

# Tracking mammoths and mastodons: Reconstruction of migratory behavior using strontium isotope ratios

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## ABSTRACT

Variations in the strontium isotope ratio ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) of tooth enamel are used to examine the migration patterns of late Pleistocene mammoths and mastodons from Florida. An animal's  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio tracks the ratios of its environment, which vary with differences in bedrock and soil. Consequently, the environmentally controlled differences in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio recorded in mineralized tissue, such as tooth enamel, may be used to reconstruct the movement patterns of an individual. We map variations in local  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios across modern Florida and Georgia through analysis of rodent teeth, plants, and surface water, then use this map to interpret the movement patterns of extinct mammals. Mastodons from northern and central Florida have higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios than both modern environmental samples from Florida and fossils from nonmigratory species, suggesting that mastodons migrated north into Georgia. Mammoths display ratios similar to those of environmental samples and resident species, suggesting that they did not migrate outside Florida.

## INTRODUCTION

An understanding of the migration patterns and home-range sizes of extinct animals is critical for evaluating hypotheses of extinction, speciation, evolutionary change, and paleoclimatic or paleoenvironmental studies based on fossil remains. However, estimates of migration distances for extinct species are often problematic. This is especially true for large animals, such as proboscideans or dinosaurs, that have few or no surviving analogs.

During the Pleistocene, proboscideans were important members of mammalian faunas. In North America, three proboscidean families coexisted until ca. 11,500 B.P., when they disappeared, along with a majority of the mammalian megafauna (Meltzer and Mead, 1985; Webb, 1992). Some researchers attribute these extinctions to the actions of human hunters who exploited proboscidean movement patterns. Churcher (1980) suggested that human hunters preyed on mammoths as they crossed natural traps during seasonal migrations that covered as much as 2400 km one way. Owen-Smith (1988) and Haynes (1991) proposed that changes in habitat forced animals to reduce their home-range sizes, thus rendering them more vulnerable to hunters.

Alternatively, these climate changes may have played a more direct role in extinction (Martin and Klein, 1984). Mammoths and mastodons may have needed to migrate in order to escape harsh winters or to exploit seasonally available resources (Olivier, 1982; Holman et al., 1988). If climate-driven ecological changes disrupted migrations, then overfeeding or limited access to resources may have led to nutritional stress, directly

contributing to extinction (Martin and Klein, 1984; Holman et al., 1988). Alternatively, animals may increase their range size when stressed (Owen-Smith, 1988). Thus, changes in proboscidean movement patterns may indicate environmental stress. Direct assessment of proboscidean migratory behavior would provide potential explanations for their demise. Current ideas about the migratory behavior of extinct proboscideans are based largely on analogy with the movements of living elephants (Olivier, 1982), which are controversial in their own right. For example, the longest documented elephant migration is 130 km one way (Owen-Smith, 1988), yet historical accounts suggest that past migrations were much longer (Eltringham, 1982).

Here we assess proboscidean movements through analysis of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of tooth enamel. The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of an herbivore, and thus its teeth, equals the average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of ingested plants (Lenihan et al., 1967; Price et al., 1985). The ratios of plants, in turn, equal the soluble Sr in soils, which is derived from bedrock weathering and atmospheric deposition (e.g., aerosols, and precipitation) (Gosz and Moore, 1989; Miller et al., 1993). Environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios thus vary with differences in bedrock age, bedrock composition, and atmospheric input. Variations in Sr isotope ratios have been used to track the movements of modern elephants (Koch et al., 1995), salmon (Kennedy et al., 1997), and birds (Chamberlain et al., 1997), as well as prehistoric humans (Sealy et al., 1995; Ezzo et al., 1997) and fossil salmon (Koch et al., 1992).

