1995

Strontium isotope stratigraphy and age estimates for the Leisey Shell Pit faunas, Hillsborough County, Florida

Douglas S. Jones
University of Florida

Paul A. Mueller
University of Florida

Teresa Acosta

Robert Duncan Shuster
University of Nebraska at Omaha, rshuster@unomaha.edu

STRONTIUM ISOTOPIC STRATIGRAPHY AND AGE ESTIMATES FOR THE LEISEY SHELL PIT FAUNAS, HILLSBOROUGH COUNTY, FLORIDA

Douglas S. Jones[1], Paul A. Mueller[2], Teresa Acosta[3], and Robert D. Shuster[4]

ABSTRACT

The vertebrate fauna of the Leisey Shell Pit near Tampa Bay, Florida, represents one of the more significant Irvingtonian mammalian faunas of North America. The fossil vertebrates occur in thin bone beds bounded above and below by massive shell beds containing a rich invertebrate (chiefly molluscan) fauna. Debate has arisen concerning the precise age of the faunas at Leisey. Although generally agreed to be Pleistocene, estimates based upon vertebrate biostratigraphy suggest a somewhat older age than do estimates based upon molluscan biostratigraphy. To help resolve this controversy, $^{87}Sr/^{86}Sr$ ratios were determined on molluscan shells throughout the section. These ratios were then correlated to the global sea water $^{87}Sr/^{86}Sr$ curve for age determination. The Sr isotopes support an early Pleistocene age for the vertebrate fauna and suggest a complex history for the shell accumulations.

RESUMEN

La fauna de vertebrados de la Excavación de Conchuelas de Leisey cerca de la Bahía de Tampa, Florida, representa una de las faunas Irvingtonianas más importantes de América del Norte. Los vertebrados fósiles se encuentran en capas delgadas de huesos limitadas por arriba y por abajo por gruesas capas de conchuelas que contienen una rica fauna de invertebrados (principalmente moluscos). La edad precisa de las faunas en Leisey se encuentra en debate. Aún cuando en general se ha aceptado que pertenecen al período Pleistoceno, estimaciones basadas en bioestratigrafía de vertebrados sugieren una edad algo mayor que las estimaciones basadas en bioestratigrafía de moluscos. Para ayudar a resolver esta controversia, se determinaron las proporciones de $^{87}Sr/^{86}Sr$ de conchuelas de moluscos a travéz de toda la sección.

1 The senior author is Curator of Invertebrate Paleontology at the Florida Museum of Natural History, University of Florida,
2 P. O. Box 117800, Gainesville FL 32611-7800, USA.
3 Dr. Mueller is Professor of Geology at the University of Florida, Gainesville FL 32611, USA.
4 Ms. Acosta is an environmental geologist in Jacksonville FL, USA.
Dr. Shuster is Associate Professor of Geology & Geography at the University of Nebraska, Omaha NB 68182, USA.

JONES, D.S., P.A. MUELLER, T. ACOSTA, AND R.D. SHUSTER. 1995. Strontium isotopic stratigraphy and age estimates for the Leisey Shell Pit faunas, Hillsborough County, Florida. Bull. Florida Mus. Nat. Hist. 37 Pt. I(2)93-105.

Posteriormente, y con el propósito de determinar la edad, estas proporciones fueron correlacionadas con la curva global para agua de mar de la proporción de $^{87}Sr/^{86}Sr$. Los isótopos de Sr señalan que la fauna de vertebrados pertenecen al Pleistoceno temprano, sugiriendo una compleja historia para las acumulaciones de conchuelas.

INTRODUCTION

Among paleontological sites in Florida, those which expose rich terrestrial and freshwater vertebrate faunas interbedded with robust marine invertebrate faunas have special significance (Tedford and Hunter 1984). Such sites offer unique opportunities for biostratigraphic correlation between marine and terrestrial chronologies as well as for assessment of paleoclimatic and paleobiogeographic changes in both realms. One of the most important of these sections is exposed in the Leisey Shell Pit, situated on the southeastern edge of Tampa Bay, approximately 7 km southwest of the town of Ruskin in Hillsborough County (Fig. 1).

A sizable, early Pleistocene vertebrate fauna was discovered during commercial shell-mining operations in two of the shell pits, Leisey 1 and Leisey 3. The sites within these pits that produced the majority of the vertebrate fossils were referred to as Leisey 1A and 3A (Hulbert and Morgan 1989). The fossils have been completely excavated and most of the significant vertebrate groups have been described (Hulbert and Morgan 1989; companion papers in this volume). Of the over 200 vertebrate species, at least 10 are diagnostic of the Irvingtonian Land Mammal Age (2.0 to 0.3 Ma). In fact, when completely studied, the Leisey vertebrate fauna will rank among the richest Irvingtonian faunas in North America. The occurrence of mammoths (*Mammuthus*) helps to further refine the age estimation, indicating a post-earliest Irvingtonian age (younger than 1.6 Ma). The co-occurrence of other taxa (e.g. *Smilodon gracilis*, *Canis edwardii*) is most suggestive of a late early Irvingtonian age (about 1.5 to 1.0 Ma) for the mammalian faunas (Hulbert and Morgan 1989).

