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Using Strontium Isotopes to Study Site Accumulation Processes

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Strontium isotopes (^{87}Sr/^{86}Sr) in tooth enamel reflect the geological substrate on which an animal lived during tooth development. Therefore, strontium isotopes of teeth in fossil cave accumulations are potentially useful in determining whether an animal was native to the vicinity of the site or was brought in by other agents such as predators from farther afield. In this study, we tested the ability of strontium isotopes to help determine the origins of fossil rodents in Gladysvale Cave, South Africa. First, biologically available ^{87}Sr/^{86}Sr ratios were established using modern plants recovered from three geologically distinct areas, the Malmani dolomite, the Hekpoort andesite/basalt, and the Timeball Hill shale, all of which were found to be significantly different. Strontium isotope values were then measured on tooth enamel of rodents from a modern barn owl (*Tyto alba*) roost in Gladysvale Cave. The results clearly distinguished modern owl roost rodents that came from local dolomite (67%) versus those from other geological zones. We then measured strontium isotope values of enamel from 14 fossil rodent teeth from Gladysvale Cave. The average and range of values for the fossil rodents is similar to that of the modern owl roost rodents. Fifty-seven percent of the fossil rodents probably derived from the local dolomite, while others were brought in from at least 0.8 km away. A pilot study of ^{87}Sr/^{86}Sr ratios of fossil rodent teeth from Swartkrans Member 1 and Sterkfontein Member 4 indicates that 81% and 55% of those rodents, respectively, are from the local dolomite substrate. Overall, this study shows that strontium isotopes can be a useful tool in taphonomic analyses by identifying non-local individuals, and has great potential for elucidating more of the taphonomic history of fossil accumulations in the dolomitic cave sites of South Africa.

Keywords: STRONTIUM ISOTOPES, CAVE FILL, TAPHONOMY, FOSSIL RODENTS, STERKFONTEIN, SWARTKRANS, GLADYSVALE

Introduction

Over the past two decades, strontium isotopes have been used successfully as geographic markers in a number of archaeological and ecological applications, such as to determine whether archaeological humans are local or non-local to their burial sites (e.g., Price *et al.*, 1994; Sealy *et al.*, 1995; Montgomery *et al.*, 2005), to investigate animal home range sizes and migration patterns (e.g., Hoppe *et al.*, 1999; Feranec *et al.*, 2007; Barnett-Johnson *et al.*, 2008; Britton et al., 2009), and to determine source areas for archaeological materials such as wood and maize (e.g., Benson *et al.*, 2003, 2009; Reynolds *et al.*, 2005). In this study, we examine the potential for using strontium isotopes as a tool to help decipher the taphonomic history of fossil accumulations.

The ^{87}Sr/^{86}Sr composition of rock is determined largely by its initial rubidium and strontium concentrations and its age (^{87}Rb decays into ^{87}Sr over time), and because of this ^{87}Sr/^{86}Sr differs among rock types (Faure & Powell, 1972). As local rocks weather into soils, strontium isotope ratios that characterize the biologically available soil fluids become incorporated into plants and animals without isotopic fractionation due to their very small relative mass differences. In animals, strontium substitutes for calcium in enamel apatite, and the ^{87}Sr/^{86}Sr of tooth enamel becomes fixed at the time of enamel mineralization. Thus, the tooth enamel of an adult animal will reflect the geological substrate on which it was living and/or acquiring resources when its teeth formed. If an animal such as a rodent is picked up by an avian predator and carried to a geological substrate with a biologically available ^{87}Sr/^{86}Sr different from that on which it lived while its teeth were forming, then this should be apparent by comparing the strontium isotopes in its teeth with local values at the bone accumulation site.

We propose that strontium isotopes can be useful taphonomic indicators of the geographic origins of fossils in the dolomitic caves of South Africa, and in particular may help to elucidate the role of predators as agents in the accumulation process. Our initial approach is in a modern setting, using rodent teeth that accumulated in a modern owl roost at Gladysvale Cave (Berger *et al*., 1993). We measured the biologically available strontium in localities around Gladysvale to test for, and characterize, isotopic distinction across geological substrates potentially within the owl's hunting range. We also measured strontium isotopes in the modern owl roost rodents in order to determine whether they conform to the expected pattern based on the predicted hunting area of the owls and the biologically available $^{87}Sr/^{86}Sr$ from three geological zones. We then examined the strontium isotope ratios in a fossil rodent accumulation from Gladysvale Cave, to assess the feasibility of strontium isotopes for determining whether animals in a fossil accumulation died locally or were brought in by taphonomic agents from farther away. As a trial for our proposal, we present new data for fossil rodent accumulations at the nearby Sterkfontein and Swartkrans caves, and compare these with patterns observed in modern and fossil rodents from Gladysvale.

Study Areas and Sampling Methods

Gladysvale Cave is known for its fossil-bearing breccias and is part of the Cradle of Humankind World Heritage Site located northwest of Johannesburg in Gauteng, South Africa (Berger *et al*., 1993). Gladysvale is located within the John Nash Nature Reserve and is about 14 km northeast of Sterkfontein and Swartkrans Caves (Figure 1). All three cave sites are situated within a northeast – southwest band of Malmani dolomite, which is part of the Precambrian Transvaal Supergroup. Bands of progressively younger geological units of the Transvaal Supergroup extend northwest of the dolomite band, including the Timeball Hill shale and the Hekpoort andesite/basalt, while very ancient rocks from the Witwatersrand and Ventersdoorp Supergroups and the Archaean granites outcrop southeast of the dolomite (Figure 1).

