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Taphonomic and Sedimentologic Study of the Cretaceous Tepee Buttes Limestone

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TAPHONOMIC AND SEDIMENTOLOGIC STUDY OF THE

CRETACEOUS TEPEE BUTTES LIMESTONE

HONORS THESIS

DEPARTMENT OF GEOLOGY

BY

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OBERLIN, OHIO

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ABSTRACT

The Tepee Buttes methane seep deposits exist today as topographically defined limestone features in the surrounding Pierre Shale of the Campanian Western Interior Seaway. The present sloping surface has previously been assumed to be indicative of original seep structure, and biofacies were interpreted as roughly ringing a central vent core. Contradictory field observations in this study have prompted a more detailed taphonomic approach to the Tepee Buttes limestone, and certain depositional features such as reworked horizontal shell beds were noted and examined in detail for the first time. The results of a taphonomic and sedimentologic analysis reveal a complex history of reworking that likely involved current action and bioturbation by burrowing seep fauna. We found no clear evidence for deposition along a sloping surface as inclined as today, and buttes are interpreted as having low/uneven original relief.

CONTENTS

Introduction

The Tepee Buttes are anomalous limestone mounds standing out above the surrounding Campanian Pierre Shale in the western United States. These formations are known to span from New Mexico into southern South Dakota, ranging from Middle Campanian to Early Maastrichtian in age (Metz, 2000) and roughly following Laramide faults in the Front Range of the Rocky Mountains (Howe, 1987). First described by Gilbert and Gulliver in 1895, the Tepee Buttes (TPB) have long been suspected as marine spring or seep deposits. Hydrocarbon seep settings host biologically unique communities and interactions in unusually adverse conditions. Modern seeps have been identified only recently, and many details of seep mechanisms and faunal interactions are yet unknown. Fossilized seeps may record the entire lifespan of communities and interactions within them, and thus are a valuable research tool for understanding seeps in general.

A particularly dense and accessible accumulation of buttes occurs in the undeveloped ranchlands south of Colorado Springs, CO, and has served as a major locus of geologic exploration of the mounds. Notably, Howe (1987) performed an in-depth faunal analysis of formations east of Boone, CO, and Arthur, et al. (1982) completed a geochemical analysis that confirmed the origin of the TPB limestone as a methane cold-seep environment of the Cretaceous Western Interior Seaway (Fig. 1). The TPB limestone has been found to span four ammonite zones: *Baculites scotti* through *Exiteloceras jenneyi* (Kauffman, 1977).

Within a single butte, lithologic character can be highly variable, with facies ranging from inferred microbial micrite textures, to blocky calcite void fill, to highly fossiliferous detrital fabrics including shell beds. The dominant macrofaunal taxon in almost all fossiliferous facies

(barring a couple occurrences where inoceramid species seem to dominate) is the presumed chemosymbiont-hosting infaunal clam, *Nymphalucina occidentalis*. Modern lucinids have been shown to host chemosymbionts in reducing conditions and seeps (Campbell and Bottjer, 1995), so a symbiotic relationship with methanotrophic microbes at the ancient seep is considered likely. *N. occidentalis* is believed to have lived below the sediment-water interface, umbo-up as is the case in the modern species of seep clam *Thyasira*, which are constrained to a depth of several body-lengths, from which their siphons can reach the surface for oxygen and waste exchanges (Kauffman, E.G., personal communication, 2005; Kauffman, 1967; Fig. 2).

Even with the infaunal life habit of lucinids, the presence of a high percentage of aligned and articulated (two valves together as in life) clams in many of the fossil-rich facies is fairly unusual for dense shell concentrations, and can help to narrow the possibility of depositional scenarios. The ligament holding together the two valves of a clam is likely to decompose soon after death, resulting in disarticulated valves. For valves to retain articulation in life position, early cementation or sustained and undisturbed burial is necessary. To retain articulation while being moved out of life position, the clam would likely have to be moved while alive, or cemented together soon after death (and before transport). Thus, retained articulation in fossil assemblages can be indicative of the sequence and timing of clam mortality and depositional occurrences.

The literature regarding biological and geochemical processes at hydrocarbon seeps has expanded greatly in the past decade, in part due to the implications of their chemoautotrophic components for early and/or extraterrestrial life (Campbell, 2006). Campbell (2006) compiled a comprehensive assessment of existing studies regarding modern and ancient hydrocarbon seeps, as well as their occurrence and general characteristics. Modern hydrocarbon seeps typically
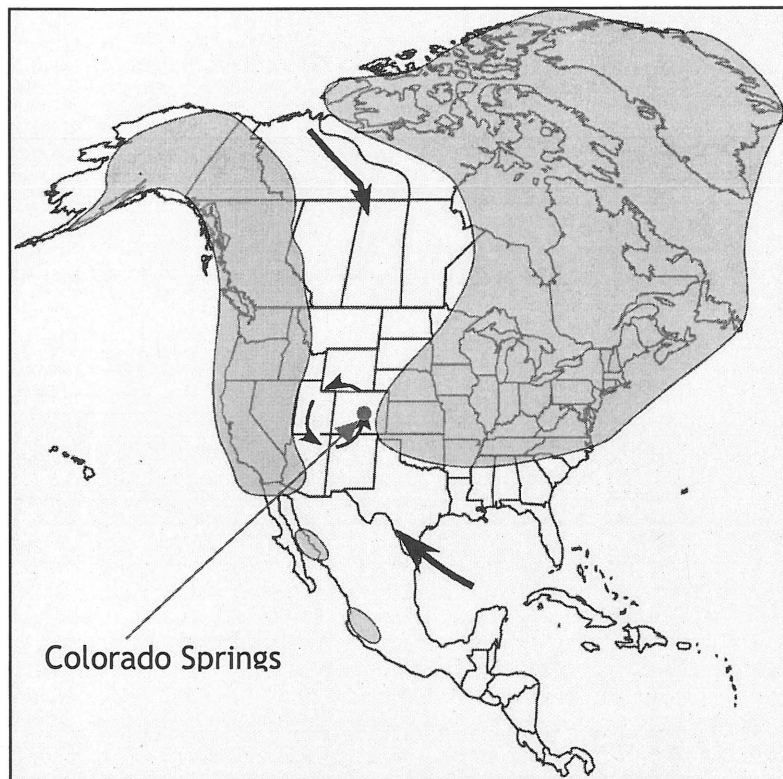
Figure 1. Map of the Western Interior Seaway in the Middle/Late Campanian; arrow points to approximate location of modern Colorado Springs (north of study area); orange blobs show approximate location of landmasses.
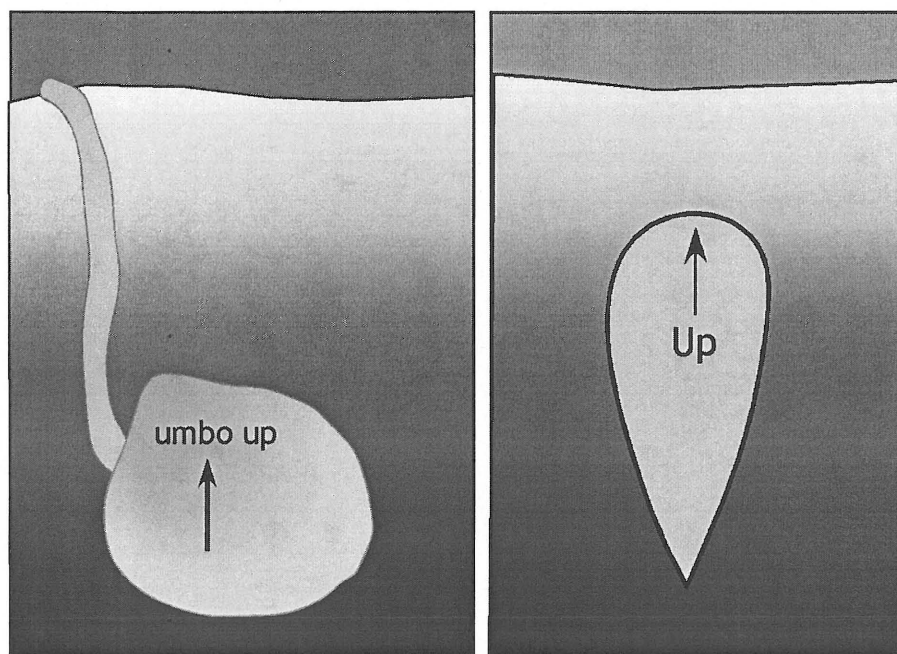
Figure 2. Inferred life position of *Nymphalucina occidentalis*. (Illustration by Karla Parsons-Hubbard.)

occur at or near the seafloor, along plate boundaries and other places where organic-rich pore waters find conduits to the surface. Campbell cites authigenic carbonate with a light carbon isotope signature and cemented shelly fauna as characteristic of seeps. Thriving macrofaunal seep communities are often supported by symbiotic relationships with chemosynthetic microbes. At methane seeps, these microbes engage in the sulfate-dependent process of anaerobic oxidation of methane (AOM), which helps form the vast amounts of authigenic carbonate that are typical in hydrocarbon cold seep settings (Timothy Lyons, personal communication, 2005).

Still lacking in the literature, however, is a coherent method for addressing many of the taphonomic aspects of macrofauna in fossil seep environments. Physical processes surrounding a seep are highly variable, including many factors not usually considered in traditional shell-bed analyses. Understanding the balance between the effects of gas-release, fluid reworking and biological reworking, as well as overprinting caused by diagenesis, is central in developing a picture of the paleoecology of ancient seeps.

Previous Studies

The Tepee Buttes (TPB) seeps are perhaps the best exposed and most extensive fossil seeps in the world, and have accordingly spawned several studies and comparisons. Howe's 1987 work is the most extensive study to date, and still holds as a major precedent when considering many of the TPB features. Howe's work took the form of a detailed faunal analysis that involved systematic sampling across two axes of a limited number of buttes, and destructive techniques to extract and identify fossils. Articulated clams were considered "in place", and no apparent survey of *in situ* fossil orientations was conducted.

Central to Howe's resulting paleoenvironmental interpretation were field observations such as structural elongation of individual butte forms, identification of a central spring vent core surrounded by a dense accumulation of in-place articulated lucinids, and further faunal distribution patterns that roughly radiated from this core and showed evidence of downslope reworking on the inferred elongated "lee side" of buttes. Howe's identification of these features implies the presence of unidirectional currents (which further suggests a fairly shallow depth), a paleotopography inclined enough to impose chemical gradients, and the strong influence of a central vent on faunal distribution.

Several conclusions from Howe's study have been accepted as a basis for other work. The assignment of shallow depth by Howe (1987) and Kauffman, et al. (1996; 30-100m, Kauffman), for example, has been used by Callender, et al. (1998) as a basis for comparing the taphonomy of modern near-shore seep organisms to those of slope seeps. In contrast, Krause, et al. (2003) have made a case for methane hydrates at the seeps, which would imply a much deeper setting. Clearly, a reasonable depth estimate would be useful in reconstructing the paleoenvironment. Algal traces (photic zone) or taphonomic evidence for storm reworking, for instance, would restrict the seeps to a fairly shallow environment.

Paleotopography of the buttes is another feature that has received inconsistent appraisal. Arthur, et al. (1982) describe the original structures as low-relief mounds, while Howe (1987) cites a "consistent downslope distribution of [micro]biofacies" (p. 143) as evidence for differential chemical and substrate conditions on a sloping original depositional surface, thus implying a more defined paleotopography centered around seeps. Further works either have not addressed this feature, or have assumed an idealized moderate-relief mound with concentric facies distribution, based on the often-cited work of Kauffman, et al. (1996; Fig. 3). Again,

geometric features of shell beds could help to clarify whether original deposition occurred across a significantly inclined slope or a flatter but uneven surface.

Motivation for Current Study

With literature precedent in mind, it was surprising to find that field observations in this study of tens of buttes have contradicted previous generalizations of faunal distribution by Howe (1987) and Kauffman, et al. (1996). This study observed a less regular distribution of lithofacies and fossil genera, as well as laterally-aligned shell bedding visible in many butte outcrops (Fig. 4). Due to the apparent presence of shell beds and the unexpected dominance of articulated clams out of life position, it was decidedly advantageous to take a new, taphonomic and sedimentologic approach to fossil distribution and sedimentary features in fossil-rich TPB limestone samples. The dominance of a few fossil taxa in the Tepee Buttes offers an opportunity to compare shell condition (preservation, orientation, etc.) within a specific population that spans facies reflecting varying depositional and diagenetic conditions at the seep. This study attempts to relate taphonomic and sedimentologic character to the processes affecting deposition, and to reconstruct the original conditions and structure of the seep habitat.

I will attempt to show that the original seep surface was much less inclined than at present, and that gradients emplaced by original topographic relief did not have the effect on faunal patterns that Howe concluded. Faunal distributions recognized in this study were more likely the result of differing seep chemical/faunal interactions as the seep carbonates built upwards, adding roughly horizontal or gently sloping strata through time. It seems likely that current butte shape is mostly due to (geologically) recent erosion, so fossils cannot be correlated across the surface of the current slope. Opposing hypotheses that we consider for this study are:
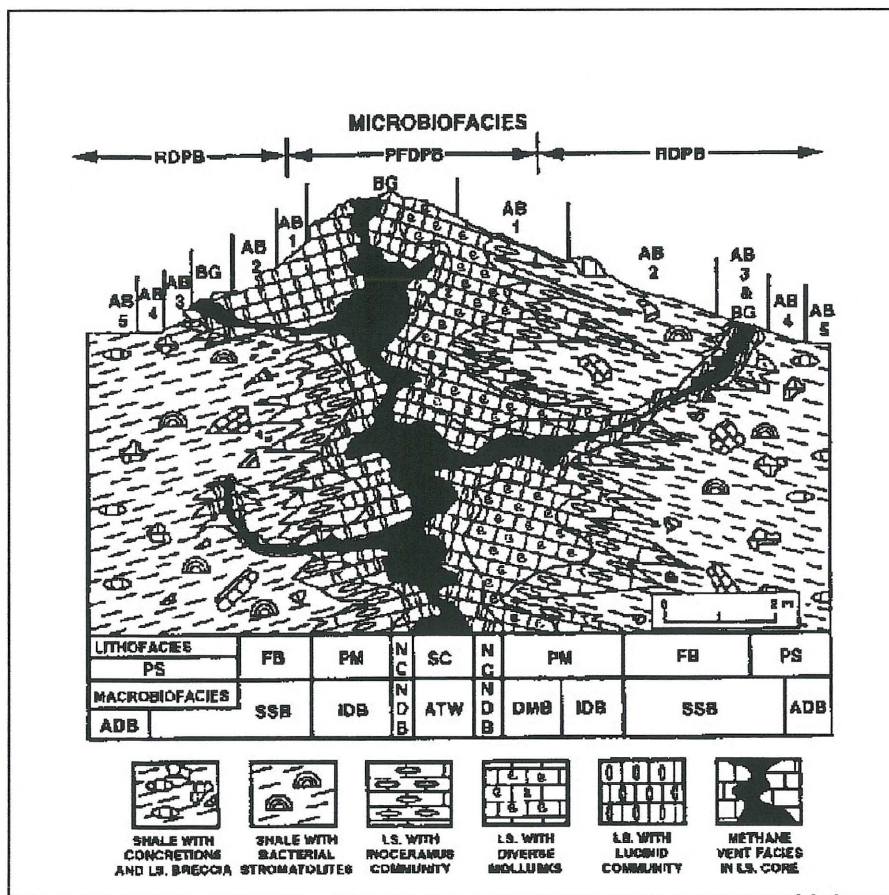
Figure 3. Commonly cited idealized concentric facies distribution model, from Kauffman, et al. (1996).