The marine shell beds containing the vertebrate-bearing units at Leisey have been tentatively assigned to the Bermont Formation (Portell et al., this volume). At present, the Bermont is recognized only from southern Florida where it overlies the Caloosahatchee Formation and underlies the Fort Thompson Formation and has been considered to range in age between 0.40 and 0.14 Ma (DuBar 1974). Oakes and DuBar (1974) correlated the Bermont Formation with the Canepatch Formation (Middle Atlantic Coastal Plain), for which Szabo (1985) recently obtained an age of 0.46 Ma based upon uranium-series dates of unaltered corals. Blackwelder (1981), on the basis of molluscan assemblages, had earlier considered the age of both formations to be 0.4-0.5 Ma.

Clearly a major discrepancy exists (on the order of 0.5 to 1.0 million years) between the age of the deposits at the Leisey Shell Pit interpreted from the

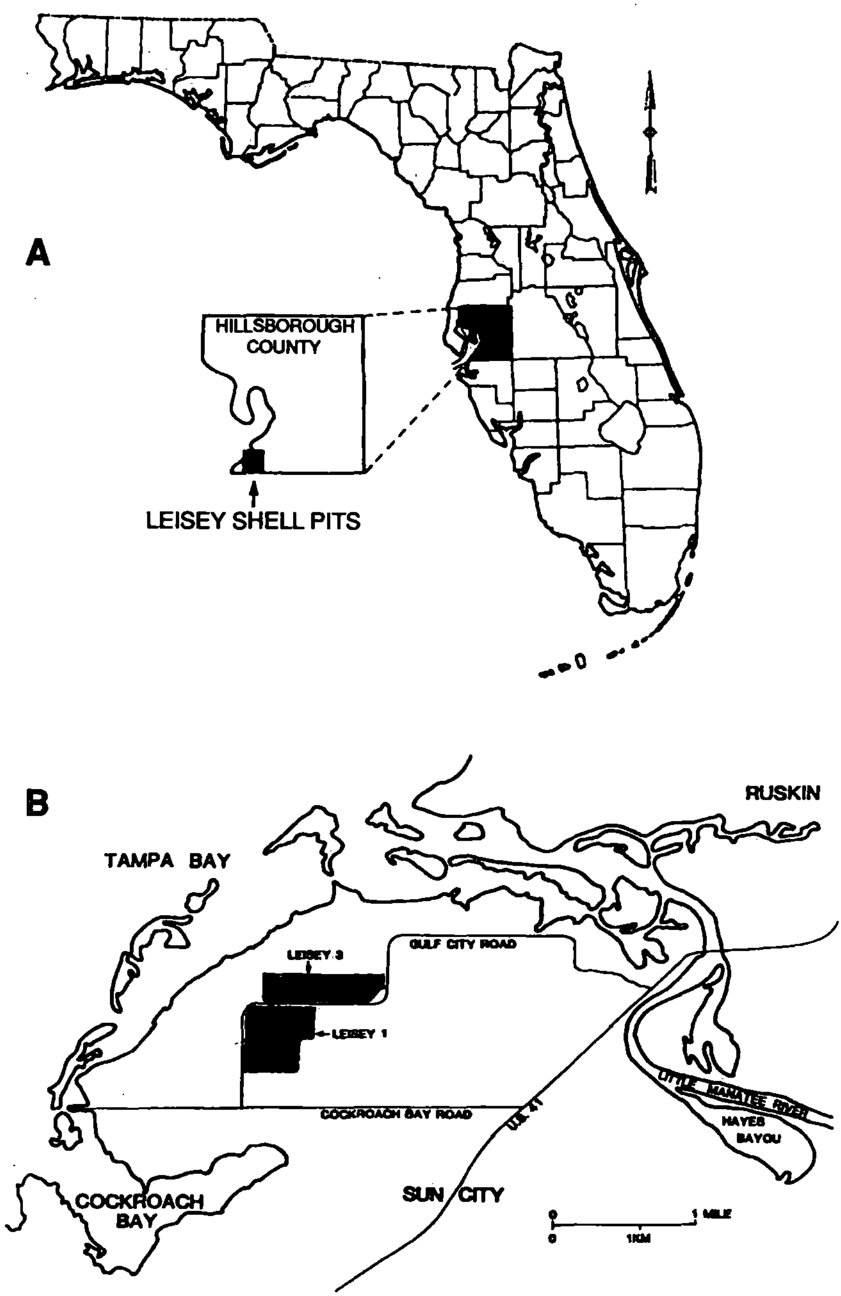

Figure 1. Location map of the Leisey Shell Pit area. (A) General location of the shell pits within Hillsborough County. (B) Location of Leisey Shell Pits 1 and 3. Leisey 1A was situated in the southeast corner of the Leisey 1 quarry while Leisey 3A was located along the southern edge of the Leisey 3 quarry, just west of the center of the pit.