A modern owl roost used by barn owls (*Tyto alba*) occurs within the roofed area of the underground caves at Gladysvale. At the base of a shaft below the roost, along the passage from the upper chamber to the lower chambers of the cave (Pickering *et al*., 2007), modern micromammal remains dropped by the owls accumulate and have formed a massive pile dominated by rodent bones and teeth. We collected rodent skulls from the top of this accumulation in January 2007, July 2007, and January 2008 for the purpose of measuring the strontium isotope ratios in the rodent teeth.

Barn owls typically use roosts repeatedly (Bunn *et al*., 1982; Reed, 2005) and have a hunting radius of about 1-2 km from the roost site, but depending on the type of habitat and prey abundance, are known to travel and hunt up to 5 km from their roost site (Taylor, 1994). Since Gladysvale Cave is located on the dolomites and this geological substrate extends to the east, west, and south for several kilometers (Figure 1), we expect the majority of the rodents hunted by the owls that roost at Gladysvale to derive from dolomite areas. Since the Timeball Hill shale substrate lies only 0.8 km north, and the Hekpoort andesite/basalt substrate is only about 2.5 km north of Gladysvale, we expect a smaller portion of the rodents hunted by the owls to come from those substrates as well.

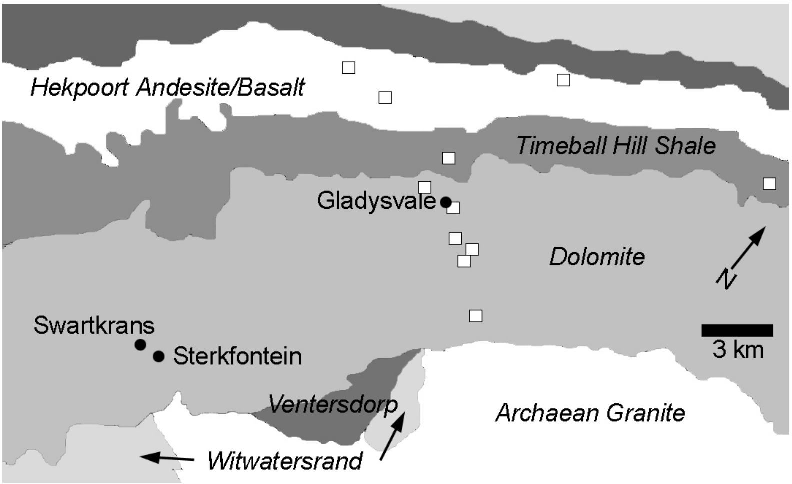

Figure 1. Map showing the major geological zones (in italics) around Gladysvale, Sterkfontein, and Swartkrans caves, South Africa. Cave sites are depicted as black circles, and white squares represent the localities where plants were sampled for biologically available $^{87}Sr/^{86}Sr$. Based on the 1:250,000 maps published by the Geological Survey, Republic of South Africa, 1981.

We analyzed 14 isolated fossil rodent incisors from Gladysvale that were collected during the 2005 excavations at the site. The fossil rodent teeth derive from the decalcified sediments of the External Deposits, which have been estimated to be 570 Ka by U-Th dating (Pickering *et al.*, 2007). The incisors were chosen randomly out of a collection of fossil rodent teeth.

As part of a pilot study, we also analyzed strontium isotope ratios in fossil rodent teeth from Sterkfontein and Swartkrans. Situated within the Malmani dolomite, Sterkfontein and Swartkrans are a minimum of about 5 km and 8 km from the Timeball Hill Shale and Hekpoort andesite/basalt geological zones, respectively (Figure 1). Further studies are currently underway to characterize the biologically available $^{87}Sr/^{86}Sr$ from the geological zones to the south of Sterkfontein and Swartkrans in order to better interpret the findings at those sites, but the dolomite, Timeball Hill shale, and Hekpoort andesite/basalt zones are potentially relevant to the geographical origin of animals ultimately deposited in Sterkfontein and Swartkrans (de Ruiter *et al.*, 2010).

The Sterkfontein fossils examined in this study include 11 isolated rodent incisors from different individuals, which were chosen randomly from a general collection of fossil rodent teeth from the Member 4/Type Site housed at the Transvaal Museum. The Swartkrans fossils examined here include 21 isolated rodent incisors, all from different individuals, also chosen randomly from a general collection of fossil rodents from Member 1 (the Hanging Remnant), also housed at the Transvaal Museum.

Analytical Methods

Teeth. For the fossils, we chose to analyze enamel rather than bone or dentine because enamel has been shown to be far more resistant to potential post-depositional diagenetic contamination in ^{87}Sr/^{86}Sr ratios (Hoppe *et al*., 2003; Lee-Thorp & Sponheimer, 2003). For both modern and fossil teeth, the enamel side of the rodent incisor was first gently cleaned by abrasion with a dental drill equipped with a 1 mm spherical diamond drill bit. The enamel surface was then rinsed with ultrapure deionized water, swabbed with acetone, and swabbed once with 0.1 M acetic acid.