The bedrock of Florida and southern Georgia consists primarily of Cretaceous to Holocene

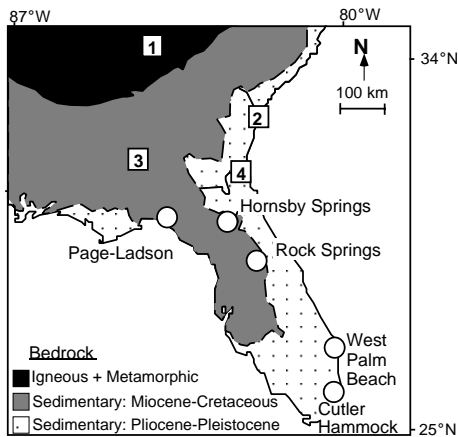
marine carbonates, which are locally covered by thin siliciclastic sediments (Scott, 1992). Because marine carbonates track the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of seawater, the bedrock of this area should display relatively uniform  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranging from 0.7075 to 0.7092 (Hess et al., 1986). The homogeneity of the Florida environment is demonstrated by modern bivalves, which record the average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the water in which they live. Bivalves from the Suwannee and Peace Rivers in northern and central Florida have ratios of 0.7084 and 0.7082, respectively (Bryant et al., 1995). Environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios change in central Georgia, however, with the appearance of the Paleozoic metamorphic and igneous terrains of the Appalachian Mountains. These terrains have relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, ranging from 0.7103 to 0.7633 (van Breemen and Dallmeyer, 1984; Samson et al., 1995). Thus, animals that migrated north toward the Appalachians should display higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios than individuals that ranged only locally.

## METHODS

We analyzed tooth enamel from 58 individuals from 5 localities in Florida (Fig. 1). We compared bulk samples from mammoths (*Mammuthus* sp.) and mastodons (*Mammot americanum*) with cooccurring taxa, such as deer (*Odocoileus virginianus*), rabbits (*Sylvilagus* sp.), and locally extinct tapirs (*Tapirus* sp.). Bulk samples were collected in order to sample the average isotopic composition of each tooth (Koch et al., 1998). We also examined intratooth variability within a mastodon molar, from which a petrographic thin section had been made. We used a Lohmann computerized micro-sampler to collect samples from a series of grooves (~0.15 mm deep, ~0.12 mm thick, and ~5.0 mm long) milled parallel to growth increments.

The distribution of environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in Florida was mapped through analysis of modern plant and water samples collected at or near Hornsby Springs, Rock Springs, and the Page-Ladson fossil quarry (Fig. 1). Measurements from a minimum of four plant specimens from each site were combined to determine average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. To test for temporal changes in the regional Sr budget, we compared a modern and a fossil bivalve from the Page-Ladson quarry. The distribution of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios across

Data Repository item 9937 contains additional material related to this article.



**Figure 1. Bedrock geology of Florida and Georgia showing locations of modern rodent sites (squares) and fossil quarries (circles). Average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of modern rodents sites are (1)  $0.7143 \pm 0.0004$ , (2)  $0.7092 \pm 0.0000$ , (3)  $0.7117 \pm 0.0016$ , (4)  $0.7087 \pm 0.0015$ . Average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of modern plants collected at fossil sites are Page-Ladson,  $0.7090 \pm 0.0001$ ; Hornsby Springs,  $0.7095 \pm 0.0003$ ; and Rock Springs,  $0.7085 \pm 0.0004$ .**

Georgia was mapped through analysis of bones and teeth from modern rodents (*Sigmodon hispidus*). Three rodents were measured from each site, except for site 1, where only two individuals were measured (Fig. 1).

To eliminate diagenetic contaminants from fossils, the outer surface of each tooth was removed before sampling, and all samples were pretreated before analysis (Sillen, 1986; Koch et al., 1998). Each sample was reacted once with 0.5 ml of 0.5 N acetic acid for 30 min, then reacted 3 times with 0.5 ml of 0.1 N acetic acid for another 30 min each. After each acid treatment samples were rinsed with deionized water. The microsample thin section was reacted with 10 ml of 0.5 N acetic acid for 5 min, then rinsed with deionized water prior to sampling. Modern plants were combusted at 500 °C for 5 hr, then soluble Sr was extracted by reacting the ash with concentrated  $\text{HNO}_3$  overnight. Water samples were acidified with HCl to 0.1 N, allowed to sit overnight, then centrifuged and analyzed. Bivalve shells were powdered and rinsed with 0.1 N acetic acid for ~5 min. Samples from modern rodents were ashed at 400 °C for >4 hr to remove organic material.