Figure 4. Field photo of lateral bedding in cap limestone of a Tepee Butte, CO. (Photo courtesy Karla Parsons-Hubbard.)

(a) the current topography and orientation of biological components are reflective of original conditions, or (b) diagenesis and erosion have completely removed any evidence of original depositional conditions.

It will be useful to assess the results of this study in terms of several possible origins: (1) typical seafloor shell concentrations, including those caused by physical reworking, i.e. currents or waves, (2) subsurface shell concentrations formed by burrowers, (3) downslope deposition, and (4) an assemblage with geometry formed strictly by diagenetic processes. Evidence pointing toward (1) would constrain the setting to a shallow depth. All other results would be useful for paleoecologic interpretation, but would not address the issue of water depth. Clear evidence for (3) would also be useful to some degree in inferring paleotopography. I believe that the present limestone condition likely reflects some complex combination of most of these factors, and the results of this study do show strong support for processes in (1) among these.

Methods

Field Sampling

The current Tepee Buttes study at Oberlin College began in February 2005 with training and background work by four undergraduates working under Professor Karla Parsons-Hubbard. Undergraduates at Gustavus Adolphus College (GAC) in Saint Peter, MN, working with Professor Russell Shapiro, were also involved in the project. Fieldwork was conducted during two weeks in June 2005 at sites south of Colorado Springs, CO. Eleanor Bash (GAC) devised a systematized numbering of the TPB, using satellite images, and revising from the field. Buttes were numbered geographically, increasing in value to the north. The southernmost buttes considered in this study were east of Boone, CO (buttes 274-335), with another locality to the north on Hanna Ranch (buttes 562-769; Fig. 5). No constraints were made on accessibility, and thus over forty buttes were examined, making this study of the TPB quite geographically extensive in comparison to others. (Howe, for example, studied a total of six buttes, all within 0.25 miles of a passable road). Important field descriptions included rough surveys of faunal diversity and fossil density on selected buttes, qualitative descriptions of lithologic character in different facies of the buttes, and a poll of relative butte height and spatial distribution using survey equipment in the northern study area.

Collection related to this project comprised taking oriented samples from all field-defined lithofacies, with a special preference toward shell-rich samples and samples from facies contact/transition areas. The Oberlin group took samples from 39 buttes and made 25 slabs from 12 different buttes. No methodical sampling from butte to butte was conducted, making the resulting sample suite less systematic. Due to variability in taxonomy, butte character, and likely formative processes across the field area (Kauffman, personal communication, 2005), samples
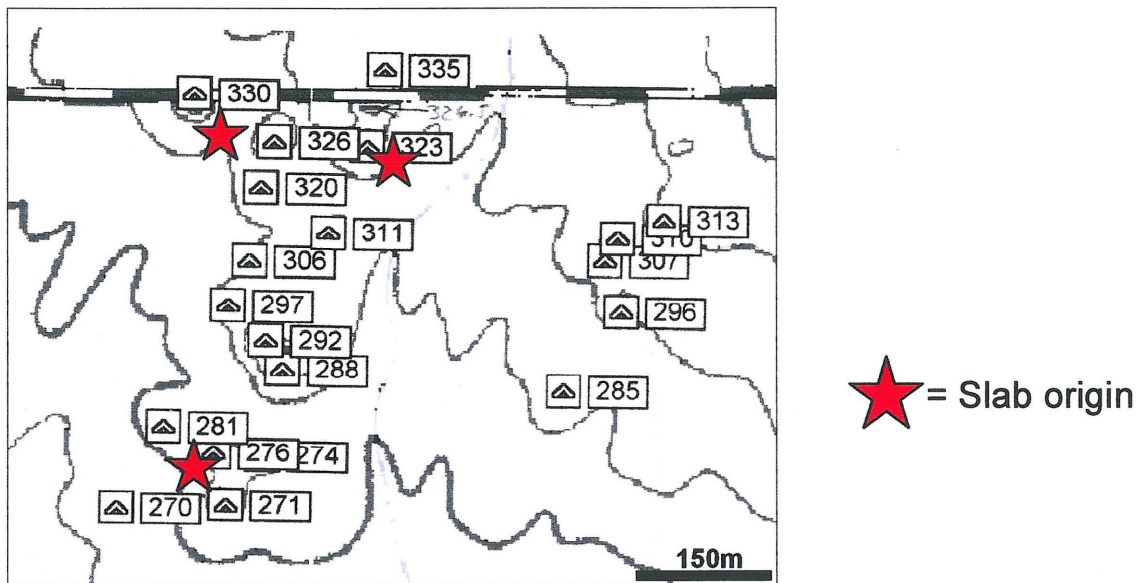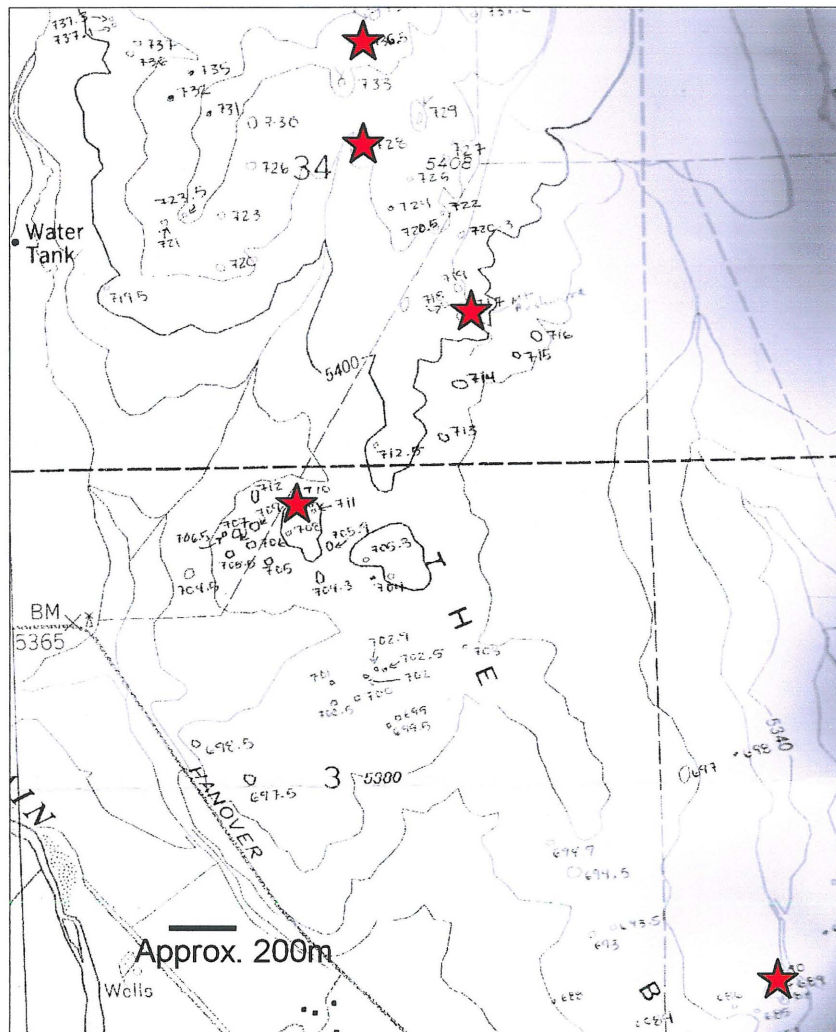
Figure 5. Butte fields examined, with numbering system devised by Eleanor Bash; Top- buttes east of Boone, Co; Bottom- buttes on Hanna Ranch. The two study sites are separated by approximately 35 miles. Stars indicate buttes from which slabs used in this study were taken.

were collected from a wide range of buttes, especially to determine whether processes were consistent over a wide geographic extent.

Field Characterization of Lithofacies

Initial examination of a wide range of buttes in both the Hanna Ranch and Boone localities revealed a few controlling factors that defined readily-distinguishable lithofacies. Immediately evident in weathered limestone outcrops were variations according to (a) presence or absence of abundant vugs filled by botryoidal and sparry calcite (b) presence or absence of abundant lucinid fossils, and (c) presence or absence of inferred microbial "clotted" (thrombolite) textures. The existing combinations of these variables defined six lithofacies (Table 1): I – vuggy (cement-rich), few clams; II – vuggy, with clams; III – muddy (micrite) texture, with clams; V – muddy (micrite), few clams; and VI – "thrombolite" texture. Facies IV comprised limestone concretions found scattered among the Pierre Shale, sometimes in discrete layers around the limestone-shale contact.

Laboratory Methods and Analysis

Slabs were cut preferentially from samples of shell-rich facies (lithofacies II and III), and thin-sections were made from many of the opposite cut surfaces. For this study, a total of twelve slabs was examined, with surface area from 51-150 square centimeters, and representing at least eight buttes (Table 2). When possible, rocks were cut perpendicular to any observed bedding, or parallel to the *in situ* "up" direction marked during sampling. The determination of the original "up" direction in some cases was estimated based on consistent geopetal mudfill surfaces in articulated lucinids, and some other sedimentary characteristics (Fig. 6). Both marks

Lithofacies	Limestone character	Fossils	Occurrence	Literature references?
I Vuggy	Many vugs, several generations of void-filling cement rinds, sparry calcite	few/none	Variable, often higher on butte	Vent facies, Howe, Kauffman
II Articulated Clams	Peloidal grainstone, some void-filling cements	often dense, many articulated	Variable, often higher on butte	Near-vent facies, Howe, Kauffman
III Clams, mud	Fine-grained, some peloidal, often highly micritized, few/no void-filling cements	often dense, mixed articulated/disarticulated	At/near top	Sedimentary breccia, Howe
IV Concretions	fine-grained micrite, occur as rounded lumps in shale	few/none	Near shale/limestone boundary	Kauffman, Howe
V Micrite	dense, fine-grained peloidal micrite, few/no void-filling cements	few/none	Lower on buttes	
VI "Thrombolite"	fine, greyish mottled texture, orange weathering, few small vugs, cement rims	few/none	Lower on buttes	Microbial texture, Shapiro

Table 1. Field-defined lithofacies descriptions.

Slab	Butte	Marked with *in situ* position?	Up direction determined by:	Lithofacies present in slab
X-1-A	unknown	no	several aligned geopetal surfaces	I, II
14	710	yes	collection mark	III
16	281	yes	aligned geopetals, shelter porosity	II
17	736.5	yes	collection mark	III
18	326.5	no	aligned geopetals	II, III
19	330	yes	several aligned geopetal surfaces	III
20	728	yes	several aligned geopetal surfaces	III
21	326.5	yes	collection mark	I, III
24	689	yes	collection mark	III
25	736.5	yes	collection mark	III
UA2	unknown	no	aligned geopetals, peloid settling	I, II
C-717-B	717	yes	collection mark	III

Table 2. Details of slabs examined – identification number, butte of origin, collection details, and lithofacies present in slab.

made at collection and estimations from slab features have the potential to introduce error in the determination of "up" direction, and therefore into data based on shell orientation. These and other potential sources for error will be discussed further.

Data were generally collected by inspection of slabs using a 10-40x power dissecting microscope. An initial broad survey of sedimentologic and taphonomic characteristics familiarized the author with the varying features of the slabs. Next, a comprehensive taphonomic analysis of the slabs was conducted to identify "taphofacies" boundaries within slabs. According to precedents for categorizing shell concentration type (e.g. Kidwell and Bosence, 1991), particular notice was given to taphonomic and sedimentologic characteristics like articulation, shell size and sorting, orientation, concavity, and shell density (packing). Shell counts were restricted to pieces 4mm in longest dimension or larger, as suggested by Kidwell (1991). Because the primary preserved species is overwhelmingly *N. occidentalis*, species diversity is not a major focus. Only shell pieces clearly from Order Veneroida (here, non-inoceramid clams, mostly lucinids) were counted. Other taxa were often fragmented and minor components whose orientations could not be measured accurately, so their presence was simply noted in other data categories.

