract Eocene strata of the Elko Formation record lacustrine deposition within the Nevada hinterland of the North American Cordillera. We present a detailed geochemical stratigraphy enabled by high-sampling-resolution geochronology from lacustrine limestone and interbedded volcanic rocks of the Elko Formation. Two intervals of lacustrine deposition, an early Eocene “Lake Adobe” of limited aerial extent and a laterally extensive middle Eocene “Lake Elko,” are separated by ~5 m.y. of apparent unconformity. Sediments deposited in the apparently short-lived (49.5–48.5 Ma) early Eocene Lake Adobe exhibit high-amplitude covariation of δ18O, δ13C and 87Sr/86Sr, which suggests a dynamically changing catchment and precipitation regime. Lake Elko formed during the middle Eocene, and its strata record three geochemically distinct phases, indicating it was a single interconnected water body that became increasingly evaporative over time. The lower Elko Formation (44.0–42.5 Ma) was deposited in a freshwater lake. Middle Elko Formation (42.5–41.2 Ma) lithofacies and geochemistry suggest that an increasingly saline and alkaline Lake Elko experienced salinity stratification-induced hypolimnion disoxia and burial of 12C-rich organic matter. The upper Elko Formation (41.2–40.5 Ma) records a shallow final phase of Lake Elko that experienced short residence times and a breakdown in stratification. A sharp decline of 87Sr/86Sr in the upper Elko Formation reflects an increasing aerial extent of low, 87Sr/86Sr volcanic deposits from nearby calderas. Middle Eocene strata record ponding of paleodrainage, increasing hydrologic isolation and volcanism, consistent with progressive north to south removal of the Farallon flat slab and/or delamination of the lower lithospheric mantle of the North American plate.

Plain Language Summary Large lakes formed in the region that is now northeast Nevada between 50 and 40 million years ago. This region was at high elevation and undergoing a transition from compressional to extensional plate tectonic forces at that time. The geologic record shows that lakes formation started locally at 49.5 million years ago with a short-lived freshwater Lake Adobe. Later, approximately 43.5 million years ago, a broad Lake Elko formed and then became increasingly evaporative over the next 3 million years, likely due to removal of the shallowly subducting Farallon slab from beneath the region.

1. Introduction
Lacustrine basins can collect highly detailed accounts of geochemical and sedimentologic variation resulting from tectonic and climatic forcing in orogenic landscapes, which are otherwise prone to erosion and non-deposition (e.g., Benson & Peterman, 1995; Carroll & Bohacs, 1999; Cohen, 2003; Doebbert et al., 2014). As a lake basin evolves, changes in accommodation, hydrology, and climate drive variability in lake water geochemistry and the distribution of sedimentary lithofacies (e.g., Bohacs et al., 2000; Carroll et al., 2008; Cohen et al., 2015; Grove et al., 2003; Smith et al., 2008). Obtaining continuous records from lake basins in orogenic settings is often difficult due to subsequent structural deformation (e.g., Benvenuti et al., 2014; Haynes, 2003; Leier et al., 2010; Potter et al., 1995; Umhoefer et al., 2010). The resultant overprinting complicates the interpretation of paleoclimate and paleoecology records from these settings, particularly since these records are also affected by processes intrinsic to lakes and their catchments, that is: upstream drainage capture; lake level dropping below an outlet; or shifting carbonate formation from lake to soil environments (e.g., Graf et al., 2015; Hart et al., 2004; Smith et al., 2017). The North American Cordillera constitutes one of Earth’s major orogens. The orogen formed due to a variety of tectonic events and processes over approximately 200 m.y., most prominently the subduction of...
the Farallon plate beneath the North American plate (Burchfiel & Davis, 1975; DeCelles, 2004; Yonkee & Weil, 2015). During the Cordilleran's closing phase, a series of enigmatic terrestrial basins formed within its hinterland, between the Sierra Nevada volcanic arc and the Sevier fold and thrust belt, and isolated exposures of the resulting strata occur from southern Canada to southern Nevada (Figure 1; Drushke et al., 2011; Janecke, 1994; Smith et al., 2017). These strata have been variously interpreted to reflect early extensional graben or half-graben development that preceded or accompanied the formation of metamorphic core complexes (Haynes, 2003; Janecke et al., 1999; Rahl et al., 2002), damming of paleovalleys by landslides or magmatism (Henry et al., 2012), the effects of broad wavelength drainage reversal due to dynamic and/or thermal effects of shallow slab removal (Cassel et al., 2018; Smith et al., 2014), and/or the formation and removal of a Rayleigh-Taylor instability from the base of the lithosphere (Smith et al., 2017). To better differentiate between proposed lake-forming mechanisms, their relationship to the later stage of development and collapse of the North American Cordillera, and the influence of the waning Eocene hothouse climate, we compare multi-proxy geochemical data from lacustrine strata of the early and middle Eocene-age Elko Formation of northeastern Nevada.

2. Geologic Setting

The Elko Formation contains a wide variety of predominantly lacustrine lithofacies that accumulated at elevations of ~2.8 km during the Eocene epoch in what is now northeast Nevada (Figure 2; Cassel et al., 2018; Smith & Ketner, 1976; Smith et al., 2017). At this time, atmospheric CO$_2$ levels were high (pCO$_2$ > 800 ppmv) and glacial ice was largely absent from high latitudes (Sluijs et al., 2013; Zachos et al., 2001). Fossil leaf and pollen floras of the Elko Formation suggest a warm-temperate local climate that was cooler and drier than the foreland province to the east due to elevation (Axelrod, 1997; Cassel et al., 2014, 2018; Wingate, 1983). Eocene strata of northeast Nevada are composed of a broad array of terrestrial lithofacies, ranging from traction-structured cobble conglomerate to laminated lacustrine marl. They occur unconformably above folded Mississippian strata of the Diamond Peak Formation and Chainman Shale (Ketner & Alpha, 1992; Madrid, 1987; Server & Solomon, 1983), and are overlain by late Eocene through Oligocene ignimbrites and volcaniclastic strata (Henry, 2008; Lund Snee et al., 2016; Smith & Ketner, 1976).

