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# Water utilization of the Cretaceous Mussentuchit Member local vertebrate fauna, Cedar Mountain Formation, Utah, USA: Using oxygen isotopic composition of phosphate

Celina A. Suarez [a,*], Luis A. González [b], Gregory A. Ludvigson [c], Richard L. Cifelli [d], Emily Tremain [e]

[a] Department of Geosciences, Boise State University, 1910 University Drive, Boise, ID 83725-1535, USA
[b] Department of Geology, University of Kansas, 1475 Jayhawk Blvd., Lawrence, KS 66045, USA
[c] Kansas Geological Survey, University of Kansas, 1930 Constant Ave., Lawrence, KS 66047, USA
[d] Sam Noble Oklahoma Museum of Natural History, 2401 Chautauqua Ave., Norman, OK 73072, USA
[e] 1430 Echo Way, Apple Valley, MN 55124, USA

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ABSTRACT

While the oxygen isotopic composition of pedogenic carbonate has successfully been used to address the effects of global climate change on the hydrologic cycle, detailed regional paleohydrologic studies are lacking. Since the hydrologic cycle can vary extensively on local or regional scales due to events such as such as mountain building, and since pedogenic carbonates (calcite) form in a narrow moisture regime, other proxies, such as vertebrate remains, must be used to decipher local *versus* regional variations in paleohydrology. In this study, the oxygen isotopic composition ($\delta^{18}O_p$) of phosphatic remains from a diverse set of vertebrate fossils (fish, turtles, crocodiles, dinosaurs, and micro-mammals) from the Mussentuchit Member (MM) of the Cedar Mountain Formation, Utah, USA (Aptian to Cenomanian) are analyzed in order to determine differences among the available water reservoirs and water utilization of each taxon. Calculated changes in water reservoir $\delta^{18}O_w$ over time are then used to determine the effects of the incursion of the Western Interior Seaway (WIS) and the Sevier Mountains on paleohydrology during the MM time.

Calculation of $\delta^{18}O_w$ from the results of isotopic analysis of phosphate oxygen suggests that turtles and crocodiles serve as another proxy for meteoric water $\delta^{18}O$ that can be used as a measure of average local precipitation $\delta^{18}O_w$ similar to pedogenic calcite. Pedogenic calcites can be slightly biased toward higher values, however, due to their formation during evaporative conditions. Turtles and crocodiles can be used in place of pedogenic calcite in environments that are not conducive to pedogenic carbonate formation. Remains of fish with rounded tooth morphology have $\delta^{18}O_p$ values that predict temperatures consistent with other estimates of mean annual temperature for this latitude and time. The $\delta^{18}O_p$ of ganoid scales and teeth with pointed morphology, however, indicates that these skeletal materials were precipitated from water that is $^{18}O$-enriched due to migration to either evaporatively enriched water, or $^{18}O$-enriched estuarine waters of the Western Interior Seaway (WIS). Another possibility that cannot be discounted and assuming all morphological remains are from the same taxon, is that the pointed teeth and ganoid scales precipitated at different temperatures than rounded teeth. Mammal and herbivorous dinosaur $\delta^{18}O_p$ suggests they primarily drank isotopically depleted river water. Coexistence of crocodiles, turtles, and mammals allows for calculation of relative humidity from site to site and these calculations suggest humidity averaged ~58% and ranged between ~42% and ~76%.

The $\delta^{18}O_w$ values estimated from semi-aquatic taxa and pedogenic calcite suggest dominance of WIS-derived moisture during their growth. Herbivorous dinosaurs particularly indicate that altitude and catchment effects from the Sevier Mountains are seemingly important for river water $\delta^{18}O_w$ in the fall through early spring. These data suggest that temporal changes in the isotopic composition of the MM fauna are produced by the small-scale regressive–transgressive cycles of the WIS.