The teeth were measured for ^{87}Sr/^{86}Sr using a New Wave 213 nm laser coupled to a NuPlasma high resolution multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) in the Africa Earth Observatory Network EarthLAB Facility at the University of Cape Town, South Africa. Each laser ablation track included a pre-ablation sweep during which any remaining surface contamination was removed along the path of analysis (250 µm spot size, 750 µm line length, 10 Hz repetition rate, 50 µm/s translation rate, ~0.25 mJ energy, and ~0.5 J/cm^2 fluency). The subsequent laser ablation followed this precleaned path while collecting data (200 µm spot size, 750 µm line length, 20 Hz repetition rate, 5 µm/s translation rate, ~1.35 mJ energy, and ~4.35 J/cm^2 fluency). Most teeth were measured with one or two laser ablation tracks, though a few of the modern rodent teeth were measured three or more times (see Table 1). The on-peak background gas composition was monitored, and ^{84}Kr and ^{86}Kr were subtracted from the signals measured during laser ablation. Following background subtraction, any interference of Ca argides and/or dimers at mass 88, 86, 84, and 83 were corrected using the measured signal at mass 82 and the stable Ca isotope relationships. Instrumental mass fractionation was then corrected using the measured ^{86}Sr/^{88}Sr ratio, an accepted value of 0.1194 for this ratio, and the exponential law. Any contribution of ^{87}Rb on the measured signal at mass 87 was corrected by measuring the interference-free ^{85}Rb signal, correcting for instrumental mass fractionation, and using the natural abundance ratio for ^{87}Rb/^{85}Rb.

The quality of the data was checked by monitoring a bracketing standard at the beginning and end of each laser session and using only values with a total strontium voltage of greater than 0.3 V (Copeland *et al*., 2008). The standard used was a modern rodent tooth with known ^{87}Sr/^{86}Sr ratios determined by solution MC-ICP-MS. We also monitored ^{84}Sr/^{86}Sr during all laser analyses, though we found that the signals measured at mass 84 become unreliable below total Sr signals of 0.9 V, prior to the deterioration of ^{87}Sr/^{86}Sr ratios (Copeland *et al*., 2010).

Although the laser ablation MC-ICP-MS technique provides slightly lower precision and accuracy than solution MC-ICP-MS, these levels are still well within the acceptable range for interpretation of the materials in this study. As detailed in Copeland *et al*. (2008), laser measurements for the 24 modern rodent teeth shown in Table 1 differed on average only 0.0003 ± 0.0002 from solution results. Other comparisons have found slightly larger laser-solution differences, on the order of 0.0005 to 0.0015, when measuring ^{87}Sr/^{86}Sr in teeth (Richards *et al*., 2008; Simonetti *et al*., 2008). However, even those differences are negligible in this study, where mean biologically available ^{87}Sr/^{86}Sr differences between geological zones are very large, on the order of 0.008 to 0.020 (see Results).

Plants. Since whole rock and whole soil ^{87}Sr/^{86}Sr can differ from the biologically available ^{87}Sr/^{86}Sr in a given area (Sillen *et al*., 1998), the biologically available strontium isotope ratios of a geological zone are best determined by analysis of plants or animals

Table 1. Measurements obtained on modern and fossil rodent enamel using laser ablation MC-ICP-MS. Laser external error (2σ) is equal to two times the standard deviation of ^{87}Sr/^{86}Sr measured for all laser runs on that specimen.

specimen	^{87}Sr/^{86}Sr	laser internal error (2σ)	# laser runs	laser external error (2σ)	total Sr (V)	^{85}Rb (V)/ Sr (V)
Modern Gladysvale owl roost rodents						
26-to10z	0.72989	0.00004	72	0.00028	5.1	0.03%
26-to5z	0.75074	0.00009	3		5.5	0.03%
26-r1	0.73760	0.00005	1		3.0	0.03%
26-r2	0.72892	0.00022	1		0.4	0.38%
26-r3	0.73631	0.00009	3		1.8	0.06%
26-r5	0.72832	0.00004	1		3.8	0.04%
26-r7	0.71979	0.00004	1		4.1	0.02%
26-r8	0.74923	0.00013	1		0.7	0.18%
26-r9	0.73003	0.00009	1		1.1	0.06%
26-r10	0.72707	0.00015	1		0.5	0.09%
26-r23x	0.73146	0.00016	1		0.3	0.60%
26-r26x	0.73092	0.00010	1		0.9	0.17%
26-r29x	0.73293	0.00008	10	0.00036	1.9	0.03%
26-r33x	0.73171	0.00008	1		0.9	0.08%
26-r34x	0.75088	0.00007	2		2.0	0.04%
26-r36x	0.73040	0.00013	1		0.4	0.12%
26-to4z	0.73094	0.00004	3		6.1	0.05%
26-to8z	0.73367	0.00009	2		4.2	0.13%
26-to9z	0.73206	0.00017	4		0.4	0.35%
26-r39x	0.72875	0.00013	1		0.8	0.05%
26-r4	0.74368	0.00039	2		0.3	0.11%
26-r20x	0.73556	0.00024	2		0.3	0.54%
26-r21x	0.72730	0.00006	2		1.3	0.09%
26-r22x	0.73313	0.00012	1		0.9	0.13%
Gladysvale Fossil rodents						
GV1	0.73736	0.00007	1		1.3	0.04%
GV2	0.72927	0.00006	1		1.1	0.27%
GV5	0.73577	0.00007	1		1.9	0.03%
GV7	0.72339	0.00007	1		2.2	0.02%
GV8	0.73349	0.00004	1		1.9	0.13%
GV14	0.73502	0.00018	1		0.7	0.95%
GV11	0.74725	0.00016	1		0.5	0.06%
GV9	0.73267	0.00008	1		1.0	0.09%
GV28	0.72676	0.00011	1		6.5	0.01%
GV23	0.73101	0.00005	1		2.4	0.03%
GV22	0.72555	0.00015	1		0.7	0.23%
GV19	0.74704	0.00004	1		4.9	0.02%
GV18	0.72649	0.00008	1		2.0	0.10%
GV17	0.73408	0.00005	1		3.4	0.03%

