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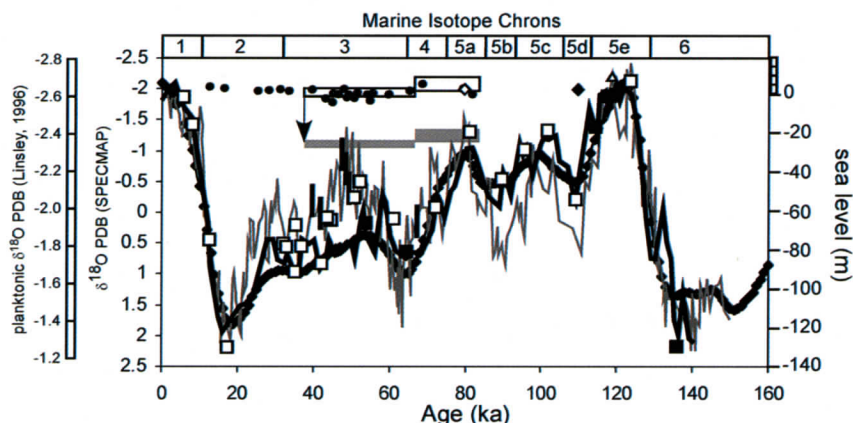
Editor in Chief: S. Duncan Heron, Jr.

### **Abstract**

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# SOUTHEASTERN GEOLOGY



## OSL ages (this study)

- ◆ HCC-01       approx. RSL
- ◆ DRC-01       RSL corrected for GIA
- △ WCQ-01

- ◆ stacked SPECMAP  $\delta^{18}\text{O}$  curve (Imbrie et al., 1989; MacIntyre et al., 1989)
- sea level estimate based on coral reef terraces (Chappell et al., 1996)
- sea level estimate based on lowstand deposits (Chappell et al., 1996)
- combined benthic and planktonic foraminiferal  $\delta^{18}\text{O}$  (Chappell et al., 1996)
- | sea level estimate based on Vanuatu coral terraces (Cabioch and Ayliffe, 2001)
- planktonic foraminiferal  $\delta^{18}\text{O}$  (Sulu Sea; Linsley, 1996)
- OSL ages (Mallinson et al., 2008)



# SOUTHEASTERN GEOLOGY

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Editor

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## OPTICAL DATING OF THE ANASTASIA FORMATION, NORTHEASTERN FLORIDA, USA

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### ABSTRACT

The single-aliquot regenerative-dose (SAR) procedure was used to obtain optically stimulated luminescence ages to determine the depositional age of the upper part of the Anastasia Formation. This unit, which crops out along the east coast of Florida, is one of the most culturally and economically important coquina deposits in North America. Rock samples from the upper three meters of exposure at three locations were collected. Additional materials for paleontological analysis were also taken. Based on our samples, the luminescence ages of the Anastasia Formation are well within marine isotope stage 5, which is supported by the results of Osmond et al. (1970) based on U/Th ages. The associated fossil assemblages support our luminescence age determinations. Associated fossils fall within the Rancholabrean North American Land Mammal Age (300 – 10 ka) and the fossil mollusk assemblage consists entirely of modern species.

### INTRODUCTION

Optical luminescence dating is a radiation-exposure dating method based on the complete loss of previous luminescence in the quartz crystals by exposure to sunlight for a relatively short period of time, followed by subsequent accumulation of the luminescence signal due to the effects of natural radiation during burial (Rink & Forrest, 2005; Wintle, 2008). The burial age is determined by measuring annual dose rate, which consists of cosmic doses from ura-

nium, thorium, and potassium amounts in the localized environment, and the amount of radiation (palaeodose) the sample has received since deposition. The ratio of the palaeodose to the dose rate yields the burial age.

Optically stimulated luminescence dating (OSL) has now become a well-established chronological tool for dating aeolian and other coastal siliciclastic deposits around the world (Stokes, 1999; Murray-Wallace et al., 2002; Ballarini et al., 2003; Madsen et al., 2005; Buynevich et al., 2007; Mallinson et al., 2008) and more authors are now applying optical dating techniques on coquina, beachrock, and aeolianites (Frenchen et al., 2001; Tatumi et al., 2003; Bateman et al., 2004; Frechen et al., 2004; Armitage et al., 2006; Tatumi et al., 2006; Hearty and O'Leary, 2008). Those who have attempted to date these materials using optical dating have had encouraging results, with ages corresponding within error to other dating techniques or geologic context.

This paper presents OSL results for three samples collected in the Anastasia Formation in Northeastern Florida in an attempt to place numerical geochronological constraints on the deposition of this unit. These constraints will allow us to define sea levels at a time in geologic history when relative sea level was at or above present.

### Anastasia Formation

Along the eastern coast of Florida, exists one of the most culturally and economically important coquina deposits in North America, the Anastasia Formation. The building blocks for



Castillo de San Marcos, a 17<sup>th</sup> century Spanish fort near St. Augustine, Florida, were quarried from this coquina. The Spanish used the Anastasia not only for its availability, but also for its ability to absorb cannon-ball impacts. The present study attempts to place numeric ages on the upper part (0–3 m) of the Anastasia Formation using OSL dating techniques.

The Anastasia Formation, named by Sellards (1912), consists of various admixtures of sand, shell, and coquinoid limestone. It occurs along the east coast of Florida from St. Johns to Palm Beach counties (Scott et al., 2001) and underlies the Atlantic Coastal Ridge geomorphic province (Scott, 2004). The formation extends inland up to 32 km (20 miles). The dominant lithology in coastal exposures is a coquinoid limestone. In the subsurface the formation can consist of unconsolidated shell and shelly sands of nearshore marine facies. The Anastasia Formation interfingers laterally with the Fort Thompson Formation and the Miami Limestone (both late Pleistocene) in the southern extent of its distribution. The Anastasia Formation is up to 30 m (100 feet) in thickness (Parker et al., 1955).

Lovejoy (1987) recognized two facies within the Anastasia Formation in Martin and Palm Beach counties. These are a coquinoid limestone facies and a shellrock facies. The coquinoid limestone facies consists of calcite-cemented whole and fragmented mollusk shells, varying percentages of quartz sand, and a small percentage of heavy minerals. The shellrock facies contains less abundant fragmented mollusk shells and is not as well cemented as the coquinoid limestone facies. Certain phases of these facies formed due to meteoric diagenesis. The coquinoid limestone facies formed in the phreatic zone (saturation zone) and the less-cemented shellrock facies formed in the vadose zone (aeration zone).

A number of sedimentary structures have been observed in the Anastasia Formation including cross-bedding, horizontal bedding, and infilled burrows. All sedimentary structures suggest that the Anastasia Formation was deposited in a near-shore, marine environment.

Fossil marine macro-invertebrates from the

Anastasia Formation include sponges, bryozoans, corals, mollusks (Johnson, 1993; Lovejoy, 1992), crabs (Portell et al., 2003), and echinoids (Portell and Oyen, 2002). Mollusks dominate the unit with the other taxa being a minor component. Bivalves are most abundant and consist primarily of infaunal species. Typically, mollusk shells occur as abraded fragments (loose or calcite-cemented) although whole shells can often be found.

Vertebrate fossils typically are uncommon in the Anastasia Formation but have been recovered, most often from the Anastasia Formation in Brevard and St. Johns counties. In Brevard County, taxa collected consist of abraded teeth of sharks and bones of turtles, tapir, horse, armadillo, and whales (Portell et al., 2003).

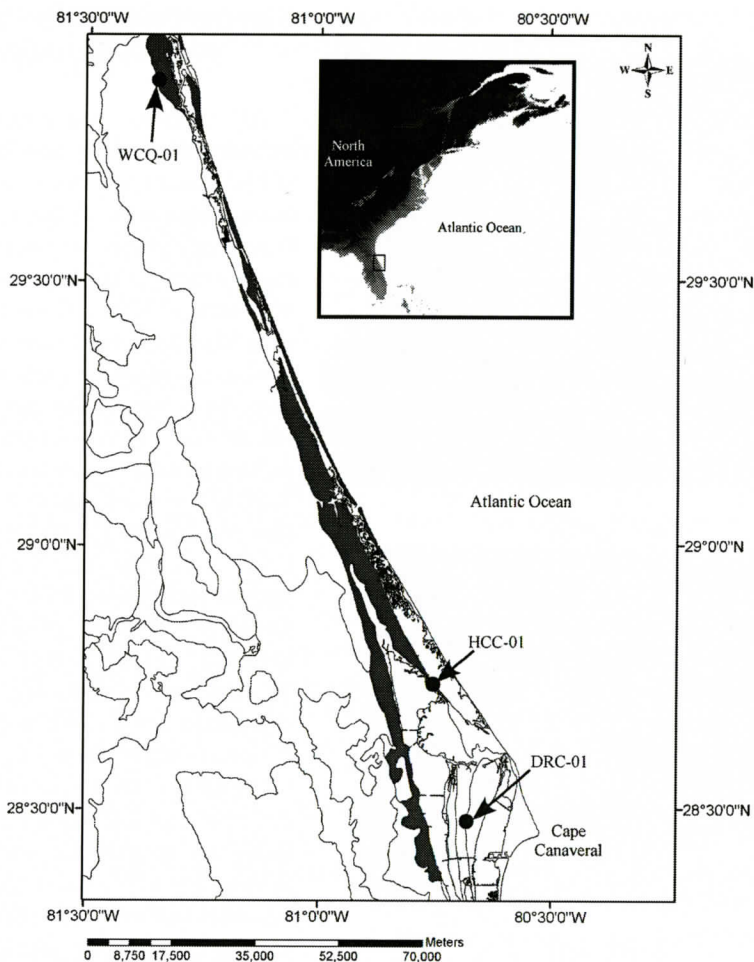
## Previous Geochronology Work

Osmond et al. (1970) used open system  $^{230}\text{Th}/^{234}\text{U}$  age determination modeling on mollusk shell and beachrock from the Cape Kennedy (Canaveral) barrier and lagoon complex to identify two major depositional events in the Merritt Island area. The first occurred between 25 and 50 ka with a majority of the shell samples (5 of 7) falling on a 30 ka isochron (MIS-3). Although eustatic sea levels during this period was ~75 m below present, Mallinson et al. (2008) identified several MIS-3 deposits at or near present sea level in the Coastal Plain of North Carolina. The second occurred between 85 and 120 ka, with a majority of the shell and coquina samples (8 of 11) falling near a 110 ka isochron. Kaufman et al. (1971) argues that dates obtained on mollusks by the U-series isotope methods are highly questionable and that isotope migration is a common phenomenon and occurs in ways which can neither be reliably corrected for, nor even detected.

## METHODS

### Sample Strategy and Acquisition

Three locations were chosen to sample the Anastasia Formation due to their location along strike of the formation and their exposure (Fig-



**Figure 1. Geologic map of Florida showing core locations. The Anastasia Formation is represented by the shaded polygons.**

ure 1). WCQ-01 (Wilson Coquina Quarry) was collected in a commercial coquina quarry; HCC-01 (Haulover Canal Coquina) was collected in a navigation canal in northern Merritt Island connecting Mosquito Lagoon and Indian River; and DRC-01 (Dalbora Road Coquina) was collected from an exposure in a drainage ditch on Dalbora Road (Figure 2). Although DRC-01 is not directly located within the Anastasia Formation boundaries on the State of Florida Geological map, it is believed that this coquinoid limestone is part of the Anastasia Formation (T. Scott, personal communication, July 2008).

Two samples (HCC-01 & WCQ-01) were

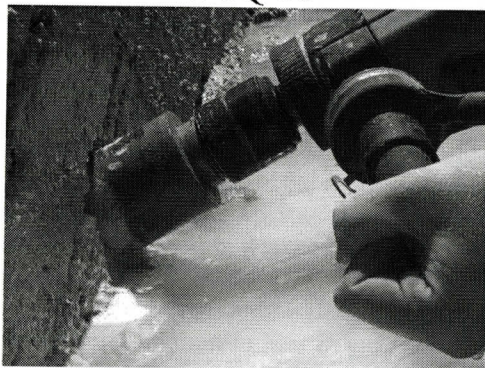
collected using a hand-held diamond core drill with a three-inch (7.62 cm) core barrel. The cores were placed from the core barrel directly into an opaque black photograph-paper bag to minimize exposure to sunlight. DRC-01 was collected at night using a red-filtered flashlight and was hand excavated using a wrecking bar. For the latter sample, exposed coquina on the outcrop was removed using a rock hammer, and an unexposed sample from inside the outcrop was removed and placed into an opaque black bag.



HCC-01



WCQ-01



DRC-01



Figure 2. Photographs of each sample location.

## Sample Preparation and Dose-Rate Measurements

All samples were processed at the School of Geography and Earth Sciences at McMaster University under subdued orange light with ultra-violet filtration. Pure quartz grains were obtained using a slightly modified OSL preparation method described below. The recovered cores of solid coquina were placed in 50% HCl until approximately 2 cm was removed from the outside of the core. This was to ensure that any zeroed grains from the drilling process were removed. After discarding the waste sand, the remaining core was digested in 50% HCl. Once the cores were digested, the typical OSL preparation method followed, which included 30%  $\text{H}_2\text{O}_2$  digestions to remove organics, sieving to obtain the desired 100-200 micron grain size, heavy liquid separation using Lithium Polytungstate to remove heavy minerals and feldspars, HF digestion for 40 minutes to remove the outer alpha affected layer and to remove any plagioclase, another HCl digestion for 40 minutes to remove any fluorides that may have precipitated during the HF digestion, and finally resieving to remove any grains that no longer fall in the 100-200 micron size range.

Some dose rates were based on neutron activation analysis (NAA) of  $^{232}\text{Th}$  and  $^{40}\text{K}$  and delayed neutron counting (DNC) analysis of  $^{238}\text{U}$  (conducted at the McMaster University Nuclear Reactor). Determination of the elemental concentrations of radioactive  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  were from untreated subsamples of the original samples (Table 1). NAA-based dose rates were calculated assuming radioactive equilibrium in the  $^{238}\text{U}$  and  $^{232}\text{Th}$  decay chains. Dose rates for all three sites were also measured using in situ gamma spectrometry. Moisture contents are usually measured in the lab from the recovered sediment and used for the dose rate calculation. Due to the



**Table 1. Location, approximate elevation, and U, Th, and K values of Anastasia Formation samples, which were determined by NAA/DNC on sub-samples derived from the OSL samples prior to chemical treatments.**

Sample Name	Coordinates (WGS 84)	Approx Elevation above MSL (m) [a]	U <sup>238</sup> (ppm)	Th <sup>232</sup> (ppm)	K (%)
HCC-01	28 44.158°N 80 45.228°W	2	0.70	0.63	0.0397
WCQ-01	29 52.889°N 81 21.147°W	8	0.51	0.86	0.0674
DRC-01	28 28.694°N 80 40.535°W	2	1.48	1.16	0.0607

[a] Elevations were estimated using the Florida digital elevation model (USGS, 2005).

constant wetting of the corer, the moisture contents calculated would not represent true field moisture, therefore moisture contents of 5% and 10% were assumed for all samples. Cosmic ray dose rates were calculated using the burial depth (assuming an instant sedimentation rate) and a 2 g/cm<sup>3</sup> of overburden density using calculations by Prescott and Hutton (1988) with the ANATOL program version 0.72B (provided by N. Mercier, CNRS, Paris). The internal <sup>238</sup>U and <sup>232</sup>Th dose rates were calculated using the average concentration of those radioisotopes in granitic quartz (Rink and Odom, 1991), using an alpha efficiency factor of 0.04 +/- 10%.

### OSL Measurements and Equivalent Dose Determination

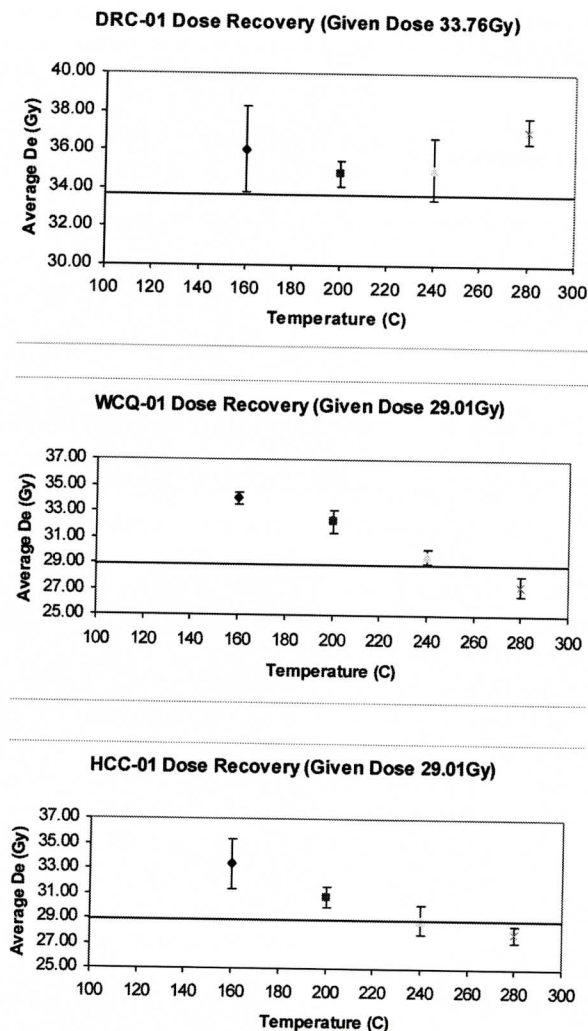
Luminescence measurements were conducted on a RISØ OSL/TL-DA-15 reader using blue light LED stimulation (470 nm) and a 7 mm-thick Hoya U-340 filter (270–400 nm). A calibrated <sup>90</sup>Sr beta source was used to perform laboratory irradiations. The single aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) was conducted on a minimum of 24 aliquots to determine a final equivalent dose (De) which was assumed to be the palaeodose. Quartz grains were mounted on aluminum discs using a 8mm mask and silicon spray. Samples were illuminated for 100 seconds at 125°C. The background (the last 4 s) of the OSL decay curve was subtracted from the “fast” component (first 0.4 s) to determine the samples lumi-

nescence signal. Only aliquots whose recycling ratios were within 10% were accepted for De determination.

Thermal transfer and dose recovery tests were performed to determine final De preheat temperature (Madsen et al., 2005). For both tests, twelve aliquots from each sample were optically bleached by blue light illumination for 40 seconds, followed by a 10,000 second pause and another 40 second illumination. For the dose recovery test, the aliquots were given a known dose (29Gy for HCC-01, 29Gy for WCQ-01, and 33Gy for DRC-01). Both tests continued with the standard SAR protocol except the preheat temperatures varied (160, 200, 240, 280°C), with 3 aliquots from each sample receiving a different preheat temperature.

A feldspar contamination check, as outlined by Thompson et al. (2007), was also performed on each sample to insure purity of the quartz grain separates. An initial De was estimated by comparing the natural OSL signal (preheat T = 200°C) of 3 aliquots to the regenerated OSL given by a single dose. A second identical regeneration dose was applied to the same aliquots and the IRSL signal was measured. If a ratio of IRSL to regenerated OSL signal was less than 1% for all aliquots, it is assumed there is no significant feldspar contamination (Forrest, 2003).

The data were analyzed using an exponential plus linear function in the RISØ Luminescence Analyst program (version 3.15b). A weighted mean and standard error was calculated using



**Figure 3.** Dose recovery tests for each sample. The line drawn represents the known dose given to each laboratory bleached sample.

the Central Age Model spreadsheet (provided by S. Hout & B. Roberts). The central age model explicitly determines the extent of paleodose over-dispersion between aliquots, and takes this into account when estimating the mean paleodoses (Galbraith et al., 2005). Over-dispersion is defined as the dispersion remaining after photon counting statistics have been taken into account (Galbraith et al., 2005).

## RESULTS

### Optical Dating Results

The thermal transfer and dose recovery tests were used to determine the preheat temperature that would give the most accurate De estimates. For each sample the dose recovery test was used to determine which preheat temperature produced a De closest to the given dose (Figure 3). Once this preheat temperature was determined the thermal transfer test was analyzed to ensure there was no induced charge transfer at that giv-

Table 2. Luminescence Dating Results [a] Cosmic dose rate value calculated using an instant accumulation model (IA) and an overburden density of 2 g/cm<sup>3</sup>. [b] All  $\beta$  and  $\gamma$  dose rates were calculated based on U, Th, and K concentrations of each sample accounting for moisture values of the sample. [c] Datum for SAR-OSL ages is A.D. 2008.