## 1. Introduction

Numerous isotopic studies have demonstrated that the mid-Cretaceous global warming caused an intensification of the hydrologic cycle, resulting in increased regional rainout in the temperate humid belts and higher evaporation in dry belts (White et al., 2001; Ufnar et

* Corresponding author. Tel.: +1 208 426 4154; fax: +1 208 426 4061.
*E-mail addresses:* celinasuarez@boisestate.edu (C.A. Suarez), lgonzlez@ku.edu (L.A. González), gludvigson@kgs.ku.edu (G.A. Ludvigson), rlc@ou.edu (R.L. Cifelli), etremain@gmail.com (E. Tremain).

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al., 2002; 2004; Suarez, 2009). While these studies have explored the hydrologic cycle at hemispheric to global scales, detailed regional isotopic studies are lacking. For example, the relative contribution of local *versus* regional water sources to rivers and other water bodies (*e.g.* lakes and ponds) can vary significantly within a particular region, but this variability is difficult to ascertain. In addition, regional events such as mountain building and transgression/regressions can affect the proximity of moisture sources and significantly alter regional moisture patterns, thereby influencing the isotopic composition of precipitation. The causes of changing isotopic compositions of precipitation are difficult to constrain using isotopic proxy records that form under a narrow moisture regime, such as pedogenic carbonates. Because of these limitations, biogenic materials are being used with greater frequency to infer paleohydrology and paleoenvironments (Dettman et al., 2001; Billon-Bruyat et al., 2005; Fricke et al., 2008). It is therefore imperative to better understand water utilization behavior of different taxa, and improve the understanding of proxy records that can provide information on the factors controlling variability in the isotopic composition of water for a given site.

Several studies have used stable isotopes in continental taxa (aquatic, semi-aquatic, and terrestrial) to determine paleoenvironmental, paleoclimatic, and paleoecologic information (Fricke and O'Neil, 1996; Billon-Bruyat et al., 2005; Lee-Thorp and Sponheimer, 2005; Fricke, 2007; Fricke et al., 2008; Amiot et al., 2009). Vertebrate taxa record the isotopic compositions of their water sources in their bone and tooth apatite [$Ca_5(PO_4, CO_3)_3(OH, CO_3)$]. While both the carbonate and phosphate components of bioapatite have been used for isotopic studies, phosphate is more resistant to diagenesis than structural carbonate (Kolodny et al., 1996). Furthermore, enamel apatite and ganoine (dense upper layer of ganoid scales, similar to enamel) are more resistant to diagenetic alteration than bone apatite and are considered a more reliable source of biogenic and paleoecologic information (Kolodny et al., 1996; Trueman et al., 2003; Fricke et al., 2008).

In this study, the isotopic composition of a diverse late Early Cretaceous vertebrate fauna is measured to investigate water utilization strategies employed by different organisms. While the isotopic composition of Mesozoic land-dwelling vertebrate faunas is now more commonly used (Billon-Bruyat et al., 2005; Fricke, 2007; Fricke et al., 2008; Amiot et al., 2009), few paleoecological isotope studies of Mesozoic terrestrial ecosystems have been conducted that elucidate the water sources utilized by a wide variety of co-existing taxa. The Mussentuchit Member (MM) of the Cedar Mountain Formation (CMF) is most amenable for such a study because it preserves a diverse continental fauna including freshwater aquatic, semi-aquatic and terrestrial vertebrates (Cifelli et al., 1999). Furthermore, the vertebrate fauna contains numerous physicochemically resistant elements such as teeth, scales, and scutes that may be used for stable isotopic analysis (Billon-Bruyat et al., 2005; Fricke et al., 2008). This diverse fauna allows us to explore water utilization strategies by vertebrates and to tease out the relative contribution of local *versus* regional water sources. The isotopic composition of fish remains are used to calculate temperature and relative humidity is estimated from the isotopic composition of co-existing mammals and semi-aquatic taxa. Furthermore, temporal changes in the isotopic composition of the different water reservoirs available to the MM fauna are tracked through the Cenomanian based on detailed stratigraphic control of the available collections. By tracking these changes the impact of the Sevier Mountains and incursions of the Western Interior Seaway on paleohydrology during Mussentuchit time is constrained. The results of this study provide the most diverse phosphate O-isotopic study to date of the Mesozoic; with over 100 phosphate analyses from seven different taxonomic groups from seven different sites as well as pedogenic and cementing carbonate.