The oldest preserved Cenozoic lacustrine rocks in the region are early Eocene strata exposed in the Adobe Range, where fluvial sandstone and conglomerate are overlain by finely bedded micritic limestone containing freshwater molluscs and abundant plant matter. These limestones are overlain by organic-rich, finely laminated mudstone containing stromatolitic carbonate and fish fossils (Figure 3; Abruzzese et al., 2005; Moore et al., 1983; Smith & Ketner, 1976; Smith et al., 2017). Lacustrine strata younger than the Adobe Range succession and older than ca. 44 Ma are poorly preserved in the region. After 44 Ma, the main body of the Elko Formation occurs regionally (Figure 4). Its lowermost 30–40 m consists of mollusc-rich, microbially-rich freshwater-deposited limestone interbedded with carbonaceous mudstone, and informally named the "cherty limestone" by Smith and Ketner (1976). This carbonate interval is overlain and interfingers laterally with 5–50 m of predominantly siliciclastic mudstone, some carbonaceous, with interbedded tuffs, sandstone beds, and thin intervals of mollusc-bearing microbiallyitic limestone. We include the carbonate ("cherty limestone") and mudstone lithofacies with the lower Elko Formation (Figure 4). Overlying these strata are 100–150 m of laminated kerogen-rich marlstone and carbonate and interbedded tuff of the middle and upper Elko Formation, which contain an increasing proportion of stromatolitic carbonate and mudcracks up section (Figure 4; Moore et al., 1983; Smith & Ketner, 1976; Smith et al., 2017; Solomon et al., 1979). These strata are interbedded with numerous volcanic tuffs and ignimbrites ranging from 1 mm to over 50 m thick. Tuffs and ignimbrites become thicker and more abundant both up section and proximal to a series of caldera complexes, recording the approach and arrival of magmatism to the region (Figures 2 and 4) (Cassel et al., 2018; Haynes, 2003; Henry et al., 2011, 2012; Smith et al., 2017). The end of lacustrine accumulation corresponds to emplacement of several felsic plutons and the eruption of thick ignimbrites from a series of calderas between 41 and 38 Ma (Figure 1) (Cassel et al., 2014; Henry et al., 2011, 2012; Lund Snee et al., 2016).

The Elko Formation has not to date produced mammalian fossils that could be used to correlate to the North American land mammal ages (Robinson et al., 2004). Fossil gastropods, ostracods, fish, and amphibians (Henrici & Haynes, 2006; Nutt & Good, 1998; Solomon et al., 1979; Swain, 1964), and palynology
Figure 1. Simplified geologic map of northeastern Nevada showing stratigraphic section and sample locations. Distribution of map units from Camilleri and Chamberlain (1997), Lund Snee et al. (2016), and Stewart and Carlson (1981); Eocene caldera locations from Henry et al. (2011). Strontium ratios are compiled from Benson and Peterman (1995), Brand et al. (2012), Farmer and DePaolo (1983), Gans et al. (1989), Kistler and Lee (1989), Kistler et al. (1981), and Wright and Snoke (1993). Strontium isotope ratios for stream water from Benson and Peterman (1995). Inset map: Overview of Idaho Batholith, Challis volcanic field, and Paleozoic and Mesozoic thrust belts in eastern Nevada modified from DeCelles and Graham (2015), Konstantinou et al. (2013), and Long (2012). Location abbreviations: BR—Bull Run Basin, CR—Cortez Range, CM—Coal Mine Canyon, DH—Dixie Hills, EH—Elko Hills, EOS3N—Noble Energy EOS3N core hole, K1L—Noble Energy K1L well, PC—Pie Creek, PR—Piñon Range, RM—Robinson Mountain, TB—Twin Bridges, TC—Taylor Canyon.
(Wingate, 1983) are broadly indicative of an Eocene age for deposition for the Elko Formation, but are not useful for high-resolution geochronology. Recent geochronology for the Elko Formation and related strata has significantly increased in resolution, and includes single crystal sanidine $^{40}$Ar/$^{39}$Ar dates (Henry et al., 2011; Smith et al., 2017), biotite incremental heating dates (Mulch et al., 2015), and U-Pb ages for zircon (Canada et al., 2020; Lund Snee et al., 2016). These results collectively show that lakes occurred first during a short early Eocene (Bridgerian) Lake Adobe phase, appear absent from 48.5 to 43.5 Ma, then reformed during a longer-duration middle Eocene (Duchesnean) Lake Elko phase (Figure 2). Several tuffs are...
identifiable within multiple field areas and permit direct correlation from lacustrine to extra-lacustrine (flu-
ivial or upland) paleolocations. In particular, the Tuff of Nelson Creek was deposited across a >10,000 km2
area at 40.45 ± 0.25 Ma, and directly overlies Elko Formation lacustrine strata in multiple field areas, pro-
viding a useful datum (Figures 2 and 4; Henry et al., 2011; Smith et al., 2017). Detrital zircon U-Pb geochro-

![Figure 3. Coal Mine Canyon section (Adobe Range) showing lithofacies and geochemistry. Fisher Assay oil yield data are taken from Moore et al. (1983). Gamma ray derived potassium values likely reflect the relative proportion of volcaniclastic detritus in marls, either due to increased fluvial input or due to stratal condensation. Symbology for lithologic characteristics inside the stratigraphic column follows USGS format. Modal grain size symbols: m, mud; 
vf, very fine sand; f, fine sand; c, coarse sand; vc, very coarse sand; p, pebble; c, cobble. Geochronology from Smith et al. (2017) and Canada et al. (2020).]
3. Materials and Methods

3.1. Stratigraphy and Sampling

Stratigraphic sections were measured at decimeter-scale at locations across the Elko Basin (Figure 1; cf., Canada, 2019) and were correlated using distinctive lithofacies, volcanic horizons, handheld and borehole gamma ray logs, and legacy Fischer Assay oil yield data (Moore et al., 1983). Carbonate and tuff samples were collected for geochemical analysis from several stratigraphic sections and cores (Figures 3 and 4; Table S1 and Figures S1 and S2 in Supporting Information S1). Samples of carbonate were collected from trenches dug to expose minimally weathered and altered material. We targeted micritic carbonates and marls for analysis due to their greater apparent resistance to alteration (Doebbert et al., 2014; Rhodes et al., 2002). These data add to the isotope values reported by Mulch et al. (2015) from the Piñon Range and lowermost Indian Wells sections (Figures 2 and 4). Samples of volcanic ash interbedded with lacustrine strata were
also collected from select areas that preserve volcanic glass for stable isotopic analysis. Much of the original volcanic glass within lacustrine-deposited ash beds has been altered to zeolite or clay minerals (cf., Cassel & Breecker, 2017; Smith et al., 2017), however, several sampled ash beds preserve unaltered volcanic glass (Figure 4; Table S2 in Supporting Information S1).

Water samples were collected from modern rivers draining a variety of bedrock (pre-Elko Formation) catchment lithologies to better interpret the Sr isotope geochemistry of Elko Formation carbonates (Figure 1; Table S3 in Supporting Information S1). Neogene basin segmentation and late Eocene–Miocene deposition of up to 5 km of volcanic and volcaniclastic strata above the Elko Formation (Camilleri et al., Table S1 in Supporting Information S1) complicates the sampling of potential Eocene source regions surrounding the Elko Basin. Consequently, we sampled modern drainages with specific pre-Eocene catchment lithologies, and combined this data with existing geochemical data for rivers, streams, and wells in the study area (Figure 1; Table S3 in Supporting Information S1). Water samples were passed through 0.45 μm filters, collected in acid-cleaned HDPE (High Density Polyethylene) bottles, and immediately acidified to a pH of 2 with concentrated nitric acid during collection.