Sample Name	Sample Depth (cm)	De (Gy)	Cosmic Dose Rate ( $\mu$ Gy/a) [a]	Water Content (%) [b]	NAA/DNC Gamma Dose ( $\mu$ Gy/a)	In Situ Gamma Dose ( $\mu$ Gy/a)	Beta Dose ( $\mu$ Gy/a)	Total Internal Dose ( $\mu$ Gy/a)	Annual Dose ( $\mu$ Gy/a) [b]	SAR-OSL age (ka) [c]	Marine Isotope Stage
HCC-01	244	33.2 $\pm$ 1.2	151.02 $\pm$ 15.1 (IA)	10.00	108.8 $\pm$ 10.7		119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	389.5 $\pm$ 16.6	91.6 – 78.8	MIS-5a
				10.00		171.8 $\pm$ 8.5	119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	452.6 $\pm$ 15.3	77.9 – 68.7	MIS-5a
				5.00	113.5 $\pm$ 11.1		119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	400.0 $\pm$ 17.4	89.1 – 76.7	MIS-5a
				5.00		179.3 $\pm$ 8.9	119.2 $\pm$ 12.5	10.5 $\pm$ 2.3	465.7 $\pm$ 16.0	75.6 – 66.8	MIS-5a
WCQ-01	266	45.6 $\pm$ 1.9	146.76 $\pm$ 14.6 (IA)	10.00	105.3 $\pm$ 10.8	N/A	120.4 $\pm$ 11.6	10.5 $\pm$ 2.3	383.1 $\pm$ 16.0	128.3 – 109.7	MIS5e-MIS5c
				5.00	109.9 $\pm$ 11.2	N/A	120.4 $\pm$ 11.6	10.5 $\pm$ 2.3	393.4 $\pm$ 16.7	124.9 – 106.9	MIS5e-MIS5c
DRC-01	60	73.0 $\pm$ 3.0	194.43 $\pm$ 19.4 (IA)	10.00	217.3 $\pm$ 11.1		233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	655.4 $\pm$ 16.3	119.4 – 103.4	MIS5e-MIS5c
				10.00		222.4 $\pm$ 10.4	233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	660.5 $\pm$ 15.9	117.5 – 103.5	MIS5e-MIS5c
				5.00	226.8 $\pm$ 11.5		233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	676.0 $\pm$ 17.1	115.7 – 100.3	MIS5e-MIS5c
				5.00		232.1 $\pm$ 10.8	233.1 $\pm$ 11.8	10.5 $\pm$ 2.3	681.3 $\pm$ 16.6	113.8 – 100.4	MIS5e-MIS5c

en temperature. For each of the samples, the thermal transfer at the chosen preheat temperatures was insignificant. Twenty-four aliquots for each sample were used to determine a final De. The De distributions with a 3 mm mask show no conclusive evidence of mixing or incomplete zeroing and radial plots indicate a relatively high individual precision of the SAR equivalent doses (Figure 4). This precision illustrated by the radial plots further adds to the confidence that using the SAR protocol on beachrock is a reliable method of dating.

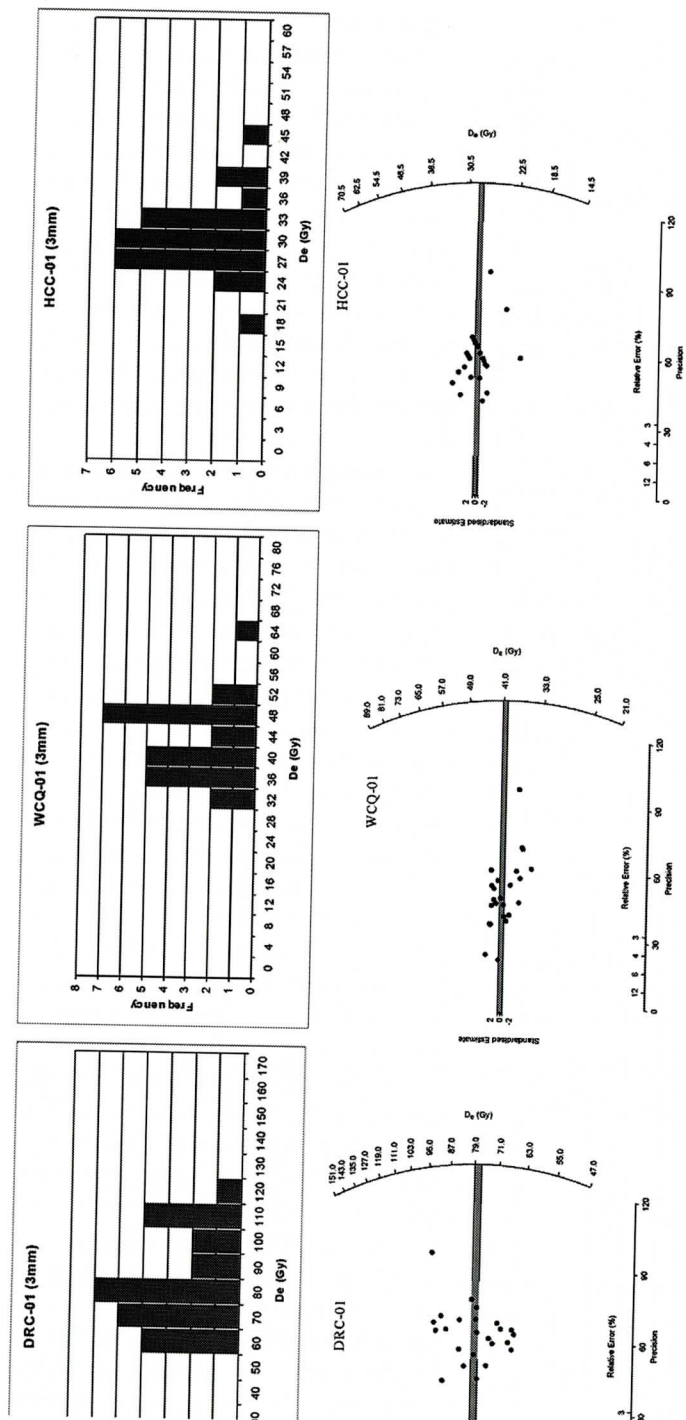
When the NAA/DNC and the gamma spectrometry dose rates are within error of each other, we believe that the gamma spectrometry dose rate should be used to calculate the OSL age (Table 2). For WCQ-01 and HCC-01 there are minor discrepancies between the ages using the NAA dose rate and the in situ gamma dose rates. We attribute the discrepancy from WCQ-01 to water trapped in the hole from the coring process. The discrepancy for HCC-01 cannot be attributed to water in the coring hole and, in fact, cannot be determined. Therefore, for WCQ-01 and HCC-01, the dose rates calculated from the NAA/DNC data were used in the interpretations of the deposit, while the gamma spectrometry dose rates were used for DRC-01.

OSL ages were calculated for each sample, using appropriate NAA/DNC dose rates or in situ Gamma Spectrometry dose rates or both, 5% moisture content, and 10% moisture content (Table 2). The ages were calculated using the instant accumulation model assuming instantaneous accumulation of sediment with minimal overburden accumulation. The weighted mean ages are given and the error is calculated using one standard error.

## Paleontology Results

At the study sites, paleontologists

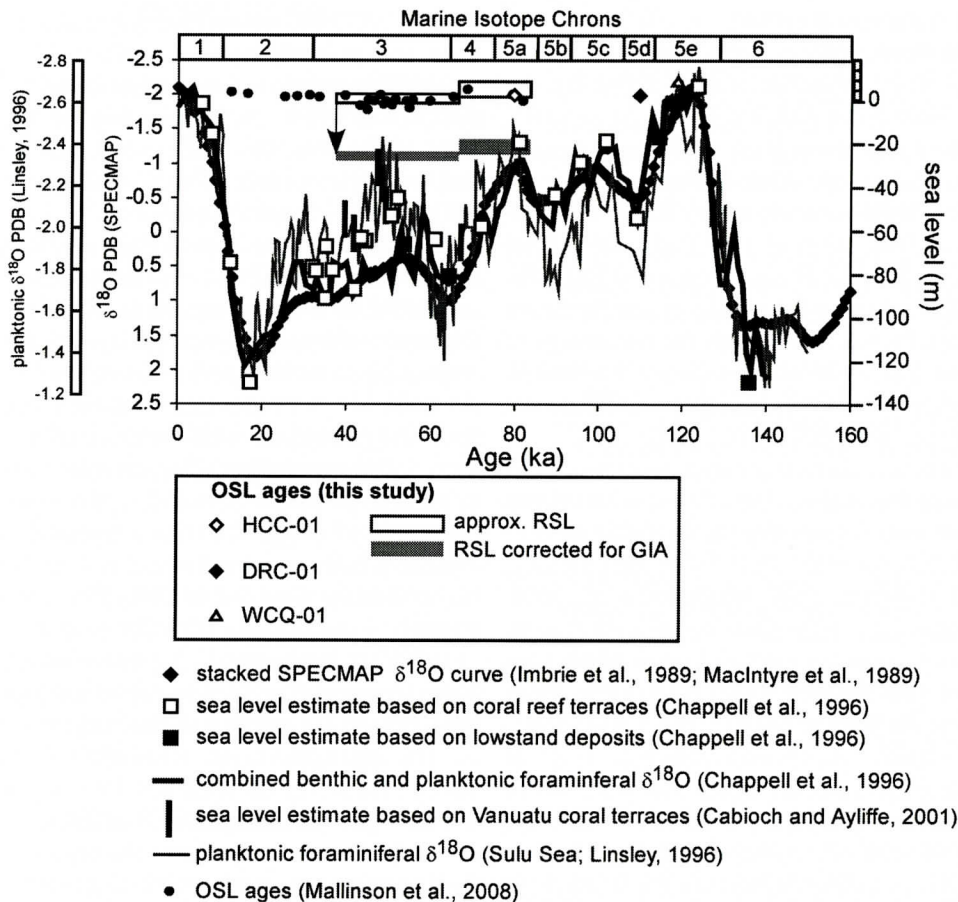




from the Florida Museum of Natural History (FLMNH) collected abundant remains of cartilaginous and bony fishes, amphibians, reptiles (especially turtles), birds, and mammals (e.g., rodent, camel, horse). Collectively the invertebrate fauna, consisting of still living species, and the vertebrate fauna, determined to represent the Rancholabrean North American Land Mammal Age (300 ka to 10 ka) (R. Hulbert, personal communication, July 2008), indicate that the time of deposition at the study site was restricted to the late Pleistocene.

At WCQ-01 (Florida Museum of Natural History IP locality SJ002) currently known as Lakeview Dirt Company, 35 marine bivalve species, 15 marine gastropod species, and one species each of freshwater and terrestrial snails were identified from bulk sampling of the shell-rock facies just below the coquinoïd limestone facies. Here the bivalves far outnumber the gastropods both in diversity and abundance. Most abundant were *Donax variabilis*, *Anomalocardia cuneimeris*, *Anadara transversa*, *Stewartia floridana*, and *Mulinia lateralis*. All of the marine mollusks identified from the site have living cognates that today inhabit nearshore, shallow water environments of Florida.

**Figure 4.** Radial Plots and De distributions for each sample using a 3 mm mask. All aliquots were included.



**Figure 5.** Comparison of the SPECMAP marine  $\delta^{18}\text{O}$  curve (Imbrie et al., 1989; MacIntyre et al., 1989), coral reef terraces (Chappell et al., 1996; Cabioch and Ayliffe, 2001), foraminiferal  $\delta^{18}\text{O}$  data (Chappell et al., 1996; Linsley, 1996), and OSL data (Mallinson et al., 2008).

## DISCUSSION

Coquina may not be an ideal material to optically date given the possible problems determining the dose rate over the entire burial period. The gamma and beta dose rates might be influenced by later addition or removal of Uranium during diagenesis or dissolution and loss of Uranium associated with dissolution of mollusk carbonates. Since OSL techniques date the deposition of the quartz sand grains and not the cementation of the sediment, OSL ages obtained should represent the time when sea level was at that location. There is little doubt the quartz grains have been optically bleached, due to its nearshore/shoreface depositional environ-

ment (Rink and Pieper, 2001).

One issue of concern about dating beachrock is the dose rate. The issue of dose rate is actually two-fold. The first issue is whether mollusks in whole matrix are closed systems with respect to U-migration after burial and the second issue is if there is any change in dose rate associated with the cementation event which might increase the dose rate significantly if the cementation event occurred much later than the depositional event associated with uncemented sediment dose rates. Previous authors have assumed that coquina acts as a closed system with respect to Uranium and therefore can be treated as such (French et al., 2001; Tatumi et al., 2003; Bateman et al., 2004; Armitage et al.,



2006; Tatum et al., 2006).

The three results presented here all fall within the range of marine isotope 5 (MIS5), the time interval that includes the last time eustatic sea level rose above present (Figure 5) (Szabo, 1985; Muhs et al., 2002; Potter and Lambeck, 2003; Wehmiller et al., 2004). Many of the results of Osmond et al. (1970) also fall within this time interval, although some also fall within MIS3 when eustatic sea level was far below present. Farther to the south, the chronology of the Key Largo Limestone indicates that sea level during MIS5e was between 5 and 8 meters above present (Muhs et al., 2004).

North of Florida, there are examples of dated deposits that indicate that relative sea level was higher than present during the latter parts of MIS5 (Cronin et al., 1981; Potter and Lambeck, 2003; Burdette, 2005; Mallinson et al., 2008; Parham et al., 2008). Cronin et al. (1981) using uranium series ages of fossil coral rubble concluded that sea level was  $7.5 \pm 1.5$  m above present sea level at 120 ka. Cronin et al. (1981) also argued that sea level was  $6.5 \pm 3.5$  m above present sea level at 94 ka, while Potter and Lambeck (2003) modeled sea level during MIS-5c to be  $\sim 10$  m below MSL.

Relative to present, MIS-5a sea levels range from -19 m to more than +3 m between Barbados, Haiti, the Bahamas, Florida, Bermuda and the U.S. Atlantic Coast (Potter and Lambeck, 2003). Geochronological studies of reefs and speleothems in the Bahamas, Bermuda, Haiti, and Barbados reconstructed MIS 5a sea level from -18 to -13 m MSL (Toscano and Lundberg, 1999), but Cronin et al. (1981) argued that 72 ka sea level was  $7 \pm 3$  m above present sea level. Mallinson et al. (2008) concluded, based on several OSL ages in the coastal plain of North Carolina, that sea level during MIS-5a was at or above present.

DRC-01, approximately 2 m above sea level, probably represents either a MIS-5e or a MIS-5c nearshore deposit. The age range of DRC-01 is 100.3 – 119.4 ka considering all age uncertainties. The  $\gamma$ -dose rates from the in situ measurements and the  $\gamma$  spectrometer measurements are statistically indistinguishable, and give us the highest confidence in this

sample. WCQ-01, approximately 8 m above sea level, also probably represents either a MIS-5e or a MIS-5c nearshore deposit. The age range of WCQ-01 is 106.9 – 128.3 ka using the NAA/DNC  $\gamma$ -dose rates. The in situ  $\gamma$ -dose rates were problematic as mentioned above and therefore not considered in age determination.

Although it cannot be definitively determined when sea level rose, due to the errors associated with OSL, the argument can be made that sea level rose to approximately 8 m above present based on the approximate elevation of WCQ-01 and the depositional environment of WCQ-01, a nearshore deposit. At DRC-01, there are Anastasia Formation deposits located to the west of Merritt Island along the shore of the mainland (Figure 1). This suggests that if these date to the same age range, sea level rose higher than the elevation of DRC-01 (2 m) and possibly to the elevation of WCQ-01 (8 m).

HCC-01, approximately 2 m above sea level, is the youngest of the three samples and probably represents a shoreline deposit during MIS-5a. The age range of HCC-01 is 66.8 – 91.6 ka considering all age uncertainties. The variations in these ages are mainly due to the choice of  $\gamma$ -dose rate. The counting rate of the in situ gamma spectrometer was very close to minimal confidence relative to instrument background. The counts per unit time were barely above 3x internal instrument background, which decreases our confidence in the use of the in situ  $\gamma$ -dose rate and therefore is leading us to favor the NAA/DNC ages (76.7 – 91.6 ka).

Cronin et al. (1981), Szabo (1985), and Wehmiller et al. (2004) who used closed-system assumption  $^{230}\text{Th}/^{234}\text{U}$  dating of corals and Mallinson et al. (2008) and Parham et al. (2008) using OSL on nearshore deposits indicate ages in the 70 – 80 ka range. Therefore if this deposit is related to nearshore sedimentation in less than a few meters of water and reflects sea level as would corals, we wish to leave open the possibility that the strip of land hosting the HCC-01 dates potentially to our youngest possible age of 66.8 ka, but could also date to as old as 91.6 ka.

## CONCLUSION

OSL dating of the upper coquinoïd limestone of the Anastasia Formation confirms the finding of Osmond et al. (1970) that some of the Anastasia dates to MIS-5 and the estimates of McNeill (1985) that the surficial deposits of this coquina were deposited around 100 ka. The results presented also confirm Brooks' (1972) idea that "the Anastasia was formed during several events..." based on the two cluster of MIS-5 OSL ages. The first cluster of OSL ages, based on two samples, groups in MIS-5e (~112 ka) or MIS-5c (~105 ka) and suggests that sea level during one of these times reached approximately 8 m above present. The second "cluster", based on one sample, dates to MIS-5a (~83 ka) and suggests that sea level during MIS-5a reached to slightly above present sea level.

Future work on the Anastasia Formation consists of using OSL and electron spin resonance optical dating (ESROD) to place numerical geochronological constraints on the lower unconsolidated shell and shelly sands.

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**"PTERIDICHNITES" (= PSAMMICHNITES) FROM THE UPPER DEVONIAN  
BRALLIER FORMATION OF SOUTHWESTERN VIRGINIA, USA:  
ICHNOTAXONOMIC STATUS, CONSTRUCTIONAL MORPHOLOGY, AND  
PALEOECOLOGY**

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**ABSTRACT**

One of the only abundant fossils in the Frasnian Brallier Formation of southwestern Virginia, and elsewhere in the central Valley and Ridge Province, is the small trace fossil known as "*Pteridichnites*" *biseriatus*. Field geologists have used this distinctive biogenic structure for many years as a guide to the Upper Devonian (and especially the lower, shaly portion of the Brallier) in the region. We can affirm the biostratigraphic potential of this trace; but based on the specimens we studied from the Saltville area, we demonstrate that the ichnotaxonomic assignment, along with interpretations of taxonomic affinity of the tracemaker, constructional morphology of the structure, and paleoecologic implications need to be revised.

The previous descriptions and interpretations appear to have focused on the basal part of the trace fossil for the most part. When preserved in full relief, however, it is a more complex structure consisting of (1) the familiar ladder-like ventral floor, (2) a meniscoid backfilled core, and (3) a dorsal roof

often having a thin, longitudinal groove. These features justify reassignment to the ichnogenus *Psammichnites*. The specimens from the Saltville area suggest that *Psammichnites biseriatus* was produced by a small, shallow-burrowing, mollusc- or annelid-like deposit feeder, that thrived in the upper parts of recently deposited muddy turbidites in a depositional basin that supported few other kinds of benthic organisms, owing to frequent erosion-deposition events, continual turbidity and influx of freshwater from Catskill deltaic lobes to the east, and possibly because of intervals/zones of stagnation and eutrophication at the seafloor.

**INTRODUCTION**

The Upper Devonian Brallier Formation in southwestern Virginia (and elsewhere) has the reputation for having a rather meager fossil record. The formation has been studied many times by stratigraphers and structural geologists—because of its connection to development of the Catskill deltaic system, involvement in subsequent folding and faulting, and the potential for development of hydrocar-



bon resources—but paleontologists have not paid much attention to it. Fossils are difficult to find at most levels within the Brallier Formation, consisting typically of a few kinds of unusual bivalves, rare ammonoids, and a low-diversity association of small, seemingly non-descript trace fossils, which can be abundant locally (Butts, 1940, 1941; Avary and Dennison, 1980; Rossbach and Dennison, 1994). Only a few systematic surveys and inventories of Brallier fossils have ever been published (e.g., Clarke and Swartz, 1913a, b; Butts, 1940, 1941; Woodward, 1943; Rossbach and Dennison, 1994); and with one notable exception (McDowell et al., 2007), the trace fossils have never been the focus of a publication.

In this paper we devote our attention to one of the only abundant fossils of any kind in the Brallier, "*Pteridichnites*" *biseriatus* Clarke and Swartz, 1913. Butts (1940, p. 320), Woodward (1943, p. 414), and especially McDowell et al. (2007) have advocated using this distinctive biogenic structure as a guide to the Brallier. Because of its special importance as a trace fossil guide, its paleobiologic properties should be understood as completely as possible. Like many ichnotaxa used by geologists to determine stratigraphic positions, propose chronostratigraphic correlations and to reconstruct ancient environments, however, the trace-making organism, constructional morphology and functional adaptations represented by this trace fossil remain unclear and controversial.

We re-evaluate the taxonomic status of this important trace fossil, describe its constructional morphology based on specimens collected or observed at outcrops near Saltville, Virginia (Figs. 1, 2), and interpret the behavioral ecology of the tracemaker based on morphology, the associated ichnofauna and sparse body fossils, and the depositional setting. We show that "*Pteridichnites*" is a junior synonym of the well-known ichnogenus *Psammichnites* Torell, 1870; that "*P.* *biseriatus*" was produced by an endobenthic animal that constructed small, essentially horizontal, straight to curved, back-filled burrows; and that the tracemaker and the other benthic organisms of the Brallier had to contend with unique environmental factors of

the enclosing foreland basin, including frequent episodes of deposition and erosion, high net deposition rates and turbidity, influx of freshwater, and possibly intervals of stagnation and eutrophy. We confirm the utility of "*Pteridichnites*" *biseriatus* as a guide fossil, particularly for the lower, shaly part of the Brallier Formation (McDowell et al., 2004, 2007). The ichnotaxonomic assignment, along with previous interpretations of trace producer and autecology, however, are in need of re-evaluation.