## 2. Geologic setting

The Cedar Mountain Formation (CMF) was deposited in Utah during the Barremian to Cenomanian and includes, from oldest to youngest, the Buckhorn Conglomerate, Yellow Cat Member, Poison Strip Sandstone, Ruby Ranch Member, and Mussentuchit Member (MM). The focus of this study, the Mussentuchit Member, primarily crops out on the western side of the San Rafael Swell anticline. It is identifiable by its high smectitic–clay content and drab gray popcorn-weathered mudstones that form extensive badlands in the Willow Springs and Short Canyon quadrangles of central-Utah. Several ash layers present in the MM give ages that range from 98.3 ± 0.1 Ma (Cifelli et al., 1999) to 96.7 ± 0.5 Ma (Garrison et al., 2007), suggesting MM deposits are Cenomanian in age. The upper part of the MM contains abundant lignitic coal layers and is commonly interbedded with the overlying Dakota Sandstone; however, locally there are erosional unconformities between the MM and Dakota. While carbonate nodules are abundant in the underlying Ruby Ranch Member, they are less common in the MM.

The MM vertebrate fauna was sampled by field crews of the Oklahoma Museum of Natural History in the Mussentuchit Wash and Short Canyon areas (Fig. 1) via screen washing techniques. Representative stratigraphic sections (Fig. 2) illustrate the relative stratigraphic position of seven different sites. Garrison et al. (2007) suggested that these sites were deposited in a lacustrine system in which a perennial lake cyclically transgressed and regressed, while Kirkland et al. (1997) suggested that the MM represents fluvial environments with small channels and overbank deposits. Taphonomically, all the sites are microvertebrate sites from either lag concentrations of channel and floodplain-derived material or oxbow-lake deposits, and so were likely transported to some degree. However, most samples with the exception of a few are well-preserved and do not show significant signs of abrasion, suggesting they were not transported far and the sites were likely parautochthonous in nature.

In a foreland basin setting similar to that in which the Mussentuchit was deposited, there are two main sources of water that continental vertebrates can utilize: 1) local precipitation or meteoric water and 2) water in larger rivers derived from distant sources. While both of these sources are ultimately derived from precipitation, water in large rivers is influenced by precipitation in the distant portions of the rivers' catchment areas. Dutton et al. (2005) provide an extensive review of the differences between river water and local meteoric water isotopic composition. The oxygen isotopic composition ($\delta^{18}O$) of meteoric water is controlled by water vapor sources (*i.e.* ocean, or large lakes), distance from the source (continental effect), elevation (altitude effect), temperature, humidity, and evaporative effects. In general, the $\delta^{18}O$ of precipitation produced from a given airmass becomes lighter by ~2‰/1000 km of transport (Rozanski et al., 1993) assuming no elevation change. Similarly, as an airmass moves to higher elevations, the precipitation will become gradually lighter by ~2.8‰/km of elevation (Dutton et al., 2005). Temperature and precipitation $\delta^{18}O$ are positively correlated with mean annual air temperature (*e.g.* Dansgaard, 1964). Humidity and evaporative effects act in concert to modify the isotopic composition of precipitation, with lower humidity resulting in greater evaporation and $^{18}O$-enrichment. The isotopic composition of river water is dominantly controlled by the $\delta^{18}O$ of precipitation in its catchment area. As altitude effects result in lower $\delta^{18}O$, river water sourced at higher elevations tends to be $^{18}O$-depleted relative to that of low elevation tributaries and ephemeral streams. In general, river water $\delta^{18}O$ decreases by ~4.2‰/km of elevation change (Dutton et al., 2005). Thus, precipitation-derived water at a given elevation will be heavier than river waters at the same elevation if the river is sourced from higher elevations.

### 2.1. Ecologic and climatic setting

The ecologic setting of these animals was affected by two main geologic events that could have impacted local hydrology: 1) mountain building from the Sevier Fold and Thrust Belt (SFTB) and 2) the incursion of the Western Interior Seaway. The SFTB is a segment of the larger Cordilleran retroarc fold-and-thrust belt that formed during the late Mesozoic to early Cenozoic times (DeCelles and Coogan, 2006).