3.2. Sample Separation and Petrology

Thin sections were prepared from samples collected at regular stratigraphic intervals within sections sampled for isotopic analysis to identify authigenic calcite and carbonate textures and avoid zones of recrystallization and overgrowth that suggest diagenetic alteration. 10–50 g of carbonate material that were not associated with visible diagenetic alteration were crushed in a porcelain mortar and wet-sieved to a <70 μm fraction using deionized water purified to 18.2 MΩ at the University of Idaho. Carbonate powder was separated from select samples (n = 14) using a New Wave Research Micromill equipped with a 787 μm diameter carbide drill bit. Finely laminated micritic samples or samples that contain zones of alteration were carefully milled to avoid sampling of diagenetic material and organic matter. Following carbonate powder separation, aliquots were separated for X-ray diffraction and isotopic analysis.

To evaluate the effect of mineralogical variation on 87Sr/86Sr, δ18O, and δ13C ratios, X-ray diffraction (XRD) was conducted on all sample separates at the University of Idaho using an X-ray diffractometer with a Cu Kα X-ray source (λ = 1.5418 Å). Samples were scanned between 20° and 55° 2-θ at a step size of 0.02° and a step time of 1–2 s to obtain a strong count intensity and to measure all significant calcite and dolomite peaks, and the dominant peaks for calcite and dolomite calibrated against a set of standard mixtures of calcite and dolomite. Select samples that are representative of a range of mineralogies were scanned across a wider 2–70° 2-θ range to test for the presence of other minerals. To approximate the proportions of calcite and dolomite, the sum of the relative areas of the calcite peaks (peaks between 29.30° and 30.00° 2-θ) and dolomite peaks (peaks between 30.40° and 31.10° 2-θ) were compared against one another following background subtraction. We did not detect any evidence for the presence of aragonite in XRD. The percentage of quartz phases in the samples was estimated by summing the software-estimated proportion of quartz peaks using deionized water purified to 18.2 MΩ at the University of Idaho. Carbonate powder was separated from select samples (n = 14) using a New Wave Research Micromill equipped with a 787 μm diam-eter carbide drill bit. Finely laminated micritic samples or samples that contain zones of alteration were carefully milled to avoid sampling of diagenetic material and organic matter. Following carbonate powder separation, aliquots were separated for X-ray diffraction and isotopic analysis.

3.3. Strontium Concentration and Isotopes

Strontium isotopes (87Sr/86Sr) can be used to trace the paleohydrology and catchment bedrock geology of lakes (e.g., Baddouh et al., 2016; Benson & Peterman, 1995; Talbot et al., 2000). Strontium has a short residence time (~10^4–10^6 years) in lacustrine systems, is not influenced by evaporation, and can be retained over geologic time in lacustrine carbonates with extremely high resolution, on the order of ~10^3 years (Doe-bbert et al., 2014). Strontium variability in lakes is primarily a function of the age and Sr concentration of bedrock within its catchment, with older bedrock generally having a higher proportion of 87Sr to 86Sr due to the decay of 87Rb to 87Sr over geologic time (Bataille & Bowen, 2012; Blum et al., 1998; Grove et al., 2003; Palmer & Edmond, 1992; Rhodes et al., 2002).

Lacustrine carbonates and modern stream waters were analyzed for Sr concentration and isotopic composition. Laboratory methods for dissolution, leaching, extraction, and purification for strontium isotopic
analysis of carbonates were modified from those outlined in Doebbert (2006) and Doebbert et al. (2014; see Supporting Information S1 for detailed description of methodology). Since many carbonate-rich samples contain variable amounts of clastic silica with high Rb/Sr and sometimes highly radiogenic Sr ratios, bulk 50–100 mg carbonate samples were first leached with 1M ammonium acetate to remove labile Rb and Sr from clay material prior to carbonate extraction with 1M acetic acid. Following separation, insoluble residues were discarded and ~10 mg aliquots were collected. This was followed by Sr separation through ion exchange chromatography using Sr-spec resin and cation exchange resin. Sample aliquots consisting of ~500 ng of Sr were then placed on Re filaments with TaO, activator and analyzed using an Isotopix Phoenix thermal ionization mass spectrometer (TIMS) at the University of Idaho. Mass analysis of Sr was conducted using a three-jump multi-collector analysis routine. Calculated $^{87}$Sr/$^{86}$Sr ratios are the average of ~150 ratios and all TIMS analyses have an analytical error (2σ) between 0.00004 and 0.00006.

3.4. Stable Isotopes of Carbonates

The stable isotope ratios of $^{18}$O/$^{16}$O and D/H ($^{18}$O and $^\delta$D) are useful for documenting ancient hydrologic change from lacustrine carbonates because O and H isotopes in water fractionate during condensation and evaporation (Dansgaard, 1964). $^{18}$O and $^\delta$D values of lake waters will reflect the composition of source waters, which are dependent on regional topography and atmospheric patterns, and on the relative amounts of input and evaporation (Carroll et al., 2008; Ezquerro et al., 2014; Rowley et al., 2001; Stuiver, 1970). Carbon isotopes ($^\delta^{13}$C) are also readily extracted from lacustrine carbonate, and provide a measure of organic productivity and preservation, but can also fractionate in response to evaporation, particularly in hyper-saline settings (Chamberlain et al., 2013; Gross & Tracey, 1966; Horton & Chamberlain, 2006).

Stable isotopic analyses of $^\delta^{13}$C and $^\delta^{18}$O values were completed at the University of Texas at Austin Isotope Geochemistry Laboratory and the Washington State University GeoAnalytical Laboratory following the methods of McCrea (1950) and Swart et al. (1991). Separates consisting of 20–60 μg of carbonate powder were loaded in vials and roasted in vacuo at 200°C for one hour to release volatile compounds. Samples and standards were then reacted under vacuum with 0.1 ml of 100% phosphoric acid ($\rho = 1.8913$ g/cm$^3$) at 75°C (e.g., Al-Aasam et al., 1990). Headspace sampling of released CO$_2$ was performed using a Finnigan Gas-Bench and CO$_2$ was transferred to a MAT253 Isotope Ratio Mass Spectrometer (IRMS) instrument eight times versus a calibrated CO$_2$ reference tank. Analyses were rejected if a >10% difference in voltage of the mass 44 beam was detected between the sample and reference gas, if the mass 44 signal of the sample was <600 mV, if the standard deviation of the 1-sigma ratios of a sample exceeds 0.07‰, or if a high leak rate (>400 mbar/minute) was detected prior to analysis (e.g., Talbot, 1990). No correction is applied for variable acid fractionation between calcite and dolomite, which may cause measured $^\delta^{18}$O values in samples containing dolomite to be as much as 0.8‰ higher (Sharma & Clayton, 1965). Precision of all analyses is ±0.2‰ for $^\delta^{13}$C and ±0.3‰ $^\delta^{18}$O (1σ standard error) based on repeated analysis of interlaboratory and internal standards.