## GEOLOGIC CONTEXT

The Upper Devonian stratigraphic units in the Saltville area consist of, in ascending order, the uppermost part of the Millboro Shale, Brallier Formation, and the Chemung Formation (the last unit is equivalent to the Greenland Gap Group and the Hampshire Formation to the north) (Dennison, 1970; Avary and Dennison, 1980; Rossbach and Dennison, 1994; Dennison et al., 1988, 1996). In general, the succession of units records an overall regressive sequence of lithic units within a collision-related foreland basin, spanning the Frasnian and Famennian series, and recording deep-water depositional settings giving way to deltaic-fluvial depositional environments over a time span of ca. 15 million years (Dennison et al., 1996, fig. 9). Ultimate controls on development of the stratigraphic framework of the area include rising global sea level and basin subsidence, followed by western progradation of the growing Catskill deltaic system-clastic wedge during the Acadian Orogeny (Castle, 2001), which resulted from closing of the Iapetus Ocean as pieces of North America and Europe collided.

The boundary between the dark colored organics-rich Millboro Shale and the overlying thick sequence of greenish-gray mudrocks of the Brallier Formation is broadly gradational and is usually placed where thin interbeds of siltstones and very fine sandstones become prominent. The lower Brallier was deposited in a deep-water basin outboard from deltaic and fluvial environments—represented by the Chemung Formation and its equivalents—at the eastern basin margin. The Brallier shales and



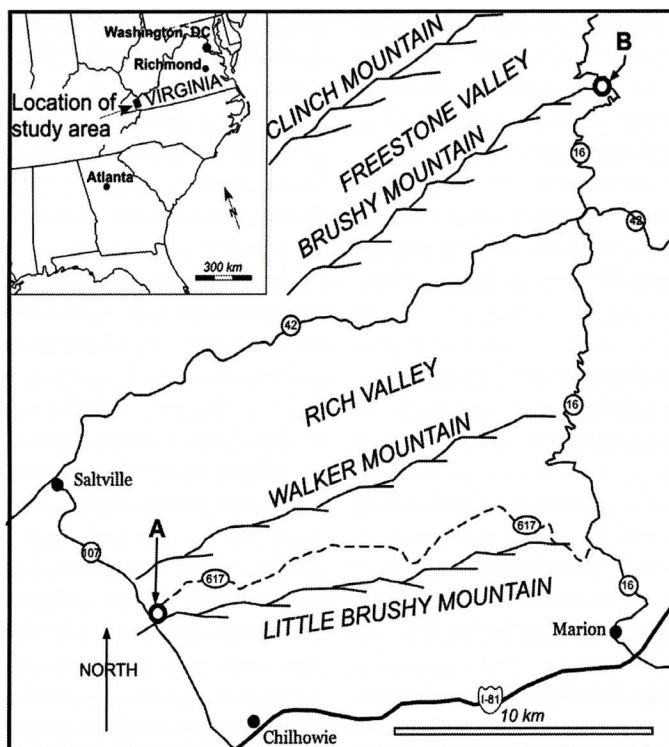
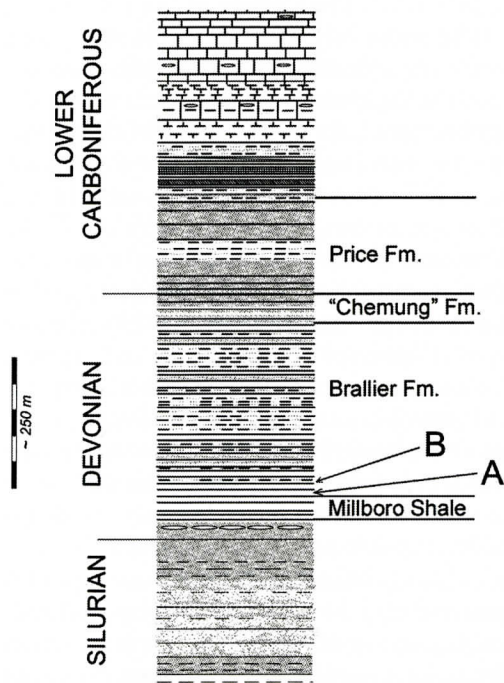


Figure 1. Location map of the study sites near Saltville, Virginia. A, quarry at Horseshoe Bend; B, roadcut exposure on Brushy Mountain.



siltstones are mostly thickly laminated and are interpreted as fine-grained turbidites displaying Bouma  $T_{de}$  divisions.

We focused our attention on the trace fossils in the shaly, lower 20-30 m of the Brallier at two locations (Figs. 1, 2). This interval also contains very fine-grained planar to cross-laminated sand interbeds a few cm thick. Some of the sand beds feature convolute lamination as part of  $T_{cde}$  sequences, again suggesting rapid deposition from turbidity currents. A few beds have low-relief flute and tool casts on bed soles, and aligned plant fragments and rare transported shallow-marine body fossils occur at some levels (Fig. 5A, B, D). The lower portion of the Brallier features characteristics of the graded-

Figure 2. Generalized stratigraphic succession of Upper Devonian rocks in southwestern Virginia. Arrows indicate the stratigraphic levels sampled at the Horseshoe Bend (A) and Brushy Mountain (B) localities.

stratified silt and graded mud facies (D2.1 and E2.1) of Pickering et al. (1989), who attributed such deposits to low-concentration turbidity currents. The increase in frequency and thickness of siltstone and sandstone beds moving up-section indicates increasing intensity of the Acadian Orogeny and progradation of deltaic lobes extending basinward from rising tectonic lands to the east (McGhee and Sutton, 1981; Castle, 2000).

### FOSSILS FROM THE LOWER BRALLIER FORMATION NEAR SALTVILLE

In terms of fossil content, the Brallier is as noteworthy for what it *does not* contain, as much as for the rather unusual taxa that actually have been collected (see Butts, 1941, pl. 120). Interpreted as a basinal deposit associated with the Catskill deltaic system, and containing many fine-grained, "base cut out" turbidites, lower Brallier beds sometimes have flute and tool marks (Fig. 5A), but lack graphoglyptid trace fossils indicative of deep-marine settings; typically do not have the usual assemblages of suspension-feeding, epibenthic invertebrates typical of associated Devonian stratigraphic units in the same region; and, although abundant at some levels, the trace fossils consist of a few small forms apparently produced by shallow-burrowing organisms. Such graphoglyptids as *Paleodictyon* and *Cosmorhapha* are common features of deep-marine turbidites by the mid-Paleozoic (Uchman, 2004, 2007, and references therein), and would be expected in the Brallier. Although more typical brachiopod-dominated autochthonous fossil associations occur at some levels higher in the Brallier Formation and in time-equivalent units (Butts, 1940; Rossbach and Dennison, 1994), they are absent from the lower Brallier at the outcrops we examined. The low-diversity association of small, shallow burrows (Figs. 3, 4) suggests that only a few kinds of opportunistic or physiologically resilient endobenthic organisms could thrive at the Brallier seafloor.

Other than "*Pteridichnites*" *biseriatus*, Butts (1940, p. 319-320; 1941, pl. 120) listed and il-

lustrated an exceptional array of invertebrate fossils from the Brallier of Virginia. These consist of small clams, including the moderately abundant cryptodont *Buchiola* (Miller et al., 1982; Rossbach and Dennison, 1994), which McKerrow (1978, fig. 38) interpreted as a pseudoplanktic bivalve that floated in the upper water column attached to allochthonous plant material or algae, and the rare pelagic or nekto-benthic ammonoid *Probeloceras*. Although we did not collect any clams at our two study sites, we found one ammonoid at the Brushy Mountain locality (Fig. 5C). Concentrations of carbonized, often aligned plant fragments, and a few transported shallow-water fossils, also occur on fracture surfaces and bedding planes in the lower Brallier beds that we examined (Fig. 5B, D). Because the body fossils are sparse and unusual, and the trace fossil associations are dominated by a few small, shallow endobenthic structures, the Brallier basin floor must have featured a rigorous environment that few invertebrate animals could tolerate—and may not have been a truly deep-marine setting.

### "PTERIDICHNITES" BISERIATUS

One of the only abundant fossils of any kind in the lower Brallier Formation is the trace fossil "*Pteridichnites*". The structure was described by Clarke and Swartz (1913a, b) from the Jennings Formation of Maryland, which is now divided into the Brallier, Foreknobs and Hampshire formations (McDowell et al., 2004). They interpreted "*Pteridichnites*" *biseriatus* (the type "species" by monotypy) as "...probably tracks of crustaceans or possibly of annelids" (Clarke and Swartz, 1913a, p. 545). In a table showing stratigraphic distribution of Upper Devonian fossils in Maryland, Pennsylvania and New York (Swartz, 1913, p. 439-444), the structure is listed under "Vermes" and is shown to occur only in the lower Jennings Formation of Maryland. Later, Butts (1940, p. 320; 1941, pl. 120, fig. 18) confirmed the biostratigraphic potential of "*P.*" *biseriatus* in Virginia and other areas, saying that it is "...fairly common throughout the Brallier and, since 1908, has been used by the writer as a guide fossil." In the



figure caption, he characterizes the structure as "Most common fossil of the Brallier" (1941, p. 204). He places the structure under the heading "Worms" in his list of Brallier fossils (1940, p. 319-320). It is also listed in the table of "Fossils of the Naples beds" (1940, p. 316) under "Worm tracks". It is clear that both Clarke and Swartz, and Butts, recognized that "*P.*" *biseriatus* was a trace fossil, not a body fossil, and that the structure was a useful stratigraphic guide. Woodward (1943, p. 414) also acknowledged the biostratigraphic utility of this trace fossil in the Upper Devonian of West Virginia.

Many of the later papers and guidebooks containing descriptions and interpretations of the Brallier Formation and related units were published by John Dennison and his colleagues and students (Dennison, 1996, and list of references therein)—a large body of detailed and important work. In a recent field guide (Schultz and Henika, 1994), the paleontology of Upper Devonian formations is summarized in the chapter by Rossbach and Dennison (p. 108-112). They state (p. 108) that based on their experience the Brallier "...is generally unfossiliferous except for the bivalve *Buchiola retrostriata* and the trace fossil *Pteridichnites biseriatus*." They reproduce the figure of "*P.*" *biseriatus* from Clarke and Swartz (1913b) and list it in their fossil range chart (fig. 10) as occurring in the Brallier and in the Blizzard Member of the Foreknobs Formation.

The latest description and interpretation of "*P.*" *biseriatus* was by McDowell et al. (2007) in the pages of this journal. They re-emphasized the biostratigraphic potential of the trace fossil, proposing an acme zone based on its abundance limited to the lower beds of the Brallier Formation (fig. 2); they also show the structure occurring in the overlying Scherr and Foreknobs formations. McDowell et al. thought the traces were locomotion tracks (repichnia) of an ophiroid.

It is interesting that practically all of these authors accepted that "*Pteridichnites*" is a trace fossil of some kind, and probably a surface track as opposed to a burrow. Many of the illustrated specimens and descriptions, however, emphasize the ventral (lower) side of the struc-

ture, either viewed at the sole of a bed or looking downward on a fracture or bedding surface—this is the "*Plagiogmus* preservation" described by Seilacher (2007, pl. 27). This means that the initial description and later work have focused on a preservational expression of a more complicated structure. None of the descriptions mentioned the associated backfilled core and dorsal roof with thin groove—properties taken together suggesting this trace fossil is actually a kind of burrow already named *Psammichnites* (recently reviewed by Mángano et al., 2002). Here, we revise the ichnotaxonomy of "*P.*" *biseriatus*, and reinterpret constructional morphology considering the properties of specimens preserved in full relief. This involves reinterpretation of *Pteridichnites* as a junior synonym of *Psammichnites*.

## SYSTEMATIC ICHNOLOGY

### ICHNOGENUS PSAMMICHNITES (TORELL, 1870)

- 1870** *Psammichnites* Torell, pp. 9-10, pl. 1, figs. 1, 2
- 1913a,b** *Pteridichnites* Clarke and Swartz, p. 545, pl. 46, fig. 6
- 1929** *Plagiogmus* Roedel, pp. 51-52, text-fig. p. 49
- 1937a** *Olivellites* Fenton and Fenton, page 452-453, fig. 1
- 1937b** *Aulichnites* Fenton and Fenton, pages 1079-1080, pl. 1, figs. 1, 2

**Emended Diagnosis of Mángano et al., 2002, p. 3:** "Predominantly horizontal, sinuous, meandering to looping traces with transverse or arcuate internal structure and a distinct median dorsal structure, commonly represented by a sinusoidal or straight ridge/groove, or regularly spaced circular mounds/holes. Preserved in full relief on top of beds or, more rarely, in negative hyporelief."

**Additional diagnostic properties:** *Psammichnites* also includes small, straight to curved

back-filled burrows featuring a ladder-like floor, a meniscoid core, and the usual dorsal groove (based on our specimens and those illustrated by Seilacher, 2007, pl. 30).

**Type ichnospecies:** *Arenicolites gigas* Torell, 1868; subsequent designation of Fischer and Paulus, 1969, p. 91.

**PSAMMICHNITES BISERIATUS**  
(CLARKE AND SWARTZ, 1913)  
FIG. 3A-D

- 1913a,b** Clarke and Swartz, p. 545-546, pl. 46, fig. 6  
**1941** Butts, pl. 120, fig. 18  
**1975** Häntzschel, p. W99, fig. 62-3  
**1994** Rossbach and Dennison, fig. 11  
**2007** McDowell et al., figs. 4b-d, 5a

**Emended diagnosis:** Small, straight to curved, unbranching, subhorizontal backfilled burrows having subround to subquadrate cross-section shapes; consisting of a ventral floor featuring a double row of shallow depressions, arrayed side-by-side or in a staggered pattern, a meniscoid core of backfilled fine sand or silt, and a dorsal roof often with a thin, longitudinal groove.

**Other ichnospecies assigned to *Pteridichnites*:** *Pteridichnites sintanensis* Yang, 1984, p. 711, fig. 3. The illustration is a generalized drawing, but it appears to represent the ventral floor of a form of *Psammichnites*.

**Material studied:** We collected approximately 40 specimens and observed many more at the localities indicated in Figure 1. We also examined the holotype illustrated by Clarke and Swartz (1913b) (USNM 178674) and the hypotype illustrated by Butts (1941) (USNM 97987). Our collection includes specimens that reveal mostly the ventral floor of the burrows, the core, or the dorsal roof with groove, and a few that feature a combination of features, indicating that they are actually parts of the same

biogenic structure. Several of our specimens showing these features have been deposited in the Smithsonian's National Museum of Natural History (USNM 538209-538211).

**Description and remarks:** The *Psammichnites biseriatus* we examined occur in full relief mostly at or near tops of shale beds and on fracture surfaces parallel to sedimentary layering, in loose aggregations of a few to several tens of specimens that occasionally over-cross, but do not penetrate each other. The burrows are slightly flattened in some cases, oriented more or less parallel to bedding, and appear to have been produced close to the sediment surface. Specimens from the Saltville area are 2-3 mm wide and up to about 10 cm long. The floor of the burrows resembles a ladder having both side rails and a central rail. The rungs and rails are thin, compared to the lacunae, which are evenly spaced side-by-side in the straight specimens (Fig. 3C, D), but alternate in position and have more irregular shapes in specimens that are curved or descend into the surrounding shale. Long specimens having straight and curved portions feature both arrangements of the lacunae. The core material is typically lighter colored and slightly coarser than the surrounding shale in most specimens, and is made up of meniscoid packets of silt or fine sand in most cases. The cores of some of the specimens from Brushy Mountain, however, are filled with mud and show no difference in coloration compared to the surrounding shale (Fig. 3C, D). The roof of "complete" specimens features a thin longitudinal groove, like some of the ichnospecies of *Psammichnites* (Häntzschel, 1975; Mángano et al., 2002; Seilacher, 2007), but the Brallier Formation structures are smaller and not as strongly curved or meandering as other forms of the ichnogenus. In some specimens there is the suggestion of a very thin burrow lining, which is easier to see in the floor portion of some specimens (Figs. 3D, 6A).

## ASSOCIATED ICHNOTAXA

The only other abundant trace fossil in the lower Brallier beds near Saltville is *Planolites*, another cylindrical, generally horizontal struc-



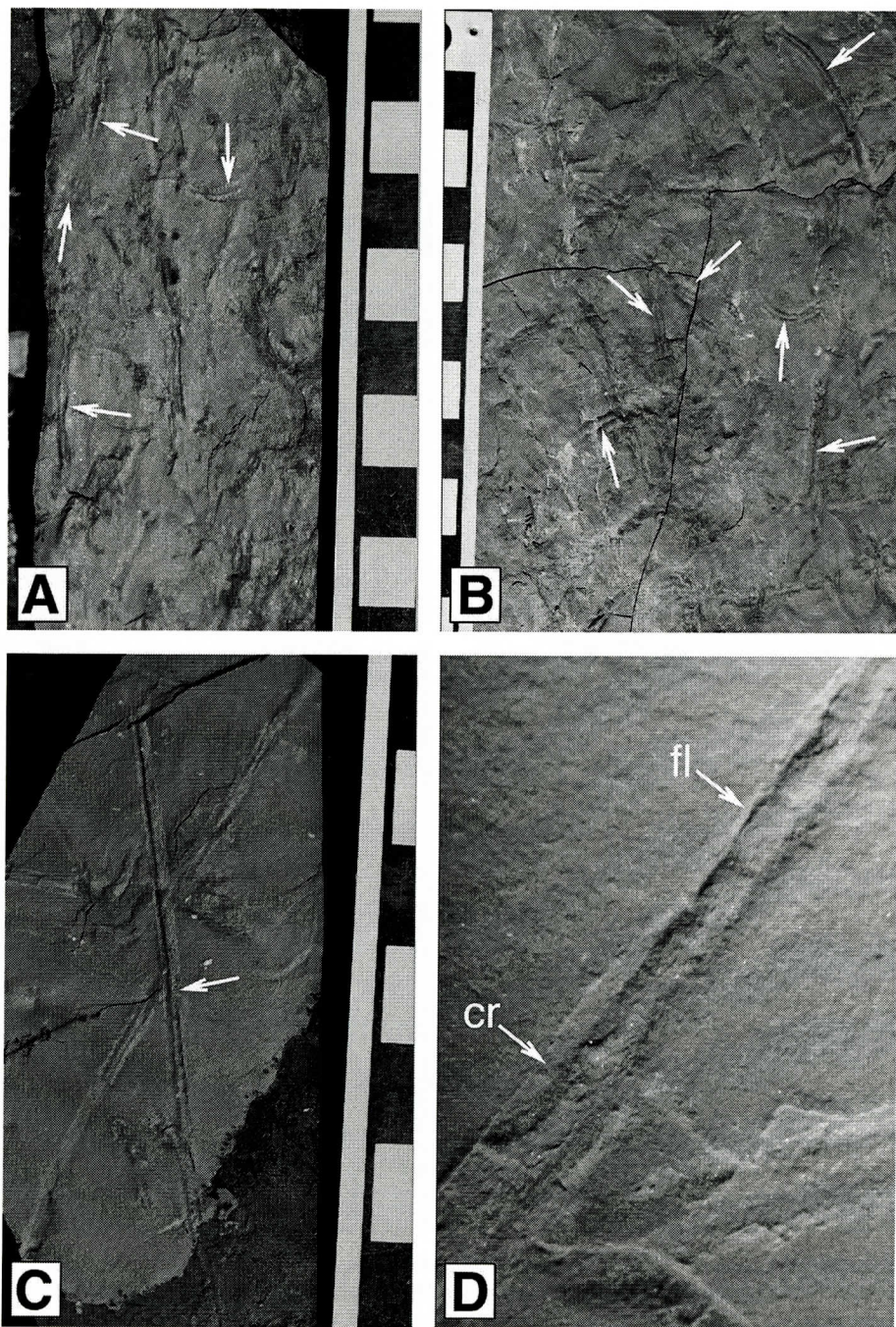


Figure 3. *Psammichnites biseriatus* from the Brallier Formation in the Saltville area. A-B, upper surfaces of shale beds having many short portions of mostly gently curved *P. biseriatus* (arrows, the specimen near upper right corner of A is USNM 538210; both slabs from Horseshoe Bend). C, several straight portions of the trace fossil that over-cross (arrow indicates the vicinity of the close view in D; Brushy Mountain); D, detail of the burrow emphasized in C, showing the ladder-like floor (fl) of the burrow and part of the muddy back-filled core (cr) (USNM 538209). Ruler is marked in cm; burrow shown in D is approximately 2 mm wide.