After pretreatment, samples were either dissolved in 2.5 N HCl and Sr extracted by standard ion exchange chromatography (Walker et al., 1989), or samples were dissolved in 8 N  $\text{HNO}_3$  and Sr was extracted using microcolumns filled with Sr-Spec resin. Bulk samples were measured on a VG 354 thermal ionization mass spectrometer, whereas microsamples were analyzed on a VG 354-S thermal ionization mass spectrometer. All measurements are referenced to a value of  $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$  for the NBS 987 Sr standard, and are precise to within  $\pm 0.00003$ .

**TABLE 1.  $^{87}\text{Sr}/^{86}\text{Sr}$  RATIOS OF FOSSILS**

Taxon	No.*	Part†	$^{87}\text{Sr}/^{86}\text{Sr}$	Taxon	No.*	Part†	$^{87}\text{Sr}/^{86}\text{Sr}$
<b>Page-Ladson 14 410–14 750 B.P.</b>				<b>Rock Springs Rancholabrean</b>			
<i>Mammuthus</i>	14779	M?	0.7095	<i>Mammuthus</i>	4473	Chk	0.7095
<i>Mammuthus</i>	14780	M <sub>3</sub>	0.7089	<i>Mammuthus</i>	4838	Chk	0.7100
<i>Mammut</i>	103505	M <sup>1</sup>	0.7099	<i>Mammuthus</i>	48987	Chk	0.7099
<i>Mammut</i>	103570	M1	0.7101	<i>Mammuthus</i>	119828	Chk	0.7092
<i>Mammut</i>	148668	M	0.7114	<i>Mammut</i>	4385	Chk	0.7099
<i>Mammut</i>	148669	M	0.7101	<i>Mammut</i>	4464	Chk	0.7099
<i>Mammut</i>	150775	M	0.7101	<i>Mammut</i>	48986	Chk	0.7099
<i>Tapirus</i>	92513	l M <sup>2</sup>	0.7087	<i>Mammut</i>	119827	l M <sub>3</sub>	0.7102
<i>Tapirus</i>	92568	M <sub>3</sub>	0.7087	<i>Tapirus</i>	48970	M <sup>2</sup>	0.7102
<i>Odocoileus</i>	92522	Chk	0.7097	<i>Tapirus</i>	148673	Chk	0.7086
<i>Odocoileus</i>	92563	Chk	0.7086	<i>Odocoileus</i>	12512	Chk	0.7097
<i>Odocoileus</i>	147359	l M <sub>1</sub>	0.7092	<i>Odocoileus</i>	155219	Chk	0.7091
<i>Odocoileus</i>	147362	l M <sub>3</sub>	0.7092	<i>Sylvilagus</i>	4467	Chk	0.7083
<i>Odocoileus</i>	147364	l M <sub>3</sub>	0.7094	<b>West Palm Beach ca. 25 000 B.P.</b>			
<i>Odocoileus</i>	147365	l M <sub>2</sub>	0.7087	<i>Mammuthus</i>	51197	Chk	0.7092
<i>Odocoileus</i>	150249	l M <sub>2</sub>	0.7087	<i>Mammuthus</i>	148672	Chk	0.7092
<i>Odocoileus</i>	150470	l M <sub>3</sub>	0.7108	<i>Mammut</i>	51192	M <sub>3</sub>	0.7093
<i>Odocoileus</i>	151916	l chk	0.7087	<i>Mammut</i>	51194	Chk	0.7093
<i>Odocoileus</i>	151917	l chk	0.7091	<i>Mammut</i>	51195	Chk	0.7093
<i>Odocoileus</i>	151941	l chk	0.7093	<i>Tapirus</i>	51178	l	0.7092
<i>Odocoileus</i>	151942	l chk	0.7089	<b>Cutler Hammock 9500–11 000 B.P.</b>			
<b>Hornsby Springs 10 750–12 000 B.P.</b>				<i>Mammuthus</i>	148679	Chk	0.7094
<i>Mammuthus</i>	987	dP4?	0.7091	<i>Mammuthus</i>	148680	Chk	0.7093
<i>Mammuthus</i>	4609	M	0.7090	<i>Mammuthus</i>	148681	Chk	0.7092
<i>Mammut</i>	919	P4	0.7093	<i>Mammuthus</i>	148682	Chk	0.7092
<i>Mammut</i>	985	M2	0.7099	<i>Mammuthus</i>	148683	Chk	0.7092
<i>Mammut</i>	1005	M <sup>1</sup>	0.7104	<i>Mammuthus</i>	148684	Chk	0.7094
<i>Mammut</i>	3356	M <sup>2</sup>	0.7099	<i>Odocoileus</i>	148687	l M <sub>3</sub>	0.7092
<i>Mammut</i>	3886	M <sup>3</sup>	0.7101	<i>Odocoileus</i>	148688	l M <sub>3</sub>	0.7092
<i>Tapirus</i>	2289	l P <sup>1</sup>	0.7100				
<i>Odocoileus</i>	990	Chk	0.7093				
<i>Odocoileus</i>	1864	r P <sub>4</sub>	0.7100				