vertebrate faunas and that based upon molluscan biostratigraphy and correlation with dated coral-bearing units of the coastal plain. The relatively young age suggested by the latter two methods is incompatible with the vertebrate faunal evidence. In an attempt to resolve this situation, a comparatively new and emerging stratigraphic method based on the variation of the strontium isotopic composition of sea water with time was applied to samples from both Leisey 1A and 3A. This approach provides an independent technique for age estimation of marine fossils over particular, amenable portions of geologic time.

ACKNOWLEDGEMENTS

We would like to thank Gary S. Morgan for providing the specimens of *Chione cancellata*, for discussion of the stratigraphy and faunas at Leisey, and for comments on an earlier draft of the manuscript. David Hodell, Richard C. Hulbert, Jr., and S. David Webb also provided important assistance and reviews. For help with sample preparation and analysis we thank David Hodell, Jose Garrido, and Kim D'Arcy. This research was supported by National Science Foundation Grant EAR 87-08045. This paper represents University of Florida Contribution to Paleontology No. 323.

STRONTIUM ISOTOPE STRATIGRAPHY

During the 1980s, strontium isotope stratigraphy ($^{87}Sr/^{86}Sr$) evolved as a major geochronologic technique. Studies of marine carbonates demonstrated significant and regular variations in the $^{87}Sr/^{86}Sr$ ratio of sea water throughout geologic time. These studies also showed that during certain intervals of rapid change in Sr isotopic ratios with respect to time, the $^{87}Sr/^{86}Sr$ ratio can be used for rather precise relative and absolute age determination of marine carbonates (e.g. Burke et al. 1982; Palmer and Elderfield 1985; DePaolo and Ingram 1985; DePaolo 1986, 1987; Hess et al. 1986; Elderfield 1986; McKenzie et al. 1988; Veizer 1989; Capo and DePaolo 1990; Hodell et al. 1990, 1991).

Refinements to selected intervals of the global sea water Sr isotope reference curve have revealed particular segments that are amenable to high resolution stratigraphy. Since much of the Neogene (except for 8.0-5.5 Ma and 4.5-2.5 Ma) is characterized by rapid increases in Sr isotopic ratios (DePaolo 1986; Hodell et al. 1991), the carbonate-rich, marine strata of southern Florida are likely targets for Sr stratigraphic studies. To date, two such investigations have been undertaken in the Pliocene-Pleistocene of Florida: (1) a preliminary study at the Leisey Shell Pit (Webb et al. 1989); and (2) a complementary study at the APAC Shell Pit in Sarasota (Jones et al. 1991).

Based upon both vertebrate and invertebrate biostratigraphy, the sections at the Leisey Shell Pit appeared to fall on a segment of the Sr sea water curve which was identified by both Elderfield (1986) and DePaolo (1986) as among the most suitable for correlation and dating. Consequently, in 1987 and 1988, an investigation was undertaken of the variation in $^{87}Sr/^{86}Sr$ ratios in biogenic carbonates throughout the sections at Leisey 1A and 3A. Age determinations were based upon the most detailed sea water Sr reference curve available at that time (DePaolo 1986). The results were integrated with other geochronologic data (vertebrate and invertebrate biochronologies, magnetostratigraphy) and used to constrain the age of the faunas as precisely as possible (Webb et al. 1989). Since this initial study at Leisey, however, the sea water Sr reference curve for the Plio-Pleistocene has undergone further refinement (e.g. Capo and DePaolo 1990; Hodell et al. 1991). In order to take advantage of the increased resolution, we reanalyzed the same 15 samples from the Webb et al. (1989) study, adding 23 duplicate $^{87}Sr/^{86}Sr$ analyses to the data set. The data were then converted to geologic ages using the most recently published sea water curve of Hodell et al. (1991).