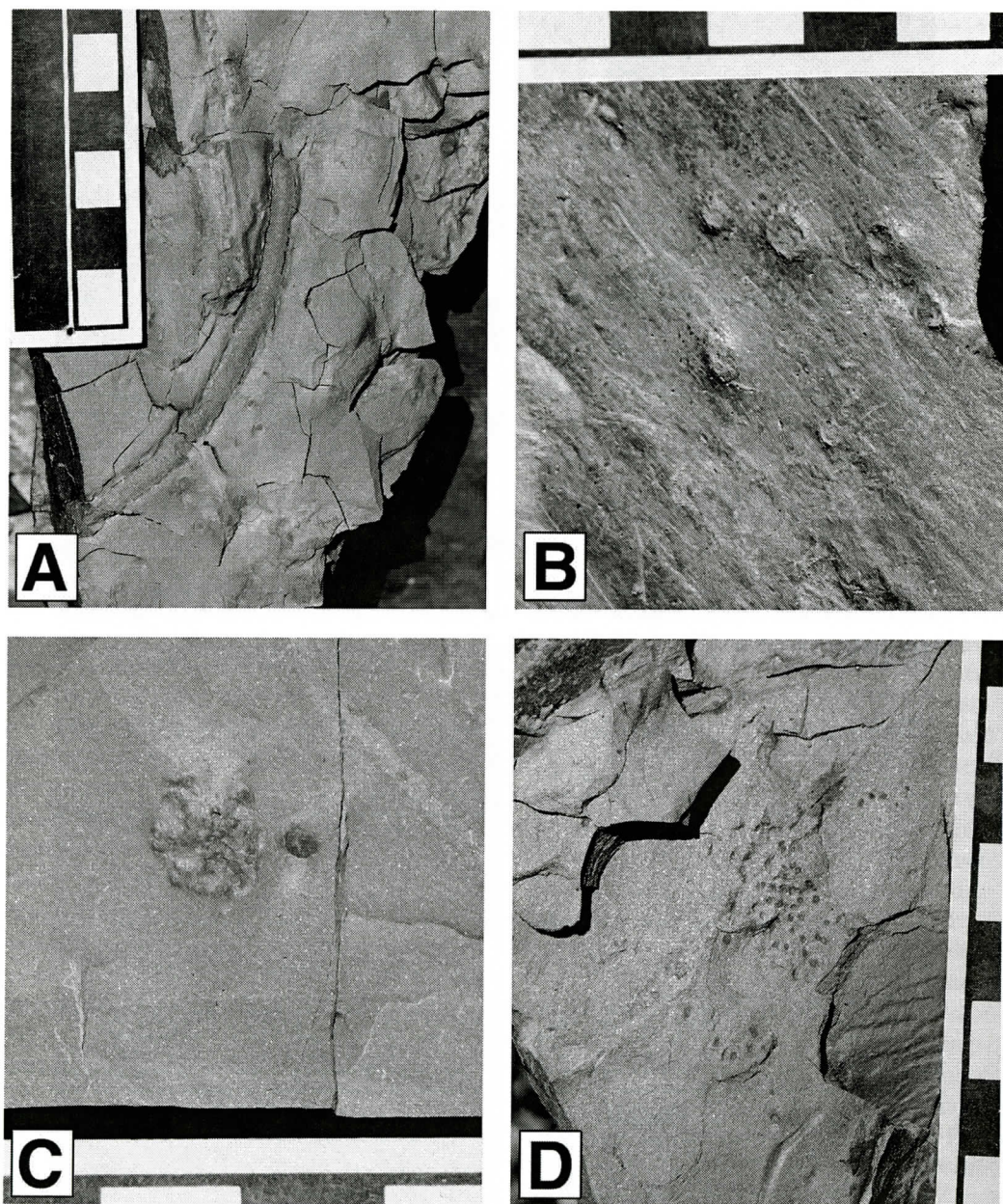


Figure 4. Other ichnotaxa occurring with *P. biseriatus*. A, *Planolites beverleyensis*; B, cluster of *Planolites*-like burrows at a bed sole; C, *Gyrophyllites* isp.; D, cluster of small dark burrows. Ruler marked in cm; all specimens from Horseshoe Bend quarry.

ture. In all, trace fossil diversity is limited to five different forms, some of which seem to be different expressions of the same ichnotaxon. The associated trace fossils are described briefly below.

*Planolites beverleyensis* (Billings, 1862) (Figs.

4A, 6D): Curved, subhorizontal, unlined, unbranched burrows filled with coarser sediment than the surrounding shale, having circular to subcircular cross sections 3-4 mm wide, and normally 6-7 cm long. The burrow fill is structureless and usually lighter colored than the ma-



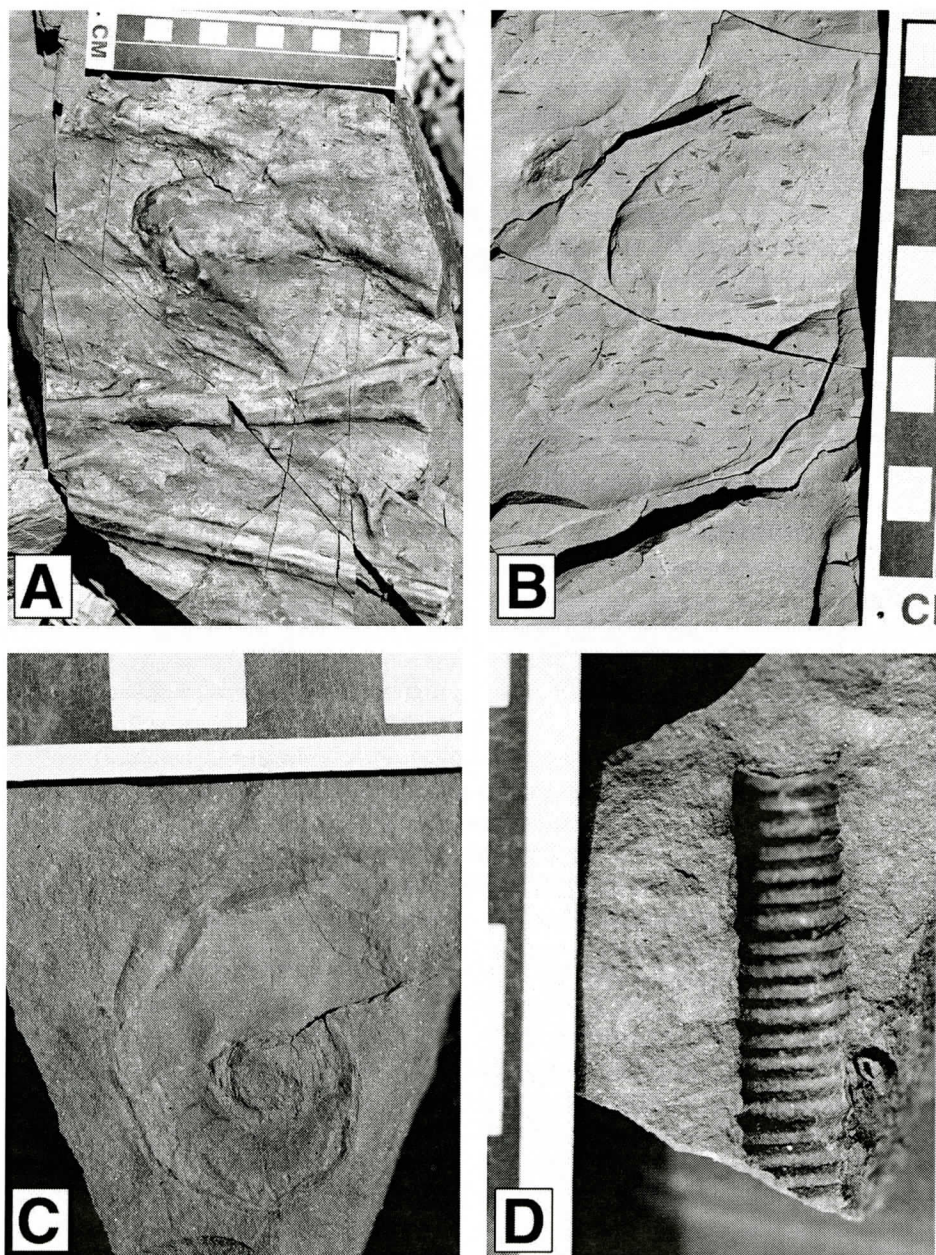


Figure 5. Sole marks and body fossils. A, flute and tool marks on sole of a bed; B, aligned, carbonized plant fragments; C, unidentified ammonoid; D, unidentified pelmatozoan column fragment. Ruler marked in cm; A and B from Horseshoe Bend, C and D from Brushy Mountain.

trix. These burrows are concentrated mostly near bed tops, but some appear to penetrate up to several cm to bed soles (see below). They were probably produced by deposit feeders moving through soft (but not soupy) mud, possibly homing in on thin sand or silt layers or on

sand-mud boundaries. Abundant in the lower portion of the Brallier Formation in the Saltville area.

***Gyrophyllites* isp. (Figs. 4C, 6E):** Small, radial structures consisting of curved, fan blade-like elements that emerge from a central tunnel or



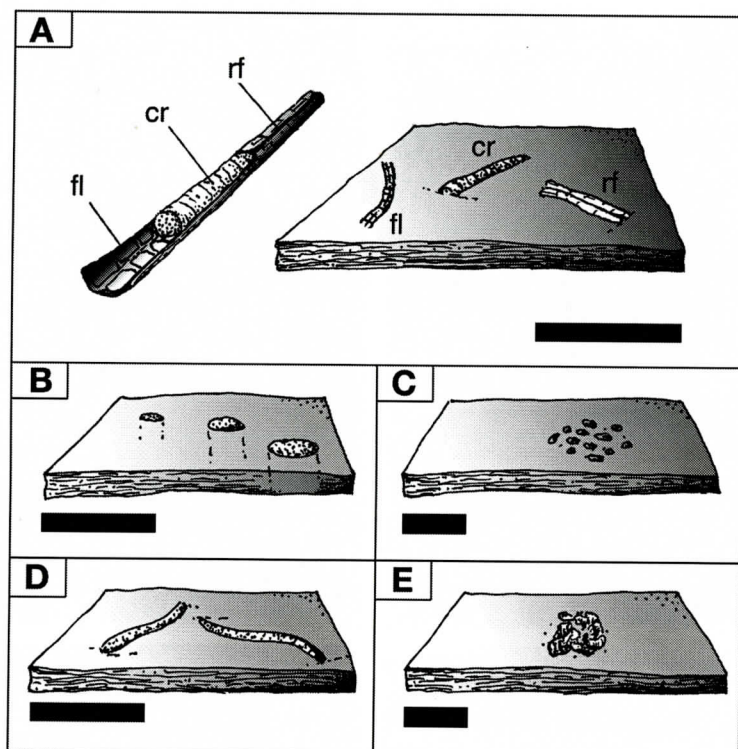


Figure 6. Sketches of ichnotaxa from the lower Brallier beds in the Saltville area. A, *Psammichnites biseriatus* (fl = ventral floor with ladder-like pattern, cr = backfilled meniscoid core, rf = dorsal roof with thin longitudinal groove); B, cluster of vertical *Planolites*-like burrows; C, cluster of small dark burrows; D, *Planolites beverleyensis*; E, *Gyrophyllites* isp. Bar scales in A, B and D = 2 cm, C and E = 1 cm.

tunnels, together resembling a motorboat propeller (see Fu, 1991, p. 37-45, for a review of this unusual ichnogenus). The Brallier specimens are darker than the surrounding rock and look like puckered clumps of organics-rich sediment; the curved, weakly meniscoid blades are evident under low magnification. This structure also appears to be the work of a deposit feeder, in this case concentrating its effort in one place at the seafloor. Uncommon.

**Large, clustered vertical burrows (Figs. 4B, 6B):** Vertical to oblique, cylindrical to subcylindrical, sand- or silt-filled, unlined burrows, 2-5 mm wide, and visible at both tops and soles of shale beds. These appear to be portions of *P. beverleyensis* that depart from the usual subhorizontal orientation. Connection to possible horizontal portions, however, was not observed, and the vertical burrows have greater maximum

diameters in some cases than the *P. beverleyensis* specimens described above. Abundant.

**Small, clustered vertical burrows (Figs. 4D, 6C):** Groups of very small, vertical to oblique, dark colored tunnels, which are rarely greater than 1 mm in diameter, occurring in aggregations up to 2 cm wide. These may represent "underdeveloped" examples or the upper levels of *Gyrophyllites* (Seilacher, 2007, pl. 48). Some of the clusters occur in the vicinity of other clusters—clusters of clusters up to 5 cm in longest dimension. Uncommon.

## CONSTRUCTIONAL MORPHOLOGY

*Psammichnites biseriatus* was constructed by a small, slug- or worm-like, shallow burrowing deposit feeder that thrived in the upper parts of muddy gravity flow deposits in a setting that



supported few other kinds of benthic organisms. The burrows consist of three separate parts, as mentioned above: a ladder-like floor, a meniscoid core of back-filled sediment, and a roof or dorsal side often featuring a thin, longitudinal groove. The double row of shallow depressions at the floor (the lacunae in the "ladder") could have been made by a burrowing animal employing a muscular sole or similar ventral organ producing a biserial pattern of rhythmic pushing, synchronized on either side of the body during straight tunneling, but alternating in the turns (McIlroy and Heys, 1997; Seilacher, 2007). Sediment was transported around the body of the trace producer, in some cases producing fairly obvious meniscoid lamellae, not necessarily corresponding to shapes of the lacunae at the floor, but sometimes resulting in an essentially structureless core. The roof with thin groove suggests a siphon or snorkel (for breathing, feeding?), sensory organ, or some other extended body part deployed upward either into a thin covering of overlying mud or possibly to the seafloor (see the interpretation of *Psammichnites* by Seilacher, 2007, p. 80-82, 86-88, pls. 27-28, 30). The organism that made the Brallier *Psammichnites* could have fed either from the level of the main tunnel, or from above the tunnel (including the seafloor) if the organ producing the dorsal groove functioned as a food-collecting device.

The identity of the organism that produced *P. biseriatus* remains a mystery. The body was approximately 1-2 mm wide and may have been a few cm long; constructional elements of the burrow point to an elongate animal having a muscular sole and a snorkel-like organ near the anterior end of the body. Seilacher (2007) speculated that *Psammichnites* was produced by a clade of burrowers that did not survive the end of the Paleozoic, possibly endobenthic shell-less halkieriids. The morphology of the floor of some of the ichnospecies, including *P. biseriatus*, certainly suggests an animal equipped with a muscular sole (as in the gastropods; Lissman, 1945). Because the double row of depressions at the floor, and the dividing rail and rungs, are well preserved (Fig. 3C, D and Fig. 6A), mucus secretions may have been used to facilitate the

tunneling process (Brusca and Brusca, 1990). McIlroy and Heys (1997, p. 172), in their interpretation of *Plagiogmus* (another junior synonym of *Psammichnites*), pointed out that the same kind of floor structure could result from waves of muscle contractions produced by a burrowing annelid. As with many ichnotaxa restricted to the Paleozoic, *Psammichnites* may very well be the work of a clade of soft-bodied, burrowing animals having no living representatives.

Finally, two unusual characteristics of the Brallier burrows are the commonly occurring straight portions and the absence of frequent over-crossings, quite unlike patterns observed in other ichnospecies of *Psammichnites*, which are typically meandering or exhibit a complicated "scribbling" pattern and often exhibit multiple over-crossings. Also, it appears that specimens of *P. biseriatus* increase slightly in size in the coarser beds of the Brallier Formation.

## **PALEOECOLOGIC IMPLICATIONS— LIFE AT THE BRALLIER SEAFLOOR**

The unusual association of body and trace fossils in the Brallier Formation—especially in the lower shaly part of the unit—suggests some unique environmental factors. As the seaward equivalent of the deposits of the Catskill deltaic system, the mudrocks of the Brallier accumulated in a basin that may have never gotten much deeper than 50-100 m (see the environmental reconstruction in Castle, 2000, fig. 15; also note the caution in depth interpretation by Avary and Dennison, 1980, p. 140). Although many of the beds in the lower Brallier appear to be fine-grained turbidites, such features of a deep-marine setting as graphoglyptid trace fossils or undoubted deep-water body fossils were not found at the two localities studied. It is important to note that the basal Brallier records the transition from the O<sub>2</sub>-limited environments of the Millboro Shale to presumably less stressful conditions. The low-diversity trace fossil associations and the paucity of body fossils of benthic animals may indicate that stagnation was still a significant factor in parts of the Bral-

lier basin. It is also likely that the basin floor experienced frequent episodes of erosion-deposition, and that turbidity and possibly "salinity crashes" may have been common, owing to large and frequent marine flooding events originating at the active deltaic lobes to the east (McGhee and Sutton, 1981, fig. 11). Intervals of eutrophication, caused by frequent influx of plant fragments and other land-derived organic material, could have been an additional factor controlling diversity and composition of benthic ecosystems (Gage and Tyler, 1991).

It is interesting to speculate that there may have been times and places in the development of the Brallier basin when the environment was more like that of a large, muddy estuary than an open sea. This is not the typical picture we have in mind of a deep-marine basin. In a popular historical geology textbook, Prothero and Dott (2004, p. 289) suggested that the region including the Indonesian orogenic belt, Arafura Sea and northern margin of Australia represents a modern model of the Late Devonian deltaic complex-ramp-basin-epieric sea spectrum of depositional environments in eastern North America, which of course included the Brallier basin.

The inhabitants of the Brallier sea included a few kinds of pelagic or nekto-benthic organisms such as ammonoids, but the benthic ecosystems consisted of only a few kinds of animals able to tolerate conditions at the seafloor. *Psammichnites biseriatus* was produced by one of the only animals that seems to have actually thrived in the Brallier mud, which was delivered mostly as pulses of low-concentration turbidity currents. The tracemakers inhabited the upper parts of the mud beds resulting from these possibly frequent depositional events, feeding either from the surface or from just below the seafloor. In this view, the tracemakers were post-depositional opportunistic deposit feeders, exploiting windfalls of recently delivered organic detritus, possibly accompanied by short intervals of improved ventilation. Subsequent muddy turbidity currents eroded and buried the trace fossils, which may account for some of the preservational expressions of *P. biseriatus*.

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# A NEW SPECIES OF *PLAGIOBRISSE* FROM THE EARLY LATE PLIOCENE (PIACENZIAN) GOOSE CREEK LIMESTONE OF NORTHEASTERN SOUTH CAROLINA

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## ABSTRACT

A new species of brissid echinoid, *Plagiobrissus sarae* n. sp., from the Pliocene Goose Creek Limestone of northeastern South Carolina is described and discussed. Along with other definitive traits, *Plagiobrissus sarae* n. sp. has sparser tuberculation and is more rotund than *Plagiobrissus grandis* (Gmelin). *Plagiobrissus sarae* n. sp. is now the largest described spatangoid echinoid from the Cenozoic of the United States, and is the first definitive species of *Plagiobrissus* described from the Pliocene of North America. The addition of *Plagiobrissus sarae* n. sp. brings the known echinoid fauna of the Goose Creek Limestone to fifteen species.

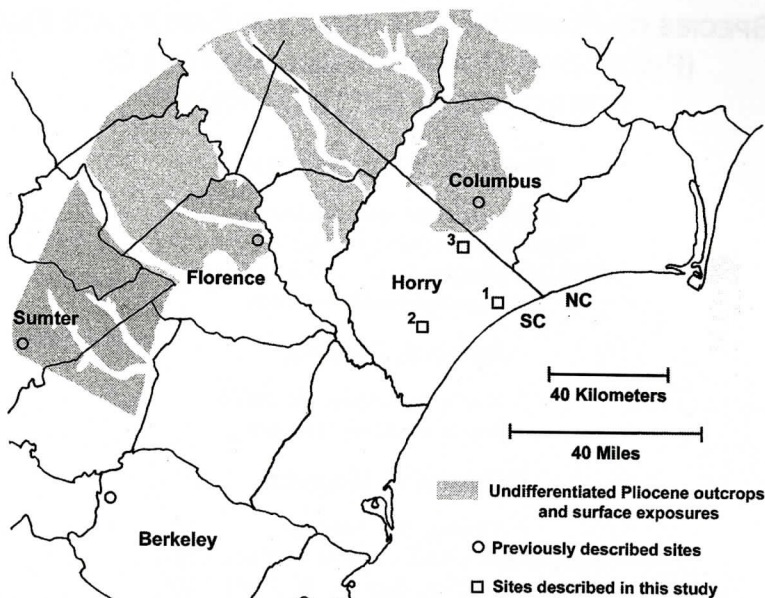
## INTRODUCTION

The echinoid fauna of the middle Pliocene Goose Creek Limestone of eastern South Carolina was first documented by Ravenel in the mid-nineteenth century (Ravenel, 1842, 1848). McCrady (1857) added to the fauna with a more definitive work on the echinoids of the Goose Creek Formation; however, the specimens available to McCrady were limited to largely

fragmented material gleaned from sporadic and fleeting pits and riverbank exposures north of Charleston, Berkeley County, South Carolina. In his enthusiasm to document the fauna, McCrady described *Plagionotus holmesi*, *Brissus spatiosus* and *Plagionotus ravenelianus* from test fragments that preserved insufficient detail for proper identification. Agassiz (1872) placed *Plagionotus holmesi* and *P. ravenelianus* in synonymy with *Metalia pectoralis* (= *Plagiobrissus grandis*) though two years later (1874) he regarded them as separate species. Clark and Twitchell's (1915) seminal work on North American echinoids added *Arbacia sloani* to the Pliocene fauna of South Carolina, though, Cooke (1941) suspected this species to be conspecific with *Arbacia improcera*. Kier (1972) also postulated that these two species were synonymous.

Material exposed during the dredging of the Intracoastal Waterway in Horry County, northeastern South Carolina, in the early twentieth century, provided for study more complete representatives of the echinoid fauna of the Goose Creek Limestone. This material was sufficient for Cooke to add *Spatangus glenni*, *Arbacia rivuli* and *Brissus glenni* to the fauna (Cooke, 1941; 1942; 1959), though the understanding at





**Figure 1: Map of the study area showing outcrop zone of undifferentiated Pliocene strata, collecting localities cited in the text, and Pliocene collecting localities described in other literature.**

that time suggested a Miocene age for the material.

The last twenty years have provided the finest opportunity for collecting the Goose Creek Limestone. In order to fill the demand for aggregate supporting the housing boom in the Grand Strand area, a series of quarries in Horry County, northeastern South Carolina, have intermittently excavated deep into the upper Goose Creek Limestone, providing an unprecedented opportunity for clarifying the Pliocene stratigraphy of South Carolina (Campbell and Campbell, 1995). The quarries also allowed a more complete knowledge of the echinoid fauna of this unit (Campbell and Campbell, 1995; Donovan and Clements, 2002; Lewis, Donovan and Clements, 2006). The *Plagiobrissus* specimens documented within this paper were collected between 2002 and 2008 as part of an ongoing study of the echinoid fauna of the upper Goose Creek Limestone in Horry County, South Carolina (Figure 1).