Table 1 (cont.)

specimen	$^{87}Sr/^{86}Sr$	laser internal error (2σ)	# laser runs	laser external error (2σ)	total Sr (V)	^{85}Rb (V)/ Sr (V)
Swartkrans Fossil Rodents						
sk24664a	0.72659	0.00003	2	0.00011	2.6	0.03%
sk24664b	0.72650	0.00003	2	0.00005	6.2	0.02%
sk24664c	0.72670	0.00005	2	0.00012	2.2	0.03%
sk24664d	0.72674	0.00005	2	0.00005	2.4	0.04%
sk24665a	0.74524	0.00003	2	0.00005	8.7	0.01%
sk24665b	0.73233	0.00003	2	0.00000	9.4	0.01%
sk24665c	0.73123	0.00004	2	0.00005	6.8	0.03%
sk24665d	0.72520	0.00003	2	0.00007	8.1	0.02%
sk24665e	0.74632	0.00004	2	0.00013	8.6	0.01%
sk24665f	0.73130	0.00005	2	0.00006	7.5	0.02%
sk24665g	0.72741	0.00006	2	0.00017	3.9	0.04%
sk24665h	0.75048	0.00006	2	0.00017	3.0	0.03%
sk24665i	0.72532	0.00005	2	0.00001	4.0	0.06%
sk24665j	0.72724	0.00005	2	0.00013	4.9	0.02%
sk24665k	0.72763	0.00006	2	0.00052	4.4	0.03%
sk24665l	0.73029	0.00003	2	0.00016	5.4	0.01%
sk24665m	0.73115	0.00004	2	0.00036	5.3	0.03%
sk24665n	0.73008	0.00006	2	0.00025	4.0	0.03%
sk24665o	0.73273	0.00006	2	0.00062	2.4	0.04%
sk24665p	0.74525	0.00004	2	0.00006	9.4	0.01%
Sterkfontein fossil rodents:						
sts3502a	0.72690	0.00010	2	0.00035	1.5	0.07%
sts3502b	0.73367	0.00031	2	0.00140	4.7	0.03%
sts3502c	0.72518	0.00003	2	0.00003	5.1	0.01%
sts3502d	0.72930	0.00008	2	0.00013	1.7	0.09%
sts3502e	0.76919	0.00004	2	0.00011	6.1	0.04%
sts3502f	0.78848	0.00004	2	0.00002	7.9	0.04%
sts3502h	0.78445	0.00004	2	0.00009	3.4	0.05%
sts3502i	0.74749	0.00003	2	0.00005	7.2	0.01%
sts3502j	0.73120	0.00005	2	0.00006	2.4	0.05%
sts3502k	0.74124	0.00007	2	0.00017	1.8	0.08%
sts3502l	0.72894	0.00007	2	0.00026	1.3	0.31%

that live on that substrate (Price *et al*., 2002). In this study we determined biologically available strontium isotope ratios by collecting plants in the three main geological zones within the vicinity of Gladysvale Cave.

Plant sampling localities were in areas away from agricultural land use, and not disturbed by road development, mining, or other activities that might contaminate the natural local soil with foreign substances. At several sampling localities within each geological zone (see Figure 1), leaves and stems were collected from up to ten different plants, which included a variety of grass, forb, and tree species. For each plant, about two grams of air-dried leaves and/or stems were ashed in a porcelain crucible in a muffle oven at 500ºC for 8 hours in the Department of Archaeology, University of Cape Town, South Africa.

The plant ash was then prepared and analyzed for $^{87}Sr/^{86}Sr$ at the Max Planck Institute

Table 2. Biologically available $^{87}Sr/^{86}Sr$ for the three main geological units in the area surrounding Gladysvale Cave as represented by plants. $^{87}Sr/^{86}Sr$ was calculated as the mean of the means of plants at each sampling locality.