MATERIALS AND METHODS

The Leisey 3A site is located approximately 1 km north of Leisey 1A (Fig. 1). The vertebrate faunas at both sites occur in well-defined, unconsolidated, bone-rich layers whose relative elevations are shown in Figure 2. At Leisey 1A, the bone bed is composed of a poorly sorted mixture of marine and freshwater mollusks, bones, fossilized mangrove roots, fine-grained sand, silt, and dark brown clay, varying between 5 and 50 cm thick. The bone bed at Leisey 3A is similar, but lacks fossil mangrove roots and is not as thick. Unconformably overlying the bone bed at Leisey 1A, but not present at 3A, is a 30-50 cm thick layer of indurated calcareous marl containing abundant freshwater gastropods, reworked marine mollusks, assorted bones of freshwater vertebrates, and fine-grained sand. Erosional unconformities above the marl and below the bone bed at 1A and above and below the bone bed at 3A, separate them from upper and lower massive marine shell beds, which, like the bone beds, lack distinct bedding. These massive shell beds of nearshore, marine mollusks contain fewer freshwater gastropods than the bone beds, lack mangrove roots, have a higher percentage of sand and a lower percentage of silt and clay, and are nearly devoid of terrestrial vertebrate fossils (Morgan and Hulbert, this volume; Portell et al., this volume).

The exposed sections (1A and 3A) vary from 7-10 m in thickness. At the base of each is the Arcadia Formation of the Hawthorne Group (not seen in place at 3A because of higher water levels in the pit), consisting of indurated phosphatic dolomite and separated from the lower shell bed at 1A by an erosional unconformity. The upper shell beds are overlain by thick layers of unconsolidated quartz sand which do not contain fossils (Morgan and Hulbert, this volume).

To minimize variability, shells of only one species of bivalve mollusk, *Chione cancellata*, were used. A total of 15 specimens, 8 from Leisey 1A and 7 from Leisey 3A, were analyzed from throughout the sections (Table 1; Fig. 2). The

