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The impact of lithification on the diversity, size distribution, and recovery dynamics of marine invertebrate assemblages.

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All measurements and abundance data can be downloaded from the Paleobiology Database (http://paleodb.org) by searching for this publication (Sessa, Geology) in the "Reference search form".

Stratigraphic extent of samples:

Assemblages immediately following the K-Pg mass extinction in the GCP are known to be depauperate in species and to contain unusually small sized taxa (Hansen, et al., 1987). To mitigate for these actual diversity and size trends confounding lithification patterns, samples and specimens from the oldest Danian, foraminiferal zone P0 and subzone P1a, are excluded from all comparisons of lithified versus unlithified units. Comparisons are performed on collections that span foraminiferal subzone P1b through zone P2 (from about 64.8 through ~61.7 Ma) (Fig. DR1).

Collection methods:

Since this article combines abundance data from bulk samples collected by several different authors, the collection methods of those studies are described here. In all studies, the total numbers of bivalved organisms are halved and identifications made to the species level whenever possible. All bulk samples represent an unbiased collection of individuals from a constrained area of one outcrop. Hansen et al. (1993) report that unprocessed bulk samples were taken from a bed ranging from 5-12.5cm thick, which agrees with the general size of unprocessed bulk samples collected by J. Sessa. Toulmin (1977) does not report the size of an unprocessed bulk sample, but the re-collection of several Toulmin localities by J. Sessa finds similar taxonomic lists and diversities, indicating that his collection techniques were not widely divergent from the other studies. Sieve size was not reported by either Toulmin (1977) or Hansen et al. (1993); we used a 2mm sieve. Figures DR2a and b display comparisons of lithified and unlithified samples collected and processed by an individual.

Potential paleoenvironmental confounds:

A potential concern is whether unlithified and lithified samples come from the same environments and whether environments with low diversity and/or larger sized organisms are prone to lithification. Lithified, oyster dominated collections are found within the Clayton Fm, but these collections are excluded from analyses because this type of depositional setting is likely to be both preferentially lithified and to have low diversity assemblages. In general, samples from Alabama were deposited in a mixed, carbonate platform setting, whereas the Texas samples were deposited in deeper, siliciclastic dominated environments. Overall, this translates into higher lithification potential for units in Alabama. Indeed, bulk samples are unevenly distributed with respect to geographic area and lithification type: 3 unlithified samples come from AL, 12 unlithified samples from TX, 11 lithified samples from AL, 2 lithified samples from TX, and 3 poorly lithified samples from AL (Fig. DR1). To evaluate these potential confounds, lithified and unlithified units from the same bed, lithology, and paleoenvironment are compared (Figs. DR2a,b). Although sample size is small, we are able to compare lithified sandstone to unlithified sands from the same bed and geographic area, and lithified claystones to unlithified clays, again from the same bed and geographic area. Regardless of the particular lithology/environment examined, lithified samples are statistically less diverse than their unlithified counterparts, the same pattern displayed in Figure 2. In Figure 2, analyses are constrained to glauconitic, silty to sandy, calcareous marls and their lithified equivalents, glauconitic silty to sandy limestones, both of which occur predominately in AL, and to silty clays, which occur predominately in TX.

In contrast to the abundance data, the size data comes almost entirely from two formations in Texas that are both variably lithified (Figs. DR1, 3a-d, and Table DR1). This variable lithification is even observed at the outcrop level (C. Garvie, L. Zachos, pers. comm.). Although the exact mechanism of lithification has not been studied, it seems plausible that fossiliferous horizons are variably lithified due to the local movement of carbonate saturated groundwater, which precipitates carbonate cement when reaching a fossiliferous horizon (via a similar mechanism as described in Fursich and Pandey, 2003).