The orientation of articulated clams in the slabs was measured to the nearest 5-degrees, and any geopetal surface within these was also measured to about 5-degrees. Angles were recorded azimuthally, measuring relative to the long axis of the clam in cross section, and with the origin placed on the left corner of the shell (Fig. 7). A few cuts show a prominently projecting hinge, but hinge/commisure was usually difficult to distinguish, probably due to the angle of slab cross-section. Because this distinction is not made, the maximum away-from-life orientation recorded is 90 degrees (though some could actually be 90-180 degrees from life
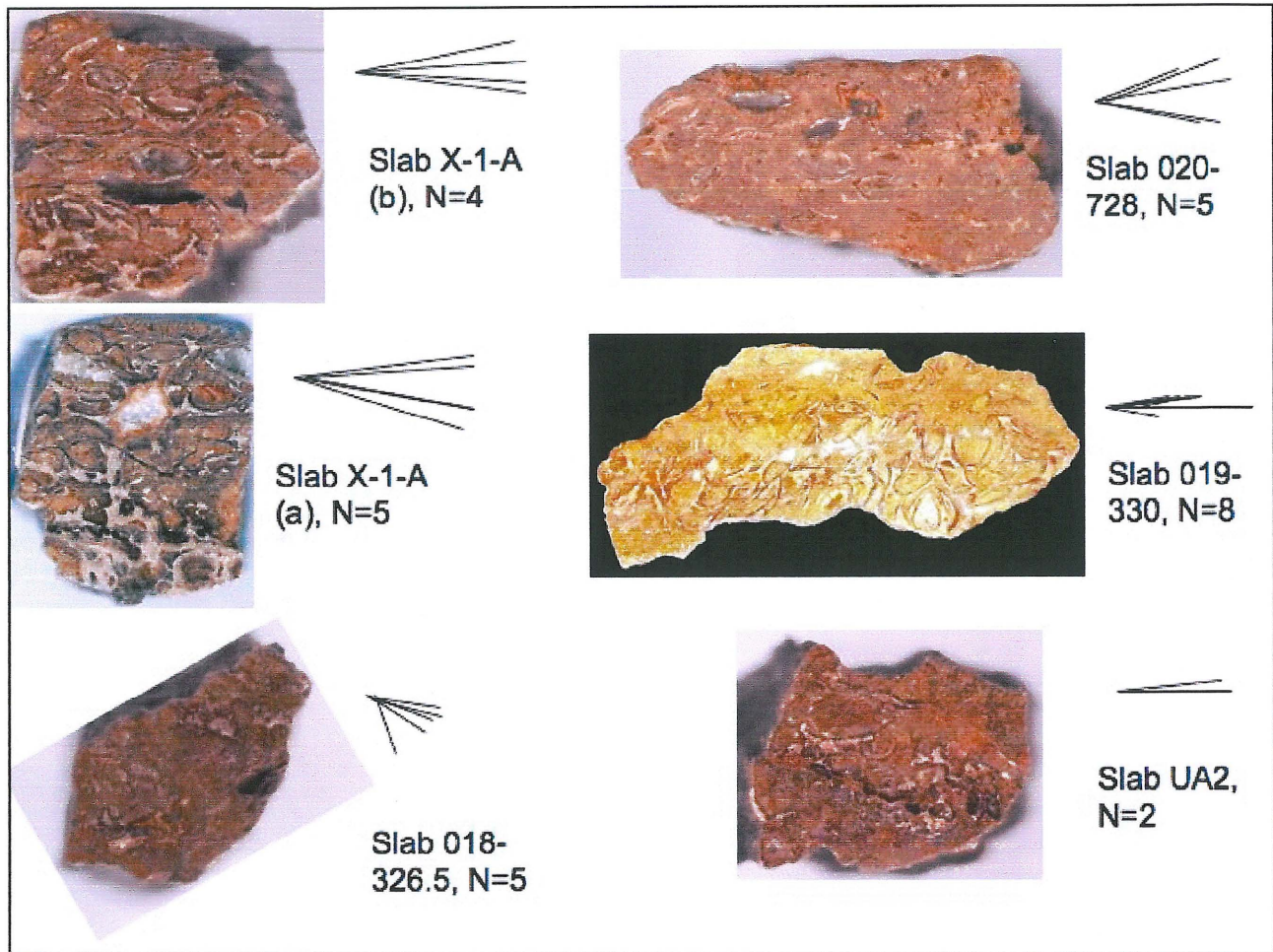
Figure 6. Example slabs showing geopetals aligned well enough to determine "up" direction; N=number of measurable geopetal surfaces on slab, angles shown.

Figure 7. Method for azimuthally measuring orientation in slabs: left - articulated clam, origin placed on left corner of shell; right - geopetal surfaces, origin placed on left contact of geopetal surface and inner shell wall. Position of axes determined by slab orientation (0 degrees = up).

position), and any possible hydraulic behavior based on intrinsic shell properties could not be recorded Orientation measurements were converted to one quadrant to regularize angles into terms of distance from horizontal and vertical axes. To partially account for measurement error based on angle of slab cut, orientations are reported broadly in three 30-degree categories of "near-vertical", "inclined", and "near-horizontal" (Fig. 8). In addition, shells whose orientation was unclear due to the angle of slab cut were recorded only as a component of shell density, and not for orientation.

Disarticulated shells were similarly counted, with orientation categorized broadly as vertical, inclined, horizontal- concave up, or horizontal- concave down. Based on personal assessment, as well as literature precedent (Kidwell, 1991), concavity was recorded only for shells within 30-degrees above or below a horizontal position in cross-section. Verticality was recorded when disarticulated shells lay within 15-20 degrees to the right or left of a vertical position.

Surveys of taphonomic features were conducted by placing a 1-square-cm grid transparency on a polished slab under the microscope, counting shells per square, and recording details of orientation, concavity, etc. Placement of the grid resulted in a good measure of slab surface area. The counts of shells divided by the area therefore yielded a "grid-count shell density" (GCSD). This measure includes both a packing and a size component, as larger shells spanned more than one 1-cm square, and were thus counted more than once. A high GCSD indicates that a higher percentage of the slab is composed of shell pieces. Placement of a grid also allowed for easy spatial representation of primary features like shell density and articulation. Based on how these two variables separated the slab, tentative taphofacies boundaries were determined, and further data were collected within these "slab zones". (Note: separate
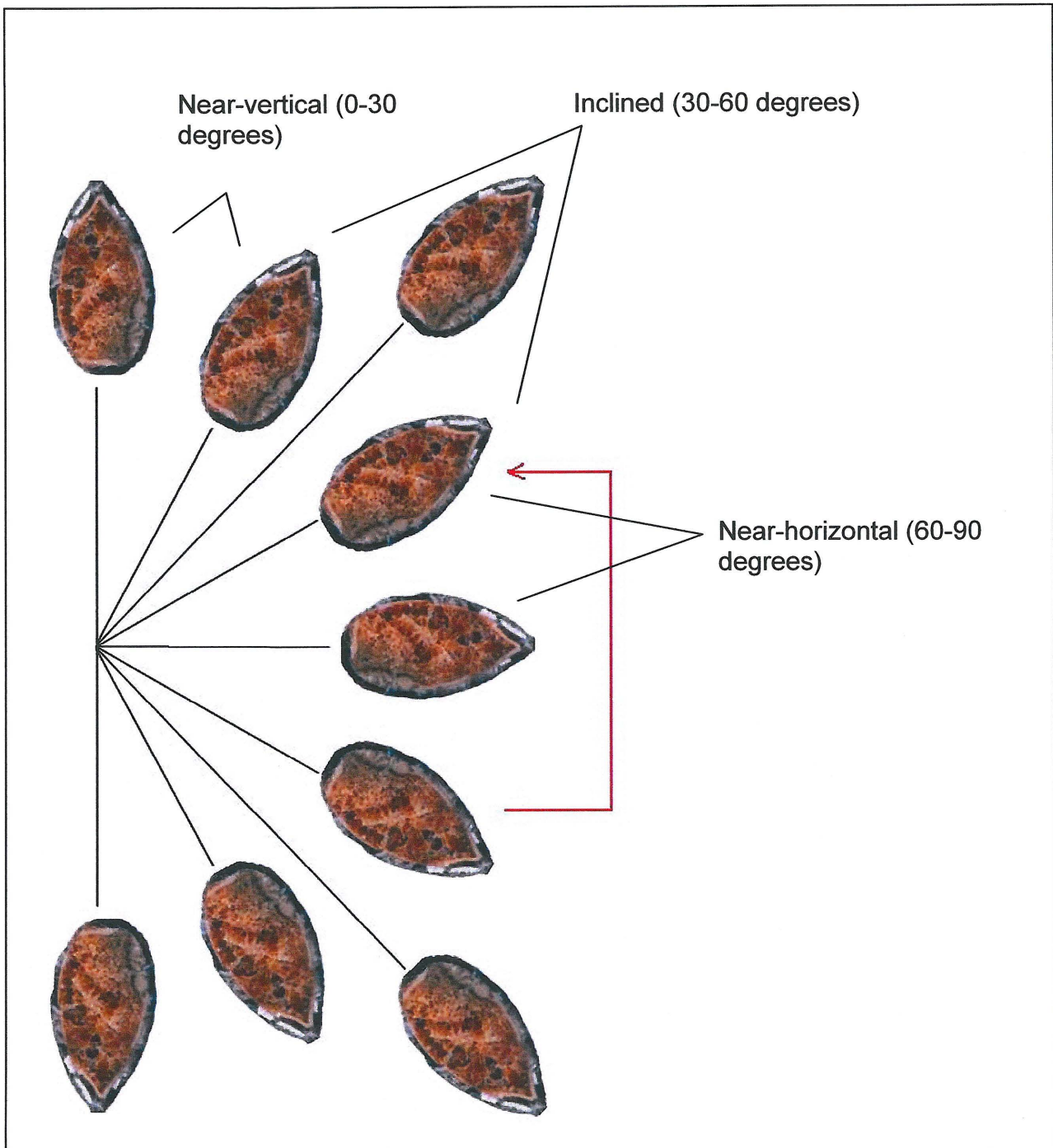
Figure 8. Categorization of shell angles; shells measured azimuthally in quadrant IV are of equivalent angular distance from life position as corresponding orientations in quadrant I, and are thus regularized to those orientation zones. 45-degree orientation shown for comparison.

taphofacies data can be combined to yield whole-slab data.) This division is the first step in working towards finding a correlation between taphonomic state and surrounding sedimentologic features.

The GCSD usually differs considerably from the "shell-count shell density" (SCSD), which is simply the number of shells in the slab divided by the inspected area. Shell count shell density (SCSD) reflects solely the number of countable shells per unit area. The highest numbers here will reflect a dense hash of smaller shell pieces. Dense accumulations of large shells and less-dense accumulations of smaller shells thus have the potential to be indistinguishable in this measurement. It is important, therefore, to utilize the GCSD, which more accurately reflects composition: how much of the slab is composed of fossil shell material. The disparity between SCSD and GCSD reflects the average size of shells in the slab - the closer the two numbers, the more common it is that shells appear only in one grid square, and are thus likely well under 1cm in longest dimension.

As a quick proxy for en masse tallies of shell size, I have made the difference between the two density measures into a percentage of the SCSD. The larger the number, the larger the average size of shell pieces in the slab. As a result, the presence of a few very large clams is effectively neutralized by the presence of a large number of small or medium shell pieces. Separating articulated and disarticulated components somewhat remedies this neutralization, and the resulting size proxies for articulated versus disarticulated components also presumably will reflect the degree to which articulated shells are sedimentologically equivalent to disarticulated shells in a given slab – this may help determine whether articulated shells were deposited as clasts. It must be noted that these size proxies are completely relative: this size estimate can reflect sedimentologic properties, but cannot be extrapolated to original size differences between

articulated and disarticulated components, as articulated shells will naturally span two or more times the number of grid squares as disarticulated shells (this extrapolation would force the erroneous conclusion that small clams were more often disarticulated).

While a quantitative assessment of shell data was achieved, sedimentologic features were more readily translated into semi-quantitative terms. The same slabs were evaluated within taphofacies boundaries for sedimentologic features like peloidal content and packing, matrix composition, amount of calcite cement, sediment size gradation, and shelter porosity. Each variable was measured in semi-quantitative terms like "absent", "present', "dominant", "minor component", "major component", etc. Sedimentary features measured are listed in Table 3.

Resulting taphonomic and sedimentologic feature data were associated with within-slab facies, which were given names in order to distinguish. All data, including counts and semi-quantitative results, were entered into the PAST statistical program and run through a cluster analysis.

Sedimentary feature	Scale
Peloids	Absent/minor/major component (0-2)
Peloid packing	Loose packed/grain-supported (0-1)
Mud clumps/rip-up clasts	Absent/present (0-1)
Graded features	Absent/present/consistent (0-2)
Shell fragments in matrix	Absent/present/abundant (0-2)
Stacking of disarticulated valves	Absent/present (0-1)
Shelter porosity	Absent/present (0-1)
Abrupt boundary to sedimentary facies?	No/Yes (0-1)
Material filling articulated shells	Calcite spar (0), mud (1), mud and spar (2)
Mudfill character	Same as surrounding sediment/some different/all very different from surrounding sediment (0-2)
Different species present?	Absent/present/abundant (0-2)
Shell packing	Barren/dispersed/loosely packed/dense (0-3); (Kidwell, 1991)
Cements	Absent/little, minor/significant/most or all of fabric (0-3)

Table 3. Sedimentary features recorded.

Results

Field Observations

Typical medium to large-sized buttes (~20-25m high) tend to have limestone outcrops at and near the top, and a steep, weathered scree slope with some limestone outcrops, phasing into the surrounding Pierre shale (Fig. 9). The "caprocks" were usually highly fossiliferous, with noticeable bedding of clam shells, though varying from a dense shell "hash" to a loosely-packed assemblage of articulated valves. The top outcrops often appeared in large lateral layers, usually with some dip that was determined by compass not to be correlative from butte to butte (see Fig. 4). Though most noticeable in the cap rocks, the clam-rich facies can also be found in outcrops much further down the sides of the buttes. Any hope to trace a shell bed in these lower outcrops is precluded by the patchiness of exposure amongst the eroded scree slope.

Though lucinids dominate the fossil fauna, other taxa do occur in the TPB limestone, and with much higher abundance than the surrounding shale (Howe, 1987). On many buttes, inoceramid clams (Family Inoceramidae) were the next most abundant taxa, with multiple species distinguished but not identified in this study (Morgan, et al., 2005). Inoceramids are easily distinguished from other bivalves by outer features such as size and strong growth banding, as well as acicular-crystal shell growth. Ammonites represent the most abundant fossilized predatory genera, most commonly *Baculites scotti* and the heteromorphs *Didymoceras nebrascense*, *D. stevensoni*, and *Solenoceras sp.* (Fig. 10). Some gastropods were also found, but not identified more specifically.

Members of the research team observed a variation in overall character across the studied butte field, having much to do with faunal diversity, extent of limestone weathering, prevalence of outcrop and lithofacies therein, and general size and spatial density of buttes within a

Figure 9. Tepee Buttes, Hanna Ranch, CO. People standing on side of left butte and top of middle butte can be seen for scale. (Photo courtesy Russell Shapiro.)

Hoploscaphites sp.

Solenoceras sp.