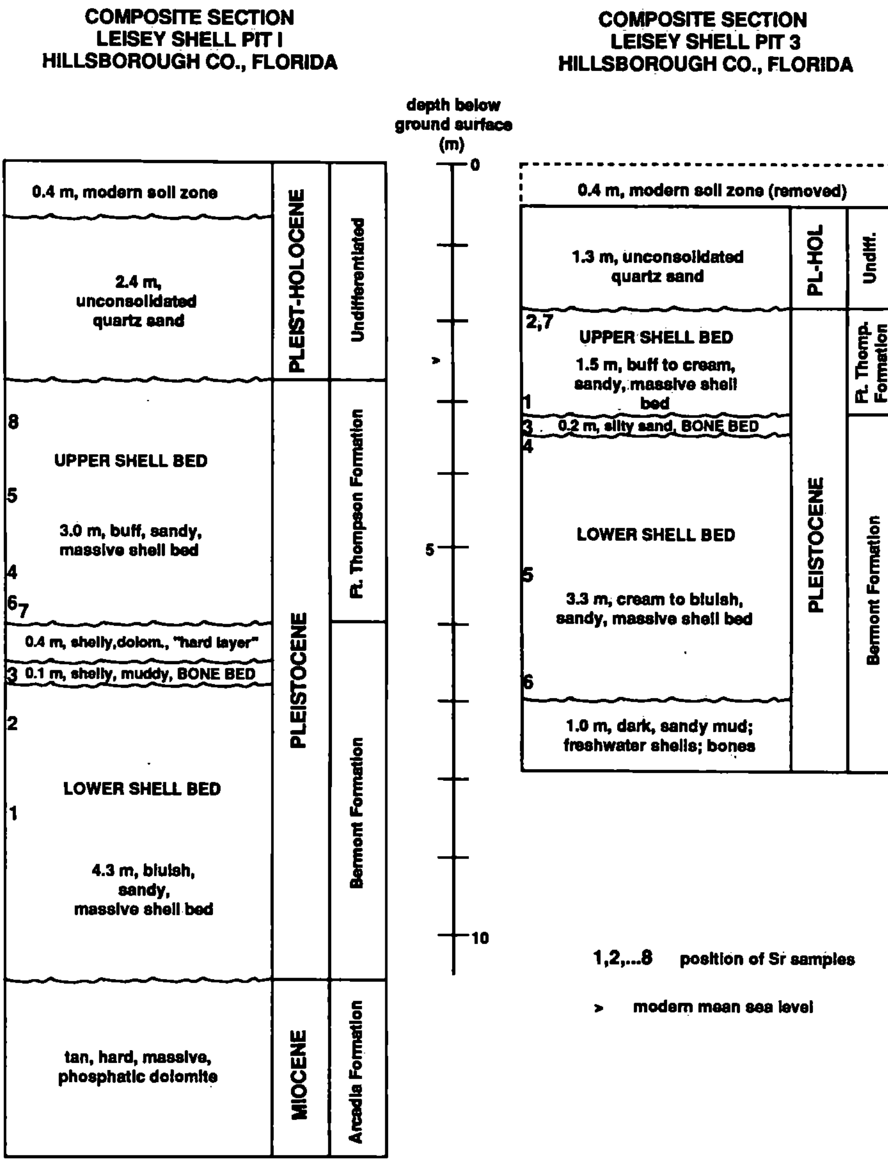

Figure 2. Composite stratigraphic section from the Leisey Shell Pit 1A site and stratigraphic section from Leisey Shell Pit 3A. Bold numbers indicate the sample number and position (see Table 1 and Fig. 2) of strontium samples collected from each site.

initial study (Webb et al. 1989) reported only one analysis per sample specimen (15 total). In the present study we analyzed at least one, and as many as six duplicate, sample splits from each of the same specimens (23 total, Table 1). X-ray diffraction analysis on two samples, thin section examination of four shells, and the non-chalky, fresh appearance of all of the shells suggests little or no diagenetic complications.

In the original sample preparation, valves of *Chione cancellata* were first scrubbed with a stiff brush using soap and water to remove dirt and encrusted materials which could contaminate the shell. The valves were then crushed in a mortar, washed in 0.10N HCl, and rinsed with distilled water. The samples were then air-dried and crushed into a fine $CaCO_3$ powder in the mortar. Sample powders were prepared according to the standard techniques (McKenzie et al. 1988; Hodell et al. 1990) used by Webb et al (1989); however, the current samples were centrifuged and not passed through filter paper. Isotopic ratios were measured on a triple collector VG Isomass 354 mass spectrometer in the dynamic mode with mass fractionation normalized to 86/88 = 0.1194. All runs involved a minimum of 200 ratios, with NBS Standard Reference Material (SRM) 987 = 0.710235, and $2\sigma = 2 \times 10^{-5}$.

RESULTS

Each Sr isotopic ratio determination is reported in Table 1. The ratios are also plotted in Figure 3 as a function of stratigraphic position. The $^{87}Sr/^{86}Sr$ ratios at Leisey 1A range between 0.709020 and 0.709160. At Leisey 3A the range is somewhat less, 0.709029 to 0.709133. A clear trend toward higher ratios with increasing height in the section characterizes both sites (Fig. 3). This overall trend is consistent with published curves for the late Neogene (e.g. DePaolo 1986; Hodell et al. 1991).

Age estimates were calculated for the mean (or best) value of the $^{87}Sr/^{86}Sr$ ratio from each sample (Table 1). The ages were calculated from the regression equation for interval N-1 (2.5-0.0 Ma) on the Neogene $^{87}Sr/^{86}Sr$ sea water curve of Hodell et al. (1991). These ages, then, represent a direct correlation of the $^{87}Sr/^{86}Sr$ ratios determined here to the Hodell et al. (1991) curve. Theoretical considerations indicate that the minimum 95% confidence interval about each of these ages is ±0.56 m.y. (Hodell et al. 1991).

Samples 3A-2 and 3A-7 represent specimens collected from the same horizon which were analyzed to provide an internal check on the degree of variability to be expected. Though the $^{87}Sr/^{86}Sr$ ratios associated with these two samples lie within analytical error of each other, suggesting the shells were contemporaneous, the possibility that the shells may actually be of different ages can not be dismissed. Various physical geologic processes, such as reworking or stratigraphic

Table 1. $^{87}Sr/^{86}Sr$ ratios of biogenic carbonate samples (shells of *Chione cancellata*) from Leisey Shell Pit sites 1A and 3A. Elevations are relative to the Bone Bed datum at each site (see Fig. 2). Ages are calculated from the regression equation for the interval 2.5-0.0 Ma on the Neogene strontium sea water curve of Hodell et al. (1991). The minimum 95% confidence interval about these ages is ±0.56 Ma.

Sample	Elevation (m)	$^{87}Sr/^{86}Sr$ Values	$^{87}Sr/^{86}Sr$ Mean or Best	Age (Ma)	Age (Ma)*
1A - 8	+3.0	0.709160*	0.709142	0.62	0.55
		0.709136			
		0.709137			
		0.709146			
		0.709155			
		0.709132			
		0.709128			
1A - 5	+2.0	0.709143*	0.709123	0.94	0.80
		0.709118			
		0.709109			
1A - 4	+1.0	0.709087*#	0.709130	0.82	1.60
		0.709130			
1A - 6	+0.5 to +1.0	0.709150*	0.709130	0.82	0.70
		0.709121			
		0.709118			
1A - 7	+0.7	0.709133*	0.709131	0.80	0.95
		0.709128			
1A - 3	Bone Bed	0.709079*	0.709055	2.08	1.80
		0.709030			
1A - 2	-1.0	0.709051*	0.709036	2.40	2.30
		0.709020			
1A - 1	-2.0	0.709051*	0.709038	2.37	2.30
		0.709024			