Geological unit	^{87}Sr/^{86}Sr (mean of sampling localities) ± 1σ	Number of sampling localities	Total number of individual plants measured
Malmani dolomite	0.72971 ± 0.00330	6	30
Timeball Hill shale	0.75326 ± 0.00330	2	15
Hekpoort andesite/basalt	0.74548 ± 0.00578	3	9

for Evolutionary Anthropology (MPI-EVA) in Leipzig, Germany following established strontium separation procedures (Copeland *et al*., 2008). In the MPI-EVA class-100 clean lab facility, 15-20 mg of plant ash was weighed out into pre-cleaned 3 ml Savillex™ vials and digested in 2 ml of 14.3 M nitric acid (HNO_3) at 120ºC for 8 hours. The resulting liquid was transferred to clean 2 ml tubes and centrifuged and the non-digested residues were discarded. After separation, the liquid was transferred back to 3 ml Savillex™ vials, dried down and re-dissolved in 1 ml 3 M HNO_3. The sample was then loaded onto clean 2 ml columns containing preconditioned (see Charlier *et al*., 2006 for resin conditioning procedure) 50-100 µm bead Sr-Spec resin (EiChrom Technologies, Inc.). Following several washes with 3 M HNO_3, the Sr was eluted in ultrapure deionized water and dried, then re-dissolved in 3% HNO_3 for MC-ICP-MS analysis. Solution measurements were made using a Thermo Fisher Neptune MC-ICP-MS instrument at MPI-EVA, (details of analytical parameters in Copeland *et al*., 2008). Repeated measurement of SRM 987, which was run concurrently with the samples, gave ^{87}Sr/^{86}Sr values of 0.710273 ± 0.000033 (2σ, n = 97). Data were corrected to an accepted SRM 987 value of 0.71024 ± 0.00004 (2σ, n=6) (Terakado *et al*., 1988; Johnson *et al*., 1990).

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Results

Analysis of variance of the plant data demonstrates a difference in biologically available strontium isotope ratios between the three geological zones ($F_{2,51} = 325.965$, $P < 0.001$) (Table 2). The dolomite plants have a site mean of 0.730 ± 0.003 and there is no overlap in any of their values with plants from the Timeball Hill shale or Hekpoort andesite/basalt (Fischer's PLSD; $P < 0.0001$). The Timeball Hill shale and Hekpoort andesite/basalt plants are also significantly different from one another (Fischer's PLSD; $P < 0.0001$) with site means of 0.753 ± 0.003 and 0.745 ± 0.006, respectively, but there is some overlap between their ranges (Figure 2).

Of the 24 modern owl roost rodents from Gladysvale, the majority (67%; n=16) have values that fall within the dolomite plant range (Figure 2), which is consistent with the expectation that the majority of the rodents hunted by the owls derive from the dolomite substrate. Seven of the modern owl roost rodents (29%) have higher ^{87}Sr/^{86}Sr values that fall either within the range of Timeball Hill shale or Hekpoort andesite/basalt plants, or in-between those and dolomite plant values. One rodent (4%) has a value lower than any of the three geological zones (Figure 2).

Thus 23 of the 24 modern rodents have values consistent with a home range on or shared between the dolomite, Timeball Hill shale, and Hekpoort andesite/basalt geological zones.

Strontium isotope ratios of the fossil rodents from Gladysvale (n=15) as a group show no statistical difference from the modern Gladysvale rodents (t-test, t = -0.227; DF = 36; $P = 0.8213$; Figure 2), and the spread of values is also similar between the two groups (Table 1). The majority of Gladysvale fossil rodents (57%, n=8) have values that fall within the range of dolomite plant values, five (36%) have higher values that are within the range of Hekpoort andesite/basalt or in-between the Timeball Hill shale, Hekpoort andesite/basalt, and dolomite values, whereas one (7%) has a value lower than the dolomite and outside the known range of biologically available $^{87}Sr/^{86}Sr$ for all three zones.

Strontium isotope ratios in 21 fossil rodents from Swartkrans are not significantly different from the modern owl roost rodents at Gladysvale (Fischer's PLSD; $P = 0.6684$), nor from the fossil rodents at Gladysvale ($P = 0.8176$) (Figure 2). The mean $^{87}Sr/^{86}Sr$ for Swartkrans fossil rodent enamel (0.732) is close to the dolomite plant mean (0.730). Seventeen (81%) of the Swartkrans fossil rodents have values within the dolomite plant range, whereas the remaining four (19%) have higher values suggesting that they could have derived from Timeball Hill shale, Hekpoort andesite/basalt, or a mixture of those substrates with dolomite.

The 11 Sterkfontein fossil rodents have a significantly different mean strontium isotope ratio and range relative to the modern Gladysvale, fossil Gladysvale, and fossil Swartkrans assemblages (Fischer's PLSD; $P < 0.01$) (Figure 2). Nonetheless, six of the Sterkfontein specimens (55%) have values within the biologically available range for dolomite, and two (18%) have values that could have derived from Hekpoort andesite/basalt, or a mixture of Timeball Hill shale, Hekpoort andesite/basalt, and/or dolomite. The remaining three specimens (27%) have very high $^{87}Sr/^{86}Sr$ values (0.788, 0.784, and 0.769), which lie outside the 95% confidence limits of the biologically available strontium in the three geological zones measured for this study.

Discussion

In order for strontium isotope ratios to be useful taphonomic indicators in a given area, they must differ between geological zones, and those geological zones must occur at spatial scales relevant to the questions being addressed. The distinction between biologically available strontium isotope ratios as determined by plants in the three geological zones around Gladysvale is therefore highly promising for the potential use of strontium isotopes in this area of South Africa.