Didymoceras nebrascense
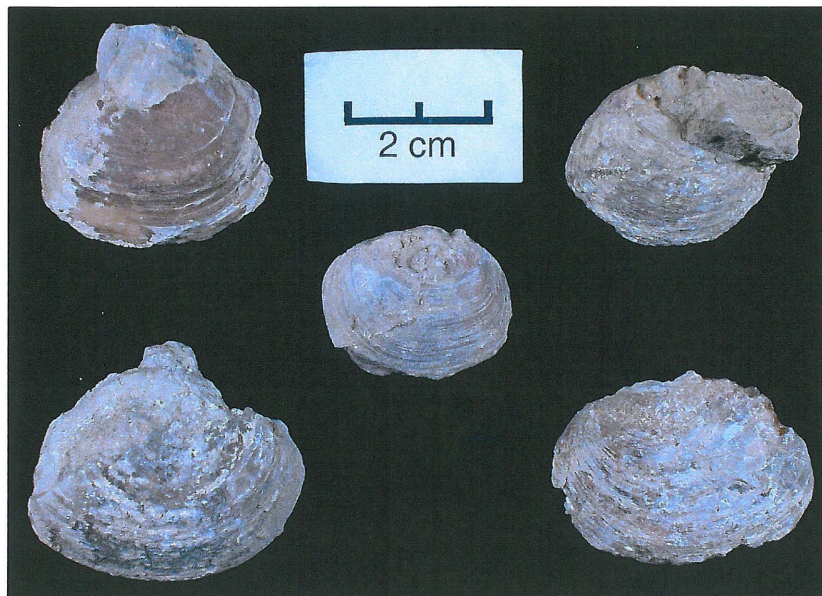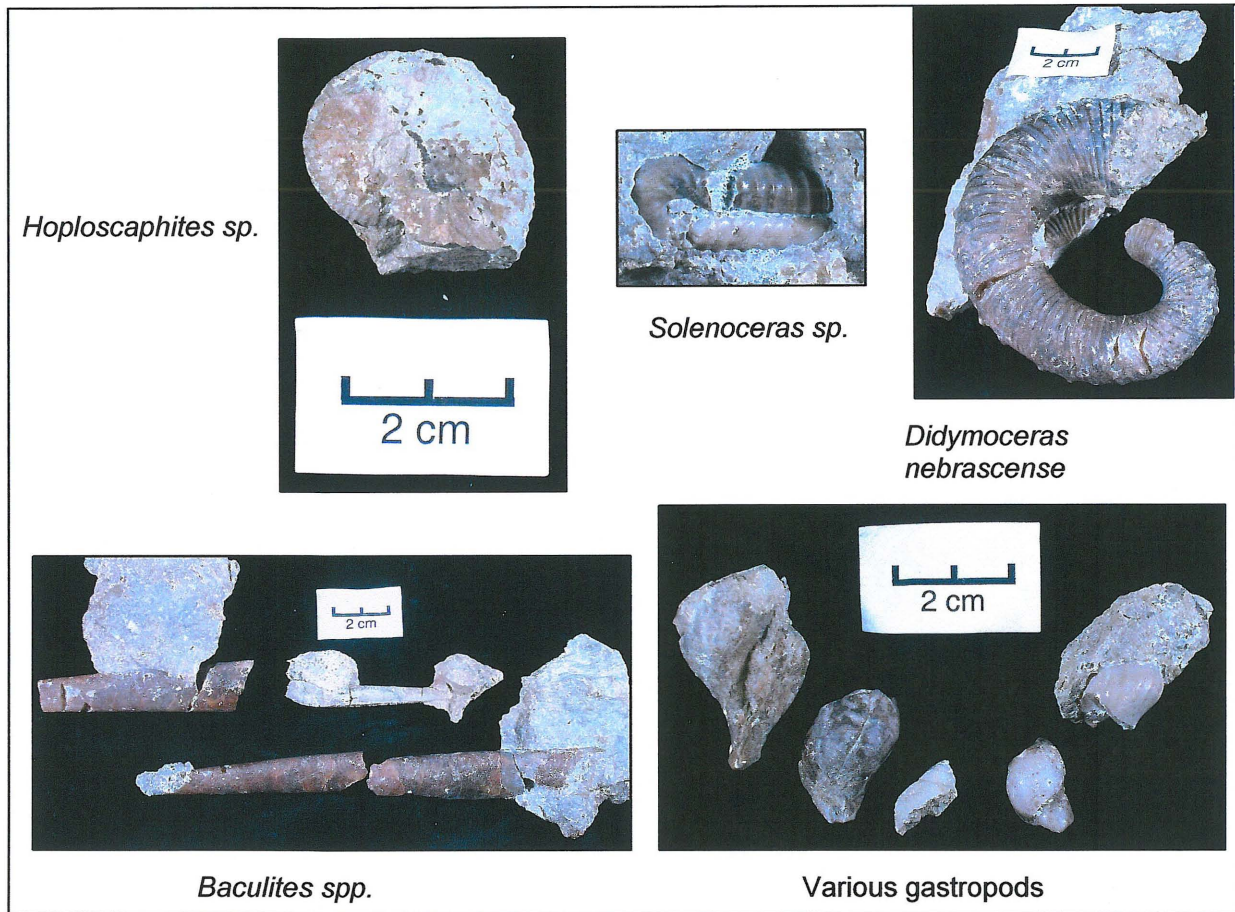
Baculites spp.

Various gastropods

Figure 10 a,b. Top (a) – Ammonites and gastropods found in Tepee Buttes, CO; Bottom (b) – individual fossilized lucinids from Tepee Buttes, CO. (Photos courtesy Valerie Morgan, Robyn Dahl, Rebecca Rudolph.)

geographic area. In broad qualitative terms, buttes in the southern range east of Boone, CO did

not reach the height of northern buttes, and tended to yield limestone samples that were less

weathered and sometimes denser or harder (this may reflect a chemical compositional difference,

or simply differential weathering). The faunal diversity seemed to have patterns of concentration

in these buttes also, with a few buttes (e.g. buttes 274, 285) being noted for a high density of

articulated medium-sized inoceramids, and another (butte 335) noted for a dense accumulation of

near-whole ammonite fossils. These observations over a wide expanse of buttes are markedly

different from Howe's observation of consistent faunal diversity amongst the more limited

number of buttes in that study.

Besides faunal diversity and abundance, limestone outcrops in the buttes varied according

to a number of lithologic characteristics. The six field-defined lithofacies are important as a

broad-scale characterization of limestone fabric: much of the butte limestone is nonfossiliferous,

and it is important to map out where fossiliferous intervals occur in relation to the other fabrics.

The lithologic character of the six facies is detailed in Table 1. The recorded occurrence of

facies reflects estimates by the author based mostly on field notes and mapping data. Certain

descriptions overlap with those of previous studies, but most observations of facies distribution

do not correlate to these earlier works. Most notably, this study never observed the central "vent

core" referred to by most other studies (e.g. Kauffman, et al., 1996; Howe, 1987; Fig. 3).

Laboratory Results

One of the most useful results of this taphonomic and sedimentologic inspection has been

a qualitative assessment of the extreme variability of the TPB limestone fabric and its tendency

for small-scale changes. It can be safely said that, qualitatively, taphofacies change wholesale on

a smaller scale than sedimentary facies, with taphonomic character varying within a slab (average slab size 92 square-cm), both according to expected bedding, and sometimes laterally as well. Within-slab variations tend to occur with density and articulation, while slab to slab variations encompass all variables, with size, dis/articulation and orientation determining a general "taphonomic character" for a given slab as a whole.

Sedimentary Features

Perhaps surprisingly, certain sedimentary features are fairly consistent across the suite of slabs. The matrix material of nearly every slab zone is comprised in some part – often mostly – of peloids, which in many cases are close-packed enough to be considered grain-supported. Due to the large amount of peloidal fabric and micrite even in very shell-rich facies, most fossiliferous TPB limestone fabric should be classified as biopelmicrite, sometimes verging on biopelsparite, instead of the coquina referred to by most TPB workers (Kauffman, et al., 1996; Howe, 1987). In some slabs, matrix components are not easily distinguishable due to great variations in the weathering of the limestone – more samples from the northern set of buttes are highly weathered, often making primary fabric difficult to discern

In thin-section, a great variation in peloid composition can be seen. Most appear to be near-round, and many are of carbonate mud or micritic composition, though some show silicate components. Some can be distinguished as definite rounded remnants of detrital mud, with tiny shell fragments and occasionally possible sponge spicules (Fig. 11). A few areas show definite oblong peloid shapes that usually are identified as fecal pellets, but these seem not to be the dominant peloidal component (Fig. 12). Peloidal fabrics are also sometimes clearly ripped up to form large clasts, resulting in distinct "mud clumps", themselves of a peloidal fabric (Fig. 13).
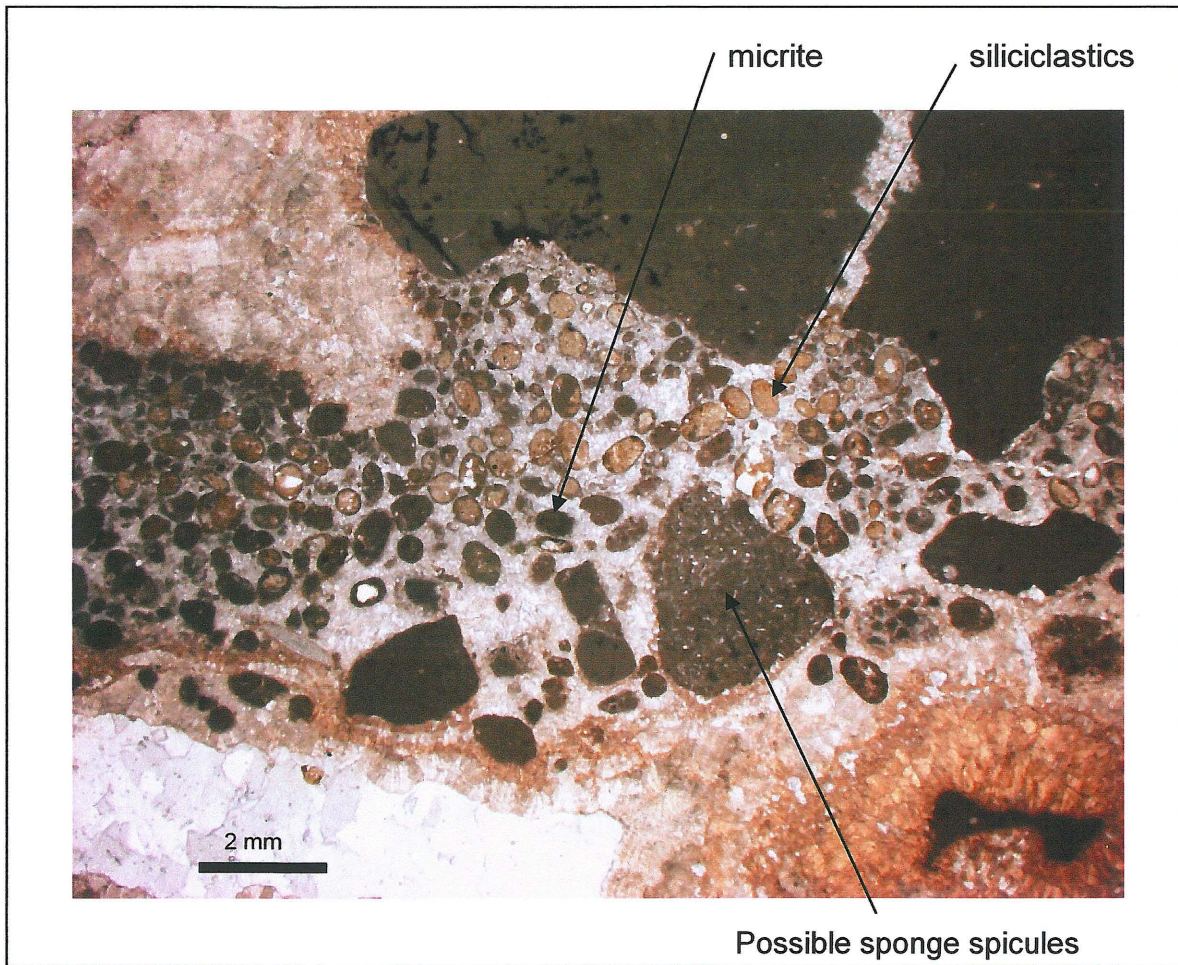
Figure 11. Photomicrograph – peloids showing micritic, siliciclastic, and possible sponge spicule composition.
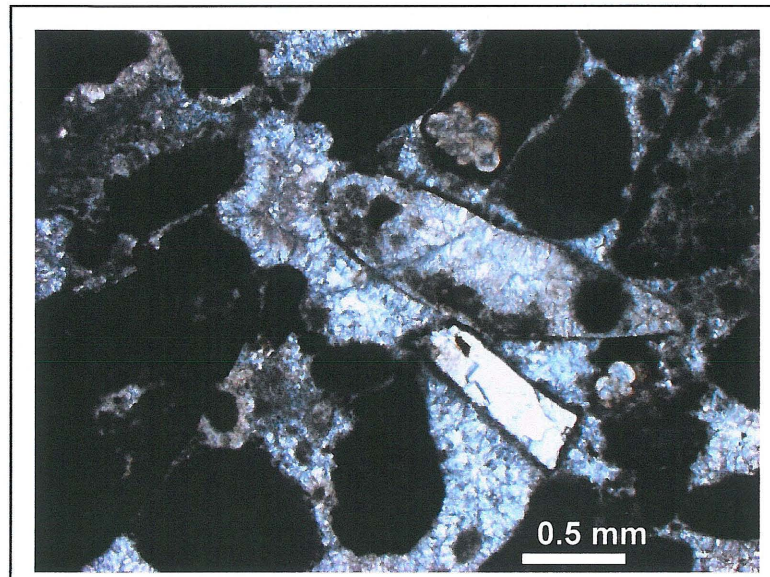
Figure 12. Photomicrograph – oblong peloids are presumed fecal pellets (central peloid replaced by blocky calcite).
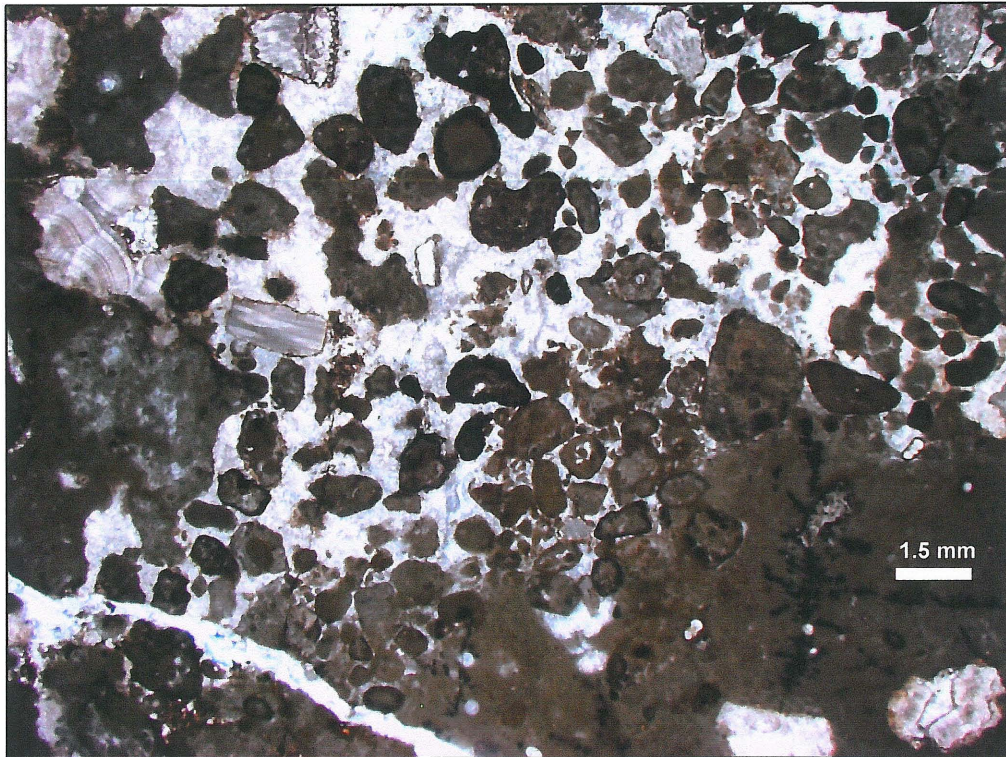
Figure 13. Photomicrograph showing larger, irregular intraclasts in a recrystallized matrix.
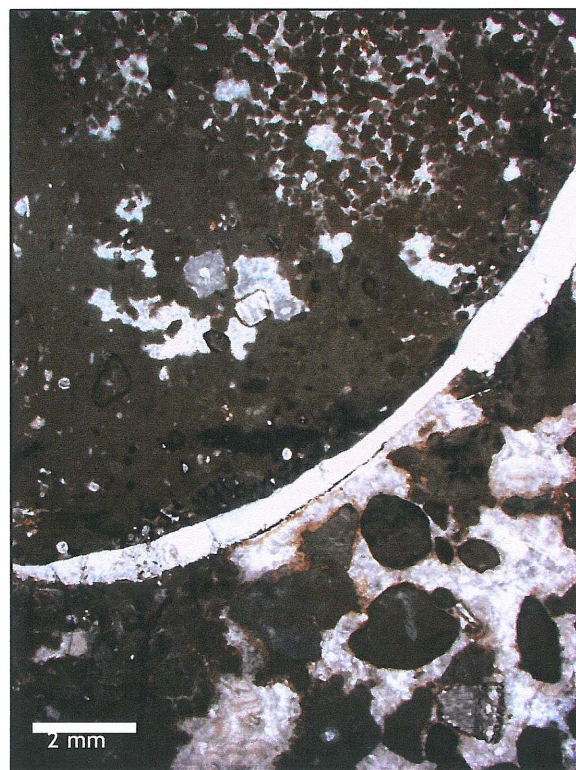
Figure 14. Photomicrograph showing a range of peloidal components. Central calcite piece is a lucinid valve: small rounded peloids are trapped within (above). Large detrital intraclasts are surrounded by recrystallized matrix outside of the shell (below).