Several different comparisons of the size distributions of unlithified and lithified specimens were performed to further assess potential confounds. Figure DR3a displays unlithified and lithified size distribution plots for one unit, the Wills Point Fm in TX. Table DR1 provides the lithologies and lithification state of all museum specimens - we use lithology as a proxy for paleoenvironment. Unlithified Wills Point specimens largely come from silty to sandy calcareous marls and lithified specimens predominately from the corresponding lithified lithology, silty to sandy limestones. Restricting analyses to this paleoenvironment finds the same patterns as including all Wills Point lithologies – the mean, median, and size distributions of lithified and unlithified specimens are all significantly different (Wilcoxon rank-sum test (Mann-Whitney test) $p < 0.001$, t-test $p < 0.001$, and Kolmogorov-Smirnov test, $p < 0.001$) for both height and width. This also suggests that lithification does not correlate with environments that sustain larger sized organisms, as the same environment (as best we can tell by using lithology as a proxy) is compared here. There are more lithified lithologies than unlithified ones, but this may partially result from the fact that unlithified specimens often do not have matrix archived with them (i.e., the ‘no information’ category in Table DR1).

Figure DR3b shows an example of unlithified and lithified specimens from the same unit (Kincaid Fm) at one locality. The lithology (silty clay) of the unlithified portion of this bed appears identical to that of the lithified portion of this unit, except that the lithified portion is indurated. Figures DR3c and DR3d contain similar comparisons to further illustrate that in TX, lithification does not appear to result from differing environmental conditions. Although it is possible that subtle environmental parameters not recorded by lithology differ between lithified and unlithified samples, we have tried to rule this possibility out by vetting the data in several different ways (Figs. DR2, DR3).

Potential stratigraphic trend confounds:

To assess whether any size trends that may occur through the Danian are confounding results, the size distributions of lithified and unlithified specimens from one unit are compared (Fig. DR3a-d). These distributions mirror the patterns found when data from multiple stratigraphic horizons are combined.

Size estimates:

There are several different ways to assess the body size of fossils. We did not use the common methods of geometric mean size or centroid size because many of the museum specimens were not whole, and restricting analyses to whole specimens would reduce sample size. We note that height and width measurements are generally correlated with these more accurate assessments of body size (Lockwood, 2005).

Figure 1:

The averaged value of samples rarified to 70 individuals is plotted with corresponding standard deviations. No additional standardizations, such as subsampling, were used because of the small number of samples that comprise unlithified and lithified bins. Box and whisker plots, showing medians and quartiles, display the same patterns as shown with averages and standard deviations.

Although there are lithified late Cretaceous units in the Gulf Coastal Plain, there is no abundance data from these units that is comparable to the Paleocene samples used in this study in terms of collection and processing methods.

Figure 3:

The median size, average size, and the shape of the distributions of the two lithification states are significantly different (Wilcoxon rank-sum test (Mann-Whitney test) $p < 0.001$, t-test $p < 0.001$, and Kolmogorov-Smirnov test, $p < 0.001$) for both height and width.

Museum data

Collections from the Paleontological Research Institution (PRI), the Department of Geology and Geophysics at Texas A&M University (TAMU), the Non-vertebrate Paleontology Laboratory at the University of Texas, Austin (NVPL), the Yale Peabody Museum (YPM), and from the private collections of Mr. Christopher Garvie (Austin, TX) were used in this study. All measured specimens come from stratigraphic collections, rather than taxonomic collections, except for the PRI, where specimens from both stratigraphic and taxonomic collections were measured. No type specimens were measured in this study. The size of taxa in museum collections very likely represents an overestimation of taxon size relative to that in bulk samples (Barbour Wood et al., 2004). However, both unlithified and lithified collections will be affected in the same way by this bias. Because we use stratigraphic collections that frequently contain many individuals of a single taxon, the magnitude of this museum size bias should be less than if we had used only single estimates of taxon size or the size of type or published specimens, which often greatly overestimate a taxon’s size relative to than in bulk samples (Kosnik et al., 2006).