3.5. Volcanic Glass Hydrogen Isotopes

Volcanic glass was collected and separated from Eocene ash beds using the procedures of Cassel and Breecker (2017). Of all tuff and ash bed samples collected within the Elko Basin, only ~15% preserve unaltered volcanic glass suitable for isotopic analysis. This poor preservation is likely a product of increased dissolution of Si-O bonds within alkaline lacustrine waters (Cassel & Breecker, 2017; Pollard et al., 2003). Preserved volcanic glass was separated via crushing, wet-separation sieving, hydrochloric and hydrofluoric acid abrasion, magnetic separation, lithium metatungstate density separation, and deionized water ultrasonication. Separates (3–5 mg/ aliquot, 3–6 aliquots/sample) consisting of >98% glass shards were then loaded in 3 × 5 mm Ag capsules. The samples were dried in a vacuum oven for 24 hr prior to analysis to remove any physically adsorbed water. Samples were immediately loaded into a zero-blank autosampler and flushed with UHP He carrier gas, then run on a thermal conversion/elemental analyzer (TC/EA), coupled to a Thermo MAT 253 isotope ratio mass spectrometer operated in continuous-flow mode at the University of Texas at Austin Isotope Geochemistry Laboratory. Four international reference standards and an in-house volcanic glass standard were dispersed at regular intervals and exhibited reproducibility. The NBS22, IAEA-CH7, and
IAEA-C3 standards were used to normalize measured values to the standard mean ocean water (SMOW) scale. Ground NBS-30 biotite with a known concentration of water (3.5 wt.%) was used to calculate water concentrations based on sample masses and peak areas. Grinding of the NBS-30 is necessary to ensure conversion to molecular hydrogen (Qi et al., 2014). The values reported here add to a growing suite of 5D<sub>glass</sub> values from Paleogene and Neogene strata across the Cordillera (Table S2 in Supporting Information S1; Cassel et al., 2014, 2018; Smith et al., 2017).

4. Results

4.1. Strontium Isotope Geochemistry of Bedrock and Modern Rivers

Northeast Nevada is underlain by a variety of bedrock units which span the Proterozoic through Cenozoic (Figure 1). During the Eocene, prior to Miocene development of the horst and grabens that characterize the Basin and Range physiographic province, clasts within Elko Formation-equivalent conglomerates suggest that Paleozoic carbonate and siliciclastic strata of the Cordilleran “Miogeocline” were the most aerially extensive in the basin's catchment. These strata have 87Sr/86Sr ratios of 0.7077–0.7110 that reflect Paleozoic seawater, and feature a large range of Sr concentrations, from 10 to 1,380 ppm (Figure 5). 87Sr/86Sr ratios of Mesozoic intrusive rocks and Cenozoic volcanics exposed proximal to the Elko Basin have similar values to Paleozoic strata: 0.7055–0.7120, and high Sr concentrations of 400–900 ppm (Figures 1 and 5; Wright & Snoke, 1993). The R-EH-W-P core complex which bisects the Elko Basin exposes upper-amphibolite-facies metamorphic rocks and associated Mesozoic intrusive rocks with much higher 87Sr/86Sr ratios: 0.7125 and 0.7615, but these rocks have relatively low Sr concentrations of 10–300 ppm (Figure 5; Lee et al., 2003; Wright & Snoke, 1993).

Modern water samples collected from 6 rivers draining a variety of bedrock source lithologies have Sr concentrations between 0.014 and 0.022 ppm (Table S3 in Supporting Information S1). Rivers draining the Ruby Mountains-East Humboldt Range metamorphic core complex have significantly elevated 87Sr/86Sr (mean = 0.7120) in comparison to rivers draining Paleozoic sedimentary bedrock (mean = 0.7079). Paleozoic carbonate and siliciclastic strata have low 87Sr/86Sr ratios of 0.707–0.709 and higher Sr concentrations (Brand, 2004; Brand et al., 2012; Edwards et al., 2015; Pasco et al., 2007) than the igneous and metamorphic rocks in the Ruby Mountains-East Humboldt Range (Kistler et al., 1981; Wright & Snoke, 1993). Rivers with higher Sr concentrations have lower 87Sr/86Sr ratios than rivers with low Sr concentrations, reflecting the high Sr content of carbonate strata (cf., Figures 1 and 5). Eocene volcanic rocks in northeastern Nevada also have relatively low 87Sr/86Sr ratios (Figures 1 and 5; mean = 0.7069; Gans et al., 1989; Stevens, 2013; Wright & Wooden, 1991). Jurassic and Cretaceous backarc plutons in Nevada and Utah have variable 87Sr/86Sr ratios (Farmer & DePaolo, 1983; Kistler & Lee, 1989), but the highest 87Sr/86Sr ratios in these plutons significantly exceed all Paleozoic rocks in the region.

4.2. Lacustrine Carbonate Isotope Geochemistry

Samples collected across the stratigraphic range of the Elko Formation have 87Sr/86Sr ratios that range from 0.7076 to 0.7108, with a mean of 0.7086 (Table S4 in Supporting Information S1; Figures 3 and 4). All carbonate and water samples have low 87Rb/86Sr ratios (<0.001), indicating a lack of silicate contamination of Sr separates following sample leaching and dissolution. Samples from early Eocene strata deposited by Lake Adobe have higher 87Sr/86Sr ratios (mean = 0.7090, σ = 0.0009) and greater 87Sr/86Sr variation (Figure 3) than middle Eocene strata deposited in Lake Elko (mean = 0.7085, σ = 0.0006). Lake Elko strata exhibit less var...
ation and record a basin-wide 0.001–0.002 decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ between 43.4 and 40.7 Ma (Figure 4).

Elko Formation carbonate samples from both the Lake Adobe and Lake Elko successions exhibit a wide variation between calcitic and dolomitic mineralogy and $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Table S1 in Supporting Information S1). Dolomitic samples have average $\delta^{13}\text{C}$ values 1.5‰ higher and $\delta^{18}\text{O}$ values 6‰ higher than the mean of all samples with calcitic mineralogy (Figures 6 and 8). A similar trend is also observed in Green River Formation lacustrine strata, where values for dolomitic samples are 3‰ higher than calcite samples (i.e., Doebbert, 2006; Graf et al., 2015). This likely reflects enhanced fractionation by dolomite (Fritz & Smith, 1970), but could also result from dolomite being preferentially precipitated from lake water during more evaporative periods. The shift toward higher values for dolomite is significant, but is only approximately one half of the range of observed values (~10 ‰ for $\delta^{13}\text{C}$ values, ~20 ‰ for $\delta^{18}\text{O}$ values), suggesting that other processes were required to produce the observed isotopic record for Lake Adobe or Lake Elko. Within the Lake Elko succession, the lower Elko Formation has the lowest average $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, the middle Elko Formation has the highest $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, and the upper portion has intermediate average values (Figure 8 and Table S4 in Supporting Information S1).