Within the same stratigraphic horizon as *Plagiobrissus sarae* n. sp., there is a diverse fauna of robust echinoids (Figure 2), including *Spatangus glenni*, which is the most characteristic element of the echinoid fauna of this horizon,

and notably large specimens of *Mellita* cf. *caroliniana*, *Echinocardium orthonotum*, and *Lytechinus* cf. *variegatus*. *Arbacia waccamaw* is first encountered near the top of the *Spatangus* biozone, and completes the echinoid fauna of this horizon. Whether or not the *Mellita* and *Lytechinus* from the *Spatangus* biozone differ from those of the overlying Waccamaw Formation, by more than merely their exceptional size, has yet to be determined. An undescribed species of *Arbacia*, with a large, very depressed test, with primary tubercles on alternating plates on the abactinal surface, occurs below the *Spatangus* biozone, and is currently being studied by the authors.

The echinoids occur with an abundant molluscan assemblage, dominated by *Carolinapecten eboreus walkerensis*, which is found in concentrated horizons both above and below the *Spatangus* biozone near the Intracoastal Waterway. Other molluscan constituents of this biozone include the bivalves *Hytissa haitensis*, *Nodipecten peedensis* and the ornate gastropod *Ecphora bradleyae*, a short-lived species useful for stratigraphic correlation (Campbell and Campbell, 1995).

Although future work by the authors will

Species	lower Goose Cr. LS	upper Goose Cr. LS	Waccamaw Fm	Canepatch Fm	Recent
<i>Lytechinus variegatus</i>					
<i>Lytechinus cf. variegatus</i>					
<i>Arbacia improcera</i>					
<i>Arbacia punctulata</i>					
<i>Arbacia rivuli</i>					
<i>Arbacia sp.</i>					
<i>Arbacia waccamaw</i>					
<i>Clypeaster romani</i>					
<i>Echinarachnius parma</i>					
<i>Mellita caroliniana</i>					
<i>Mellita isometra</i>					
<i>Encope macrophora</i>					
<i>Encope michelini</i>					
<i>Rhyncholampas sabistonensis</i>					
<i>Agassizia porifera</i>					
<i>Echinocardium orthotum</i>					
<i>Spatangus glenni</i>					
<i>Brissus glenni</i>					
<i>Brissus cf. unicolor</i>					
<i>Plagiobrissus sarae</i> n. sp.					

**Figure 2: Fossil Echinoid distribution in the Neogene of South Carolina. Data accumulated through literature review and extensive collecting by the authors.**

document the remaining elements of the fauna, described herein is the first definitive species of the genus *Plagiobrissus* described from the Pliocene of North America. Donovan and Clements (2002) discussed and illustrated a representative of this species, mistakenly identifying it as *Meoma ventricosa*. In the succeeding years since their work, numerous well preserved specimens have been recovered. Careful analysis clearly demonstrates that this species belongs to the genus *Plagiobrissus*.

## GEOLOGIC SETTING

Toumey (1848) originally described the Goose Creek Limestone from outcrops exposed in and around Charleston, South Carolina. Campbell and Campbell (1995) divided the formation into informal lower and upper units which are separated by an unconformity. Both units are lithologically identical, but may be distinguished biostratigraphically when molluscan diagnostic faunas are sufficiently rich (Campbell and Campbell, 1995). Both units consist primarily of leached, gray, sandy calcarenites, with the lower unit resting unconformably upon late Cretaceous to Paleocene strata.

The upper unit is separated from the overlying Waccamaw Formation (Figure 3) by a sharp unconformity (Dunbar and Dunbar, 1980). Aragonitic molluscan shell material, once abundant in the Goose Creek Limestone, has been extensively leached, leaving only molds and casts.

Campbell and Campbell (1995) correlated portions of the Duplin Formation with the lower unit of the Goose Creek Limestone based on its molluscan and echinoid fauna. In the study area of Conway and all of Horry County, mid-Pliocene calcarenites formerly referred to as the Bear Bluff Formation have been reassigned to the upper Goose Creek Limestone by Campbell and Campbell (1995). Though maximum thickness of the Goose Creek Limestone is unknown, its thickness in many places exceeds 35m (Dunbar and Dunbar, 1980). Based upon molluscan taxa the Upper Goose Creek Limestone is biostratigraphically equivalent to the inshore siliciclastics and offshore leached calcarenites of the Raysor Marl (Weems et al., 1982; Campbell and Campbell, 1995).

*Plagiobrissus* specimens described herein were collected from the upper Goose Creek Limestone at three sites in Horry County, South Carolina (Figure 1). Specimens collected from



	South Carolina	North Carolina	Florida
<b>Pleistocene, Upper</b>			
<b>Pleistocene, Middle</b>	Canepatch Formation		Bermont Formation
<b>Pleistocene, Lower</b>	Waccamaw Formation	James City Formation	Caloosahatchee Formation
<b>Pliocene, Upper</b>			
<b>Pliocene, Middle</b>	upper Goose Creek Limestone (Raysor/Bear Bluff Limestone)	Chowan River Formation  Yorktown Formation	Tamiami and Jackson Bluff Formations
<b>Pliocene, Lower</b>	lower Goose Creek limestone (Duplin Limestone...extent of the Duplin's correlation is not defined)	Yorktown Formation	Tamiami Formation

**Figure 3: Generalized correlation of Pliocene-Pleistocene strata discussed in this paper from North Carolina to Florida.**

Site 1 (N33° 49.10', W78° 44.00') occur in a one-meter thick zone of gray, leached, medium to coarse-grained calcarenite of the upper Goose Creek Limestone, 10 to 12 meters below the unconformable contact with the overlying Waccamaw Formation. Specimens obtained from Site 2 (N33° 51.90, W78° 59.90') occur in a one-meter zone of fine-grained, gray calcarenite, barren of mollusks, that lies two meters above the underlying Late Cretaceous Peedee Formation, and 6 to 8 meters below the top of the Pliocene section. Specimens obtained from Site 3 (N34° 1.00', W78° 47.90') occur in a coarse, gray, dense limestone, associated with abundant scallop fragments, and are nearly always fragmented and incomplete.

### Depositional Environment

The Goose Creek Limestone formed during the transgressive phase of the glacio-eustatic cycle corresponding to the K5 level of the

Krantz model indicating an approximate age of 3.5 my (Krantz, 1991; Campbell and Campbell, 1995). During the maximum transgression, the Goose Creek Embayment submerged the coastal plain of current day South Carolina, reaching an altitude of approximately 42 meters and resulted in the formation of the Mechanicsville Scarp (Dunbar and Dunbar, 1980). Resulting carbonate deposition, responsible for the Goose Creek Limestone, spread from northeastern Georgia, north across the South Carolina coastal plain, and into southeastern North Carolina (Campbell and Campbell, 1995; Weems et al, 1982).

Molluscan assemblages indicate the fauna inhabited a warm temperate to subtropical marine climate (Dunbar and Dunbar, 1980), and the echinoid fauna agrees with this assessment. The lower unit appears to consist mostly of inner shelf molluscan species (Campbell and Campbell, 1995), and the upper Goose Creek biofacies indicate an open marine, shallow shelf

depositional environment (Dunbar and Dunbar, 1980).

## PALEOECOLOGY

The Goose Creek Limestone contains fifteen species of echinoids (Figure 2) representing ten genera. Two species are found in the lower Goose Creek Limestone, *Encope macrophora* and *Arbacia improcera*; although, only *E. macrophora*, which is locally abundant and characteristic of the lower unit of the Goose Creek Limestone, extends into the lower portion of the upper unit where it is rare. Of the remaining thirteen echinoid species, six are found within the upper Goose Creek Limestone that do not extend into the Waccamaw Formation. These include *Spatangus glenni*, *Echinocardium orthonotum*, *Arbacia rivuli*, *Arbacia* sp., *Lytechinus* cf. *variegatus*, and *Plagiobrissus sarae* n. sp. Species which continue into the overlying Waccamaw Formation (Figure 3) include: *Mellita caroliniana*, *Agassizia porifera*, *Brissus glenni*, *Rhyncholampas sabistonensis*, *Arbacia waccamaw*, and *Lytechinus variegatus*. The upper-Pleistocene Canepatch Formation overlies the Waccamaw Formation in the study area of Horry County, South Carolina, and contains notable concentrations of *Encope michileni* and *Mellita isometra*, as well as rare occurrences of *Echinarachnius parma* and *Arbacia punctulata*.

Though never common, *Plagiobrissus sarae* n. sp. has been collected from all three Horry County sites (Figure 1) suggesting the distribution of the species was widespread throughout the northeastern depositional area of the Goose Creek Limestone.

Echinoids co-occurring with *Plagiobrissus sarae* n. sp. near the Intracoastal Waterway are often remarkably well preserved. Barnacle and oyster attachments, commonly found on *Spatangus*, *Plagiobrissus*, *Mellita* and *Echinocardium* in this horizon, indicate a significant delay between death and deposition. Donovan and Clements (2002) postulated that a similarly preserved *Plagiobrissus* with oyster and barnacle attachments from the Thompkins Pit near Conway (Figure 1) might have had a minimum residence time of five months on the sea floor

before burial, to account for the encrustations. The haphazard positions in which the specimens are often found indicate that they likely lay exposed on the ocean floor, tumbling in the current, before being buried. They were certainly not entombed in their burrows. Contrarily, in a zone immediately above the *Spatangus/Plagiobrissus* horizon near the Intracoastal Waterway, specimens of *Echinocardium orthonotum* are infrequently found retaining some of their glassy spines, especially on the oral surface, indicating a lack of post-mortem transportation and relatively rapid burial.

The similarities of *Plagiobrissus sarae* n. sp. to its recent relative *P. grandis*, suggest that the habits of the two were likely very similar. *P. grandis* (Figure 4A & B) is found in sandy areas off shore, in water depths from 1 to 210 meters, though most commonly in less than 50 meter depths (Serafy, 1979). Kier and Grant (1965) found *Plagiobrissus grandis* in 4 to 26 meters of water off the Florida Keys where it prefers deep sand. They observed *P. grandis* burrowing just below the sandy surface along the edges of sea grass beds, and noted that *P. grandis* was capable of rapidly moving across a foot of sand in as little as three seconds. The specimens of *Plagiobrissus sarae* n. sp. collected as part of the current study were most commonly associated with other burrowing species such as *Spatangus glenni* and *Echinocardium orthonotum*. The presence of *Lytechinus* cf. *variegatus* suggests deposition in proximity to turtle grass beds (Kier and Grant, 1965).

## Systematic Paleontology

Figured specimens of *Plagiobrissus sarae* n. sp. are housed at the North Carolina Museum of Natural Sciences (NCSM) in Raleigh.

**Order SPATANGOIDA Claus, 1876**

**Suborder MICRASTERINA Fischer, 1966**

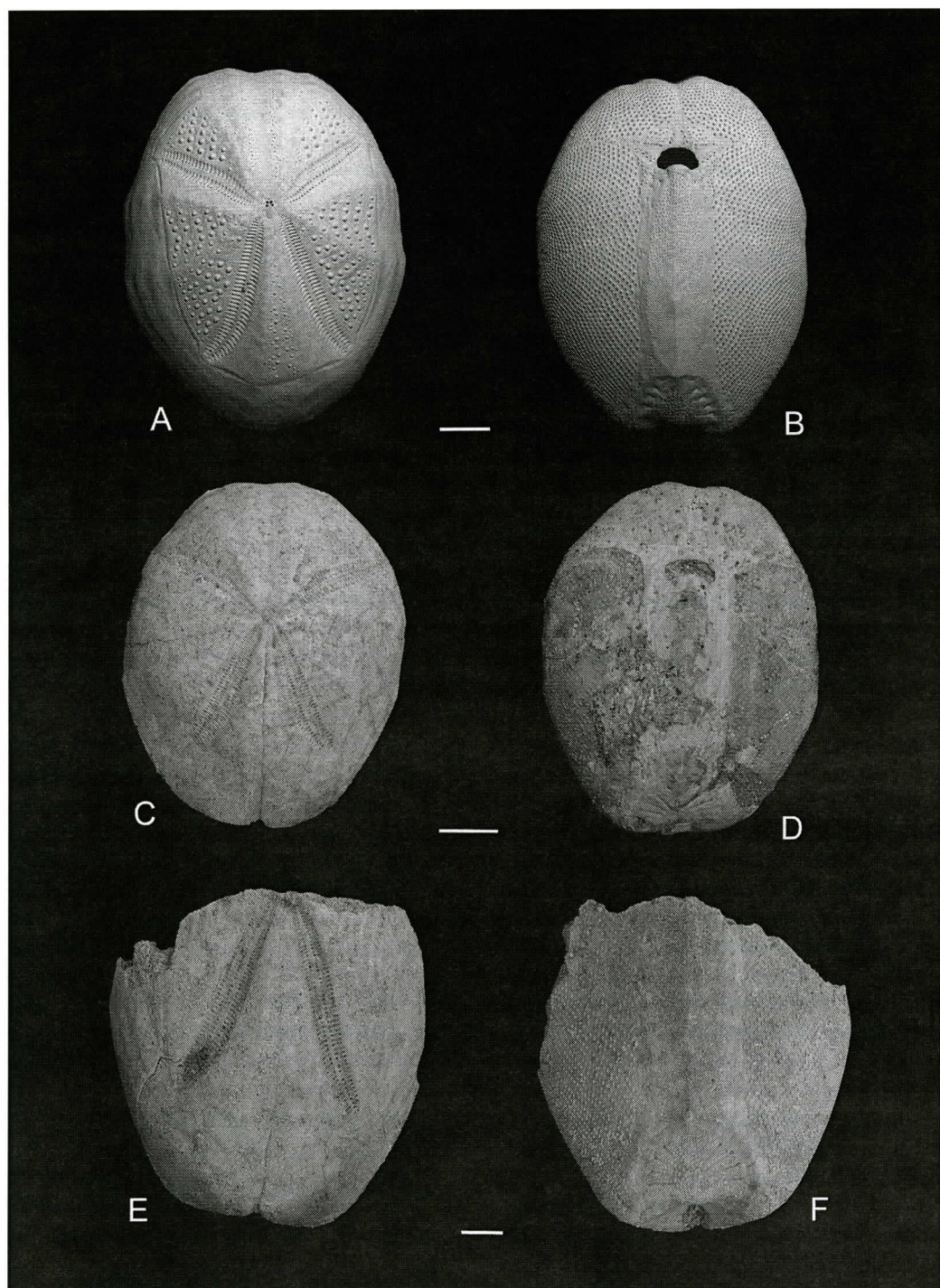
**Family BRISSIDAE Gray, 1855**

**Genus *Plagiobrissus* Pomel, 1883**

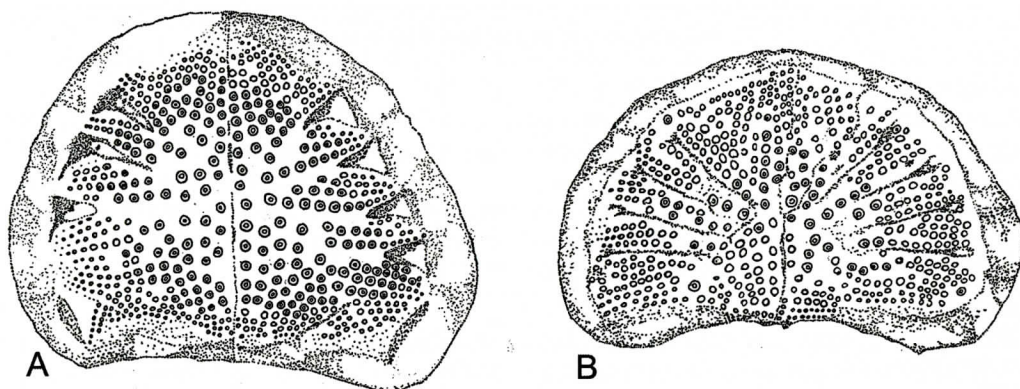
***Plagiobrissus sarae*, new species**

**(Figures 4 C, D, E & F; 5 A & B)**









**Figure 5: Camera Lucida comparison of sub-anal fasciole of (A) *Plagiobrissus grandis* and (B) *Plagiobrissus sarae* n. sp.**

**Diagnosis:** *Plagiobrissus* in which the test is very large, sub-oval, low in profile, and more sparsely tuberculated on the abactinal surface than *P. grandis* (Gmelin, 1788). Test is more rotund than other described Cenozoic *Plagiobrissus*, inflated anteriorly, with a very broad subanal fasciole.

**Description:** Test thin, very large, outline sub-oval in profile becoming more swollen and rotund with increasing size. Margin rounded, test obliquely truncated at the posterior, upper surface flat in the apical area, swollen anteriorly with the vertex anterior of the apical system. Test gently sloped downward from just forward of the apical system to the posterior apex; this feature is most pronounced in larger specimens. Oral surface gently convex. Apical disc slightly anterior, ethmolytic, with four circular genital pores. Comma-shaped madeporite extends far beyond ocular plates into interambulacrum 5. Petals narrow, somewhat flexuous, depressed.

Ambulacra II and IV shorter than ambulacra I and V and slightly curved anteriorly; ambulacra I and V flexed outward towards the extremity. Petals extend more than two-thirds the way to the margin. Ambulacral pores circular, conjugate. Ambulacrum III weakly sunken in slight groove; pore-pairs small. Abactinal ambulacra naked, narrow with ambulacra II and IV nearly parallel to each other. Peripetalous fasciole often somewhat sunken, narrow, does not indent between the ambulacra, but rather remains parallel with the edge of the test except the anterior angle made previous to traversing the ambulacrum III. Sub-anal fasciole well developed, shield-shaped, not lobed, broader than high, with anal branches; four well defined, prominent, pores present on each side of the sub-anal fasciole, tubercles arranged in conspicuous radiating lines (Figure 5B). Periproct large, pear shaped, in a depression in the truncated posterior extremity of the test, upper end turned up-

**Figure 4: Type Specimens of *Plagiobrissus sarae* n. sp., and comparison image of *Plagiobrissus grandis*. Type specimens are housed at the North Carolina Museum of Natural Science. Recent specimen is courtesy of Boris Savic. Scale is 2cm.**

- A: *Plagiobrissus grandis*, aboral view, trawled off Andros Island, Bahamas, 150mm x 115mm
- B: *Plagiobrissus grandis*, oral view, trawled off Andros Island, Bahamas, 150mm x 115mm
- C: *Plagiobrissus sarae* n. sp., holotype NCSM 11246: aboral view, Goose Creek Limestone, locality 1: Horry County SC, 143mm x 114mm
- D: *Plagiobrissus sarae* n. sp., holotype NCSM 11246: oral view, Goose Creek Limestone, locality 1: Horry county SC, 143mm x 114mm
- E: *Plagiobrissus sarae* n. sp., paratype NCSM 11247: aboral view of partial specimen, locality 1; Horry County SC, 106mm x 138mm
- F: *Plagiobrissus sarae* n. sp., paratype NCSM 11247: oral view of partial specimen, locality 1; Horry County SC 106mm x 138mm



Measurements of <i>Plagiobrissus sarae</i> n. sp.								
Specimen	Holotype NCSM 11246	Paratype NCSM 11247	1	2	3	4 (partial)	5 (partial)	6 (partial)
Length (mm)	143	179	160	168	149	155	?	?
Width (mm)	114	?	?	124	118	125	150	145
Height (mm)	47	?	56	64	62	?	?	?
Anterior Ambs (mm)	49	?	54	64	53	?	65	?
Posterior Ambs (mm)	54	?	64	55	61	?	?	?
Periproct height (mm)	16	?	19	?	21	?	19	20
Peristome height (mm)	21	?	?	25	23	?	?	?
Subanal Fasc. Width (mm)	37	?	45	45	40	44	49	52

Figure 6: Measurements of *Plagiobrissus sarae* n. sp. Dimensions that are indeterminable due to matrix obstruction or incompleteness are not included, and are thus indicated by a question mark. Specimens one through six reside in private collections. (Ambs=Ambulacra; ht=height; Fasc=Fasciole)

wards towards abactinal pole, rising above the edge of the test. Peristome located in the posterior quarter of the actinal surface; semilunate; floscelle very conspicuous. Labrum short, wide, in contact with sternal plates. Plastron elongate, narrow, with keel that becomes more pronounced at posterior extremity and is sharpest where the plastron meets the subanal fasciole. Entire abactinal surface of test crowded by minute tubercles, forming a regular granulation. Large perforate, crenulate, primary tubercles confined within the peripetalous fasciole, concentrated within interambulacra 1 and 4 forming horizontal rows; tubercles not sunken. Primary tubercles sparse in interambulacra 2 and 3; small but numerous primary tubercles present adjacent to ambulacrum III. Tubercles of interambulacra 2 and 3 smaller than those of interambulacra 1 and 4, concentrated adjacent to a slight ridge that extends from the apical area to the posterior end of the test. Tubercles of actinal surface largest outside of the ambulacral rows, gradually decreasing towards the edge of the test; tubercles of actinal plastron considerably smaller and more condensed.