In this type of study it is most significant to distinguish "local" versus "non-local" individuals, which in this case means dolomite versus non-dolomite individuals, and this is possible due to the unique strontium isotope ratios on the dolomite. One cannot necessarily trace all of the rodents to a particular geological source, for example, due to the slight overlap in $^{87}Sr/^{86}Sr$ ranges for Timeball Hill shale and Hekpoort andesite/basalt, some rodents might derive from either substrate. The fact that the majority of the modern rodents come from the dolomite substrate is consistent with observations of barn owl behavior, in which owls will preferentially take prey in proximity to their roost, only venturing farther when lack of prey requires it (Taylor, 1994). Another possible explanation for the presence of an animal with non-

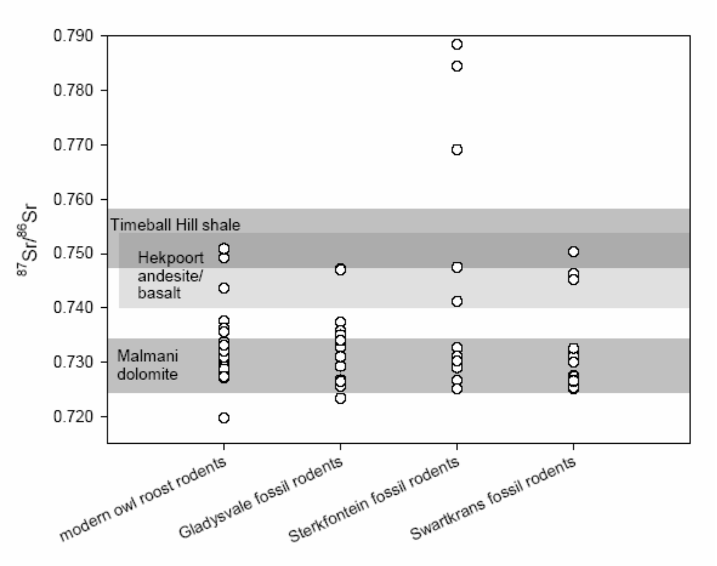

Figure 2. Strontium isotope ratios of incisor enamel in modern owl roost rodents from Gladysvale, fossil rodents from the Gladysvale external deposits, fossil rodents from Sterkfontein Member 4, and fossil rodents from Swartkrans Member 1. The shaded rectangles show the range of plant $^{87}Sr/^{86}Sr$ values found in each of the three geological zones.

local, in this case non-dolomite $^{87}Sr/^{86}Sr$ ratios at a dolomite bone/teeth accumulation site, is that the animal migrated to that location from elsewhere after its teeth had finished mineralizing. This is an important consideration when dealing with animals of large home range size (de Ruiter *et al.*, 2010), but rodents have very small home ranges. For example, the African striped mouse *Rhabdomis pumilio*, a common prey species of the barn owl in South Africa (Herholdt, 1986), has an average home range size of only 0.001 km^2 to 0.015 km^2 (Schradin & Pillay, 2005). Even taking into account the possibility that some rodent individuals may disperse up to one kilometer from their birth place after tooth enamel mineralization, but before breeding, that would not explain the "non-locals" among the modern owl roost rodents, nor among the fossil rodents at Gladysvale, Swartkrans, or Sterkfontein, where most non-dolomite substrates are farther than one kilometer away.

The similarity of the mean and range of $^{87}Sr/^{86}Sr$ ratios between the Gladysvale fossil rodents and the Gladysvale modern owl roost rodents provides strong evidence against diagenetic alteration of the fossil enamel. If diagenetic overprinting had occurred, it would be expected to reduce or increase all of the fossil elements towards the $^{87}Sr/^{86}Sr$ value of the cave fill . (Copeland *et al.*, 2010). Instead, the fossil enamel values from Gladysvale are extremely variable, and span the wide range of known surrounding biologically available $^{87}Sr/^{86}Sr$ values. In contrast to the fossil enamel, dentine values in fossil rodent teeth have a slightly decreased range of values that is more consistent with diagenetic contamination (Copeland *et al.*, 2010). The range of $^{87}Sr/^{86}Sr$ values of the fossil rodent teeth at Gladysvale also suggests that their accumulating agent(s), like the modern Gladysvale rodents, may have been an owl or another predator with a similar hunting area.

The pilot study of $^{87}Sr/^{86}Sr$ in fossil rodents from Swartkrans and Sterkfontein suggests that $^{87}Sr/^{86}Sr$ is a promising technique for deciphering the potential geographic origins of fossil accumulations in these caves. Strontium isotope analysis has the potential to help assess aspects of the taphonomic history and/or behavior of many fossil fauna in isotopically diverse regions such as the current study area; such applications would also apply to early hominins from sites like Swartkrans and Sterkfontein. While in many other parts of the world the spread of biologically available strontium isotope ratios is smaller and different geological zones have more overlap, the utility of $^{87}Sr/^{86}Sr$ in such settings has already been demonstrated with provenience studies of archaeological human skeletons (e.g., Price *et al*., 1994; Sealy *et al*., 1995; Montgomery *et al*., 2005). Therefore there is every reason to suspect that $^{87}Sr/^{86}Sr$ would be useful as a taphonomic sourcing tool for cave fauna or other faunal accumulations in such areas as well.