4.3. Volcanic Glass Isotope Geochemistry

Volcanic glass separated from Eocene tuffs and ash beds in the field area show variation in $\delta D$ values ranging from −60‰ to −175‰, coincident with lithologic differences (Table S2 in Supporting Information S1). Ash beds intercalated with lacustrine intervals of the Elko Formation have $\delta D_{\text{glass}}$ values from −60‰ to −118‰ whereas samples intercalated with fluvial strata have $\delta D_{\text{glass}}$ values from −160‰ to −175‰ (Figure 7; Cassel & Breecker, 2017; Cassel et al., 2014; Smith et al., 2017). Low $\delta D_{\text{glass}}$ values of approximately −150 to −110‰ within the lower Elko Formation increase to −110‰ to −60‰ in the middle and upper Elko Formation (Figure 4).

5. Discussion

5.1. Isotopic Stratigraphy

Covariance in $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ occurs within several portions of the Elko Formation (Figure 6), particularly within intervals where increased solute concentrations are apparent from Sr concentration. Increased $\delta^{18}\text{O}$ values likely signify enhanced evaporation and increased residence time in the lake. Increasing evaporative concentration in the later phases of Lake Elko is also suggested by the $\delta D_{\text{glass}}$ values from the upper Elko Formation, which are ~60‰ higher on average than $\delta D_{\text{glass}}$ values from contemporaneous non-lacustrine ash beds (Figure 7; Table S2 in Supporting Information S1). Photosynthetic algae in lakes preferentially remove $^{12}\text{C}$ and enrich lake water in $^{13}\text{C}$ if they are buried prior to decomposition or becoming subject to methanogenesis (Bohacs, 1998; Kirby et al., 2002; Lettéron et al., 2018; Pitman, 1996). Higher $\delta^{13}\text{C}$ values for Lake Elko correspond well to kerogen-content based on Fisher Assay (Figure 4), are consistent an organic burial mechanism for the observed fractionation. Higher $\delta^{13}\text{C}$ values could also result in some cases from evaporation of $^{12}\text{C}$-rich CO$_2$ from the lake (Horton & Chamberlain, 2006).
5.2. Drainage Basin Evolution

Samples taken across the stratigraphic extent of the Elko Formation have generally low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.7076 and 0.7108 (analytical uncertainty = ±0.0002), with a mean value of 0.7086 ($\sigma = 0.0007$). These values have a similar range of variability to, but are significantly lower than, Green River Formation $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, which range from 0.712 to 0.715 (Carroll et al., 2008; Doebbert et al., 2010, 2014; Pietras, 2003). Green River Formation values are likely high due to drainage from the radiogenic Precambrian bedrock-cored uplifts of the Laramide broken foreland (Rhodes & Carroll, 2015; Smith et al., 2014). Strontium isotope values from both early and middle Eocene strata overlap those observed in local Paleozoic bedrock. Prior Eocene clast assemblages and detrital zircon geo- and thermo-chronology also reflect local Paleozoic sediment sources (e.g., Canada et al., 2020; Haynes, 2003; Smith & Ketner, 1976).

Overall, Elko Formation $^{87}\text{Sr}/^{86}\text{Sr}$ ratios indicate that the radiogenic-rich deep crustal rocks of the RM-EH MCC (Figure 5) had not been exhumed by middle Eocene time, consistent with the observation that metamorphic clasts first appear in the Miocene Humboldt Formation (Colgan et al., 2010). Elevated $^{87}\text{Sr}/^{86}\text{Sr}$ ratios observed over several thin intervals of the Elko Formation instead likely reflect exhumation of shallowly emplaced Cretaceous and Jurassic backarc plutonic rocks (Figure 5; Camillieri et al., 2017; Miller & Hoisch, 1995; Schmidt, 1992), as shown by the presence of Cretaceous- and Jurassic-age zircons in Eocene clastic strata (Canada et al., 2020). The basin-wide decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the upper Elko Formation likely reflects drainage from middle Eocene igneous rocks, which have significantly lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than Paleozoic strata or Mesozoic plutons in northeast Nevada.

5.3. Landscape and Paleolimnologic Evolution

The Elko Formation contains two intervals of lacustrine deposition with increasingly evaporative conditions, suggested by sedimentary lithofacies, isotope geochemistry, and Sr concentrations. Conditions were never sufficiently evaporative to accumulate bedded evaporites, which occurred in the foreland lakes to the east (Smith et al., 2008), but did result in elevated Sr concentrations and increased $\delta^{18}O$ values, and likely promoted salinity stratification that enhanced burial of $^{12}C$-rich organic matter. The geochemistry of middle Eocene Lake Elko abruptly shifted twice during its history, across the boundaries between the here-defined lower, middle, and upper Elko Formation (Figure 4). These boundaries record the systematic rearrangement of the hydrologic boundary conditions and are good candidates for xenocoformities sensu Carroll (2017). The following is a series of synoptic accounts of the changing Eocene landscape and lakes of northeast Nevada (Figure 9).

5.3.1. Paleogene Paleovalleys and Fluvial Strata

Outcrops of ca. 50–45 Ma traction-structured and laterally discontinuous conglomerate beds are exposed in the Adobe Range (Cassel et al., 2014), the Piñon Range (Hollingsworth et al., 2018), and the Elko Hills (Canada et al., 2020; Haynes, 2003), below lacustrine facies of the Elko Formation. Conglomerate strata are coarse, locally sourced, and moderately sorted, with clast imbrication and lenticular sandstone interbeds, suggesting deposition from gravel-bedded streams. Some paleostreams that traversed the area of the modern Elko Hills were competent enough to transport boulders (Haynes, 2003; Smith & Ketner, 1976). Aggradational bed sets indicate sustained high sediment flux, whereas the erosional bases and lenticular geometry of beds suggests turbulent and channelized flow dominated by bedload transport (Bridge, 1993; Cassel & Graham, 2011). Documented paleovalleys are generally oriented west to east, and appear to have drained eastward toward the foreland and west toward the Pacific Ocean from a divide located just west of the Elko Basin study area (Cassel et al., 2014, 2018; Henry et al., 2012).
5.3.2. Lake Adobe: 50–48.5 Ma