\*Florida Museum of Natural History collection number.

†Tooth analyzed: l—left, r—right, d—deciduous, l—incisor, M—molar, P—premolar, chk—cheek tooth, numbers or ? indicate upper (superscript) or lower (subscript).

Data were analyzed statistically with a one-way analysis of variance. In order to resolve differences between pair-wise comparisons of taxa, data were adjusted for simultaneous significance by sequential Bonferroni treatments (Rice, 1988).

## RESULTS

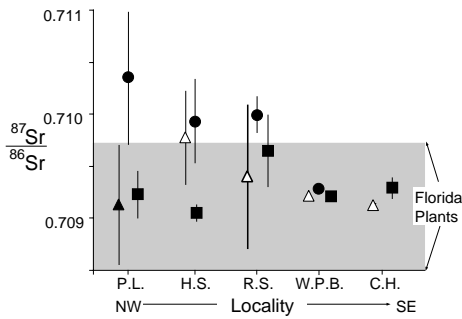
The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of plants from Florida range from 0.7080 to 0.7097. Variability within sites is, in some cases, as great as variability among sites (Fig. 1)<sup>1</sup>. Although the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of soil can vary with depth in some geologic settings (Gosz and Moore, 1989), we found no significant differences between plants rooting at different depths (e.g., between grasses and trees). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of water samples are similar to those of plants, equaling 0.7086, 0.7094, and 0.7081, for sites near Page-Ladson, Hornsby Springs, and Rock Springs, respectively. Ratios

from a modern bivalve (0.7084) and Pleistocene bivalve (0.7086) from the Page-Ladson site are similar to one another as well as to modern river water. While analysis of plants provides a measure of environmental heterogeneity, analysis of small herbivores can provide an estimate of the average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in a local area. Thus, we mapped variations in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of environments across Georgia through analysis of modern rodents. Average values for each sites ranged from 0.7087, in southern Georgia, to 0.7144 in the Appalachians (Fig. 1).

At West Palm Beach and Cutler Hammock, in southern Florida, individuals of all fossil species exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios that are similar to those of recent marine carbonates (Table 1 and Fig. 2). The presumed resident taxa, deer and tapir, have ratios identical to one another (0.7092), and mastodons and mammoths both have average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of  $0.7093 \pm 0.0001$ .

A different pattern emerges in northern Florida, at the Page-Ladson site, where individuals exhibit a much greater range of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. As in south Florida, the resident species

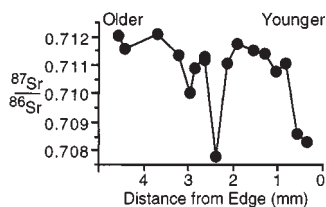
<sup>1</sup>Data Repository item 9937, Strontium isotope ratios of modern plants from Florida, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.