In the collections of the PRI, NPL, and YPM specimens did not have individual museum identification numbers, but rather were listed in lots under a locality number. Specimens from TAMU and Mr. Garvie’s collections were not assigned individual or locality numbers, nor were some PRI specimens. Table DR2 lists the locality numbers for collections measured from the PRI, NPL, and YPM.

Supplemental References

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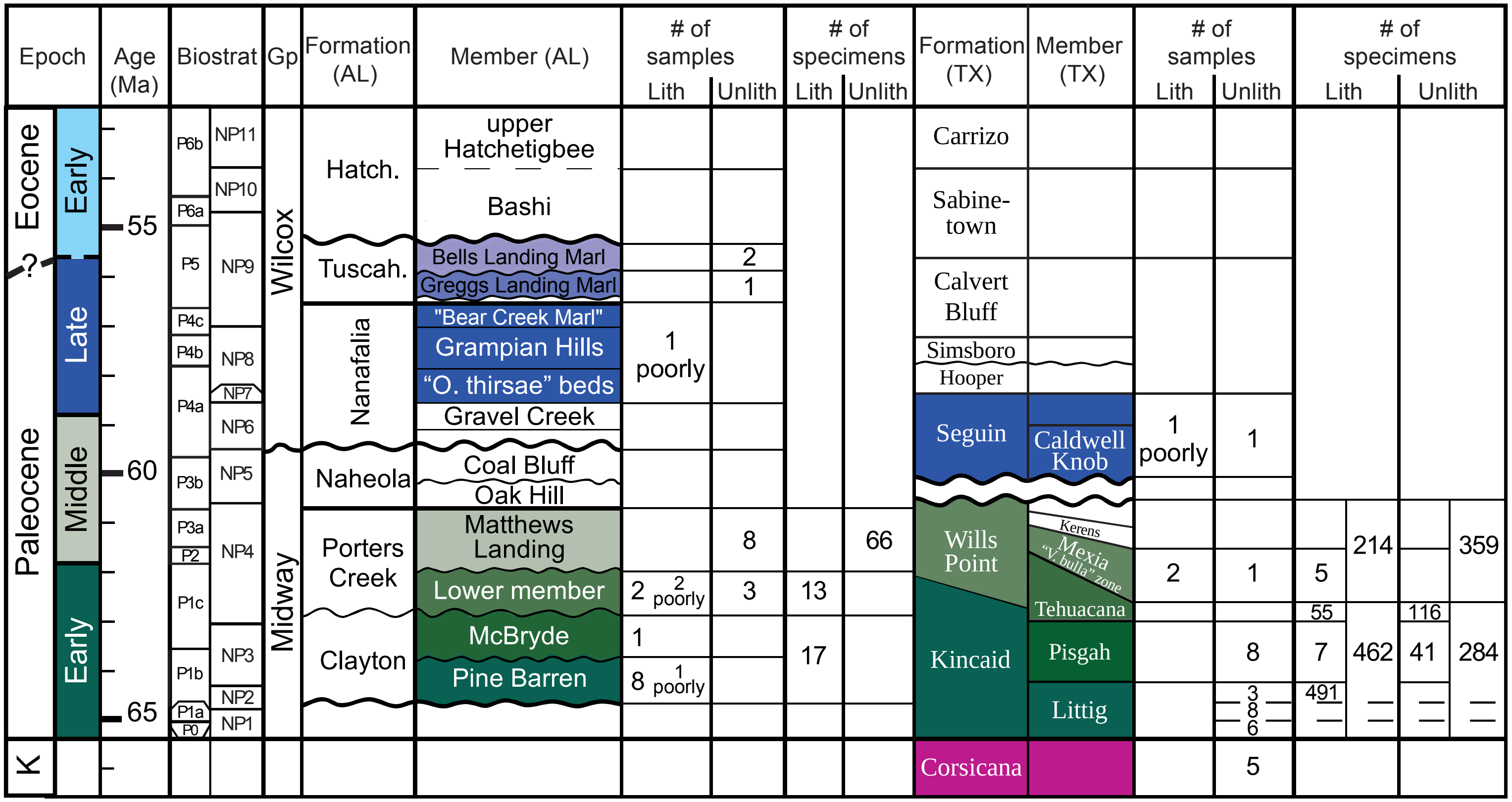