Lacustrine strata crop out at an isolated 180 meter-thick exposure in the Adobe Range at Coal Mine Canyon, and record an early phase of hinterland lacustrine deposition. These strata overlie fluvial lithofacies (Figure 3) which correspond to the ≥1 km deep “Central Paleovalley” of Henry (2008). These fluvial strata contain detrital zircon grains with ca. 52–49 Ma U-Pb ages, a grain age population consistent with sourcing from the Challis volcanic field to the north, suggesting either fluvial transport from the north or reworking of Challis ash fall deposits (Cassel et al., 2018; Canada et al., 2020). Lacustrine strata immediately overlying fluvial facies consist of plant and fish fossil-bearing carbonaceous and siliciclastic mudstone and marl with intercalated thin coal beds, suggesting deposition in a palustrine to open sublittoral freshwater setting with abundant plant-derived organic matter. Micritic carbonates from this interval have low δ¹³C and δ¹⁸O values and ⁸⁷Sr/⁸⁶Sr ratios (Figure 3). About 90 meters above the base of the exposure, lithofacies transition into more kerogen-rich laminated marlstone and stromatolitic kerogen-poor marlstone containing leaf and fish fossils. Values for δ¹³C, δ¹⁸O, and ⁸⁷Sr/⁸⁶Sr vary significantly in this ∼80 meter-thick upper interval. In particular, δ¹³C values briefly decrease to less than 10 per mil, the lowest observed values for the entire Elko Formation, before returning to “background” values. These values correspond to an increase in ⁸⁷Sr/⁸⁶Sr of ∼0.002 (Figure 3), which could suggest the brief integration of a new paleo-drainage or local exhumation of ⁸⁷Sr-rich bedrock by a surface-breaking fault in the catchment. The uppermost exposed strata at Coal Mine Canyon are composed of sandy pro-deltaic lithofacies and thin interbedded air-fall tuffs, one of which

![Figure 8.](image-url)
is dated at 48.7 ± 0.3 Ma based on sanidine $^{40}$Ar/$^{39}$Ar geochronology (Smith et al., 2017). The existence, aerial extent, and true duration of the overlying unconformity is difficult to assess due to the paucity of exposure and extensive regional faulting (Figure 1). A lake may have continued in the basin between 48.5 and 43.5 Ma, but outcrops of lacustrine strata from this time interval have yet to be identified in the region.
5.3.3. Lake Elko, Phase 1: 43.5–42.4 Ma

Following an apparent 5 m.y. depositional hiatus after Lake Adobe sedimentation, lacustrine deposition resumed during the middle Eocene across a broad area of what is now northeast Nevada. This lake system, referred to here as “Lake Elko,” deposited the bulk of the extant Elko Formation. Strata deposited in Lake Elko conformably overlie Eocene fluvial strata, or onlap an erosional surface cut into folded Paleozoic bedrock by paleodrainages (Henry et al., 2012). The lowermost 20–30 m of the Elko Formation consists of chert-rich micobioblastic limestone beds (the “cherty limestone” of Smith & Ketner, 1976) (Figures 2 and 4). Overlying the “cherty limestone” is a 5–50 meter-thick interval consisting predominantly of micritic mudstone, ostracodal and gastropodal limestone, and carbonaceous mudstone containing abundant plant material, suggesting sub-littoral to littoral deposition in a freshwater lake (Figure 4). These lithofacies are generally kerogen-poor based on Fisher Assay, and are interbedded with mudstone and sandstone containing root traces and incipient paleosol fabrics, suggesting the section locale experienced occasional subaerial exposure during lowstands. Carbonate sampled from both the “cherty limestone” and overlying mudstone intervals of the lower Elko Formation have low δ¹⁸O and δ¹³C values, consistent with freshwater deposition and oxygenated bottom waters (Figure 8; Graf et al., 2015). Freshwater conditions suggest that Lake Elko likely had an outlet during deposition of the lower Elko Formation (Figure 9).

5.3.4. Lake Elko, Phase 2: 42.4–41.3 Ma

The middle Elko Formation consists of deeper-water lithofacies that were deposited in an increasingly evaporative Lake Elko after ca. 42.4 Ma. This shift is recorded by elevated δ¹⁸O and δ¹³C values, Sr concentrations, δD glass values, and kerogen content (Figure 4; Table S2 in Supporting Information S1). Lithofacies of the middle Elko Formation consist predominantly of laminated kerogen-rich dolomitic mudstone containing fish fossils, which is interbedded with massive to mudcracked dolomitic mudstone and marl and thin intervals of ostracode grainstone, consistent with deposition in a closed or partly closed lake with salinity-stratified disoxic bottom waters devoid of burrowing organisms. Geochemistry, Fisher Assay oil yields, and lithofacies indicate deposition in an intermittently closed “balanced fill” lake system with long residence times, fluctuating salinity, and stratification that led to increased burial and sequestration of ¹²C-rich organic matter (Graf et al., 2015; Johnson & Birdwell, 2016; Mulch et al., 2015).

5.3.5. Lake Elko, Phase 3: 41.3–40.5 Ma

Other than a few thin intervals of laminated kerogen-rich mudstone, upper Elko Formation lithofacies are generally kerogen-poor, and include stromatolitic and mudcracked carbonate, ostracode grainstones, and bioturbated tuffaceous siltstone. These lithofacies indicate deposition in a shallow, likely saline and evaporative lake that experienced periodic dessication and exposure (Figure 4). Volcanic ash beds become more abundant up-section, culminating in the accumulation of thick (>10 m) ignimbrites. A switch to lower δ¹³C and δ¹⁸O values in the uppermost Elko Formation presents an interesting conundrum given the lithofacies evidence for sub-aerial exposure and high alkalinity. One possible explanation is that shallower conditions promoted carbonate precipitation from meteoric waters along fringing mudflats, which could also have promoted less effective organic burial, resulting in a decrease in the δ¹³C value for lake water. The δ¹⁸O values of the uppermost Elko Formation indeed resemble the values for soil carbonates of the lowermost (middle Eocene) Indian Wells Formation, which formed in equilibrium with meteoric soil waters ~1 m.y. after final infill of Lake Elko (Figure 2; Mulch et al., 2015). An increase in the frequency and magnitude of landscape-mantling volcanism across the region is likely responsible for the 0.001 decrease in ⁸⁷Sr/⁸⁶Sr observed in the upper Elko Formation (Figure 4). Caldera-forming eruptions in the Tuscarora volcanic field released large volumes of volcanioclastic debris that filled existing topographic lows over a >10,000 km² area (Figures 1 and 9; Brooks et al., 1995; Henry, 2008).

5.4. Comparison to Global Climate Trends

Deposition in Lake Adobe occurred in greenhouse conditions near the end of the early Eocene climatic optimum (EECO) (Figure 2). It also corresponds in time with the greatest expansion of lacustrine conditions across the Laramide foreland (Figures 1 and 2) (Smith et al., 2008). Lake Elko, in contrast, occurred during a cooler middle Eocene climate phase that preceded the middle Eocene climate optimum (MECO), after dep
osition in the Green River Formation lakes had ceased. $\delta^{18}$O values for carbonates deposited by Lake Adobe exhibit the largest variations in the Elko Formation ($\sim$25‰) and lowest recorded values for all Eocene lacustrine strata of the region. We interpret this high variation to be consistent with a high sensitivity of the lake system to climate-induced changes in precipitation due to its small size, small catchment, open hydrology, and low residence times. Lake Elko carbonates also exhibit high-frequency variation ($\sim$15‰) in $\delta^{18}$O values, however, this variation is lower in magnitude than the variation observed in the Lake Adobe record, which we interpret to reflect a lower sensitivity to short term climate signals due to the larger aerial extent of Lake Elko and its paleo-catchment. The Elko Formation stable isotope record shows no clear resemblance to the global marine record, and appears to have changed independently of the global ocean (Cramer et al., 2009; Sluijs et al., 2013). Several interesting correspondences may bear further scrutiny nevertheless (Figure 2).