3A - 7	+1.5	0.709122*	0.709122	0.96	1.10
3A - 2	+1.5	0.709109*	0.709121	0.97	1.35
		0.709133			
3A - 1	+0.1 to +0.5	0.709100*	0.709098	1.36	1.40
		0.709104			
		0.709090			
3A - 3	Bone Bed	0.709090*	0.709100	1.33	1.60
		0.709109			
3A - 4	-0.1 to -0.3	0.709094*	0.709076	1.73	1.55
		0.709057			
3A - 5	-1.8	0.709074*	0.709061	1.98	1.85
		0.709049			
		0.709059			
3A - 6	-3.3	0.709083*	0.709056	2.07	1.70
		0.709029			

* = value from Webb et al. (1989).
# = value omitted from calculation.

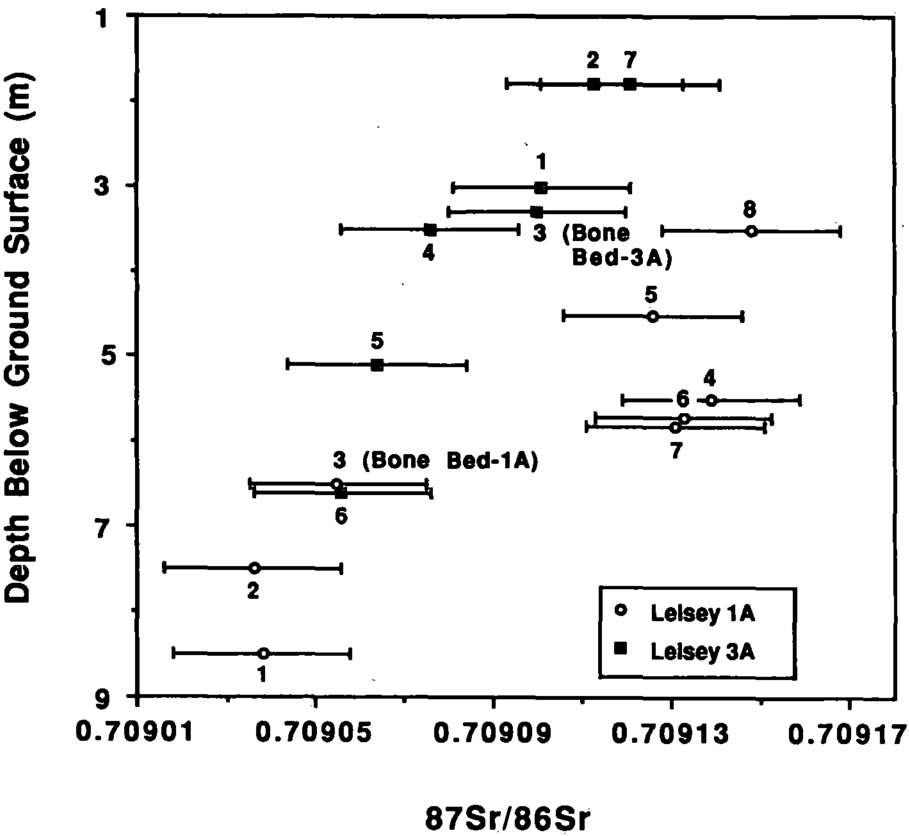

Figure 3. Plot of $^{87}Sr/^{86}Sr$ ratios of samples from Table 1 versus depth below ground surface for both Leisey 1A (open circles) and Leisey 3A (black squares) sites. Elevation of ground surface is nearly identical at each site. Horizontal error bars ($\pm 2 \times 10^{-5}$) represent long-term sample reproducibility which takes into account all errors associated with the analytical procedures (see Hodell et al. 1990).

condensation, could have resulted in shells of different ages occurring in the same horizon so that strict superposition is not necessarily to be expected at either locality.

DISCUSSION AND CONCLUSION

The general pattern of the $^{87}Sr/^{86}Sr$ ratios at Leisey 1A is an up-section increase across the 5 m interval sampled (Fig. 3). The section at 1A shows more variability and a greater range in $^{87}Sr/^{86}Sr$ ratios than Leisey 3A. A strict interpretation of the Sr age estimates (Table 1) places the lower shell bed and the mollusk sample from the bone bed at 1A in the upper Pliocene. Such an interpretation is inconsistent with the biostratigraphic evidence from both mollusks (Portell et al., this volume) and terrestrial vertebrates (Hulbert and Morgan 1989), which suggests a Pleistocene age. Given the uncertainties in precision associated with the global $^{87}Sr/^{86}Sr$ sea water curve, an early Pleistocene age is not unreasonable. Ratios measured in samples from the upper shell bed at 1A seem to indicate that fossils in this unit are of early to mid Pleistocene age.