Epoch
Age (Ma)
Biostrat
Gp
Formation (AL)
Member (AL)
# of samples
Lith
Unlith
# of specimens
Lith
Unlith
Formation (TX)
Member (TX)
# of samples
Lith
Unlith
# of specimens
Lith
Unlith
Eocene
Early
?
Paleocene
Late
Middle
Early
K
55
60
65
P6b
P6a
P5
P4c
P4b
P4a
P3b
P3a
P2
P1c
P1b
P1a
P0
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
Wilcox
Midway
Hatch.
Tuscah.
Nanafalia
Naheola
Porters Creek
Clayton
upper Hatchetigbee
Bashi
Bells Landing Marl
Greggs Landing Marl
"Bear Creek Marl"
Grampian Hills
"O. thirsae" beds
Gravel Creek
Coal Bluff
Oak Hill
Matthews Landing
Lower member
McBryde
Pine Barren
2
1
1 poorly
8
66
2
2 poorly
3
13
1
17
8
1 poorly
Carrizo
Sabine-town
Calvert Bluff
Simsboro
Hooper
Seguin
Caldwell Knob
Wills Point
Kerens
Mexia
"V. bulla" zone
Tehuacana
Kincaid
Pisgah
Littig
Corsicana
1 poorly
1
2
1
5
214
359
55
116
8
7
462
41
284
3
8
6
491
5

Figure DR1. Stratigraphic column of the latest Cretaceous and early Paleogene in Alabama (AL) and Texas (TX), showing the number of bulk samples with abundance data (i.e., samples that can be rarified) and the number of measured museum specimens by stratigraphic unit. Colored units indicate that we have data from that unit. The timescale follows that of Gradstein et al., 2004. Correlations and biostratigraphic placement follow Gibson et al., 1982; Siesser, 1983, Mancini and Tew, 1995; Frederiksen, 1998; Crabaugh and Elsik, 2000 and others.