For example, the kerogen-rich middle Elko Formation corresponds with a brief warm interval at $\sim$41.6 Ma within this overall cooler period of the middle Eocene, the Late Lutetian thermal maximum (LLTM) (Westerhold et al., 2018), which could have contributed to the increasingly evaporative and stratified conditions observed in Lake Elko at the time. Another possible example is the shared lacustrine and global negative carbon isotope excursions at $\sim$40.7 Ma, during the interval between the LLTM and MECO.

### 5.5. Paleoelevation Interpretations

Lake water oxygen isotope ratios ($\delta^{18}$O) can be used to evaluate water provenance, paleoelevation, paleoclimate, and diagenesis. Evaporation of lake water, however, is common and can substantially increase lacustrine values relative to source or meteoric water $\delta^{18}$O values. The presence of micritic carbonates, which are often used as a $\delta^{18}$O proxy material, support the occurrence of evaporation as a method of driving carbonate insolubility in the lake basin. The co-occurrence of lake-water evaporation and carbonate formation is also influenced by warmer season temperatures, which creates an additional isotope bias toward higher formation temperatures, which can reduce fractionation during crystallization. Lacustrine carbonate $\delta^{18}$O values thus reflect local evaporation and lacustrine residence times as much, if not more than, the elevation of the drainage basin or the isotopic value of the source(s) of atmospheric moisture (e.g., Horton et al., 2016).

Horton et al. (2004) interpreted a $\sim$6‰ decrease in $\delta^{18}$O values between upper Elko Formation strata and Indian Wells Formation strata in the Pioche Range to record a coeval 2 km increase in surface elevations in northern Nevada. Subsequent studies have also cited this isotopic shift as evidence for migratory Eocene–Oligocene surface uplift, termed the “southward encroachment of an Eocene Plateau” (SLEEP; Chamberlain et al., 2012; Mix et al., 2011; Mulch et al., 2015). Similarly, Mulch et al. (2015) attribute a 14.7‰ decrease in $\delta^{18}$O values between evaporative lacustrine strata deposited at ca. 40.4 Ma and paleosol carbonates in ca. 39.4 Ma volcaniclastic strata of the Indian Wells Formation to regional surface uplift. Evaporation, however, can account for shifts observed in $\delta^{18}$O/δD values among dissimilar depositional environments without any elevation change (Cassel & Breecker, 2017; Horton et al., 2016; Smith et al., 2017). Smith et al. (2017) showed large variations in $\delta D_{\text{glass}}$ values for hydration waters within the same regionally correlative and $^{40}$Ar/$^{39}$Ar-dated ignimbrite deposited in non-lacustrine ($\sim$165‰) and lacustrine ($\sim$65‰) settings.

Ibarra et al. (2021) recently reported triple oxygen isotope ($\delta^{17}$O) values from chert in the lowermost “cherty limestone” portion of the Elko Formation and carbonate clumped isotope (D47) values from the overlying Elko Formation. These results unsurprisingly suggest that both chert and carbonate precipitation occurred from evaporated waters at high temperatures (60 ± 10°C and 32.5 ± 3.5°C, respectively). To better understand the influence of evaporation, Ibarra et al. (2021) then used the model of Passey and Ji (2019) to back-calculate a source water $\delta^{18}$O value of $-16.0 \pm 3.5$‰ from their temperature and $\delta^{17}$O values, estimating that this represents unevaporated water and is thus reflective of elevation. They compare this to an average $\delta^{18}$O value of $-18.4 \pm 1.0$‰, based on converting $\delta D$ values of hydrated volcanic glass data from Cassel et al. (2014; 2018) and Smith et al. (2017), using the GMWL and Friedman et al. (1993). Ibarra et al. (2021) use the difference between these values to argue for either a lower relative paleoelevation during deposition of the lowermost Elko Formation than previously inferred, or for alteration of the hydrated volcanic glass isotope signature via meteoric diagenesis. We disagree with these interpretations based on both the fundamental inequivalence of the comparison and on the estimate calculations themselves.
We first note that two key Cassel et al. (2014; 2018) data points were not included in the Ibarra et al. (2021) average: the values that were closest in age (41.22, 41 Ma) and location to the Elko chert and carbonate sample location. They instead used values from 36 to 40 Ma glasses from further south and east. And while the comparison of back-calculated source waters from a lacustrine/diagenetic setting at ∼46–43 Ma to meteoric waters from a fluvial setting at ∼41 Ma is still inapt, these ca. 41 Ma values convert to δ¹⁸O values of −16‰ and −17.6‰, much closer to the preferred source water estimate of Ibarra et al. (2021). Their estimate of source water, however, does not include or account for the outstanding issue with using δ¹⁷O values to reconstruct source water δ¹⁸O values according to Passey and Ji (2019). Based on modern data, Passey and Ji (2019) found that their method consistently overestimated the δ¹⁸O values of primary precipitation by 2‰ and concluded that further study of triple oxygen systematics is necessary before this method can faithfully reconstruct primary precipitation values. Applying this correction directly, the δ¹⁸O value estimate of primary precipitation is −18‰ ± 3.5‰, based on the δ¹⁷O values. Considering these key discrepancies, the results of Ibarra et al. (2021) do not support any alteration signal in hydrated volcanic glass or provide meaningful paleoelevation evidence for lower elevations during deposition of the lower Elko Formation.

New δ¹⁸O values reported here from ca. 49 Ma Lake Adobe strata resemble the values in Lake Elko strata, further suggesting that the long-term baseline likely did not change significantly from the early to middle Eocene. Moreover, the lowest δ¹⁸O value for the Elko Formation occurs in the Lake Adobe succession. This would indicate that regional elevation was relatively unchanged through the early to middle Eocene, and the observed high magnitude variations in δ¹⁸O result are most parsimoniously attributed to varying rates of evaporation and residence time in lakes rather than a systematic increase in elevation as hypothesized by previous authors. This finding is more consistent with the majority of the regional elevation of the Neoadaplan having existing by the Paleogene. Only modest (400–600 m) middle Eocene to Oligocene surface uplift implied by non-lacustrine δ¹⁸O values (Figure 7; Cassel et al., 2018) rather than the larger magnitude (>1 km) changes interpreted by previous workers (Chamberlain et al., 2012; Horton et al., 2004; Mix et al., 2011; Mulch et al., 2015).