The samples from the upper shell bed at 1A all have substantially higher $^{87}Sr/^{86}Sr$ ratios than were determined for the lower shell bed or the bone bed. The corresponding ages for these samples cluster between about 0.6 and 0.9 Ma. These comparatively young ages, distinct from those of samples collected lower in the section, suggest a significant portion of time is "missing" or unrepresented at Leisey 1A. The presence of a large, erosional unconformity between the dolomitic "hard layer" and the overlying upper shell bed (Fig. 2) almost certainly accounts for the disparity in ages. The molluscan fauna of the upper shell bed at Leisey 1A suggests this unit may belong in the Ft. Thompson Formation (Portell et al., this volume).

At Leisey 3A, the $^{87}Sr/^{86}Sr$ ratios are much less variable and are spread over a narrower range than at 1A. An overall trend of increasing ratios with increasing elevation is again noted (Fig. 3) with the observation that most ratios are within analytical error of one another. The ages assigned to the Leisey 3A samples range from latest Pliocene in the lower shell bed, to early Pleistocene in the bone bed and immediately above, to middle Pleistocene near the top of the upper shell bed. The age disparity between the upper and lower shell beds observed at 1A is not seen here, nor is the "hard layer" or the large unconformity noted at 1A (Morgan, pers. comm.). The accumulation history of the units at Leisey 3A appears to be more uniform and continuous than at Leisey 1A. However, the small sample numbers and the complex histories of shell bed accumulations (Kidwell et al. 1986) do not justify the calculation of sedimentation rates or completeness estimates.

The $^{87}Sr/^{86}Sr$ ratios of the bone bed shells from Leisey 1A and 3A are notably different, lying outside of the error bars associated with each other (Fig. 3). Upon initial consideration, these data seem to suggest that the vertebrate fossils from the former site were not deposited at the same time as the latter and possibly are older. At Leisey 3A the 1.33 ± 0.56 Ma age calculated for the bone bed sample is consistent with the North American Land Mammal Age (NALMA) estimate of 1.5-1.0 Ma (Hulbert and Morgan 1989). The 95% confidence interval about this age (1.89-0.77 Ma), however, overlaps the 95% confidence interval (2.64-1.52 Ma) about the 2.08 ± 0.56 Ma age calculated for the bone bed sample from Leisey 1A. Given these limits to stratigraphic resolution associated with the sea water $^{87}Sr/^{86}Sr$ curve of Hodell et al. (1991), it is therefore impossible to distinguish between these two ages or between the Sr ages and the NALMA estimate.

At Leisey 1A the $^{87}Sr/^{86}Sr$ ratios from the bone bed and the lower shell bed are indistinguishable from one another, but are clearly distinct from the upper shell bed (Fig. 3). With the presence of such a large hiatus, it is entirely possible that the bones at 1A are coeval with those at 3A, but not with the shells in the 1A bone bed (i.e. sample 1A-3). Terrestrial and freshwater vertebrates probably inhabited the region during the "missing time" between samples 1A-3 and 1A-7. Their bones were deposited on top of, and condensed into, older, pre-existing marine shell accumulations (i.e. the lower shell bed).

In the Introduction it was noted that a discrepancy exists between the age estimate for the strata at the Leisey Shell Pit provided by vertebrate biostratigraphy (1.5-1.0 Ma) and that of molluscan biostratigraphy and correlation with coral-bearing units dated by uranium-series methods (0.4-0.5 Ma). The Sr age of 1.33 Ma for the bone bed at Leisey 3A and the age bracket of 2.08-0.80 Ma for the bone bed at Leisey 1A clearly favor the older age proposed by the vertebrate paleontologists. The lower shell beds at each site contain molluscan faunas which, on the basis of their $^{87}Sr/^{86}Sr$ ratios, seem to be latest Pliocene to early Pleistocene in age. In contrast, molluscan biostratigraphy suggests placement in the much younger (middle Pleistocene) Bermont Formation (Portell et al., this volume). Three alternatives exist: (1) the sea water $^{87}Sr/^{86}Sr$ curve of Hodell et al. (1991) needs refinement and the Sr ages calculated here are too old; (2) the assignment to the Bermont Formation is in error and the lower shell beds actually belong to an older stratigraphic unit; or (3) the conventional age designations for the Bermont Formation are too young. We believe that age diachroneity of the few "key" molluscan taxa and/or poor correlation to the more diverse, shelly faunas of southern Florida may account for the apparent age discrepancy.