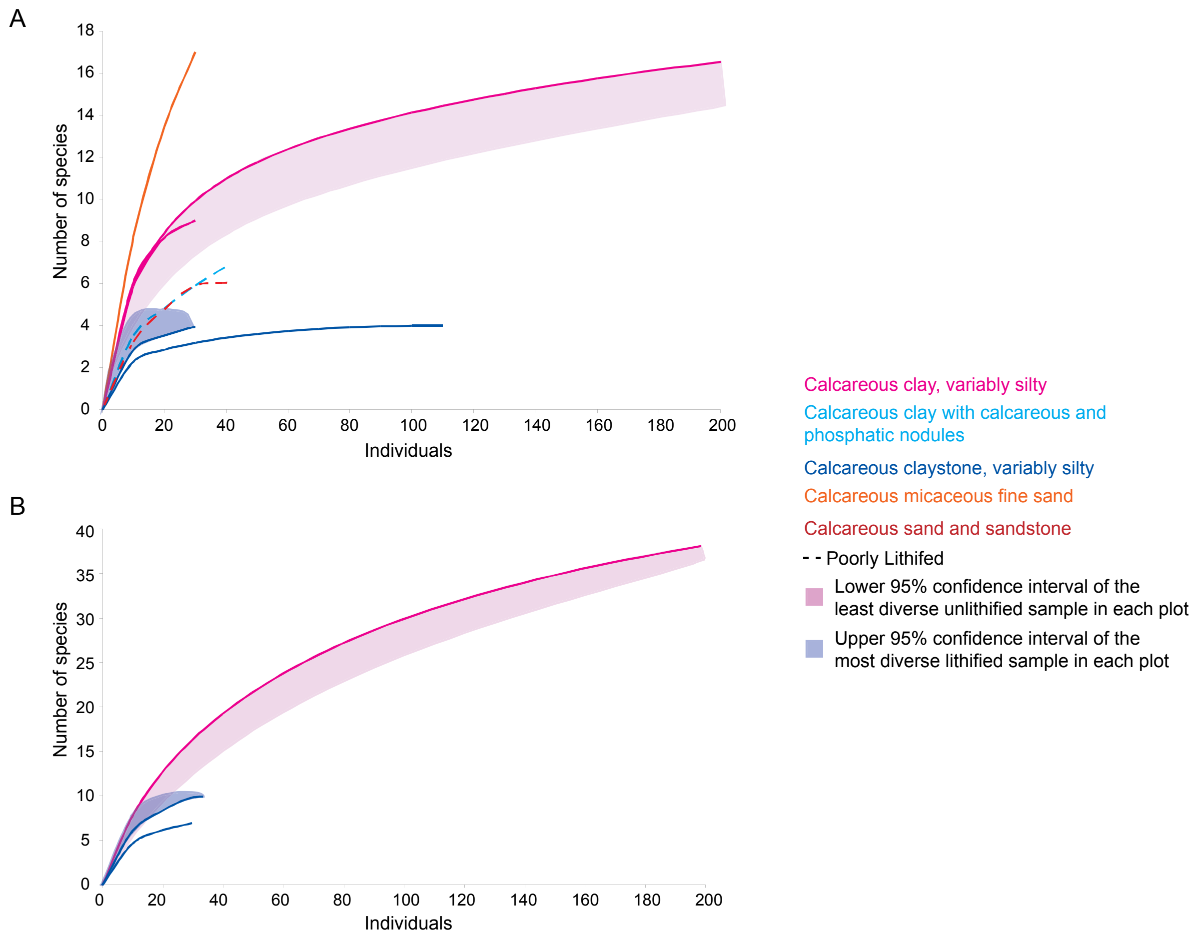

Figure DR2. A: Rarefaction curves for lithified, poorly lithified, and unlithified lower Porters Creek samples from a restricted geographical area in AL (samples were identified by Toulmin, 1977).

B: Rarefaction curves for lithified and unlithified Wills Point samples from a restricted geographical area in TX (samples were identified by J. Sessa).

Several rarefaction curves are truncated at 200 individuals to show detail. The lower 95% confidence interval of the least diverse unlithified sample and the upper 95% confidence interval of the most diverse lithified sample are plotted in each graph to show the nonoverlap of confidence intervals at sample sizes greater than ~20 individuals. As in figure 2, rarefaction finds statistically less diverse lithified samples at equivalent sizes.