In sum, peloids occur nearly everywhere, but the small-scale variation in peloidal fabric characteristics is astounding (Fig. 14).

Graded features were another common sedimentary characteristic, and often comprised some differential settling of peloids into the bottoms of shell cavities and other sedimentary depressions, with gradation up into a finer micritic composition (Fig. 15). Slabs that lacked graded features were those high-density, highly fragmented shell accumulations commonly referred to in this study as "disarticulated shell hash" taphofacies (Fig. 16). "Stacking" or "nesting" of disarticulated valves was a dominant feature in four slabs (Fig. 17), and is commonly considered evidence of storm reworking (Kidwell and Bosence, 1991). Shell accumulations with particularly dense mixed dis/articulated constituents were also less likely to be bounded by abrupt cement facies or apparent dissolution surfaces.

Cluster analysis reflects the general consistency of sedimentary characteristics: grouping of slab zones based on taphonomic features alone (described below) almost exactly matches the grouping of slab zones after sedimentary features are added as well. This could reflect that (a) sedimentary features are roughly constant across all slabs, or (b) sedimentary features vary almost directly with taphonomic features. It appears that neither of these options is exclusively controlling the outcome, but that some combination is in play. For instance, peloids are present in almost every slab zone, and are most often grain-supported. However, features like exotic mudfill in articulated clams are relegated to a few samples, and are most likely diagnostic of some controlling sedimentary process (Fig. 18).

At the same time it must be noted that, while the overall character of the sedimentary matrix does not usually vary *wholesale* from one zone of a slab to another, it could nevertheless be described as very patchy – slight variations often occur in odd patches across a slab. The
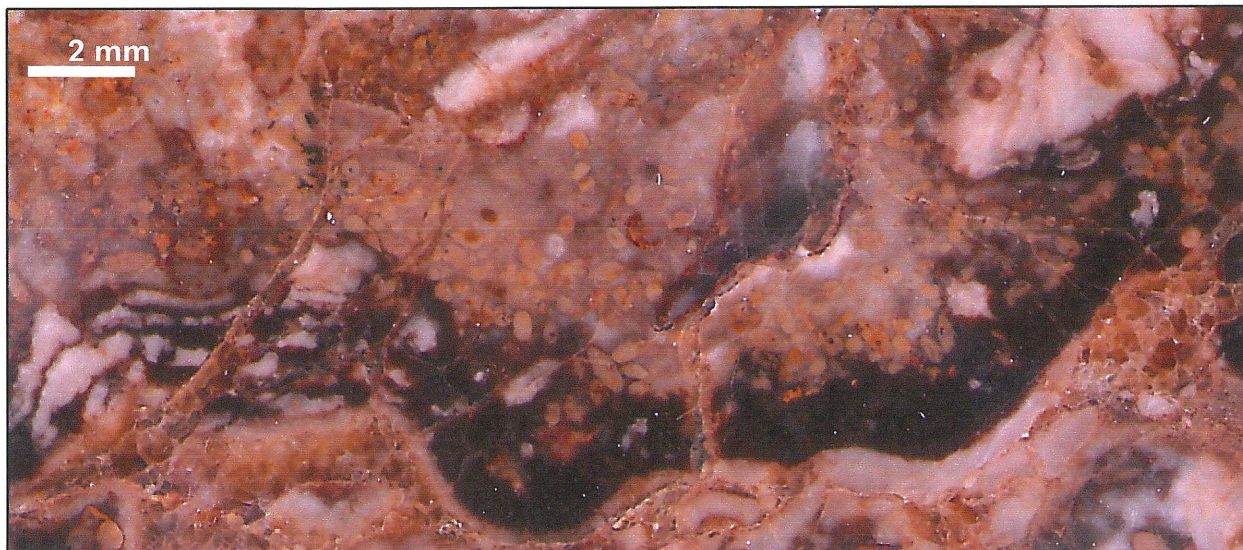
Figure 15. Peloids along a cement surface – possible grading, Slab UA2.

Figure 16. Disarticulated shell hash taphofacies, Slab 717E.
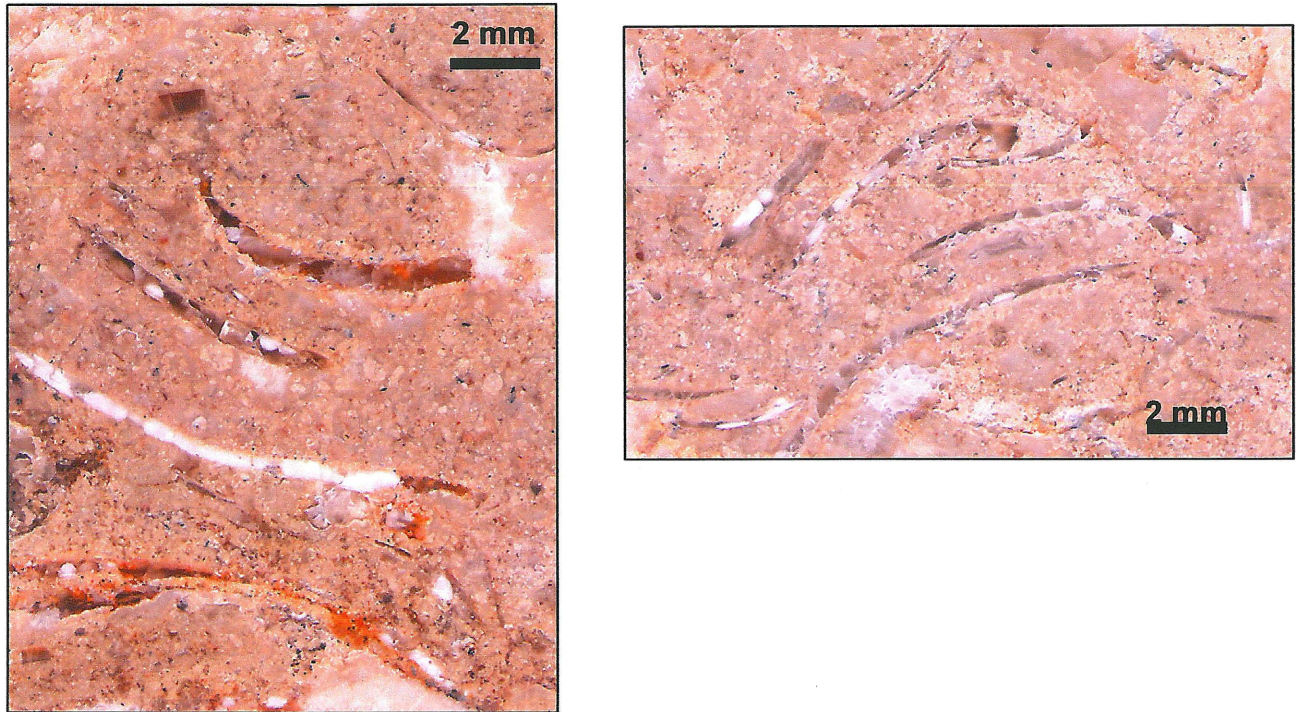
Figure 17. Stacking of disarticulated shells, Slab 20-728.
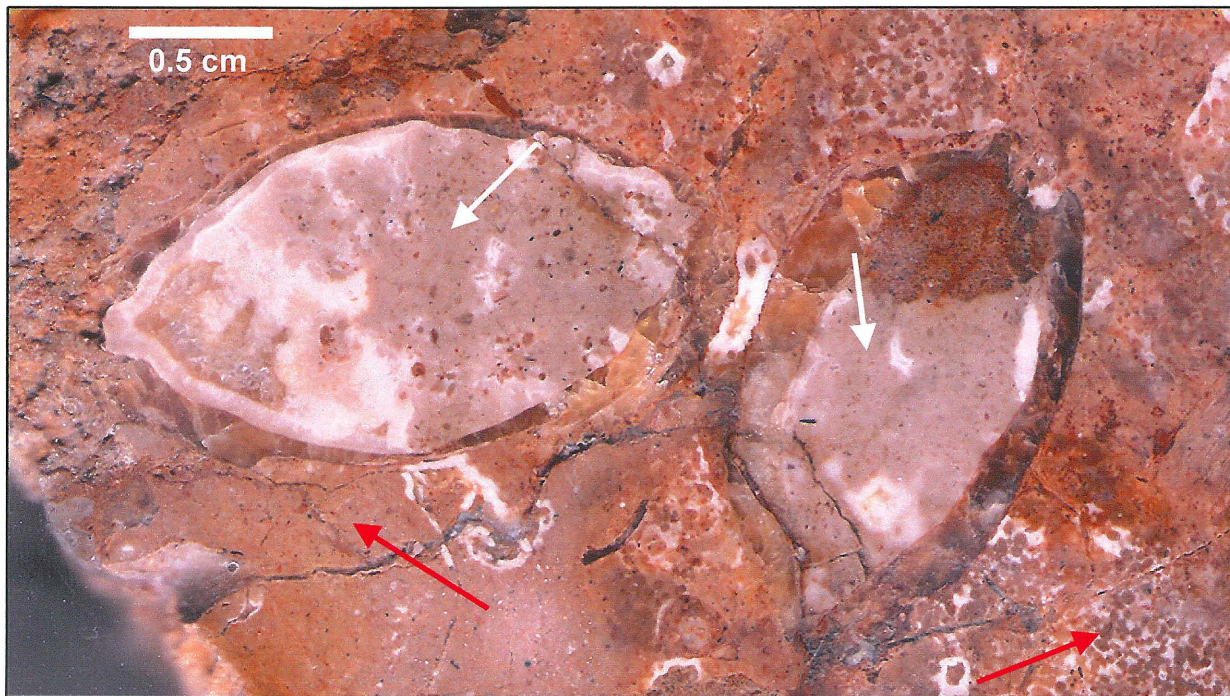

Figure 18. Exotic or differentially weathered mud fill in articulated clams (shown by white arrows), in contrast with surrounding matrix material (shown by red arrows). Slab 14-710.

presence of gradational features is one localized feature, with peloids often gathered in concave-up shells or along cement or presumed stylolitic surfaces. The presence of "mud clumps" – presumably rip-up clasts – is another feature that is usually very localized. Localized variation in sedimentary character is likely due to later alteration like micritization, compression, cementation, etc. which presumably could be controlled by very localized conditions.

Taphonomic Features

Taphonomic data yielded quantitative results that reflect well any broad qualitative categorization of slabs. Taphonomic character could generally be placed into four rough categories: (1) high shell density, high proportion articulated, (2) medium shell density, mostly disarticulated, (3) high-density disarticulated shell hash, and (4) shell-poor (low shell density). These categories roughly define taphofacies, which sometimes vary within a slab (Table 4). Cluster analysis supported this division fairly consistently by grouping the defined taphofacies together.