On the basis of their molluscan faunas, the upper shell beds at each site were assigned to the Fort Thompson Formation (Portell et al., this volume). The same set of three alternatives and potential biostratigraphic problems apply to the age disparity here as to the lower shell beds. However, given the 95% confidence interval of ±0.56 m.y. about each of the ages, the magnitude of the age disparity is much less than for the lower shell beds.

LITERATURE CITED

Blackwelder, B. W. 1981. Late Cenozoic stages and molluscan zones of the U.S. Middle Atlantic Coastal Plain. J. Paleon. Mem. 12:1-34.

Burke, W. H., R. E. Denison, E. A. Hetherington, R. B. Koepnick, H. F. Nelson, and J. B. Otto. 1982. Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time. Geology 10:516-519.

Capo, R. C., and D. J. DePaolo. 1990. Seawater strontium isotopic variations from 2.5 million years ago to the present. Science 249:51-55.

DePaolo, D. J. 1986. Detailed record of the Neogene Sr isotopic evolution of seawater from DSDP Site 590B. Geology 14:103-106.

_____. 1987. Correlating rocks with strontium isotopes. Geotimes 32(12):16-18.

_____, and B. L. Ingram. 1985. High-resolution stratigraphy with strontium isotopes. Science 227: 938-941.

DuBar, J. R. 1974. Summary of the Neogene stratigraphy of the late Neogene strata of the Caloosahatchee River area of southern Florida. Pp.206-231 *in* R.Q. Oakes and J.R. DuBar, eds. Post-Miocene Stratigraphy, Central and Southern Atlantic Coastal Plain. Utah State Univ. Press, Logan.

Elderfield, H. 1986. Strontium isotope stratigraphy. Palaeogeogr., Palaeoclimatol., Palaeoecol. 57:71-90.

Hess, J., M. L. Bender, and J- G. Schilling. 1986. Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to present. Science 231:979-984.

Hodell, D. A., G. A. Mead, and P. A. Mueller. 1990. Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans. Chem. Geol. (Isotope Geoscience Sect.) 80:291-307.

_____, P. A. Mueller, and J. R. Garrido. 1991. Variations in the strontium isotopic composition of seawater during the Neogene. Geology 19:24-27.

Hulbert, R. C., Jr., and G. S. Morgan. 1989. Stratigraphy, paleoecology, and vertebrate fauna of the Leisey Shell Pit Local Fauna, early Pleistocene (Irvingtonian) of southwestern Florida. Pap. Florida Paleon. 2:1-19.

Jones, D. S., B. J. MacFadden, S. D. Webb, P. A. Mueller, D. A. Hodell, and T. M. Cronin. 1991. Integrated geochronology of a classic Pliocene fossil site in Florida: Linking marine and terrestrial biochronologies. J. Geol. 99:637-648.

Kidwell, S. M., F. T. Fürsich, and T. Aigner. 1986. Conceptual framework for the analysis and classification of fossil concentrations. Palaios 1:228-238.

McKenzie, J. A., D. A. Hodell, P. A. Mueller, and D. W. Müller. 1988. Application of strontium isotopes to late Miocene-early Pliocene stratigraphy. Geology 16:1022-1025.

Oakes, R. Q., Jr., and J. R. DuBar. 1974. Tentative correlation of post-Miocene units, central and southern Atlantic Coastal Plain. Pp. 232-245 *in* R. Q. Oakes, Jr., and J. R. DuBar, eds. Post-Miocene Stratigraphy, Central and Southern Atlantic Coastal Plain. Utah State Univ. Press, Logan.

Palmer, M. R., and H. Elderfield. 1985. Sr isotope composition of sea water over the past 75 Myr. Nature 314:526-528.

Szabo, B. J. 1985. Uranium-series dating of fossil corals from marine sediments of southeastern United States Coastal Plain. Geol. Soc. Amer. Bull. 96:398-406.

Tedford, R. H., and M. E. Hunter. 1984. Miocene marine-nonmarine correlations, Atlantic and Gulf Coastal Plains, North America. Palaeogeogr., Palaeoclimatol., Palaeoecol. 47:129-151.

Veizer, J. 1989. Strontium isotopes in seawater through time. Ann. Rev. Earth Planet. Sci. 17:141-167.

Webb, S. D., G. S. Morgan, R. C. Hulbert, Jr., D. S. Jones, B. J. MacFadden, and P. A. Mueller. 1989. Geochronology of a rich early Pleistocene vertebrate fauna, Leisey Shell Pit, Tampa Bay, Florida. Quat. Res. 32:96-110.