5.6. Landscape and Tectonic Evolution

Lake Elko formed in northeast Nevada near the end of a long interval of contraction across the Cordillera (DeCelles, 2004), just prior to and contemporaneous with the arrival of magmatism to the region (Best et al., 2009). Recent detrital zircon U-Th/Pb-He double dating and lag time analysis show that minimum nonvolcanic detrital zircon (U-Th)/He age lag times relative to depositional age decreased to <100 m.y in 45–43 Ma strata and to <10 m.y in 43–41 Ma strata (Canada et al., 2019). This implies that extension began in the Eocene locally and likely influenced lake evolution. Elko Formation lithofacies and spatial accumulation patterns, however, differ in several ways from typical syn-extensional sedimentary strata deposited in basins bound by range-uplifting normal faults (e.g., Canada et al., 2019; Ezquerro et al., 2014; Gawthorpe & Leeder, 2000; Janecke et al., 1997). In particular, the Elko Formation lacks detectable associated coarse-grained, footwall-generated alluvium and has a broad, roughly symmetrical isopach pattern, with the thickest accumulations in the center (Canada et al., 2019; Smith et al., 2017), implying that an alternate basin forming mechanism(s) may have contributed to its accumulation.

Several additional processes can promote lake formation in orogenic settings affected by flat or shallow subducting slabs. Slab removal could have altered the stress field across the hinterland or thermally altered bulk crustal rheology (Bendick & Baldwin, 2009), contributing to extensional fault displacement and modified surface hydrology. While Elko Formation strata do not exhibit clear indications of extension, that is, asymmetric strata adjacent to clear footwall escarpments, it is certainly possible that good evidence has been erased by Neogene tectonism. Slab motion through the mantle can also generate migrating regions of subsidence and uplift through the dynamic effects of slab-induced mantle motion and changes to the thermal and composition structure of the overlying lithosphere. Subsidence, uplift, and changes to surface drainage induced by southwest-migrating slab rollback beneath the Laramide foreland have been proposed to contribute to the formation of the Green River Formation lake system during the early Eocene (Smith et al., 2014). Numerical models and empirical observations suggest that initial slab and/or lithospheric delamination is accompanied by dynamic subsidence from suction at the slab hinge, soon after followed by magmatism and uplift when asthenosphere replaces the removed material (Best et al., 2009; Cassel et al., 2014).
et al., 2018; Göğüş & Pysklywec, 2008; Heller & Liu, 2016; Smith et al., 2014). Uplift in such settings could be promoted by several mechanisms that are also characteristic of volcanic arcs such as mantle-driven dynamic uplift, thermal effects on buoyancy, isostatic adjustment to pluton emplacement, garnet hydration in the lower crust, or delamination from the base of the lithosphere (Humphreys, 2009; Jones et al., 2015; Porter et al., 2017). In Cordilleran settings with high crustal thicknesses, localized subsidence can also occur due to focused downwellings from the base of the lithosphere, that is, Rayleigh-Taylor instabilities or “drips,” as has been interpreted in the central Andes (DeCelles et al., 2015).

Lake Elko reached its greatest apparent depth and extent roughly coincident with the arrival of rollback magmatism in northeast Nevada (Canada et al., 2019; Henry et al., 2011; Lund Snee et al., 2016). This would locate the basin roughly above the slab hinge (Figure 9), where dynamic subsidence is predicted (Göğüş & Pysklywec, 2008; Heller & Liu, 2016). In addition to subsidence, uplift, magmatism or faulting caused by slab removal beneath areas to the north and northeast of the basin could have blocked headwater catchments or the outlet stream of Lake Elko, reducing stream flow to the basin and causing more evaporative conditions and deposition of shallow water lithofacies. The formation of the Tuscarora caldera complex, emplacement of several large plutons (Figure 1), and infill of the region by ignimbrites from ca. 41 to 38 Ma likely tracks the arrival of upwelled asthenosphere beneath northeast Nevada. These events coincided with terminal infill of Lake Elko and its immediate aftermath (Figure 9). Surface uplift, volcanism, unconformity and localized extension developed from the late middle Eocene into the Oligocene across northeast Nevada, prior to the Miocene inception of high-angle normal faulting that defines the modern Basin-and-Range landscape (Figure 1; Colgan et al., 2010; Henry et al., 2011).

6. Conclusions

Two distinct lake systems occurred in northeast Nevada during the Eocene Epoch: A short-lived early Eocene Lake Adobe; and longer-lived middle Eocene Lake Elko. Lake Adobe (ca., 49.5–48.5 Ma) coincided with the end of the hottest interval of the Cenozoic and was of limited aerial extent and duration. Carbonate mudstone and marlstone yield highly covariant 87Sr/86Sr, δ13C, and δ18O values which exhibit high frequency oscillations, and generally low Sr concentrations, suggesting a freshwater to brackish Lake Adobe that was sensitive to fluctuations in insolation and local influences during its short existence. After a 5 m.y. interval of apparent unconformity, Lake Elko inundated a broad area (>1,000 km2) of northeast Nevada for 3 m.y. during the middle Eocene, during a slightly cooler global climate interval preceding the MECO. Carbonate mudstone and marlstone strata deposited in Lake Elko record three stable geochemical phases in 87Sr/86Sr, δ13C, and δ18O values, corresponding to the lower, middle, and upper Elko Formation. These intervals record initial deepening of a freshwater Lake Elko during the first phase, increasing salinity and alkalinity accompanied by increasing organic burial due to stratification during the second phase, then a third phase trend toward shallower lithofacies and desiccation, and ultimately filling of the lake with volcaniclastic detritus. δDgas values preserved in volcanic ash beds and ignimbrites confirm a trend toward greater evaporation during deposition of the upper Elko Formation (Figure 4). Similar geochemical trends across multiple correlative locations suggest that Lake Elko existed as a single hydrologic entity across the 3.5 m.y. of its evolution.

The Eocene lake systems of northeast Nevada likely received drainage from a modestly large area of the central Cordilleran hinterland. Mean 87Sr/86Sr ratios for all Elko Formation strata (0.7086) are consistent with Paleozoic strata that would have been exposed across the hinterland during the Eocene, and inconsistent with significant exhumation of deeper crustal rocks by MCCs at the surface at the time. Some prominent variation in 87Sr/86Sr ratios in early Eocene strata deposited in Lake Adobe could record drainage capture or, alternately, local exhumation of high-87Sr basement within the lake catchment. A systematic decrease in 87Sr/86Sr ratios in the upper Elko Formation likely resulting from the increasing aerial extent of contemporaneous felsic magmatism in the paleo-catchment. Lake formation and expansion, followed by increasing hydrologic isolation, magmatism, and subsequent regional unconformity appear consistent with hypothesized surface effects of removal of a shallow Farallon plate slab and/or delamination of the lithosphere from beneath the North American plate.
Acknowledgments
National Science Foundation grant EAR-1322073 to Cassel and Smith and student grants to Canada from the American Association of Petroleum Geologists, the Rocky Mountain Association of Geologists, and the Elko Chapter of the Geological Society of Nevada supported this research. The authors thank D. Breecker and T. Larson at the University of Texas-Austin, P. Larson, C. Knaack, and J. Vervoort at Washington State University, T. Williams and B. Kennedy at the University of Idaho, J. Faulds at the University of Nevada Reno, and the Great Basin Sample and Records Library.

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