*Discussion:* *Plagiobrissus sarae* n. sp. is readily

differentiated from the recent species *Plagiobrissus grandis* (Gmelin, 1788) by the following traits: 1) Much sparser tuberculation: large primary tubercles on the abactinal surface are largely limited to interambulacra 1 and 4 in *P. sarae* n. sp. whereas these large primary tubercles are also prevalent in interambulacra 2 and 3 of *P. grandis*. Tuberculation within interambulacra 1 and 4 is also much sparser in *P. sarae* n. sp. than in the *P. grandis*. 2) The outline of the test: *P. sarae* n. sp. is often more rotund in larger specimens, whereas *P. grandis* is more elongate; *P. grandis* is also characterized by a flat abactinal surface, whereas the test of *P. sarae* n. sp. is more inflated anteriorly, and gently slopes posteriorly from the apical area to the posterior margin of the test. 3) The subanal fasciole of *P. sarae* n. sp. is generally broader than that of *P. grandis* in relation to the size of the test (Figure 5). 4) Ambulacral II and IV are proportionately longer on *P. sarae* n. sp. than *P. grandis*. The above features are consistent in all specimens examined.

*Material:* Holotype NCSM 11246 (Figure 4 C & D). Paratype NCSM 11247 (Figure 4 E & F). Material examined includes the holotype, para-

type, four additional specimens collected by the second author in Horry County, South Carolina which reside in his private collection, and two specimens from the collection of Boris Savic.

*Measurements:* Measurements for all examined specimens are given in Figure 6.

*Etymology:* This species is named in honor of Sara Osborn, the daughter of the second author and collector.

*Occurrence:* *Plagiobrissus sarae* n. sp. is restricted to the lower portion of the mid-Pliocene, upper Goose Creek Limestone, and has not been reported outside of the outer coastal plain of South Carolina.

## DISCUSSION

The addition of *Plagiobrissus sarae* n. sp. brings the known echinoid fauna of the Goose Creek Limestone to fifteen species (Figure 2). Reaching a length of at least 179mm, *Plagiobrissus sarae* n. sp. is now the largest described Cenozoic spatangoid echinoid from North America. This is not surprising considering that it is undoubtedly the ancestor of *Plagiobrissus grandis*, which attains lengths upwards of 220 mm (Seraphy, 1979; Kier and Grant, 1965) and is the largest spatangoid echinoid in the extant fauna.

McCrary (1857) described *Plagionotus holmesi* and *Plagionotus ravenelianus* from the Pliocene of the Charleston, South Carolina area, which is roughly 100 km southwest of the current study area of Horry County, South Carolina. However, these two species are indeterminable because the fragments used to describe them represent less than 5% of the creature they represent. Cooke (1959) postulated as such when he stated that these two nominal species, based on fragments, are unrecognizable from their figures and descriptions. Agassiz (1872) placed *Plagionotus holmesi* and *P. ravenelianus* in synonymy with *Metalia pectoralis* (= *Plagiobrissus grandis*). It is not possible to definitively attribute the specimens described within this paper to either of these species based on McCrary's descriptions or illustrations.

Oyen and Portell (2001) list *Plagiobrissus* as

occurring in the Tamiami Formation of south Florida, and Oyen (2001) illustrates incomplete material of this species in his unpublished doctoral thesis. He tentatively refers this material to *Plagiobrissus grandis*, but admits to uncertainty due to the incompleteness of the test. Further study will be necessary to determine if this Tamiami Formation *Plagiobrissus* is synonymous with *Plagiobrissus sarae* n. sp.

A future publication, as part of an ongoing study by the authors, will more fully detail echinoid zonation and assemblages within the upper Goose Creek Limestone of the South Carolina coastal plain, and formalize as yet undescribed elements of the echinoid fauna.

## ACKNOWLEDGEMENTS

We thank Boris Savic of West Hills California for loaning specimens of *Plagiobrissus sarae* n. sp. from his collection for measurements and study. We are also indebted to Dwayne Varnam, of Varnamtown, North Carolina, for sharing his knowledge of the echinoid fauna of the Waccamaw Formation, and leading the second author on numerous collecting trips in search of Pliocene and Pleistocene age echinoids. We also thank Andrea Ciampaglio, whose assistance was vital to the completion of the illustrations. We are also indebted to George Phillips and Burt Carter for their critical reviews, which were invaluable in the completion of this manuscript.

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# COMMENTS ABOUT PLEISTOCENE STRATIGRAPHY IN “GULF COASTAL PLAIN REGIONAL CONTRASTS: KEY TO LOWSTAND AND UPLIFT-DRIVEN EXTENSIVE PLEISTOCENE DENUDATION”

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## INTRODUCTION

Otvos (2009) presents a fascinating and thought-provoking discussion of sharp contrasts in Quaternary geology between the Mississippi-Alabama and Louisiana Gulf coastal plains. Unfortunately, his paper is partially marred by the use of antiquated stratigraphic nomenclature that has either been abandoned or greatly revised within the Gulf coastal plain. First, Otvos (2009) incorrectly indicates that the Williana Formation (Member or Terrace) of Fisk (1938, 1939a, 1940, 1944), which also has been discredited and abandoned as a valid stratigraphic unit, correlates with the Citronelle Formation. Second, Otvos (2009) incorrectly regards the Bentley and Montgomery formations (members or terraces) of Fisk (1938, 1939a, 1940, 1944) as being valid coast-wise stratigraphic units when they are no longer mapped as extending outside of the Red River alluvial valley region. As a result, it is incorrect for Otvos (2009) to write about “Montgomery alluvial terrace deposits” in Mississippi when the Montgomery Formation, which has been redesignated as the “Montgomery Alloformation”, is now only recognized as being a valid stratigraphic unit for Pleistocene sediments underlying fluvial terraces along the Red River. Third, the interpretation of published evidence indicates that the Lissie Formation of Texas, which is correlative in part with Otvos' (2005) “Bentley and Montgomery terraces” in Southwest Louisiana, is considerably older than Marine Isotope Stage 7. The relationship of the sediments dated in Southwest Louisiana by Ot-

vos (2005) to Otvos' (2009) “Montgomery alluvial terrace deposits” in Mississippi is matter of speculation. Therefore, the assignment of these “terrace deposits” to the Montgomery Alloformation currently lacks any scientific basis. Finally, Otvos (2009) is unclear about the precise manner in which the Biloxi and Prairie formations of Mississippi correlate with the Beaumont Formation of Texas and the equivalent Beaumont Alloformation of Louisiana.

## EARLY AND MIDDLE PLEISTOCENE STRATIGRAPHY

### Williana Formation

In Otvos (2009), a brief note is made that the Williana Formation is correlative to the Citronelle Formation. There are two major problems with this statement. First, the commonly graveliferous sediments within Grant, LaSalle, and Rapides parishes, which Fisk (1938, 1940) designated and mapped either as the Williana Formation or Member are Pleistocene, not Pliocene, in age. Pliocene sediments are absent within the type region of the Williana Formation between the Calcasieu and Mississippi rivers (Doering 1956, Heinrich and McCulloh 2000, 2002). Winker (1991) also shows his Pliocene Pre-Lissie surface is absent within the type area of the Williana Formation. He maps this region as the Pleistocene Lissie surface. The deeply dissected and eroded and graveliferous sediments that Fisk (1938, 1940) mapped as either the Williana Formation or Member lies well below the base of the coarse-grained and



often gravelly Pliocene sediments of the Willis Formation that cap hills and ridges west of the Calcasieu River in Fort Polk area and East Texas. The stratigraphic position and significantly less weathered nature of the gravelly sediments that compose Fisk's Williana Formation relative to the Willis Formation in west-central Louisiana and East Texas demonstrates that the Fisk's Williana Formation is significantly younger than the Willis Formation and is Pleistocene in age (Doering 1956:Figure 4, Heinrich and McCulloh 2000, 2002).

The Pleistocene age of the Williana Formation is further demonstrated by the presence of igneous and metamorphic rocks derived from sources in the Lake Superior and Central Interior regions (Fisk 1939b). The presence of these rocks within these sediments shows that they contain a glacial outwash component that is lacking in the Pliocene Citronelle and Willis formations. Igneous and metamorphic rocks, which are lacking in the Citronelle Formation and indicative of a glacial outwash component, occur within the Natchez Formation, which correlates with the Bentley Alloformation. The Natchez Formation crops out along the eastern valley wall of the Mississippi River Alluvial Valley in Mississippi well below the level of the base of the adjacent Citronelle Formation (Rhinehart and Meylan, 1992).

Finally, geological research within the type area of the Williana Formation found a lack of any evidence for it being a valid stratigraphic unit. Cores and a gravel pit studied by Autin et al. (1993) found that the Williana Formation within its type region near Williana, Louisiana, typically consists of deeply weathered, gravelly Pleistocene pedisegment about 1 to 3 meters (3 to 9 feet) thick overlying weathered Paleogene strata. Additional research, including the construction of topographic profiles from 7.5 minute quadrangles, examination of LIGHT Detection And Ranging (LIDAR) digital elevation models (DEMs), and field studies conducted for McCulloh and Heinrich (2004) found a lack of any recognizable bounding unconformity, terrace surfaces, or lithologic characteristics that could be used to differentiate the Williana and Bentley formations from each other. The

Williana and Bentley terraces as mapped by Fisk (1938, 1940) and other published research within this region were found to be nonexistent. Because of the absence of morphologic, lithologic, and stratigraphic criteria for separating it from the Bentley formation within Fisk's type area, the Williana Formation was abandoned as a valid stratigraphic unit and the Bentley Formation was redefined as the Bentley Alloformation. Thus, it is not only incorrect to correlate the Williana Formation with the Citronelle Formation but the Williana Formation is a nonexistent and invalid stratigraphic unit.

### **Bentley and Montgomery Formations**

The stratigraphic units that Fisk (1938, 1939a, 1940, 1944) designated and mapped as the Montgomery and Bentley formations, members or terraces and used by Otvos (2005, 2009) have been abandoned as coast-wise stratigraphic units. Geologic mapping and research has found that they are restricted in distribution to the region of the Red River Alluvial Valley. Regional mapping of the Gulf of Mexico coastal plain mapping by Doering (1956) and Winker (1991) found a lack of evidence for the differentiation by Fisk (1938, 1940) of what they found to be a single coast-wise stratigraphic unit into his Bentley and Montgomery formations or terraces. As a result, Doering (1956) merged the Bentley and Montgomery formations within the coastal plain back into a single stratigraphic unit, the Lissie Formation. Similarly, Dubar et al. (1991) and Winker (1991) merged Fisk's Bentley and Montgomery terraces into a single coast-parallel terrace that they mapped as the Lissie surface. As noted by Aronow (1993) and Johnson et al. (2008), later sheets of the Geologic Atlas of Texas discarded the Bentley and Montgomery formations in favor of the Lissie Formation in the 1:250,000 scale geological quadrangle maps published between 1979 and 1992. Neither the Texas Bureau of Economic Geology nor the Louisiana Geological Survey currently recognized either the Bentley or Montgomery formations as being found outside of the Red River Alluvial Valley region (Barnes

1992, Snead et al. 2002a, 2002b, McCulloh et al. 2003, McCulloh and Heinrich 2004).

In his figure 2, Otvos (2005) illustrates his Bentley and Montgomery terraces as a single, undifferentiated map unit. Similarly, in both Figures 1 and 11 of Mange and Otvos (2005), the Bentley and Montgomery terraces are also illustrated as a single map unit. Neither Otvos (2005) nor Mange and Otvos (2005) illustrate the location of the Bentley-Montgomery contact within Southwest Louisiana. If the Bentley and Montgomery terraces are indeed the distinct terraces as shown in Figure 1 of and assumed by Otvos (2005) and given the complete coverage of Southwest Louisiana by LIDAR DEMs, it should have been relatively easy for the contact between these terraces to have been mapped and each of the two terraces illustrated as separate, not combined, map units in both papers.

In addition, the geomorphology and stratigraphy of Pliocene and Quaternary sediments were examined in great detail as part of USGS funded projects for the compilation of 1:100,000-scale 30 by 60 degree geologic maps for Southwest Louisiana (Heinrich et al. 2002, 2003, Snead et al. 2002a, 2002b). This research involved a review of published and unpublished geological maps, papers, and manuscripts. This geologic mapping involved fieldwork, which included a limited number of cores. This mapping also involved the analysis of 7.5-minute quadrangles, numerous topographic profiles, soil surveys, aerial imagery of various types and dates, water well logs, and other data. This detailed examination of the area now mapped as Lissie Alloformation in Southwest Louisiana for the preparation of Heinrich et al. (2002, 2003) and Snead et al. (2002a, 2002b) found a lack of either surface or subsurface evidence that could be used to justify the subdivision of the Lissie Alloformation into the Bentley and Montgomery formations (terraces) as mapped by Fisk (1939a) and Holland et al. (1952). The coast-parallel terrace that forms the surface of the Lissie Alloformation exhibits coast-parallel scarp trends. However, detailed study of these scarps demonstrated that they are fault-line scarps of tectonic, not depositional, origin

(Heinrich 2000, 2005). Given the lack of credible evidence for two coast-parallel subdivisions within the Lissie Alloformation (Formation), the Bentley and Montgomery formations (terraces) of Fisk (1938, 1939a, 1940, 1944) and Holland et al. (1952) are no longer recognized by the Louisiana Geological Survey as coast-parallel stratigraphic units and both have been restricted to Pleistocene sediments occurring within and adjacent to the Red River Alluvial Valley (McCulloh and Heinrich 2004, Snead et al. 2002a, 2002b).

Furthermore, Doering (1956), Dubar et al. (1991), and Winker (1991) recognized and mapped prominent terraces largely restricted to Allen and Evangeline parishes, Louisiana, belonging to stratigraphic units intermediate in age and stratigraphic position between the Lissie and Beaumont alloformations. One of these very distinct terrace surfaces was mapped separately as the Oberlin terrace by Doering (1956) and mapped as part of the "intermediate terraces" of Dubar et al. (1991) and Winker (1991). Snead et al. (2002b) mapped the Oberlin terrace as the surface of the Oakdale alloformation and the additional Elizabeth alloformation. Without explanation, Otvos (2005) completely disregards these two alloformations and their well-defined terraces. As a result, this paper indiscriminately conflates and maps three well-defined alloformations together part of his undifferentiated coast-parallel Bentley and Montgomery terraces which have been discredited by Doering (1956), Dubar et al. (1991), and Winker (1991) in their published research.

The age of the Lissie Formation of Texas, which is the same stratigraphic unit as the Lissie Alloformation of Louisiana, has been traditionally argued to be Early Pleistocene in age. Duessen (1924) reports the presence of many Early Pleistocene vertebrate fossils, i.e. *Trucifelis fatalis*, *Elephas imperator*, *Bison latifrons*, and *Glyptodon* spp., from it. In addition, the Lissie Formation, which originally was designated as the "Equus beds" by Dumble (1894), contains two species of extinct horse, *Equus francisci* and *Equus complicatus*. Kukla and Opdyke (1972) found that samples of the Lissie Alloformation exhibited reverse magnetic po-



larity. The reverse magnetic polarity of its sediments indicated to Dubar et al. (1991) that the Lissie Alloformation (Formation) dated between 0.79 and 2.48 mya (million years ago). Dubar et al. (1991) and Winker (1991) also assigned an Early Pleistocene age to the Lissie Alloformation based on down-dip projections to biostratigraphic markers encountered in offshore wells. Thus, various researchers argue for an Early Pleistocene age for the Lissie Alloformation.

Optically stimulated luminescence (OSL) dates of older than  $0.114 \pm 0.009$  mya from near Glenmora, Louisiana, and older than 0.277 mya from near Longville, Louisiana have been reported by Otvos (2005). Because they are older-than-dates, they provide only minimum ages for the Lissie Alloformation. Such older-than-dates also fail to indicate the age of the younger Elizabeth and Oakdale alloformations of Snead et al. (2002b), whose well-defined terrace surfaces Otvos (2005) groups indiscriminately together with the terrace surface of the Lissie Alloformation as his "Bentley and Montgomery terraces" within Southwest Louisiana. Similarly, Otvos (2005) reports an OSL date from the Lissie Formation near Buna, Jasper County, Texas, of  $0.216 \pm 0.089$  mya. Over large parts of East Texas and southwest Louisiana, the Lissie Formation is covered by a thick, as much as 1 to 2 meters thick, surficial sand mantle composed either of eolian sediments, colluvium, pedogenic biomantle, or some combination of these as discussed by Johnson et al. (2008). Because of the lack of detailed measured sections provided by Otvos (2005), it remains unknown whether the dated samples actually came from undisturbed Lissie Formation or from much younger colluvial or eolian sediments, biomantle created by the constant ongoing bioturbation of the surface of the Lissie Formation, younger incised valley fill, or some combination of these. In addition, the lack of detailed data, such as radionuclide content of the samples, water content of the sample, saturation history, sample lithology, and so forth, that normally accompanies published OSL dates prohibits any interpretation of their reliability.

Within Texas, thermoluminescence (TL)

dates from the Beaumont Formation demonstrate that the Lissie Formation is definitely older than 0.3 million years in age and clearly predates Marine Isotope Stage 7, 0.191 to 0.243 mya according to Lisiecki, (2005a, 2005b), by a considerable period of time. Blum and Price (1998) and Blum and Aslan (2006) discuss two reliable TL dates of  $0.323 \pm 0.051$  mya (W-1689) and  $0.307 \pm 0.037$  mya (W-1699) obtained from a cutbank exposure in Jackson County, Texas, of point bar sands. Detailed measured sections demonstrate that these two TL dates came from unaltered and in situ Beaumont fluvial sediments. These point bar sands are part of the Lolita valley fill, which is the oldest of three Colorado River highstand valley fills that locally comprise the Beaumont Formation. These TL dates are perfectly consistent with the oldest valley fill, the Lolita valley fill, belonging mainly to Marine Isotope Stage 9, 0.300 to 0.337 mya; the next younger and undated valley fill, the El Campo valley fill, belonging mainly to the next interglacial sea level highstand, Marine Isotope Stage 7, 0.191 to 0.243 mya; and the Bay City valley fill, as indicated by multiple TL dates, belonging mainly to last interglacial highstand, Marine Isotope Stage 5, 0.071 to 0.130 mya (Blum and Price 1998, Blum and Aslan 2006, Lisiecki 2005a, 2005b). In addition, Thomas (1990) mapped using seismic data multiple sequence boundaries and interglacial highstand valley fills within the Beaumont Formation as defined in Texas. This and similar Rice University research demonstrates that the Beaumont Formation consists of sediments that accumulated during multiple Pleistocene 100-ky glacial-interglacial cycles. Therefore, the Lissie Formation, which either is cut by valleys filled with or overlain by the Beaumont Formation that spans multiple Pleistocene 100-ky glacial-interglacial cycles, clearly is significantly older than 0.3 million years in age. Otvos (2005) dismisses the TL dates of (Blum and Price 1998, Blum and Aslan 2006) outright as being "unreliable" without providing any specific reasons and makes no mention of the findings of Thomas (1990). Otvos (2009) ignores these valid and inconveniently old TL dates.

Mandel and Caran (1992) and Caran (1992) describe fluvial sediments that contain the Lava Creek B Ash underlying the Capitol Street Terrace along the Colorado River at the Rehmet locality near Smithville, Texas. Izett and Wilcox (1982) have solidly dated the Lava Creek B Ash as being about 0.62 mya. In addition, Baksi et al. (1992) found that the fluvial sediments underlying the Capitol Street Terrace are reversely magnetized and predate 0.78 mya. Both Caran (1992) and Doering (1956) correlate the fluvial fill underlying the Capitol Terrace with the Beaumont Formation of Texas. This correlation by Caran (1992) and Doering (1956) indicates that the oldest sediments of the Beaumont Formation and the youngest sediments of the Lissie Formation in Texas, and the correlative Lissie Alloformation of southwest Louisiana, predate 0.78 mya. This correlation is perfectly consistent with the  $0.323 \pm 0.051$  mya (W-1689) and  $0.307 \pm 0.037$  mya (W-1699) OSL dates of Blum and Aslan (2006), and completely contradicts the age interpretations made by Otvos (2005) from his OSL dates

Alternatively, Blum and Aslan (2006) and Hidy and Gosse (2008) presume that the sediments underlying the Capitol Street Terrace along the Colorado River correlate with the Lissie Formation within Texas. In this case, they argue that the fluvial sediments that contain the Lava Creek B Ash and underlie the Capitol Street Terrace correlate in part with the Lissie Formation. Although this interpretation makes the Lissie Formation in Texas both younger and older than 0.78 mya, it still implies the Lissie Formation cannot be as young as Marine Isotope Stage 7, 0.191 to 0.243 mya according to Lisiecki, (2005a, 2005b), as argued by Otvos (2005). This correlation also is entirely consistent with the  $0.323 \pm 0.051$  mya (W-1689) and  $0.307 \pm 0.037$  mya (W-1699) OSL dates of Blum and Aslan (2006) for the oldest surficial valley fill of the Beaumont Formation. Similarly, this interpretation also contradicts the age interpretations made by Otvos (2005) from his OSL dates.

Finally, with the current lack of knowledge about the correlation and stratigraphy of the Intermediate allogroup, which are Pleistocene

sediments that predate the Prairie Allogroup and postdate the Citronelle and Willis formations within Louisiana, it is physically impossible to determine either the age or stratigraphic relations between the so-called "Montgomery alluvial terrace deposits" of Mississippi and the sediments underlying "Montgomery and "Bentley terraces" of Otvos (2005) in southwest Louisiana. Because the OSL date of Otvos (2005) grossly underestimate the age of the Lissie Formation in Texas, it is likely that OSL date of  $0.1765 \pm 0.0321$  mya from Three Rivers, Mississippi, similarly underestimates the age of his "Montgomery Terrace". In addition, Otvos (2005) obtained TL dates of  $0.210 \pm 0.027$  and  $0.221 \pm 0.022$  mya from near Biloxi Mississippi and  $0.188 \pm 0.024$  mya from near Three Lakes, Mississippi from his "Montgomery Terrace".