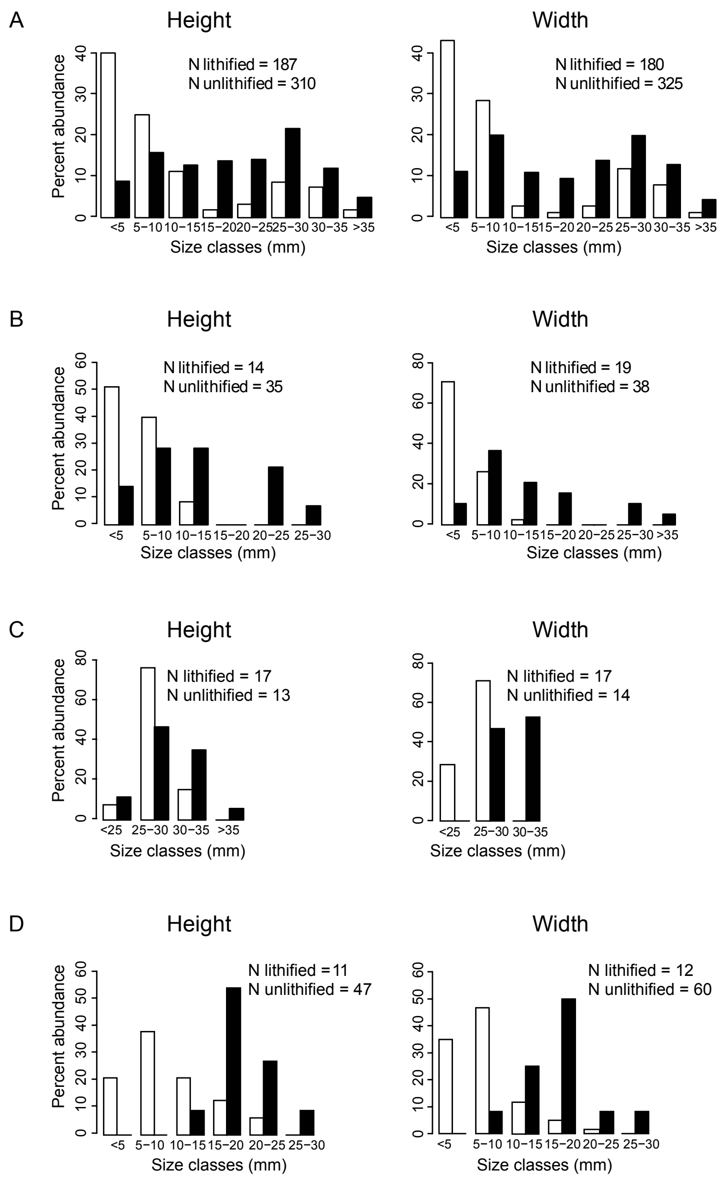

Figure DR3. A: Height and width distribution plots for unlithified and lithified museum specimens from the Wills Point Fm in TX.
B: Height and width distribution plots for unlithified and lithified specimens from the same bed at one locality: Kincaid Fm at Cedar Creek, 200' west of bridge, Bastrop Co., Tx. Lithified specimens come from an indurated silty clay, and unlithified specimens some from a silty clay.
C: Height and width distribution plots for unlithified and lithified *Venericardia* specimens from the Wills Point Fm at two nearby localities: lithified specimens are from 2.5 mi southwest of Littig, TX, and unlithified specimens are from 5 mi south of Littig, TX.
D: Height and width distribution plots for unlithified and lithified specimens from the same bed at two nearby localities: Tehuacana member, lithified specimens from 700 feet from Mexia-Wortham highway, unlithified specimens 0.2 mi from Mexia-Wortham highway, TX.

The mean size, median size, and shape of the distributions of the two lithification states are significantly different for all comparisons shown, except for DR3C height comparisons (t-test $p < 0.05$, Wilcoxon rank-sum test $p < 0.09$, and Kolmogorov-Smirnov test, $p < 0.23$).

undifferentiated Wills Point Formation					
Unlithified	# of specimens	Percentage	**Lithified**	# of specimens	Percentage
clay	11	3.06	claystone	2	0.92
silty clay	107	29.81	siltstone	5	2.29
glauconitic calcareous sandy marl	211	58.77	glauconitic calcareous sandy marl	119	54.59
			phosphatic and calcareous replaced molds, steinkerns	44	20.18
			sandstone	3	1.38
			sandy grainstone	27	12.39
no information	30	8.36	no information	18	8.26
Total	**359**		Total	**218**	

undifferentiated Kincaid Formation					
Unlithified	# of specimens	Percentage	**Lithified**	# of specimens	Percentage
clay	11	3.87	silty claystone	29	6.28
silty clay	163	57.39	glauconitic calcareous sandy marl	27	5.84
no information	110	38.73	glauconitic sandstone	92	19.91
			silty micaceous sandstone	7	1.52
			marly packstone	39	8.44
			sandy grainstone	70	15.15
			phosphatic and calcareous replaced molds, steinkerns	198	42.86
Total	**284**		Total	**462**	

Tehuacana member				Pisgah member				Littig member	
Unlithified	# of specimens	**Lithified**	# of specimens	**Unlithified**	# of specimens	**Lithified**	# of specimens	**Lithified**	# of specimens
silty marl	116	phosphatic and calcareous replaced molds, steinkerns	39	clay	31	indurated clay	7	calcareous replaced molds, steinkerns	480
				no information	10			glauconitic sandy marl	10

undifferentiated Midway Gp		Clayton Fm		Matthews Landing mbr		Lower Porters Creek mbr	
Unlithified	# of specimens	**Lithified**	# of specimens	**Unlithified**	# of specimens	**Lithified**	# of specimens
light grey clay	4	grainstone	8	silty grey clay	66	no information	13
sandy marl	1	sandy grainstone	9				
no information	1						

Table DR1. Museum specimen data separated by unit, lithology, and lithification state.