If the Swartkrans and Sterkfontein rodents were brought in by owls like the modern Gladysvale rodents, then we would expect the majority to be from the surrounding dolomite substrate; perhaps a greater majority than at Gladysvale, because the closest non-dolomite substrates to Swartkrans and Sterkfontein are 3 km and 2 km to the southeast, respectively. The Swartkrans Member 1 fossil rodents conform fairly well to this hypothesis. They have a similar spread of $^{87}Sr/^{86}Sr$ ratios to the modern and fossil rodents from Gladysvale, with a slightly larger proportion (81%) of rodents most likely deriving from the dolomite substrates. That fewer, but still a majority, of Sterkfontein Member 4 fossil rodents (55%) derive from dolomites is consistent with its being 1 km closer to non-dolomites than Swartkrans. The mean and distribution of fossil rodent values at Sterkfontein is different, however, because of the 14% with extremely high values (> 0.760) not seen in the Swartkrans or Gladysvale rodent accumulations.

Although the biologically available strontium isotope ratios of the substrates southeast of the dolomites are still under investigation, we have recorded values as high as 0.774 on plants in the hills there (Copeland, unpublished data). Therefore, this might ultimately prove to be the source area for the rodents with extremely high values that occurred at Sterkfontein. There could also be differences between fossil sites in the types of accumulating agents, such as barn owls versus predators with larger or smaller hunting areas. Overall, the strontium isotope evidence is directing us to ask new questions about the fossil accumulations that would not have been apparent otherwise, thereby contributing a unique role to broader taphonomic inquiries.

Conclusion

This study examined the potential of strontium isotopes for investigating taphonomic issues in dolomitic South African cave sites. The biologically available $^{87}Sr/^{86}Sr$ ratios as determined by plants in the three geological zones within the vicinity of Gladysvale Cave were found to be significantly different. Modern owl roost rodents in Gladysvale Cave matched expected values, showing that the hunting owls collected 67% of their prey from the local dolomite substrate, and probably took 27% of their prey from the nearby Hekpoort andesite/basalt or Timeball Hill shale substrates. Fossil rodents from Gladysvale Cave had a very similar mean and range of $^{87}Sr/^{86}Sr$ ratios as the modern rodents, indicating that the fossil enamel preserved the original $^{87}Sr/^{86}Sr$ ratios and is not affected by diagenesis. In this sample, 43% of the fossil rodents were non-local and therefore may have been accumulated by an owl as well, although other accumulating agents have not been ruled out. Analysis of fossil rodent enamel from Swartkrans and Sterkfontein shows promise, and supports Brain's (1981) contention that owls were significant accumulating agents at Swartkrans. This study augments Brain's work by identifying some potential geological sources of the owl-accumulated rodents. Three anomalously high values from Sterkfontein fossil rodents are not likely to derive from the geological zones for which the biologically available $^{87}Sr/^{86}Sr$ ratios are known, and further investigations are needed for their interpretation. This points out the importance of an understanding of the baseline biologically available $^{87}Sr/^{86}Sr$ values across a region before $^{87}Sr/^{86}Sr$ of fossils can be thoroughly interpreted. In sum, strontium isotopes were found to be highly useful as potential taphonomic indicators in general, and in the area of the dolomitic South African cave sites in particular.

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References

Barnett-Johnson, R., Pearson, T.E., Ramos, F.C., Grimes, C.B. & MacFarlane, R.B. (2008). Tracking natal origins of salmon using isotopes, otoliths, and landscape geology. *Limnology and Oceanography*, 53: 1633-1642.

Benson, L., Cordell, L., Vincent, K., Taylor, H., Stein, J., Farmer, G.L. & Futa, K. (2003). Ancient maize from Chacoan great houses: Where was it grown? *Proceedings Of The National Academy of Sciences of the United States of America*, 100: 13111-13115.

Benson, L.V., Stein, J.R. & Taylor, H.E. (2009). Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico. *Journal of Archaeological Science*, 36: 387-407.

Berger, L.R., Keyser, A.W. & Tobias, P.V. (1993). Gladysvale: First early hominid site discovered in South Africa since 1948. *American Journal of Physical Anthropology*, 92: 107-111.

Brain, C.K. (1981). The Hunters or the Hunted? University of Chicago Press, Chicago.

Britton, K., Grimes, V., Dau, J. & Richards, M.P. (2009). Reconstructing faunal migrations using intra-tooth sampling and strontium and oxygen isotope analyses: a case study of modern caribou (*Rangifer tarandus granti*). *Journal of Archaeological Science*, 36: 1163-1172.

Bunn D.S., Warburton A.B. & Wilson R.D.S. (1982). *The Barn Owl*. Buteo Books, Vermillion, South Dakota.

Charlier, B.L.A., Ginibre, C., Morgan, D., Nowell, G.M., Pearson, D.G., Davidson, J.P. & Ottley, C.J., (2006). Methods for the microsampling and high-precision analysis of strontium and rubidium isotopes at single crystal scale for petrological and geochronological applications. *Chemical Geology*, 232: 114-133.

Copeland, S.R., Sponheimer, M., le Roux, P.J., Grimes, V., Lee-Thorp, J.A., de Ruiter, D.J. & Richards, M.P. (2008). Strontium isotope ratios ($^{87}Sr/^{86}Sr$) of tooth enamel: a comparison of solution and laser ablation multicollector inductively coupled plasma mass spectrometry methods. *Rapid Communications in Mass Spectrometry*, 22: 3197-3194.