Unfortunately, it is currently impossible to physically correlate Otvos' (2009) "Montgomery alluvial terrace deposits" with either the Lissie Alloformation or other units in Southwest Louisiana and independently evaluate the validity of his TL dates. Currently, the specific age and stratigraphic relationships between the three alloformations comprising the Intermediate allogroup in Southwest Louisiana and single alloformation comprising the Intermediate allogroup in Southeast Louisiana is completely unknown. Because of the lack of required data, it is unknown whether the Montpelier alloformation of Southeast Louisiana correlates either to the Lissie Alloformation, Elizabeth alloformation, Oakdale alloformation, or some combination of them. In addition, there exists a large gap between the Tangipahoa and Pearl rivers that lacks any coast-parallel segments of the Intermediate allogroup as illustrated by Mossa and Autin (1989) and Snead et al. (2009). Because of this gap, it is impossible, except by using the highly unreliable and error prone "position-in-sequence" methodology, to determine the correlation between the Montpelier alloformation and the so-called "Montgomery alluvial terrace deposits" of Otvos (2009). Therefore, the application of the discredited "Montgomery" terminology by either Otvos (2009) to his so-called "Montgomery alluvial terrace deposits" and the application of this



same terminology by Otvos (2005) to the surface of these sediments as his “Montgomery Terrace” lacks any credible supporting evidence. If the TL dates of Otvos (2005) are accepted at face value, then the sediments comprising the alleged “Montgomery alluvial terrace deposits” of Otvos (2009) consist of Marine Isotope Stage 7 sediments that might correlate with Irene alloformation of the Prairie Allogroup within Southeast Louisiana as mapped by Snead et al. (2009) instead of the considerably older Lissie Alloformation of the Intermediate allogroup, which Otvos (2005) includes in his “Montgomery and Bentley terraces”. Clearly, there is much research that still needs to be conducted about the stratigraphy of these deposits.

## LATE PLEISTOCENE

### Prairie and Biloxi Formations

In the case of his Prairie and Biloxi formations, Otvos (2009) fails to clearly explain that the Prairie Formation is defined in a very different manner than the Beaumont Formation of Texas and the equivalent Beaumont Alloformation of southwest Louisiana. As traditionally used in Mississippi, i.e. Otvos (2009), the Prairie Formation is equivalent only to the fluvial and fluvial-deltaic facies of the various sedimentary facies comprising the Beaumont Formation of Texas and the Beaumont and Hammond alloformations of Louisiana. Similarly, as it is traditionally used in Mississippi, the Biloxi Formation of Mississippi is equivalent only to the marine and estuarine facies found within the Beaumont Formation of Texas and the Beaumont and Hammond alloformations of Louisiana. Therefore, it is incorrect to imply that the Beaumont Formation of Texas and Otvos' (1975, 2009) Prairie Formation are direct equivalents of each other. In addition, despite having been defined and used by Otvos (1975, 2005, 2009) and Otvos and Howat (1992) for the last thirty years, their definitions of the Prairie, Gulfport, and Biloxi formations have neither been routinely nor consistently

used by geologists other than Dr. Otvos in either Texas, Louisiana, Alabama, and Florida. Finally, neither the Texas Bureau of Economic Geology, Louisiana Geological Survey, Geological Survey of Alabama, nor the Florida Geological Survey officially recognize the Prairie, Gulfport, and Biloxi formations, as defined by Otvos (1975), as being valid stratigraphic units (Barnes 1992, Johnston et al. 2000, Means 2009, Osborne 2009).

## CONCLUSIONS

Geologists and other scientists, while they read Otvos (2009), need to take in consideration that some of the stratigraphic terminology used in the paper is antiquated and obsolete. At this time, it is clear that the Williana Formation, Member, or Terrace of Fisk (1938, 1939a, 1940, 1944) neither correlates with the Citronelle Formation nor is regarded any longer as a valid stratigraphic unit in either its type area or anywhere else in Louisiana. Also, recent geologic mapping has discredited the existence of separate coast-wise Montgomery and Bentley formations or terraces as mapped by either Fisk (1938, 1939a, 1940, 1944) or Otvos (2005) within the Gulf Coastal plain. Within Texas and Southwest Louisiana, both of these stratigraphic units have been merged back into either the Lissie Formation in Texas or Lissie Alloformation in Louisiana. Adjacent to the Mississippi River Alluvial Valley, younger alloformations with distinct terrace surfaces have been recognized within Otvos' (2005) “Montgomery and Bentley terraces”. In addition, the necessary subsurface and chronological data needed to correlate Pre-Prairie Allogroup Pleistocene units mapped in both Southwest Louisiana and the Red River Alluvial Valley with those mapped in either Southeast Louisiana or Mississippi is currently lacking. Finally, despite similarity in the names used, the methodology and definition of Late Pleistocene units as used by Otvos (2009) in Mississippi differ greatly from how they are used elsewhere within the Gulf of Mexico Coastal Plain.

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# GULF PLEISTOCENE COASTAL PLAIN — GAPS AND MISDIRECTIONS; SEARCH FOR A VALID STRATIGRAPHY. RESPONSE TO HEINRICH

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## INTRODUCTION

Heinrich's present comments target conclusions reached years ago in several previous articles. His discussion reminds one of the often sterile controversy that fueled growth of a mushrooming coastal nomenclature in past decades. Without full attention to stratigraphic rules, vertically undefined sediment intervals that underlie major coastal surfaces in the past have often been designated as *formations* (e.g., Fisk, 1938; Doering, 1935, 1956; Bernard and LeBlanc, 1965; Blum and Price, 1994).

Doering's study of Pliocene-Pleistocene coastal plain deposits utilized large-scale (1:62,500) topographic maps. Although providing certain valuable insights, this subjective method resulted in an overly generalized, "broad-brush" approach, without proper attention to subsurface data, field context, and sedimentary sequence characteristics. The subdivision of a uniform late Pleistocene coastal surface in SE Louisiana into multiple terrace generations, based on minor topographic differences is one striking example of artificially designated surface categories. To sidestep the dilemma of the earlier "splitting" approach, the word *complex*, a neutral but rather ambiguous designation was introduced to combine diverse topographic and stratigraphic entities, not all with clearly defined boundaries and ages (e.g., Saucier and Snead, 1989).

Reaction to the "lumping" trend led to an opposite style of mapping. The extreme "splitting" approach resulted in a plethora of surface units; a complex hierarchy with an ever-expanding terminology. A series of "virtual" allostratigraphic coastal charts, based on an invalid stratigraphic methods produced imagi-

nary Pleistocene lithostratigraphic units (Louisiana Geological Survey, 2000-2009). Despite its retrogressive nature, indeed fatal shortcomings, this well produced map series still deserves credit for its surface details and the emphasized associated topographic differences between minor but valid physiographic units, such as the Big Cane and Avoyelles surfaces of SW Louisiana.

While the Louisiana coastal plain is among the most densely drilled regions anywhere, overall progress toward establishing workable litho- and time-stratigraphic subdivision of the underlying thick Pleistocene sediment sequence was relatively quite minor. The challenge posed by the need for a valid interpretation and dating of Fisk's (1938) three basic Pleistocene surfaces and directly underlying lithosomes provided the inspiration for a modest attempt to improve their litho- and biostratigraphic characterization and vertical definition by drill and outcrop data and numerical dating. Correlations based on morphostratigraphic comparisons of terrace elevations, degrees of surface dissection and slope gradients, ideally, should be supplemented by large volumes of new litho- and chronostratigraphic data. The presently available stratigraphic "tool set" that includes but a rather limited number of datable regional seismic reflectors, paleomagnetic, paleosol, volcanic ash markers, intercalated marine-estuarine intervals, luminescence- and terrestrial cosmogenic nuclide (TCN)-based dates must be expanded greatly. Such an effort would result in critical regional correlations between onshore and nearshore sediment intervals to eventually replace results of the outmoded and sterile "splitting, lumping, naming, and renaming" exercises of the past and present.



## Citronelle, Williana, and Willis; Identities and Ages

Sellards *et al.* (1932), later Doering (1956) dated the Texas and Louisiana Citronelle as Pleistocene. Fisk (1938), Fisk and McFarlan (1955), and others used the name *Williana* as an alternate term to "Citronelle." Only in one table did Doering (1956) correlate his "Lissie" with Fisk's *Williana* of 1938. Until quite recently, Pleistocene age was generally associated with both the Citronelle and *Williana* designations. Because they define essentially the *same* lithostratigraphic unit, their comparison was *not*, as Heinrich implies, a matter of chronostratigraphic correlation between different formations at different sites, but juxtaposition of different terms, as applied to identical lithosomes.

Interchangeably employed in combination with several late Pliocene and early Pleistocene units, Saucier and Snead (1989) merged numerous formations, including the Citronelle and *Williana* into a heterogenous "Upland complex." Based on more recent field data from the NE Gulf coast, Mange and Otvos (2005) retained the Citronelle designation with a Pliocene age content for SW Louisiana as well. Doering established (1935), then abandoned (1956) the name *Willis* in favor of Citronelle. Winker (1991) substituted the term *pre-Lissie* for *Willis* and Citronelle. As in the case of the *Prairie* and *Beaumont* in SW Louisiana, it seems to be a mistake to replace the gulfwide well accepted term Citronelle with the imported *Willis* designation (McCulloh and Heinrich, 2002).

Accepting Citronelle's Pliocene age, Heinrich (2009) first assigns Citronelle's *Williana* "alterego" to the Pleistocene Epoch, only to declare it an invalid formation in the next sentence. Further clouding the issue, somehow he attempts to correlate the "nonexistent" *Williana* with the *Pleistocene* Natchez (Fisk, 1938), a Mississippi River terrace at the foot of the Citronelle Upland (Rhinehart and Meylan, 1992). Because the precise age of the Natchez is yet unknown and the *Pliocene* age of the Citronelle accepted, Heinrich's intended correlation with

the *Williana*, is inexplicable, at the best.

In yet another puzzling attempt to prove the Pleistocene age of (*Williana*-correlative?) *valley terrace* deposits in central Louisiana (Fisk, 1939), Heinrich assumes glacial transport from the Lake Superior region. However, the Pleistocene Red River terraces, studied more recently by Russ (1975), generally are isolated from the Mississippi Valley area and characterized by a distinct heavy mineral spectrum (Mange and Otvos, 2005). Enclosed coarse igneous and metamorphic clasts provide scant evidence for glacial (icefloe-based?) sediment transport during "*Williana*" times and later. Two of the total of three "*Williana*" terrace sites (Nos. 3, 4) contained detritus from *non-glaciated* South-central Interior sources. Only No. 7 contained taconite rock fragments of possible northern origin. In addition to amygdaloidal basalt clasts, found *only* in a *younger* terrace, no other fragments reflected possibly northern derivation. Their petrology and chronostratigraphic correlation between the lower Red River Valley and SW Louisiana's coastal plain will require further studies.

## "PRE-PRAIRIE/BEAUMONT" TERRACE SURFACES AND LITHOSOMES – MISSING AND MISSTATED PLEISTOCENE CORRELATIONS

Correlating them with Red River valley terraces, in 1938 Fisk has established the Bentley, Montgomery, and the *Prairie* as three predominant coastal plain terrace stairsteps that decline seaward in elevation, slope grade, degree of erosional dissection, and age. Complicating terrace recognition, surface erosion has locally reduced, even eliminated the topographic step between the Bentley and Montgomery terraces. Increasing proliferation of coastal terms characterized especially the past seventy years. By exporting a Texas terminology and introducing a host of new designations, Doering (1956) did develop a Gulf Coast-wide terrace terminology. Practicing an imaginative yet overly subjective "arm chair-style" of mapping, in a limited area of SE Louisiana, quite unreasonably, Doering

subdivided the rather uniform, evenly sloping youngest (Prairie) surface into a Prairie-equivalent Eunice, intermediate Oberlin and oldest Lissie coastal terrace (Figures 2 and 9 in: Doering, 1956). In the long stretch between the Rio Grande and Brazos River he replaced the youngest, Beaumont/Prairie coastal plain surface, landward from the Holocene, with his older Oberlin (Fig. 8), validly established only in limited parts of SW Louisiana. In a similar manner, he also introduced a series of questionable terrace and coastal surface designations and correlations throughout coastal Mississippi, Alabama, and NW Florida.

The suggested Pleistocene coastal plain stratigraphy in Louisiana that still lacks critical marker horizons is based on the gulfward extension, of the oldest, "Lissie-Bentley" terrace lithosomes into the coastal plain subsurface. Discarding separate Bentley and Montgomery terrace designations, Heinrich retains only the Lissie and Beaumont (Prairie) terraces and their assumed downdip correlatives. Until the 1990s the Louisiana Survey accepted the Montgomery, Irene, and other terrace sectors as bona-fide physiographic entities, intermediate between the Prairie and the Bentley and part of the "Intermediate complex" (Sneed and McCulloh, 1984; Saucier and Sneed, 1989). Soon afterward, the same map compilers have rejected the validity of these units. Did, in the meantime a wave of the magic wand make the Montgomery disappear into thin air? This and the meaning of Heinrich's term, "*depositional* fault-line scarp" remain most mystifying. Surface faulting commonly defined terrace morphology (e.g., the Perkins Terrace surface near the Texas state line; Otvos, 1991). However, as the Big Ridge fault-line scarp between the Prairie and Montgomery Big Ridge terraces of the Mississippi Coast clearly illustrates (Otvos, 1997, 2005), it is a fallacy to deny the role that shore-parallel faults occasionally play in separating younger terraces from older ones.

The so-called "Lissie" and the supposedly overlying "Beaumont"/"Prairie" formations are so vaguely defined in the coastal plain subsurface that they lack practical substance. DuBar *et al.* (1991), for several reasons did *not* claim that

the Lissie "Formation" or "Alloformation" dates between 0.79 Ma (mid Pleistocene) and 2.48 Ma (late Pliocene). No grounds exist for "various researchers" to "argue on these grounds for the Early Pleistocene age for the Lissie Alloformation." Absolute dates older than the ~0.78 Ma magnetic reversal are not yet known from these deposits.

Ubiquitous misstatements that must stand correction, pervade Heinrich's comments. Among them; Doering's Eunice terrace corresponds to the Prairie/Beaumont, *not* to the spatially quite limited "Elizabeth" surface, inserted between the Lissie and Oberlin (Louisiana Geological Survey, 2002c). Winker's (Table 1, 1991) intermediate terrace between the Lissie and Beaumont matches *only* Doering's Oberlin, while Doering's Eunice of SW Louisiana and adjacent Texas corresponds to the, Prairie-Beaumont, the youngest Pleistocene coastal plain surface.

Additional corrections follow. Depending on which of Fisk successive terrace tabulations is matched, Doering's Oberlin corresponds either to Fisk's 1938-40 Bentley or to Fisk and McFarlan's 1955 Montgomery Terrace. Contrary to the Heinrich claim, Doering (1956, p. 1837) did *not* merge the Bentley and Montgomery into the Lissie. He replaced the Bentley with the Lissie, the Montgomery with the Oberlin, and substituted *Eunice* for Fisk and McFarlan's *Prairie* (Table 1 in Winker, 1991). Similarly, "we" (DuBar *et al.*, 1991) did *not* assign Fisk's combined Bentley and Montgomery to the Lissie: the "Lissie" replaced *only* the Bentley terrace. It was Winker who substituted *his* "Intermediate Terrace" for Fisk and McFarlan's Montgomery.

Heinrich incorrectly attributes to Doering the opinion that the Colorado River Capitol Terrace overlies the "Beaumont Formation." Doering (1956, p. 1844), assumed the *Beaumont* as equivalent of the *Oberlin surface*. Furthermore, Baksi *et al.* (1992) did *not* "correlate sediments that underlie the Capitol Terrace of the Colorado River with the Lissie Formation." They provided revised Brunhes-Matuyama magnetic field reversal dates from *Hawaiian basalts*. Heinrich, also incorrectly claims that I have



mapped the Montgomery and Bentley “formations” separately. Although clearly separate morphostratigraphic entities, the two units were combined in order to accommodate these small maps (Otvos, 2005; Figs. 2 and 3). Advanced and extensive numerical dating of the respective lithosomes may yet lead to accurate and detailed delineation of real formation boundaries.

### Intermediate Terraces and Numerical Pleistocene Dates; the Montgomery Issue

Winker (1991) believed that only a single pre-Prairie/Beaumont Pleistocene coastal surface, the “Lissie” is sufficiently uniform and continuous to justify participation in the regional terrace nomenclature of the Texas coast and SW Louisiana. However, this does not imply total absence of lesser morphostratigraphic (intermediate terrace) units from the region. Despite rejection of the Montgomery, the Louisiana Survey still accepted the existence of certain “intermediate” terraces, such as Doering’s Oberlin and an “intermediate allogroup”. As Winker (1991) acknowledged, considerable Pleistocene intervals corresponding to the Oberlin, the Montgomery, and other locally well developed terraces (e.g., the Irene in SE Louisiana) may be left without potentially identifiable correlatives in the subsurface.

The absence of subsurface horizons and other markers stymies regional correlations in Louisiana-Texas coastal plain sequences. While alluvial and paralic-nearshore deposits, probable Montgomery correlatives occasionally associated with developed paleosols have been recognized at shallow depths in the south Louisiana and central Texas under well defined Sangamon Interglacial sediment intervals (Bridges, 1939; Otvos, 1991; Otvos and Howat, 1992, 1996, 1997), in central Texas coast drillholes (e.g., Solis, 1981) the Beaumont and the Lissie were the only units identified as Pleistocene.

The handful of markers did provide numerical dates in older Texas coastal plain deposits. This, however, does not solve the problem of subsurface subdivision of the Pleistocene into Lissie (Bentley), Montgomery (Oberlin), Beau-

mont (Prairie) and/or potentially other units. The Brunhes-Matuyama magnetic reversal, now dated between ~0.8-0.7 Ma (Baksi *et al.*, 2008), may have included “at least partly” impacted deposits that have been designated “Lissie” at Bellville, near Houston (Kukla and Opdyke, 1972). Not identified in specific Colorado Valley drillholes, this horizon was merely *projected* downdip into the “Lissie” subsurface. Correlation of “Lissie-” or pre-“Lissie”-equivalent stream terrace alluvium that includes an interbedded “Lava Creek B” tephra bed along the Colorado River at Smithville, TX provides at best an indirect link to the “Lissie” Pleistocene coastal plain alluvium. The tuff is linked to the last super-eruption of the Yellowstone Caldera (~0.64 Ma; Lanphere *et al.*, 2002). This, upper reach of the lower Colorado traverses a bedrock valley, flanked by narrow fluvial terraces. The ash-bearing terrace deposits are widely separated from the Texas “Lissie” coastal plain, in the south.

Further corrections: Doering’s (1956; Table V) Lissie correlated *not* with the Capitol but the next older and higher Asylum Terrace of the Colorado River and the Oberlin (not the Beaumont) with the Capitol Terrace. Heinrich makes incorrect attributions to Blum and Aslan (2006) and Hidy and Gosse (2008) as well. These papers do not refer to the ash layer, let alone claim the Capitol Terrace (misspelled “Capital” in Blum and Valastro) as its source. Heinrich may have mistaken the referenced items for the Mandel-Caran field trip text. Never formally published, it is now inaccessible (Caran, written comm., August, 2009). Blum and Valastro (1994) note that the tephra beneath the Asylum Terrace surface “*appears to be* interbedded with deposits *underlying* the dissected part of the Asylum Terrace.” The wording suggests that the Lissie-linked Asylum Terrace may even postdate the tephra-bearing alluvium. A highly significant, yet preliminary <sup>10</sup>Be-based TCN date, 0.55 Ma, from a Columbus-Eagle Lake gravel pit in the Texas coastal plain (29.584° N; 96.473° W; Hidy and Gosse, 2008; Hidy, written comms., 2009), represents one of merely two *directly* acquired late mid-Pleistocene numerical dates in the entire coastal region.

Responding to Heinrich; *no* “Lissie Formation OSL date” has been reported from Buna, Texas. My TL (*not* OSL) date came from Montgomery Terrace deposits (Table 1) that may coincide with an “Upper (younger) Lissie” time interval, designated by Bernard and LeBlanc (1965, p.139). As noted, *formation* designations are clearly inappropriate for poorly defined sedimentary lithosomes associated with the Bentley, Lissie, Montgomery, Beaumont, and other terrace entities. Lacking valid age constraints, Heinrich’s scheme incorporates the entire pre-Beaumont (pre-Prairie) sequence into the “Lissie ‘Formation.’” Far from discredited, OIS 7 luminescence dates 176-221 ka B.P., obtained only from coastal Mississippi and Texas but supplemented by a 187 ka B.P. Red River terrace date (Otvos, 2005; Mange and Otvos, 2005) “breathe new life” into the Montgomery. Additional dates and detailed subsurface work may in the future establish the Montgomery and its correlatives as valid litho- and chronostratigraphic entities (Tables 1 and 2; Table 1 in Otvos, 2009a).