Samples described generally as taphofacies (3), "disarticulated shell hash" (namely 17-736.5 and 717-B), cluster together, sharing distinctive characteristics of very high percent disarticulation (>90%), fairly random shell orientation, high uniformity of size between articulated and disarticulated shells (determined by GCSD-SCSD size proxy described earlier), and a fairly high density of shell material. This type of fabric stands in marked contrast to the qualitatively assessed "dense articulated clam" (1) taphofacies. Preliminary assessment shows that a high percentage of articulated lucinids is indeed the one clear commonality among slabs of this type. Similarly, shell-poor facies group well together, as do facies exhibiting a medium density of shells with few articulated. Interestingly, slab 14-710 – the only slab that shows good evidence for unaligned geopetal fill, indicating mudfill while in life position, and subsequent

Slab	Butte	Taphofacies present in slab	Lithofacies present in slab
X-1-A	unknown	1,2,4	I, II
14	710	?2,4	III
16	281	2,4	II
17	736.5	3	III
18	326.5	1,2,4	II, III
19	330	1	III
20	728	?1,2	III
21	326.5	2,4	I, III
24	689	1	III
25	736.5	1,2	III
UA2	unknown	2,4	I, II
C-717-B	717	3	III

Table 4. Table comparing presence of field-defined lithofacies and lab-defined taphofacies within individual slabs.

transportation – is grouped separately from other slabs. Its composition of few but very large articulated lucinids may be the controlling factor in this grouping.

Also important are the taphonomic statistics for the sample suite as a whole (Table 5, Fig. 19). Most notably, the samples are deficient in life position (i.e., articulated and at or near vertical) lucinid shells, the opposite of what would be expected for an autochthonous assemblage, and very different from what other workers have reported, due to consideration of *in situ* orientation as well as articulation. For samples with more than four articulated shells the highest percentage of near-vertical (shell axis pointing within 30 degrees to left or right of vertical) articulated lucinids is 25%. This drops to 19% when the range is narrowed to 15 degrees to either side of vertical. The average of all slabs for articulated shells aligned in the broad range of vertical is 14%, and only 6% in the narrower range. On the other hand, there appears to be a fairly *large* percentage of articulated shells aligned at or near horizontal: 64% in the broad range and 34% in the narrow range. Near-horizontal articulated lucinids outnumber those oriented at or near vertical in every slab except one, which has only four articulated shells – two inclined, one vertical, and one horizontal. The highest percentage of near-horizontal articulated shells in slabs with four or more articulated lucinids is 100%; the low reaches only to 25%.

The total percentage of shells with retained articulation is fairly high for a reworked shell concentration: the average percentage is 16% when considered over an entire slab. This reached a maximum of 59% within the articulated taphofacies of one slab. The maximum for whole-slab data was 35%.

Slab/Zone	Total Shell Count	Shell density	Articulated	Disarticulated	ARTICULATED			DISARTICULATED			
					At/near vertical	At/near horizontal	Inclined	Concave up	Concave down	Vertical	Inclined
X-1-A	29	0.5	24.1	75.9	0.0	24.1	0.0	24.1	6.9	24.1	20.7
14-710	21	0.2	23.8	76.2	4.8	14.3	4.8	4.8	9.5	14.3	47.6
16-281	17	0.3	35.3	64.7	0.0	29.4	5.9	11.8	5.9	5.9	41.2
17-736.5	31	0.4	9.7	90.3	3.2	6.7	0.0	9.7	6.5	25.8	48.4
18-326.5	85	1.1	9.4	90.6	1.2	2.4	5.9	29.7	12.2	25.7	20.0
19-330	110	1.1	26.4	73.6	5.5	8.2	12.7	10.9	11.8	13.6	33.6
20-728	118	1.2	13.6	86.4	3.4	5.1	5.1	28.8	9.3	15.6	30.5
21-326.5	45	0.3	8.9	91.1	2.2	2.2	4.4	17.8	11.1	28.9	33.3
24-689	124	0.8	4.0	96.0	1.6	0.8	1.6	20.2	10.5	27.4	37.1
25-736.5	85	1.7	7.1	92.9	2.4	1.2	3.5	29.4	3.5	16.5	43.5
UA2	13	0.3	15.4	84.6	0.0	7.7	7.7	23.1	7.7	0.0	53.8
C-717-B	178	1.3	3.9	96.1	0.6	2.8	0.6	26.4	13.5	10.1	34.3
Averages	71.3	0.8	15.1	84.9	2.1	8.7	4.3	19.7	9.0	17.3	37.0

Table 5. Summary of whole-slab shell constituents; shell count given as raw number, shell density given as shells per square-cm, all other numbers are percentage of whole; grayed numbers indicate likely insignificant data based on sample size of less than four articulated shells total.
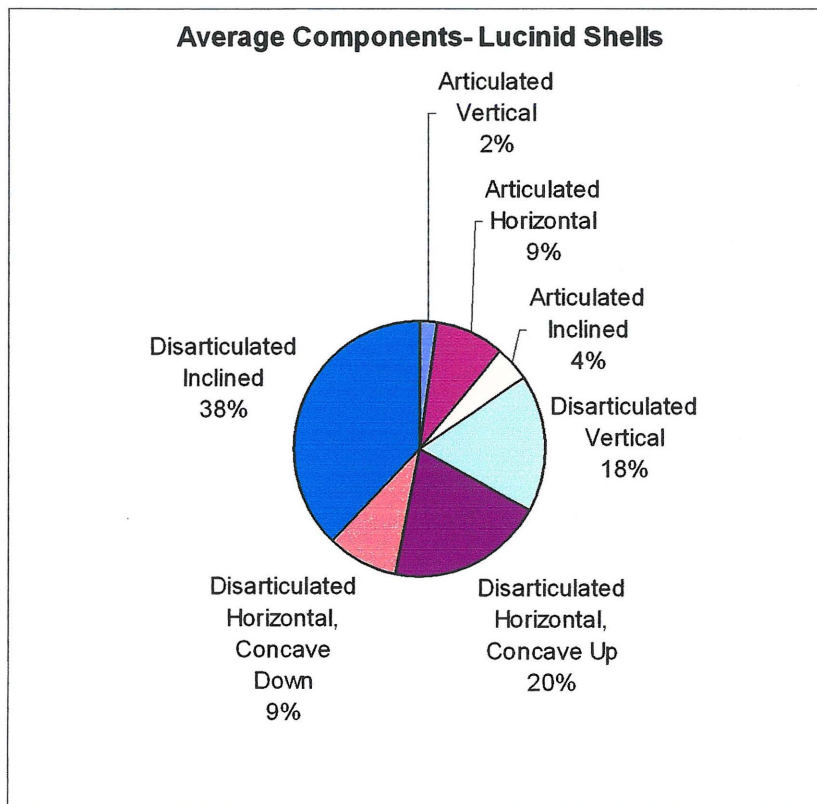
Figure 19. Average taphonomic states of lucinid shells across all slabs examined (illustrates Table 5).

Lucinid Fossil Condition

Originally aragonitic lucinid fossil components have been replaced with euhedral calcite, sometimes preserving growth banding visible in thin-section shell cross-sections. Individual uncut articulated lucinid fossils also exhibit dense, unworn, low-relief growth bands on the replaced surface, and as a whole are characterized by a highly symmetrical overall body shape (Fig. 10b). Void spaces inside articulated shells are filled with detrital mud, calcite spar, or a combination of geopetal mud fill and calcite spar. Internal molds were found, but none complete enough to reveal details of internal anatomy like muscle scars or pallial line, which might be useful in interpretation of ancient lucinid life habit.

Discussion

Peloid Origins

Purely micritic peloids are less common than expected, and the presumed prodigious microbial production of authigenic peloidal micrite is thus in question. A limited survey of thin-sections would best indicate a detrital origination of most peloids, though actual formation of a peloidal shape is not completely understood at this point. Some workers argue for biotic origin of abundant marine carbonate peloids (Kaźmierczak, et al., 1996), while others have shown abiotic formation to be equally likely, and ask that the burden of proof be on demonstrating biotic origins on a case-to-case basis (Bosak, et al., 2004). An abundance of micrite envelopes surrounding peloids in thin-section could also indicate the origin of peloids as skeletal or other detrital fragments microbored to the point of complete micritization (Tucker, 2001). Fungal, algal, and sponge microborers might all be possible in the TPB setting.

In some places there exists a transition between detrital mud and peloids that suggests that peloids originally formed from detrital mud, and subsequently at some points were compressed to form back into an even mud with or without peloidal remnants (Fig. 20). This scenario is specifically illustrated by Kaźmierczak, et al. (1996), but with an origin as a benthic coccoid mat. The remnant "ghosts" of peloids that some fabrics show could also be a result of earlier cementation, or different origin altogether. Many possibilities exist for the origin of these different types of peloids – we should not automatically assume a microbial or fecal origin.

Taphonomic Features and Depositional Scenarios

The high percentage of retained articulation in these samples is remarkable given the generally low percentage of possible life-position shells. This seems to indicate that many shells
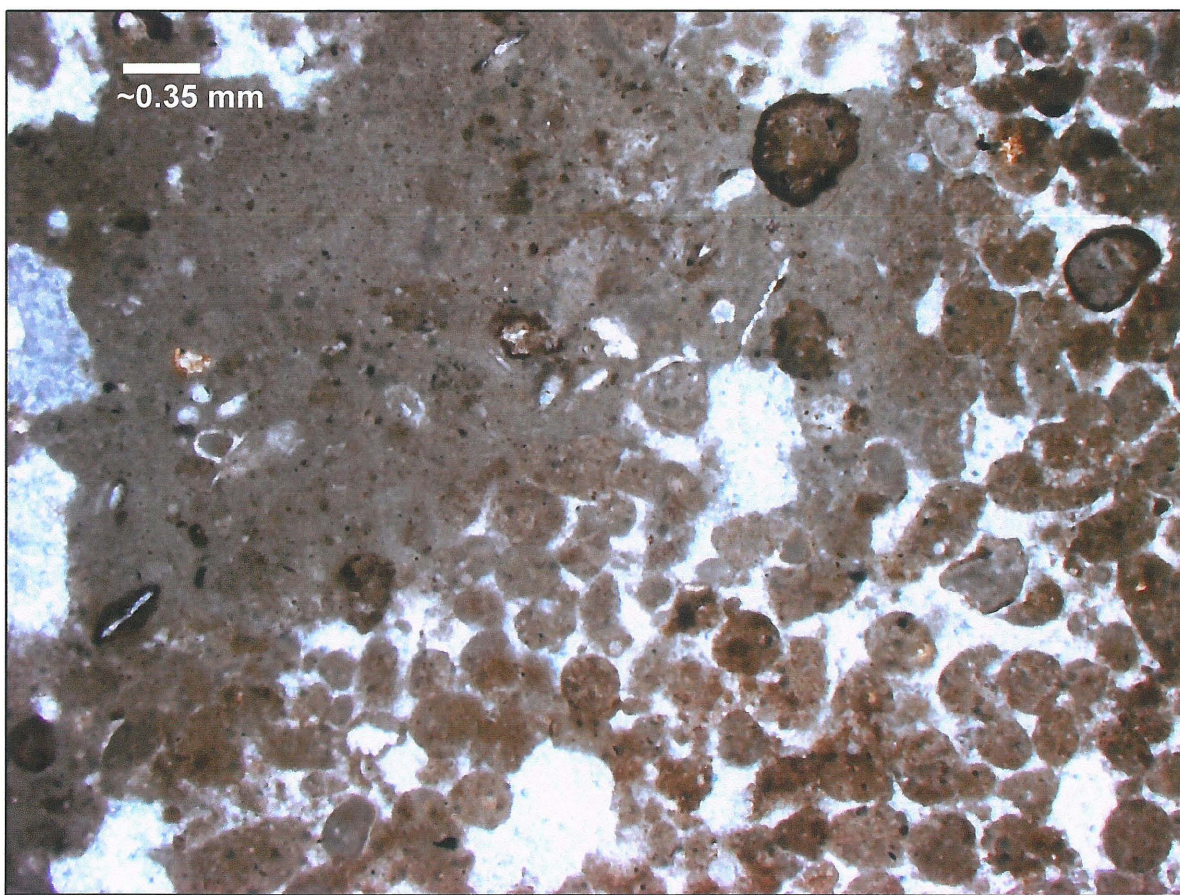
Figure 20. Photomicrograph – peloids transitioning into micrite (trapped in articulated lucinid shell).

did indeed retain articulation through some sort of transport or reorientation process. Mechanisms of this reorientation are discussed below.

The roughly concentric faunal and facies distribution described by Howe (1987) and Kauffman, et al. (1996) was not seen in this study. Tube worms were never conclusively identified, and certainly not to the extent of Howe's described "Anastomosing Worm Tube paleocommunity". A striking difference was our observation of an abundance of in-place ammonite and inoceramid fossils, often very large, at the very top caprock of many buttes. In contrast, Kauffman, et al. (1996) place their "ammonite-dominated biofacies" downslope in the shale, presumably in concretions as described by Kauffman (1977). Howe also places ammonites and inoceramids further from the center of the buttes in a "diverse mollusk community".

It should be noted that Howe did not find a regularized concentric faunal and lithofacies distribution as previously described by Kauffman, but instead found an asymmetric distribution attributed to tendency of fauna to colonize the lee side of a butte. This interpretation assumes some significant paleotopography, as well as the presence of currents in the seep setting. This study did not observe any asymmetrical distribution, but Howe's study did cover faunal distribution more systematically (though with much smaller butte sample size).