Museum and Locality Number		
Garvie 15404	NPL-UT 4584	NPL-UT 5281
NPL-UT 11187	NPL-UT 4588	NPL-UT 5424
NPL-UT 11190	NPL-UT 4591	NPL-UT 5428
NPL-UT 11233	NPL-UT 4592	NPL-UT 56-2934 (drawer #)
NPL-UT 11238	NPL-UT 4594	NPL-UT 7189
NPL-UT 12828	NPL-UT 4595	NPL-UT 7193
NPL-UT 128-T-8 (447)	NPL-UT 4596	NPL-UT 807
NPL-UT 1374	NPL-UT 4598	NPL-UT 8652
NPL-UT 17548	NPL-UT 4601	NPL-UT 8658
NPL-UT 1785	NPL-UT 4604	NPL-UT 8662
NPL-UT 1788	NPL-UT 4606	NPL-UT 9137
NPL-UT 1998	NPL-UT 4607-12	NPL-UT 9139
NPL-UT 31187	NPL-UT 4613	NPL-UT 9279
NPL-UT 31193	NPL-UT 4614	NPL-UT 9285
NPL-UT 31239	NPL-UT 4615	NPL-UT 9292
NPL-UT 31279	NPL-UT 4616	NPL-UT 9294
NPL-UT 4236	NPL-UT 4618	NPL-UT 9295
NPL-UT 4548	NPL-UT 4619	NPL-UT 9308
NPL-UT 4553	NPL-UT 4622	NPL-UT 9346
NPL-UT 4557	NPL-UT 4624	NPL-UT 9390
NPL-UT 4560	NPL-UT 4625	NPL-UT 9397
NPL-UT 4562	NPL-UT 4626	NPL-UT 9436
NPL-UT 4563	NPL-UT 4627	NPL-UT 9457
NPL-UT 4564	NPL-UT 4628	NPL-UT 9503
NPL-UT 4565	NPL-UT 4629	NPL-UT 9510
NPL-UT 4566	NPL-UT 4633	NPL-UT 9622
NPL-UT 4567	NPL-UT 4636	NPL-UT PCNo.31173, 12388
NPL-UT 4568	NPL-UT 4637	YPM 3506
NPL-UT 4569	NPL-UT 4639	YPM 3776
NPL-UT 4570	NPL-UT 4642	YPM 7045 - 04581
NPL-UT 4571	NPL-UT 4643	PRI 12018
NPL-UT 4572	NPL-UT 4646	PRI 12053
NPL-UT 4573	NPL-UT 4647	PRI 1313C
NPL-UT 4574	NPL-UT 4648	PRI 1763E
NPL-UT 4575	NPL-UT 4652	PRI 2800E
NPL-UT 4576	NPL-UT 4655	PRI 9382
NPL-UT 4577	NPL-UT 4656	PRI 9494
NPL-UT 4578	NPL-UT 4658	PRI 9521
NPL-UT 4579	NPL-UT 4668	PRI 9524
NPL-UT 4580	NPL-UT 4671	PRI 9542
NPL-UT 4582	NPL-UT 4675	PRI 9593
NPL-UT 4583	NPL-UT 4692	

Table DR2. Locality numbers for measured specimens from the Non-vertebrate Paleontology Laboratory at the University of Texas, Austin (NPL), the Paleontological Research Institution (PRI), and the Yale Peabody Museum (YPM).