### **VALLEY FILL PARCELS, COASTAL PLAIN, AND VALLEY SURFACES; LATE PLEISTOCENE LUMINESCENCE DATING**

Perhaps a tad disingenuously, Heinrich complains about the absence of detailed luminescence data from one of my earlier articles (Otvos, 2005). Facing space limitations, in six tables the paper notes the availability of supplemental analytical and other data at readers’ request. None was received from Heinrich. Taking advantage of this opportunity, I am now attaching the documentation.

Incorrect dates from the older coastal plain units are symptomatic of the severe limitations imposed on luminescence dating in all Pleistocene coastal plain deposits more than ~250-300 ka old. A >277 ka and a >114 ka TL date from the oldest exposed Pleistocene coastal plain deposits, Samples 1-Be and 2-Be, are unrealistically young. For various reasons, even younger dates may be unattainable by current methods of luminescence dating. A very old TL date,

363 ka (#6-P; Table 1), from a Texas Prairie (Beaumont) valley surface highlights the problem that could explain TL dates 303 and 323 ka from Colorado River’s “Lolita valley fill” (Blum and Aslan, 2006). Originally, the Lolita was defined as intermediate between three laterally adjacent “valley fills” (Blum and Price, 1994). After TL-dating, however, it was redesignated as the oldest of these three alluvial parcels. The youngest fill dated between 102-155 ka B.P. (OIS 5a-through-6). Final results based on more advanced dating methods that would employ many more samples from different units in the delta region should be used to establish the actual age differences between adjacent three fluvial parcels and surrounding older alluvial units.

Three times in his discussion, Heinrich vehemently objects to my doubts concerning the oldest Blum dates. To wit: the “Lolita fill” dates originated at very shallow depths under the present land surface. How could deposits, that ancient, remain in elevated position and still escape wholesale erosional elimination before being surrounded and superficially covered by a very thin late Pleistocene overburden? In comparison, the Sangamon highstand alluvium in Louisiana was buried under *only slightly younger* Eowisconsin-Wisconsin Prairie floodplain deposits. They were associated with lower pre-glacial and glacial sea-levels (Otvos, 2005). A 300+ ka old Colorado Delta “valley fill” would require an even older coastal plain surface to surround it. Following prolonged incision, the three fills would have been emplaced between 323-102 ka B.P. in a repeatedly entrenched and filled valley, characterized by erosional cross-cutting relationships between the three laterally adjacent fill parcels. Absence of coastwise alluviation after ~350 ka B.P. that may be required by this scheme, would mean that coastwise aggradation, including Beaumont-Prairie coastal plain alluviation in the surrounding higher ground ceased for hundreds of thousands of years – a patently absurd proposition in such a highly active setting.

Would, after potential age reduction, a superimposed relationship between fill units become more acceptable than the previously suggested



**Table 1. Gulf Coastal Plain Intermediate Pleistocene Coastal Terrace TL ages and Analytical Results. (Sample W2637: 2.3 m; W2638: 4.0 m below land surface) Be- Bentley; M-Montgomery; P-Prairie terrace sites (Otvos, 2005).**

Sample Number	W2859 (1-Be)	W3024 (2-Be)	W2716 (1-M)	W2637 (2-M)	W2638 (2-M)	W2515 (3-M)	W2985 (6-P)
Plateau Region (°C)	300-500	300-500	300-500	300-500	300-500	275-500	300-500
Analysis Temp (°C)	375	375	375	375	375	375	375
Palaeodose (Grays)	>158±17	>193±13	238±97	228±29	245±24	70.3±7.8	206±11
K Content (% by AES)	0.115±0.005	1.00±0.05	0.150±0.005	0.110±0.005	0.1 10±0.005	0.040±0.005	0.120±0.005
Rb Content (ppm assumed)	50±25	100±25	50±25	50±25	50±25	50±25	50±25
Moisture Content (% by weight)	3.7±3	16.3±3	12.9±3	4.1±3	14.2±3	3.5±3	1.9±3
Specific Activity (Bq/kg U+Th)	16.5±0.5	37.7±1.0	47.1±1.4	42.0±1.2	50.6±1.6	9.5±0.3	14.3±0.5
Annual Radiation Dose (μGy/yr)	569±26	1687±51	1099±29	1084±30	1108±30	374±25	568±26
Cosmic Contribution (μGy/yr assumed)	123±25	140±25	128±25	147±25	128±25	143±25	150±25
TL Age (ka)	>277	>114±9	216±89	210±27	221±22	188±24	363±25
Locations	Longville, LA	Glenmora, LA	Buna, TX	Biloxi, MS	as before	Three Rivers, MS	Franklin Lake, TX
USGS Quadrangle	30° 36.9'N	30° 58.4'N	30° 25.8'N	30° 29.0'N		30° 33.0'N	30° 28.8'N
Coordinates	93° 10.9'W	92° 33.7'W	93° 54.9'W	88° 52.5'W		88° 30.4'W	94° 01.6'W

cross-cutting linkage between laterally adjacent alluvial “fills” of drastically differing ages? Subsidence of the western Gulf coastal plain deposits, suggested also by the thickness of the Pleistocene sequence appears to reinforce the first alternative.

### Characterization of TL Sample Locations, Jasper County, Texas (Table 1)

#### Sample 6-P, Franklin Lake

The sample yielded an unrealistic, very old TL date, taken at +18 m elevation from the Prairie (Beaumont) terrace, located between the Neches River “Deweyville” terrace that embays the Prairie Terrace on the west and the Montgomery (or “intermediate”) terrace of +22 m summit elevation, to the east. 32 cm overburden in the NW wall of the Buster Kelly Dirt Pit overlies the sample location. The sample came from *undisturbed*, well sorted very fine dark reddish-orange sandy alluvium of 98.5% sand content.

### Sample 1-M, Buna

Obtained from a roadcut on the north side of Highway 253 from OSL 7 Montgomery Terrace deposits, the sampling spot was covered by 3.75 m overburden of *undisturbed* dark reddish-orange muddy fine sand, with 79.4% sand content. The terrace summit reaches +22 m. Should one arbitrarily combine all pre-Prairie/Beaumont Pleistocene deposits under the “*Lissie*” label, this terrace lithosome would correspond to the “younger Lissie” (= Montgomery) of Bernard and LeBlanc (1965). In response to Heinrich, no OIS 7 age was implied for any of the vaguely-defined “Lissie” deposits in the coastal plain region.

### DEFINITION OF SANGAMON INTERGLACIAL - WISCONSIN GLACIAL UNITS

While the confining boundaries of his purely illusory “allounits” remain unidentifiable in the Louisiana subsurface, one of the world’s most drilled regions, it is rather ironic and sad that by issuing a blanket, un-argued condemnation, Heinrich is incapable of articulating *any* specific objection to the validity of the Prairie, Gulfport, and Biloxi formations. These have been described in great detail in several publications and reports by their litho- and biofacies content, depositional conditions, *bounding unconformity surfaces, geometry*, and relationship to adjacent units. The unconformable upper bounding surface of the well-constrained Biloxi Formation provides an excellent horizon in spatially and chronologically constraining the post-Sangamon Pleistocene sediment interval. This information could have afforded Heinrich the opportunity to legitimately define certain valid, if limited Prairie allounits by the detailed drill-core data.

Some of the deposits, merged into Louisiana “allostratigraphic” units do belong to the Biloxi Formation. Without any specific reference to this affiliation, they were “lumped” into a sundry collection of allegedly “late and middle Pleistocene” alluvial and other types of sediments. Heinrich’s rejection of Eowisconsin and mid-Wisconsin luminescence dates from the

near-surface Prairie alluvium (Otvos, 2005), even if they would validate the mid-Wisconsin age of certain Prairie/“Beaumont” units, is symptomatic of Heinrich’s stolid, unreasoning refusal to judiciously apply pertinent, well-documented stratigraphic and depositional facies information from “outside” sources as well.

Robust sediment, fossil, and geomorphic evidence from several drillcores and the field notwithstanding (Otvos, 1991, 2009a; Otvos and Howat, 1997), in the face of conclusive proof for an alluvial-fluvial facies content of the *entire* ridge lithosome, a new Louisiana Survey chart (2002a) still portrays the elongated Houston Ridge near the Texas state line as a relict “coastal barrier;” part of the Ingleside barrier trend. Also, despite thorough documentation of relict SE Louisiana dune ridge clusters, including a large parabolic dune, with a similar attitude the dunes were mapped, absurdly, as “alluvial and alluvial — estuarine (!) sand hill remnants” (Map symbol “*pper*,” in: Louisiana Geological Survey, 2003b). In fact, these landforms represent rare and highly valuable paleoclimatic evidence for late Pleistocene and early Holocene drought episodes in the Deep South (Otvos and Price, 2001; Otvos, 2004).

### Prairie Formation and Beaumont, Montgomery, and Lissie Terrace lithosomes

The term *formation* implies properly defined boundaries and distinct lithostratigraphic content. Fisk, Doering, and others should have avoided designating their Prairie, Montgomery, Bentley, respectively, Beaumont, Oberlin, and Lissie coastal plain units as *formations*. However, the Sangamon Biloxi Formation that underlies the Prairie alluvium along its landward margin, provided the tool by which the Sangamon and Wisconsin Prairie alluvial deposits were constrained and defined as part of a bona-fide formation (Otvos, 1975, 1991, 2009a). Except near the landward margin of the Prairie (Beaumont), the top of the Biloxi, base of the redefined Prairie Formation, consistently occurs near present sea-level beneath the Prairie/Beaumont coastal plain surface and below the



**Table 2. Intermediate Coastal Terrace (4M) and Sangamon Gulfport Barrier (B3-to-B6) OSL Ages, and Analytical Results, Northern Gulf Coast. M-Montgomery Terrace (OIS 7); B-Gulfport barrier sectors (Sangamon Interglacial), Mississippi Coast (Otvos, 2005)**

Sample Number	OxL-1006 (4M)	OxL1059 (B3)	OxL-1068 (B5a)	OxL-1002 (B6)
De (Gy)	75.60±12.9	29.10±0.80	60.13±4.00	25.20±1.10
U (ppm)	0.48±0.03	0.050±0.05	0.710±0.050	0.19±0.02
Th (ppm)	1.06±0.10	0.720±0.036	1.890±0.095	0.52±0.07
%K	0.129±0.013	0.010±0.010	0.015±0.01	0.046±0.005
Grain Size (μ)	125-250	180-250	180-250	125-250
Total Dose Rate, (Gy/ka)	*428±27	0.25±0.03	0.48±0.03	*216±14
Moisture Content	3.6 (%wt)	0.036±0.010	0.022±0.010	2.4(%wt)
Cosmic Dose Rate(Gy/ka)	*255±21	0.180±0.020	0.179±0.019	*148±11
OSL Age (10 <sup>3</sup> yr B.P.)	176.5±32.1	117.2±12.4	124±10.8	116.1±9.1
Location USGS Quadrangle	Three Rivers, MS Biloxi, MS		Gautier S, MS	Gulf Breeze, FL
Coordinates	30° 33.0'N 88° 30.4'W	30°24.1'N 89° 00.8'W	30°20.9'N 88°41.6'N	30°22.1'N 87° 08.8'W

\*gamma dose rate (μGy/a) with asterisk includes cosmic and sediment contribution. Total dose rates in these samples expressed in μGy/a

Gulfport/Ingleside coastal barrier sequences (e.g., Andersen and Murray, 1953; Jones, 1956; McCulloh, 2007; Otvos, 1991, 2009a, b; Otvos and Howat, 1992, 1998, 1997). The base of the Prairie-Beaumont alluvial and the Gulfport Formation-Ingleside barrier lithosomes generally lies ~4.5-9 m below land surface near Biloxi's landward limit.

A rather loosely defined late Pleistocene alluvial interval is commonly referred to as *Beaumont Formation* (e.g., Solis, 2001; Blum and Aslan, 2006). It includes deposits, apparently coeval not only with Sangamon Interglacial and Wisconsin deposits but also with the assumed "Montgomery (Oberlin)" and even certain "Bentley (Lissie)" intervals. Using local seismic markers, on the central Texas coast Solis (1981) considered the "Beaumont" ~90 m thick. The Pleistocene is much thicker under the eastern Texas and Louisiana coastal plain. Although a conceptual profile proposed by Blum and Aslan (2006; Fig. 5) does project the assumed Beaumont-Lissie boundary under the

Colorado Valley, it was not linked to specific documented drillholes. Correlated with a seismic reflector, the profile includes the biostratigraphic *Trimosina A* (*Trimosina denticulata*) marker (~ 0.6 Ma; McFarlan, 1992) under the shelf slope, ~70 km offshore. However, Gulf wells that included markers or horizons that may be linked to a "Lissie" interval updip, occur at unspecified "other" sites "elsewhere" on the shelf slope. In the absence of firm markers, valid updip-downdip regional correlations between "Beaumont/Prairie" and "Lissie (Bentley)" lithosomes, and the corresponding continental shelf/slope sequence remain rather illusory in south Texas and Louisiana.

Heinrich's reference to Thomas, alleged to have mapped multiple seismic sequence boundaries corresponding to long-term glacial-interglacial cycles in the *Beaumont Formation*, is misleading. On the contrary, Thomas (1990) makes *no mention* of Beaumont sequences but states (p. 41) that "the Pleistocene oxygen isotope cycles (40 and 100 ky duration) do a very

poor job of matching isotope stages older than 150 kyBP." It was Blum and Price (1994, p. 91; 1998) who speculated that "the Beaumont deposition must span multiple Pleistocene 100-ky glacial-interglacial cycles" and "may represent the last 600 ky or more." While stratigraphic evidence is unavailable for identifying the "Beaumont" within the ill-defined "Prairie/Beaumont" subsurface interval, representing OIS 7 ("Montgomery") and older sediments, most of these deposits obviously predate Sangamon and Wisconsin units.

In summary, reliable correlation within coastal Louisiana and Texas Pleistocene sequences represents a goal yet unattained. In particular, in Louisiana the thick Pleistocene coastal plain interval is devoid of credible age-diagnostic markers, horizons, and/or datable seismic reflectors. Based only on a *single* Texas site and reflecting similar stratigraphic uncertainties, reverse polarity may date "at least part" of the Lissie sequence at Bellville, Texas (Kukla and Opdyke, 1972). This paleomagnetic chron boundary was only conceptually *projected* from Bellville into distant and assumed "Lissie" sequences downip. The magnetic polarity of this interval should have been correlated with the paleomagnetic orientation in the Bentley-Lissie terrace trend in Texas and Louisiana.

Just as in the case of the offshore biozone marker under the shelf slope, projected upip into the landward Pleistocene sequence, these horizons were not fixed firmly in the Colorado Valley section. Substituting the term "*undifferentiated Pleistocene*," the Prairie/Beaumont designations should be discontinued in all coastal plain deposits that predate the land surface and underlie dated sediment intervals, provided the Sangamon and/or Wisconsin age of those sediment parcels is proven. Until a regional system of reliable subsurface correlation is firmly established, this should also be the approach in naming sediment sequences that underlie datable Montgomery (OIS 7) surfaces and associated deposits.

### **Biloxi Formation and Its Stratigraphic Role**

The Sangamon Interglacial (MIS 5e) Biloxi is a highly fossiliferous gray sandy mud; locally muddy sand unit. 5-36 m thick and representing open marine-to-brackish paralic depositional facies, occasionally it is interlayered with adjacent and overlying Prairie deposits (Otvos, 1975, 2009a). As indicated, under its seaward margin, the Biloxi consistently underlies the Prairie Formation and the Sangamon mainland barrier chains. The barrier lithosomes represent the Gulfport Formation (Table 2), age-correlative with Ingleside barrier sectors in coastal Texas (Otvos and Howat, 1996). Pre-Sangamon Pleistocene or pre-Pleistocene deposits underlie the Biloxi.

This formation is the most extensive and best documented marker interval in the late Pleistocene coastal sequence. Without acknowledging its discrete identity, not even referencing the formation by name, unspecified Biloxi deposits were incorporated into the "Prairie complex" of Saucier and Snead (1989). Unreferenced paralic and marine Biloxi deposits, combined with newly named, sundry "alloformations" were subsequently merged into an even more amorphous and illusory; therefore meaningless "Prairie Allogroup" (Louisiana Geological Survey, 2000-2009). Just as its subdivisions, that alleged stratigraphic entity similarly lacks circumscribed bounding surfaces that enclose datable and well defined lithosome entities in the subsurface.

### **"VIRTUAL ALLOSTRATIGRAPHIC" MAPPING – LOUISIANA'S DEAD-END GEOLOGICAL SUPERHIGHWAY**

The well-produced series of geologic maps by the Louisiana Geological Survey (2000-2009) was based on redefined Pleistocene and Pliocene topographic units. A plethora of surfaces was designed to represent sediment allosequences, assumed to underlie them. The units were newly established or adopted from "Prairie, Intermediate and Upland" physiographic entities or subdivided within them. The associated unconformity "allounit" boundaries were implied; nowhere specifically defined in maps



and legends.

A few examples: the late Pleistocene Prairie coastal surface (named also Formation or complex) was subdivided between the vaguely defined “Beaumont and Prairie Allogroups.” The first designation was adopted from Texas. Diverse surfaces, each related to an assumed separate “alloformation,” are based simply on present-day topographic features. Disregarding the need for subsurface bounding unconformities, the separation line between the (western) “Beaumont” and (eastern) “Prairie allogroups” follows the *present* (!) course of the Mississippi River. Coastal plain surfaces that extend into modern tributary river valleys were given separate “alloformation” designations. For example, based not on subsurface data but current topography, the limited “Pleistocene Bush alloformation,” is artificially separated from the contiguous and extensive coastal plain “Hammond alloformation.” Lacking other distinguishing characteristics, the “Bush” unit is defined, mapped solely by its confinement to the *modern* Bogue Chitto River Valley (Louisiana Geological Survey 2007).

Curiously, even the Survey personnel does not consider certain “allo-sequence” categories as “real.” When a unit, as the “Hammond alloformation” is “not defined formally,” it is regarded merely as an “operational, informal, or working” entity and not capitalized (R. McCulloh, written comm., 2009). However, the spelling of “allo” in “Hammond” and “Beaumont alloformations” is inconsistent. Both lower-cased and capitalized “a” versions were used; occasionally within the same map legend. *Alloformation* and *allogroup* have been capitalized also in “Lissie Alloformation, Prairie, Intermediate, and Upland Allogroups,” entities that are not documented either by requisite bounding subsurface unconformities (Louisiana Geological Survey, 2000-2009).

According to Article 58 of the North American Stratigraphic Code (2005, p. 1578-1579), an allostratigraphic unit is a mappable body, identified and defined on the basis of boundary discontinuities. Disregarding this fundamental rule and based on a “potpourri” of alluvial and other coastal deposits, the “virtual” allounit ter-

minology of the Louisiana Geological Survey lacks requisite stratigraphic substance. At all rank levels, the allounits are devoid of documented lithologic, paleontological, and paleosol components defined within bounding unconformities. Because of its lack of geological utility and meaning, this “virtual” allounit system should have already been discontinued in Louisiana (Otvos, 2009b).

### Assumed Ages of Pleistocene “Allounits”

Reflecting the fundamental irrationality of the mapped “allounits,” their stated ages in the map legends (Louisiana Geological Survey, 2000-2009) display absurd inconsistencies and disregard for conventional Pleistocene subdivisions and age ranges. For instance, the glacial Eowisconsin and Wisconsin stages of lower sea-levels between 116-10 ka B.P. followed and did not (as absurdly registered in the legends) *coincide* with the late Pleistocene Sangamon Interglacial (OIS 5e). The interglacial is dated between ~132-to-116 ka B.P. (e.g., Hearty *et al.*, 2007).

The charts subdivide the Prairie Allogroup, mapped as corresponding to deposits that underlie the Prairie coastal surface, into the Early and the Late Sangamon sequence. The *Early Sangamon* has been placed in the middle Pleistocene (Louisiana Geological Survey, 2000, 2002b, 2003a,b, 2004, 2005) and the Late Sangamon interval was dated late Pleistocene (Louisiana Geological Survey, 2002a, 2003a). By what means were these intervals identified? How were “Early Sangamon” beds recorded as “dipping *beneath* Late Sangamon deposits”? The inclusion of *Wisconsin* glacial stages into the *Sangamon* Interglacial substage is similarly outlandish; the criteria by which “mid and late Pleistocene” units, including “mid and late Wisconsin” age ranges are defined, equally obscure.

Certain chart legends of the Louisiana Survey assign middle-to-late *Wisconsin* ages (Louisiana Geological Survey, 2003b, 2004, 2007), others, *middle-to-late Pleistocene* ages to the *Hammond* and *Beaumont* “alloformations,” in-

cluded in the amorphous "Prairie Allogroup." These "alloformation" "surfaces essentially coincide with Fisk's Prairie coastal surface (Louisiana Geological Survey, 2000, 2002a,b, 2003b, 2004, 2007). Considering the ~1.8 Ma starting date of the Pleistocene Epoch, this reflects a difference of ~0.6-1.0 Ma. At the same time, the "alloformations" in the map legends are listed as *Early Sangamon*. One is faced with a bizarre double contradiction. How else could a *mid*-Pleistocene interval, concurrently dated "Early *Sangamon*"(!), include also *mid-to-late* Pleistocene deposits?

Revised and closely supervised future editions of these charts, including those restricted to morphostratigraphic subdivisions of the coastal plain surface should be expected to follow established stratigraphic rules and state-of-the-art Quaternary chronostratigraphy. Map editors in the future may also consider using all important and pertinent information, even when it originates outside the state's Geological Survey.

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