Clearly non-vertical alignment of shells is dominant within the TPB samples, both at slab- and outcrop-scale (Table 5, Figure 19). Out-of-life position determinations can be fairly definitively made based on geopetal evidence. In several slabs (e.g., Fig. 21, Slab X-1-A), geopetal infilling of articulated lucinids does not occur with the surface orientation expected if the clam were filled while still in life position (Fig. 22). In addition, these slabs show a consistent alignment of shells, so infill with mud after bioturbation is not probable.
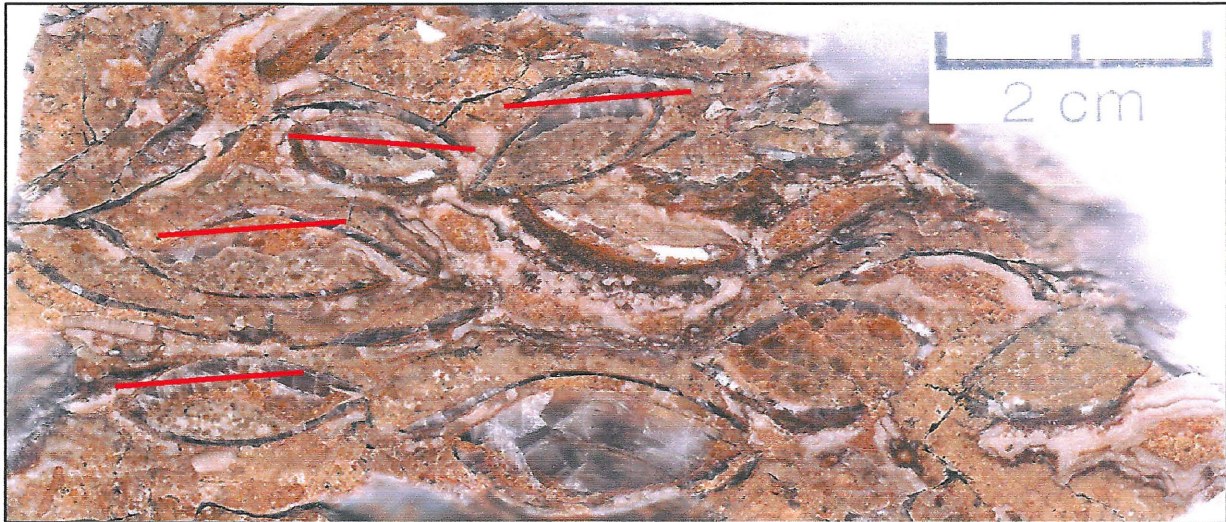
Figure 21. Out of life-position shells, based on aligned geopetal surfaces (shown by red lines). Slab X-1-A. Compare to expected positioning illustrated below.
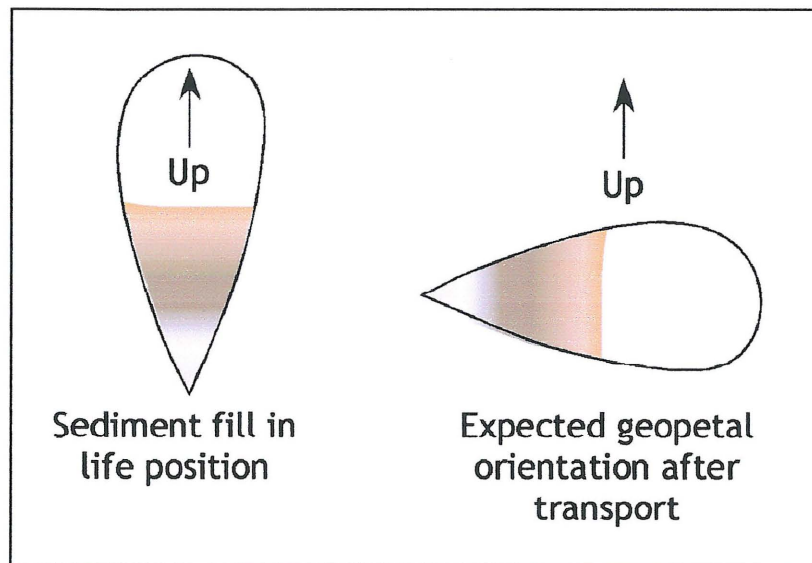

Figure 22. Expected configuration of geopetal surface for clam filled while in life position.

Since these shells appear to have been transported to some extent, the question arises of how they retained articulation in fairly good proportions. In addition, the consistent presence of growth banding indicates that shells were likely not exposed on the seafloor for long periods of time. One probable scenario is that articulated lucinids were transported live, killed in this event, and then filled with sediment in this new orientation. Lucinids could also die in the sediment, be cemented early and thus retain articulation through a transport event, after which they might be filled in with mud in that final geopetal orientation. No articulated shells have yet been seen, however, that display a cement layer clearly lain down before sediment infill. On the other hand, slabs such as 014-710 that show unaligned geopetals with (perhaps) exotic sediments probably indicate a different scenario, namely death, geopetal infill, cementation, and then transport (Fig. 18). This is the inferred scenario for the only geopetal evidence presented by Howe (1987), where she reports unaligned geopetal fills in clams in the "sedimentary breccia" facies.

Depositional Scenario: Low-energy, In-place

Callender et al. (1990) provide an interesting taphonomic comparison with a modern hydrocarbon seep below wave base. Though the authors warn that modern variables related to human activities like fishing should preclude the use of their conclusions as comparison to fossil seeps, much of their qualitative data regarding seep structure and taphonomic variability appears to be directly comparable to the TPB fossil seep. Most importantly, the Gulf of Mexico petroleum seeps studied by Callender et al. include a chemosymbiotic, infaunal lucinid community which can tentatively be compared to the TPB community. Though these modern seeps also include accumulations of other macrofauna, particularly more epifauna, the lucinid beds were usually isolated, producing species-specific taphonomic assemblages. Furthermore, human-caused taphonomic biases are limited due to the subsurface positioning of lucinid beds.

One result from Callender, et al. (1990) that seems to follow directly with the observed patterns in this study is the observation that "taphonomic parameters differed significantly within topographically and sedimentologically equivalent areas [. . .] even in immediately adjacent samples" (p. 13). As described above, sedimentary characters of TPB samples, though variable and complex, do not show the same wholesale changes that taphofacies display on within-slab scales, thus sedimentary features do not seem to have a direct varying relationship with taphofacies. With further comparisons, this may be described as an attribute characteristic of seep environments.

Other results of import in the Gulf of Mexico study relate to the taphonomic character resulting from the low-energy environment. The authors cite Kidwell for the expectation that subsurface shell accumulations in deep, low-energy environments will be characterized by high percentages of (1) retained articulation, (2) concave-up disarticulated shells, and (3) near-vertically oriented (i.e., in life position) shells in subsurface shell accumulations. All of these features can be attributed to the low-energy environment, which maintains the "pre-buried" nature of infaunal bivalves. The findings of Callender et al. differ somewhat from these expectations, with no preference for concave-up position of disarticulated valves whatsoever. In addition, articulated shells were not necessarily common in these types of settings.

While some characteristics observed by Callender, et al. were similar to TPB samples, in comparison to the known depositional environment of the Gulf of Mexico seeps the overall taphonomic data for the TPB specimens does not meet expectations for a similarly low-energy, mostly undisturbed autochthonous shell bed. Due to infaunal life habit, lucinids in the Gulf of Mexico seep were most often preserved in life position – articulated and near vertical. Dead and disarticulated lucinids at and near the surface were most likely the result of predation. Tepee

Buttes samples simply do not show the prevalence of life-position lucinids that would be expected from an in-place infaunal fossil assemblage.

Bed Formation Scenario: Diagenesis/Overburden

One of the null hypotheses was that horizontally-trending beds and preferred orientations in TPB shell beds are simply caused by compaction from overlying strata. The TPB were indeed buried for millions of years under sediments of the latest Cretaceous and the Cenozoic. Gravitational pressure from the overlying strata would tend to create features like stylolites, perhaps on a large scale. It is conceivable that shells could be reoriented in such processes to produce oriented horizontal features. However, while stylolites were evident to some extent in thin-section (Fig. 23), most could not be traced even across an entire slide. This might suggest that dissolution surfaces caused by compaction were quite localized, and though these could still consume a large amount of original material, it is unlikely that such localized effects could produce meter-scale bedding in outcrop.

Furthermore, several slabs have been oriented by virtue of having consistent geopetal alignment. Geopetal mudfill in articulated clams has been observed in this study often to be covered by a thin rind of botryoidal calcite (Fig. 24), interpreted by most workers as an early marine cement (Anderson, 2005; Julia Anderson, Russell Shapiro, personal communication, 2006). The orientation of these geopetal features thus reflects shell orientation at an early stage of burial and diagenesis – most likely still during the life of the seep, and far before compaction by overlying strata. Thus well-aligned geopetal surfaces with early cement rinds probably have been aligned since the time of the Western Interior Seaway (at least), and their orientations have not been much affected by compressional forces.
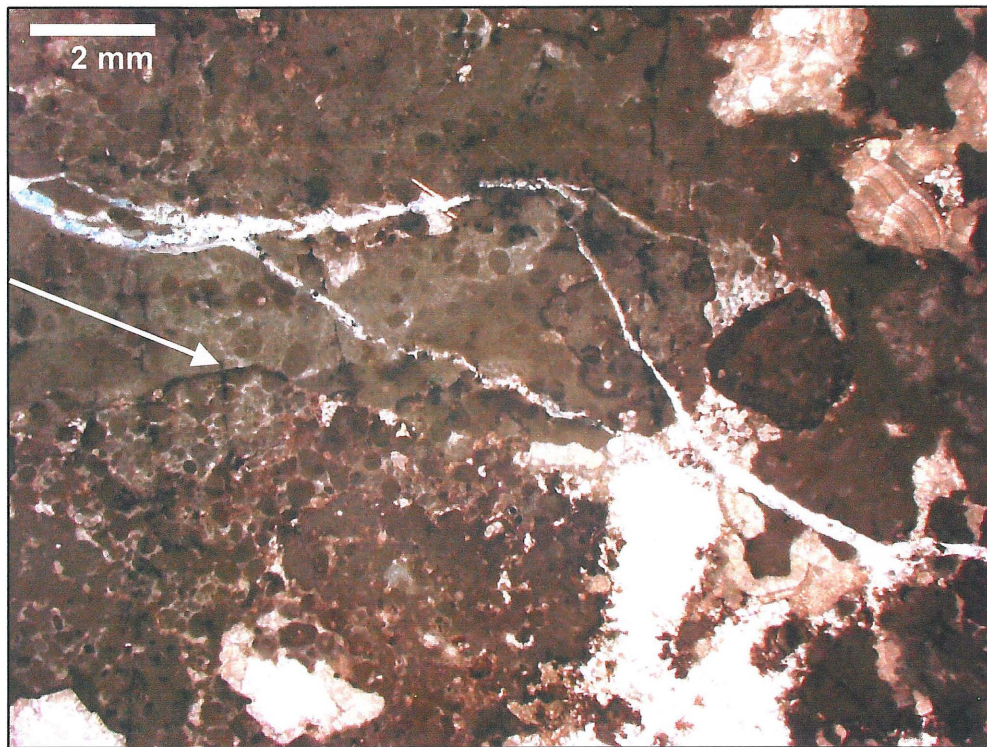
Figure 23. Photomicrograph – small-scale stylolite (white arrow) evidenced by truncated peloids and variation in peloidal fabric above and below. Note void-filling botryoidal calcite growth in upper right.
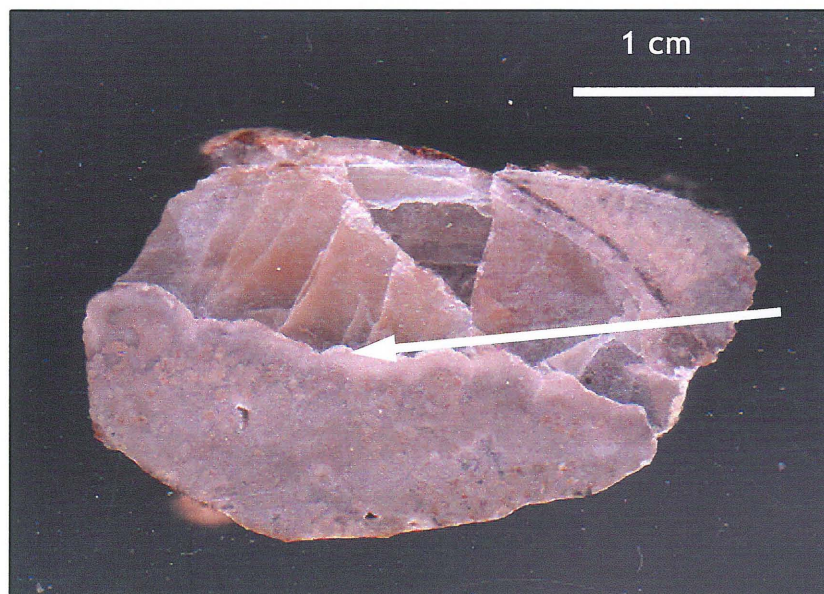

Figure 24. Articulated clam with geopetal mud infill. White arrow indicates white layer of early marine calcite cement which has grown off of the sediment surface. Remaining void space has been filled with later sparry calcite (top half).

Depositional Scenario: Disruptive Methane Release

One possible reworking agent that may have operated in the Tepee Buttes is direct disruption of sediment by the release of methane gas at the seep. At modern seeps, bubbles of hydrocarbon gas can be seen rising up from a soft sediment surface (Karla Parsons-Hubbard, personal communication, 2005). On different scales, it might be reasonable to surmise that methane gas release could proceed violently enough to locally expel pockets of sediment and fauna. In this case, we might expect to see brecciated cements and sedimentary features reflecting the subsequent settling of sediment out of the water column, such as concave-up disarticulated valves, shells aligned from settling on the sediment surface, shelter porosity beneath shells, and grading of sedimentary components.

All of these features are seen to some degree in the TPB samples. However, most expected effects of disruption by methane gas could be produced in many other depositional scenarios, so no conclusive evidence could be found to support this hypothesis. A better understanding of exactly which sedimentary and cement features indicate the location of methane release conduits might help in evaluating the likelihood of this scenario.

Depositional Scenario: Downslope Reworking

While slope-controlled deposition may not be ruled out entirely, it certainly seems that there is better evidence for some sort of pattern of lateral reworking. Perhaps the only observed characteristics that could be said to specifically support downslope deposition would be graded sedimentary features, but at least some of these (such as peloids collecting along cement surfaces) could be attributed to compressional overburden, as well as regular settling out of a water column. In addition, shells would also be expected to act as clasts in downslope deposits, and we would expect to find gradation of shell size within beds, or perhaps "piles" of shells at

the bottom of slopes. These features were not seen, but it is possible that they would be present in a larger scale cross section and with better limestone outcrops.