Copeland, S.R., Sponheimer, M., Lee-Thorp, J.A., le Roux, P.J., de Ruiter, D.J. & Richards, M.P. (2010). Strontium isotope ratios in fossil teeth from South Africa: assessing laser ablation MC-ICP-MS analysis and the extent of diagenesis. *Journal of Archaeological Science*, 37: 1437-1446.

de Ruiter, D.J., Copeland, S.R., Lee-Thorp, J.A. & Sponheimer, M. (2010). Investigating the role of eagles as accumulating agents in the dolomitic cave infills of South Africa. *Journal of Taphonomy*, 8 (2-3): 129-154.

Faure, G. & Powell, T. (1972). *Strontium Isotope Geology*. Springer-Verlag: New York.

Feranec, R.S., Hadly, E.A. & Paytan, A. (2007). Determining landscape use of Holocene mammals using strontium isotopes. *Oecologia*, 153: 943-950.

Herholdt, J.J. (1986). Diet of the barn owl at a riverine roost in the central Orange Free State. *Ostrich*, 57: 185-187.

Hoppe, K.A., Koch, P.L., Carlson, R.W. & Webb, S.D. (1999). Tracking mammoths and mastodons: Reconstruction of migratory behavior using strontium isotope ratios. *Geology*, 27: 439-442.

Hoppe, K.A. Koch, P.L. & Furutani, T.T. (2003). Assessing the preservation of biogenic strontium in fossil bones and tooth enamel. *International Journal of Osteoarchaeology*, 13: 20-28.

Johnson, C.M., Lipman, P.W. & Czamanske, G.K. (1990). H, O, Sr, Nd, and Pb isotope geochemistry of the Latir volcanic field and cogenetic intrusions, New Mexico, and relations between evolution of a continental magmatic center and modifications of the lithosphere. *Contributions to Mineralogy and Petrology*, 104: 99-124.

Lee-Thorp, J.A. & Sponheimer, M. (2003). Three case studies used to reassess the reliability of fossil bone and enamel isotope signals for paleodietary studies. *Journal of Anthropological Archaeology*, 22: 208-216.

Montgomery, J., Evans, J.A., Powlesland, D. & Roberts, C.A. (2005). Continuity or colonization in Anglo-Saxon England? Isotope evidence for mobility, subsistence practice and status at West Heslerton. *American Journal of Physical Anthropology*, 126: 123-138.

Pickering, R. Hancox, P.J., Lee-Thorp, J.A., Grün, R., Morimer, G.E., McCulloch, M. & Berger, L.R. (2007). Stratigraphy, U-Th chronology, and paleoenvironments at Gladysvale Cave: insights into the climatic control of South African hominin-bearing cave deposits. *Journal of Human Evolution*, 53: 602-619.

Price, T.D., Johnson, C.M., Ezzo, J.A., Ericson, J. & Burton, J.H. (1994). Residential mobility in the prehistoric Southwest United States: a preliminary study using strontium isotope analysis. *Journal of Archaeological Science*, 21: 315-330.

Price, T.D., Burton, J.H. & Bentley, R.A. (2002). The characterization of biologically available strontium isotope ratios for the study of prehistoric migration. *Archaeometry*, 44: 117-135.

Reed, D.N. (2005). Taphonomic implications of roosting behavior and trophic habits in two species of African owl. *Journal of Archaeological Science,* 32: 1669-1676.

Reynolds, A.C., Betancourt, J.L., Quade, J., Patchett, P.J., Dean, J.S.& Stein, J. (2005). $^{87}Sr/^{86}Sr$ sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. *Journal of Archaeological Science*, 32: 1061-1075.

Richards, M., Harvati, K., Grimes, V., Smith, C., Smith, T., Hublin, J.J., Karkanas, P. & Panagopoulou, E. (2008). Strontium isotope evidence of Neanderthal mobility at the site of Lakonis, Greece using laser-ablation PIMMS. *Journal of Archaeological Science*, 35, 1251-1256.

Schradin, C. & Pillay, N. (2005). Intraspecific variation in the spatial and social organization of the African striped mouse. *Journal of Mammalogy*, 86: 99-107.

Sealy, J.C., Armstrong, R. & Schrire, C. (1995). Beyond lifetime averages: tracing life histories through isotopic analysis of different calcified tissues from archaeological human skeletons. Antiquity, 69: 290-300.

Sillen, A., Hall, G., Richardson, S. & Armstrong, R. (1998). $^{87}Sr/^{86}Sr$ ratios in modern and fossil food-webs of the Sterkfontein Valley: Implications for early hominid habitat preferences. *Geochimica et Cosmochimica Acta*, 62: 2463–2473.

Simonetti, A., Buzon, M.R. & Creaser, R.A. (2008). In-situ elemental and Sr isotope investigation of human tooth enamel by laser ablation-(MC)-ICP-MS: successes and pitfalls. *Archaeometry*, 50: 371-385.

Taylor, I. (1994). *Barn Owls*. Cambridge University Press, Cambridge.

Terakado, Y., Shimizu, H. & Masuda, A. (1988). Nd and Sr isotopic variations in acidic rocks formed under a peculiar tectonic environment in Miocene Southwest Japan. *Contributions to Mineralogy and Petrology*, 99: 1-10.