**Figure 2.** Average Sr isotope ratios of bulk samples of mastodons (circles), mammoths (squares), and deer and/or tapirs (triangles). Lines represent calculated 1 standard deviation from average values for each population of more than three individuals, or range of sample values when only two individuals were measured. P.L. is Page-Ladson-Aucilla River, H.S. is Hornsby Springs, R.S. is Rock Springs, W.P.B. is West Palm Beach, and C.H. is Cutler Hammock.

have a combined average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio ( $0.7091 \pm 0.0006$ ) that is similar to ratios for modern plants at the site. Average ratios for mammoths ( $0.7092 \pm 0.0003$ ) do not differ significantly from those of resident species and plants. Mastodons, in contrast, have significantly higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ( $0.7103 \pm 0.0006$ ) than resident species ( $p < 0.01$ ), and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of all mastodons are higher than the highest value observed for any plant or water samples from Florida. In addition, microsamples from one mastodon show large variations in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ( $0.7078$ – $0.7121$ ) over a distance inferred to represent  $\sim 2$  yr of growth (Fig. 3).

The plant and water samples from Rock Springs in central Florida have relatively low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, whereas plant and water samples collected near Hornsby Springs display ratios higher than values expected for marine carbonates. Most individuals of the resident species from both Rock Springs and Hornsby Springs have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios similar to those of environmental samples from near Hornsby Springs, and the combined average for deer and tapir from



**Figure 3.**  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of microsamples from Page-Ladson mastodon #148668. Samples are inferred to represent approximately two years of growth based on variations in thickness of growth line.

both sites is  $0.7095 \pm 0.0006$ . However, a few individuals from Rock Springs, including the sole rabbit analyzed, have lower ratios similar to those of the Rock Springs environmental samples. Like the majority of the resident individuals, the mammoths from these sites have an average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio ( $0.7094 \pm 0.0004$ ) similar to that of environmental samples collected near Hornsby Springs. Mastodons have a slightly, but not significantly ( $p < 0.25$ ), higher average ratio ( $0.7099 \pm 0.0003$ ) than resident taxa. However, seven of the eight mastodons from central Florida have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios higher than the highest values found in plants or waters from modern Florida.

## DISCUSSION

Most animals restrict their lifetime movements to a limited area, or home range, although they may also disperse in a permanent one-way move to a new home range. However, some animals move repeatedly throughout life. Movements that are repeated in the same pattern each year are defined as seasonal migrations, and movements that occur in a less-regular fashion are defined as nomadic migrations. Bulk samples can be used to identify animals that moved outside a local area, but may not help distinguish between different migration patterns. Analysis of microsamples allows more precise reconstruction of the timing and extent of movement.

Analyses of modern environmental samples and fossil resident species confirm that Florida has relatively low ratios in comparison to central and northern Georgia. Resident species from southern Florida have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios identical to those expected for Pleistocene marine carbonates, which form the local bedrock. Most environmental samples and fossil resident species from sites in northern and central Florida have  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in the range expected for Sr derived from Cenozoic marine carbonate bedrock ( $0.7075$  to  $0.7092$ ) (Hess et al., 1986). Near Hornsby Springs, however, modern plants have higher ratios (Fig. 1), and at the other two sites in the region, Rock Springs and Page-Ladson, some resident individuals have higher ratios than local environmental samples. These higher ratios most likely reflect a contribution from terrestrial sediments, which discontinuously overlie Cenozoic bedrock in northern and central Florida (Scott, 1992). However, all  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios measured in modern Florida are significantly lower than values measured for rodents from northern and central Georgia. In addition, comparison of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between modern and Pleistocene bivalves suggests that the regional Sr budget, at least in northern Florida, has not changed significantly since the Pleistocene.

The elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of mastodons from the northern and central sites suggest that the majority of these individuals migrated outside Florida. The observed  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio for mastodons would translate into one-way travel

distances of  $\sim 250$  km (from the Page-Ladson site) to  $\sim 500$  km (from Rock Springs) if these animals moved to the Appalachian Mountains. However, if these animals moved primarily along the flood plains of rivers that drained the mountains, then soils with high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios could have been encountered at distances of  $\sim 120$  to  $\sim 300$  km. The high variability of microsamples from the Page-Ladson mastodon confirms the mobility of these animals. The lowest ratios in this tooth are similar to values for marine carbonates, while the highest ratios match those of Appalachian bedrocks, suggesting that this individual moved repeatedly between the coastal plain and the Appalachians.

Modern herbivores in mountainous regions often migrate seasonally, from lower altitude winter ranges to higher altitude summer ranges, in response to changes in temperature and snow cover (Dingle, 1996). Mastodons from northern and central Florida may have followed a similar pattern of movement. However, the variations in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of bulk samples demonstrate that the extent of such movements varied among individuals. Most mastodons appear to have migrated to the north, although one individual from Hornsby Springs appears to have ranged only locally. This variability among individuals suggests that mastodons, like modern elephants (Eltringham, 1982), were nomadic migrants rather than seasonal migrants. However, because each fossil locality represents a time-averaged accumulation of individuals, it is possible that mastodon populations migrated en masse on a seasonal basis, and that the observed variability in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios among individuals reflects the response of the local populations to century-scale climatic fluctuations.

In contrast to the mastodons, mammoths from these sites display relatively low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, indicating that they did not travel near, or into, the Appalachian Mountains. However, because environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios are relatively uniform across the coastal plain, mammoths could have moved large distances (250 or 500 km) without encountering high environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios.

Dietary differences may have contributed to differences in movement patterns. Florida mastodons consumed mainly trees and shrubs, whereas mammoths in the region were primarily grazers (Koch et al., 1998). During the late Pleistocene, southern Florida contained more open scrub and prairie habitat, whereas forests predominated in northern Florida and Georgia (Watts and Hansen, 1994). Thus, it is likely that mammoths primarily foraged in the more open southern habitats, while mastodons foraged primarily in the forested habitats to the north.

We can calculate the upper limit on distance traveled using samples from southern Florida. Because both southern sites are surrounded for at least 150 km by Pleistocene to Pliocene marine deposits, any animal that ranged less than 150 km

should exhibit  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios similar to the modern marine value. If the mastodons and mammoths at these sites had migrated a greater distance toward central Florida, where bedrock values range from  $\sim 0.7079$  to  $\sim 0.7090$ , they should exhibit greater variability and lower average  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. However, because Pleistocene deposits dominate the shoreline of Florida, individuals that foraged solely along the coast may have moved north as much as 700 km before encountering environments with high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios derived from clastic sediment. Constraints on migration routes and distances traveled should be refined further with the completion of an ongoing high-resolution study of environmental  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio variations across coastal Florida and the Georgia foothills.

## CONCLUSION

Our results provide the first reconstruction of the migration patterns of extinct proboscideans. The relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios from late glacial mastodons suggest that these animals undertook migrations of at least 120 to 300 km, but probably not more than 700 km. In contrast, the uniform ratios displayed by mammoths suggest that these animals did not regularly range more than a few hundred kilometers, and they may have ranged only locally. Mammoths do not appear to have undertaken transcontinental migration of  $\sim 2000$  km, as had been previously hypothesized (Churcher, 1980).

Several authors have suggested that modern elephants may need to migrate; when restricted to small areas, elephants often decimate local ecosystems due to their destructive feeding habits and large daily nutrient requirements (Eltringham, 1982). Pleistocene proboscideans may have also needed to migrate in order to persist without decimating their environment. If this was the case, then environmental changes associated with the end of the last glacial maximum may have restricted the movements of proboscideans and caused the destruction of local resources, which in turn may have contributed to their extinction. Alternatively, proboscideans may have responded to climatic stress by increasing their range size as resources became scarce. The potential now exists to distinguish between these possibilities, and to assess whether long-term changes in proboscidean movement patterns correlated with their extinction.

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