Depositional Scenario: Bioturbation

If TPB lucinids lived as deeply burrowed into the sediment as modern ones, it is unlikely that they could produce an assemblage like those seen in near or surface dwellers without some substantial source of reworking. One possibility for formation of shell beds that need not involve hydraulic reworking is intense bioturbation. Suchanek (1983) describes shell beds formed by *Callianassa* shrimp in shallow lagoons of the U.S. Virgin Islands. The burrowing shrimp produce a coarse/fine layer alternation that he even warns may be misinterpreted as current-reworked layers. Meldahl (1987) further describes formation of subsurface graded shell beds by burrowing deposit feeders (his "biogenic stratification"), in Cholla Bay, Gulf of California. In this modern case, polychaetes and *Callianassa* shrimp burrow into the top layers of the inner tidal flat setting, preferentially cycling lighter, fine-grained sediments in the top layers, while sequestering coarser grains like shell pieces into subsurface beds. In this scenario, low sedimentation rates need not preclude high preservation potential for even thin-shelled fauna, as they are quickly cycled down into subsurface accumulations. Furthermore, the high level of "conveyor belt" deposit feeding, as Meldahl describes it, results in prodigious fecal-peloid formation in upper sediment layers.

This mode of shell bed formation could fit with the Tepee Buttes deposits, especially since Meldahl notes that the kind of burrowers that would produce such accumulations are unlikely to be preserved, and even their burrows would be obliterated in any kind of high-energy environment. Some sedimentary features of the TPB limestone could be interpreted as burrows, and Howe (1987) specifically reports shrimp and polychaete worm burrows. Though this study

did not find conclusive evidence for worm or other burrows, the absence of these would not preclude the presence of such burrowers, since diagenetic processes could likely overprint most original features. In addition, the TPB certainly has an abundance of burrowing clams. Though it is unclear whether or not lucinids would be capable of producing the described subsurface shell beds, they no doubt played a large role in reworking the sediment, probably reorienting shells.

Still, Meldahl observes that these types of burrowers must work upon existing sedimentary features, and a shell layer previously oriented by current reworking is likely to remain in some similar orientation once cycled to the subsurface setting. Shell accumulations produced exclusively by bioturbators, on the other hand, are more likely to be randomly oriented. This fact is frequently cited, and would seem to rule out bioturbation as the exclusive mode of shell accumulations in the TPB deposits, as most slabs in this study show some preferential shell orientation. In fact, bioturbation may also be considered a mode by which orientation from hydraulic reworking has been partially obliterated.

Depositional Scenario: Current Reworking

The orientations seen in TPB shell beds are most likely the result of some combination of reworking agents. Some features like stacked disarticulated valves in shell-rich facies fit well with descriptions of storm accumulations (Aigner, 1985). However, most shell-rich facies lack the random alignment of shells usually cited in storm deposition scenarios. Given the evidence for imbrication (consistent "inclined" pattern) and other alignment of shells seen in several slabs, Howe's hypothesis of currents – though based on an asymmetrical faunal distribution not necessarily seen in this study – seems more likely. However, Howe also noted a higher

percentage of disarticulated shells "downslope", and attributed this to lee-side slope-controlled reworking.

Invoking currents, we could arrive at Howe's observed faunal and lithofacies distribution, but incorporating observations of horizontal layering. One possible scenario would be a centralized seep fauna that was frequently reworked and spread into horizontal layers away from the central area. If seep mechanisms were as variable as suggested by Callender, et al. (1990) and others who have observed active modern seeps, the locus of living lucinids would move with the variability of seeping methane, producing a complex interweaving of taphofacies, as observed in many samples.

There is a strong trend of sub-horizontal to inclined shell orientation in the TPB samples, and features such as abrupt taphofacies boundaries and cement-rich region boundaries often follow a horizontal plan as well (Fig. 25). This may be indicative of lateral bedding as the major control on facies distribution, which in turn may reflect an original near-horizontal depositional surface. The question then is what possible mechanisms might be responsible for shell bed reworking. It seems likely that hydraulic reworking would have originally extended shell beds beyond the immediate butte locality. The TPB shell concentrations as seen at present are laterally restricted to the limestone buttes – there is no evidence for massive reworking and resultant redistribution into a parautochthonous or allochthonous assemblage. Presumably, extended lenses of shell beds have been eroded away, and the buttes thus likely represent the densest, most resistant accumulation of limestone, likely centered over the methane seep itself, as assumed. If not, the question arises as to what kind of reworking mechanisms could sustain the energy to transport shells 90 degrees from life position, but without distributing them across a wider aereal expanse.

Figure 25. Roughly horizontal boundary of cement-rich facies, Slab UA2.

The Tepee Buttes and Hydrocarbon Seeps

This study of the Tepee Buttes has revealed the highly complex nature of the processes involved in the original seep setting. While more can now be said of the degree of reworking and physical processes present in the depositional setting, much more will be needed to build a good picture of how this fossilized setting relates to modern hydrocarbon seeps, and how we can use this assemblage to learn about the lifespan of seeps in general.

Though current reworking seems likely due to taphonomic evidence, one difficulty lies in imagining how a setting experiencing current reworking also produced the surrounding Pierre shale, inferred to have been deposited in a low-oxygen, low-sedimentation setting. From what has been observed in this study, the most reasonable hypothesis would be that the original setting was deep enough for only episodic current reworking, which would not produce a regular and unvarying current signature throughout the limestone. Limestone buildup may have been limited by intermittent or irregular instead of constant methane release. In this way, seeps would have maintained low relief on the seafloor instead of somehow maintaining a high topographic expression in the several hundreds of thousands of years it would likely take for Pierre sedimentation to "catch up".

If the Tepee Buttes did exhibit some sort of low relief, then it may be possible for seep communities to be thriving to the extent of the Tepee Buttes in the modern without exhibiting topographic expression on the seafloor. It is thus possible that many modern seeps are unidentified, and that those we know of may be much more prolific than can be observed without mass disruptive subsurface sampling. The subsurface seafloor is doubtlessly a place of burgeoning life, but is yet largely unexplored. Examining ancient examples gives us only an idea of what biotic interactions may exist today.

Irregularities in methane release may also have widespread effects in seep settings. As methane serves as the base of a complex food web in the seep setting, variations in its availability could shift the nature of the faunal community in terms of numbers as well as diversity and spatial extent. The possibility of mass die-offs as a result of reduced methane availability must be taken into consideration – if identified in fossil assemblages, this could be considered a possible mechanism at work in modern settings. Better recognition of methane conduits and microbial signatures in the fossil record could aid in determining how the seep biota adjusted to changes in methane availability and release. From this, we may also be able to explore exactly how seep macrofauna interact with microbial components and methane release points over the changing history of the seep setting. The mode of interaction between seep macrofauna and chemosymbionts still needs to be explored; it is therefore important when examining the fossil record to separate lithologic and fossil associations directly reflecting these kinds of interactions from those features that have been formed by the countless reworking agents present in seep settings.

Methods Assessment

Since a primary goal of this study is to identify how physical processes have formed varying geometries of shell and sediment orientation, it has been necessary to create methods of measuring and evaluating these very complex fabrics. It is thus important to assess how the study methods themselves may introduce error into the data, as well as presenting biases in interpretation.

Examination of two-dimensional slab surfaces as a primary method was important in preserving sedimentary characteristics or shell orientations that might be gravitationally

controlled. Destructive methods that aim to count fossils from whole-block samples may be necessary for studies concerned only with faunal diversity, but much useful data for paleoenvironmental interpretations is lost with this kind of method. The major difficulty in dealing with slabs is the biases that arise with the two-dimensional view. Packing of shells and other sedimentary particles is difficult to determine in this view, and any given surface can only be assumed to be roughly representative of whole-block characteristics. Some serial slabs were made of the TPB samples, and while sedimentary facies experience many small-scale changes, chosen surfaces were most often found to be very sedimentologically and taphonomically similar to the closest slices. This, of course, does not hold for samples that span significant sedimentary- or taphofacies boundaries.

The two-dimensional slab view may also be a source for error in simple shell articulation and orientation data. A cut through a single disarticulated valve can produce a circular 2-D cross section that resembles an articulated clam. When very circular shells with no apparent hinge or commisure were observed, they were thus considered disarticulated. Some cuts through articulated shells do produce recognizable hinge-commisure distinction that helps to verify the accuracy of the 2-D portrayal.

More difficult situations arise when a clam is cut across its length and no hinge/commisure distinction is apparent. One worry was that a near-life position clam could appear to be horizontal due to this kind of 2-D cut. Experimental angled cuts through a single articulated clam showed that a near-life position articulated clam will appear very inflated to circular in two dimensions. Only a cut through a clam at the far end of what is here considered near-life position (30-degrees from vertical) can result in a 2-D geometry that resembles a straight cut through a very inflated clam, and could thus be mistakenly recorded as horizontal

(Fig. 26). Length-to-height ratios were measured on some of the individual articulated clams collected, and only at their very largest do the TPB become inflated enough to resemble this deceptive geometry. This situation was rarely encountered, but the distinction is notable, as life-position statistics are central to the depositional history of the shell-rich layers.

Another difficulty arising due to two-dimensional observation is the reliability of geopetal mudfill surfaces as indicators of original horizontality. If geopetal surfaces tend to be lumpy, or if cohesion of mud inside a shell results in an inclined or meniscus-type surface, then any given cut through a mud-filled clam may indicate a false original horizontality. To test the evenness of geopetal surfaces, I have cut a few individual mud-filled articulated lucinids into serial slices to track the development of the mud surface. Results show that the surface does tend to be at least a bit lumpy, and very odd configurations of mudfill can exist, probably due to the exact mode in which the mud entered the shell (Fig. 27). However, in slabs that show multiple geopetal surfaces within a close azimuthal range, I believe it is likely that there is some trend to the filling patterns, and that we can at least roughly estimate horizontality at the time of mud infill from these orientations.

The major difficulty in assessing the TPB (and presumably other) seep limestones is the many undetermined generations of diagenetic change resulting in very small-scale sedimentary facies variations. Inspection of slabs is sufficient for assessment of certain features like geopetal surfaces and shelter porosity, but the nature of fine-scale variations in matrix composition are much more difficult to evaluate at this scale. Likewise, inspection of thin-sections can reveal the presence of certain features like stylolites, siliciclastic components, and peloid grain-contacts, but thin-sections usually do not cover broad enough areas to yield useful details about small-scale sedimentary distribution patterns. Perhaps the best way to attack sedimentary
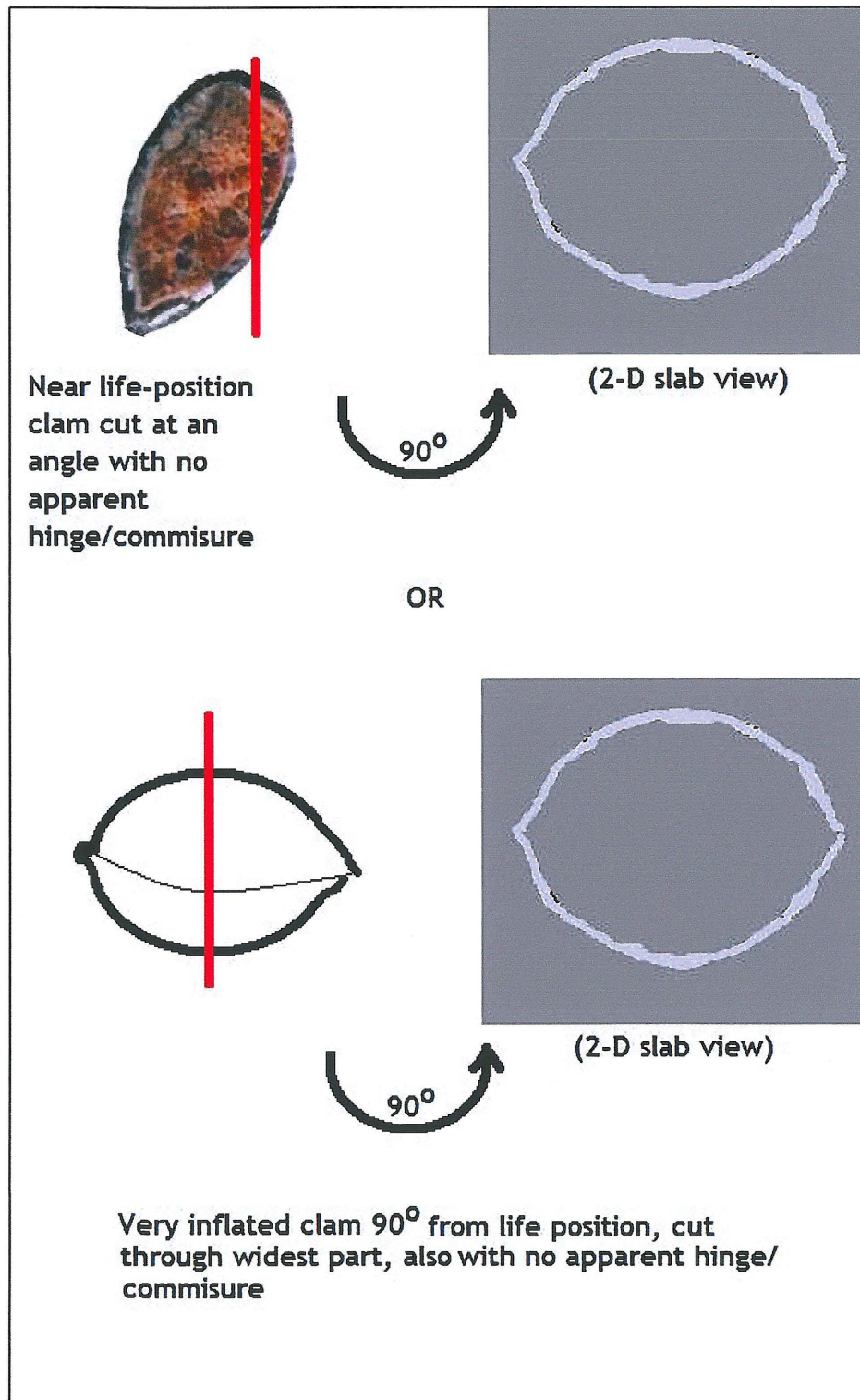
Near life-position clam cut at an angle with no apparent hinge/commisure

(2-D slab view)

OR

Very inflated clam 90° from life position, cut through widest part, also with no apparent hinge/commisure

(2-D slab view)

Figure 26. Similar two-dimensional views derived from an articulated clam oriented at 30-degrees from life position (top), and from a very inflated articulated clam oriented at 90-degrees from life position (bottom).
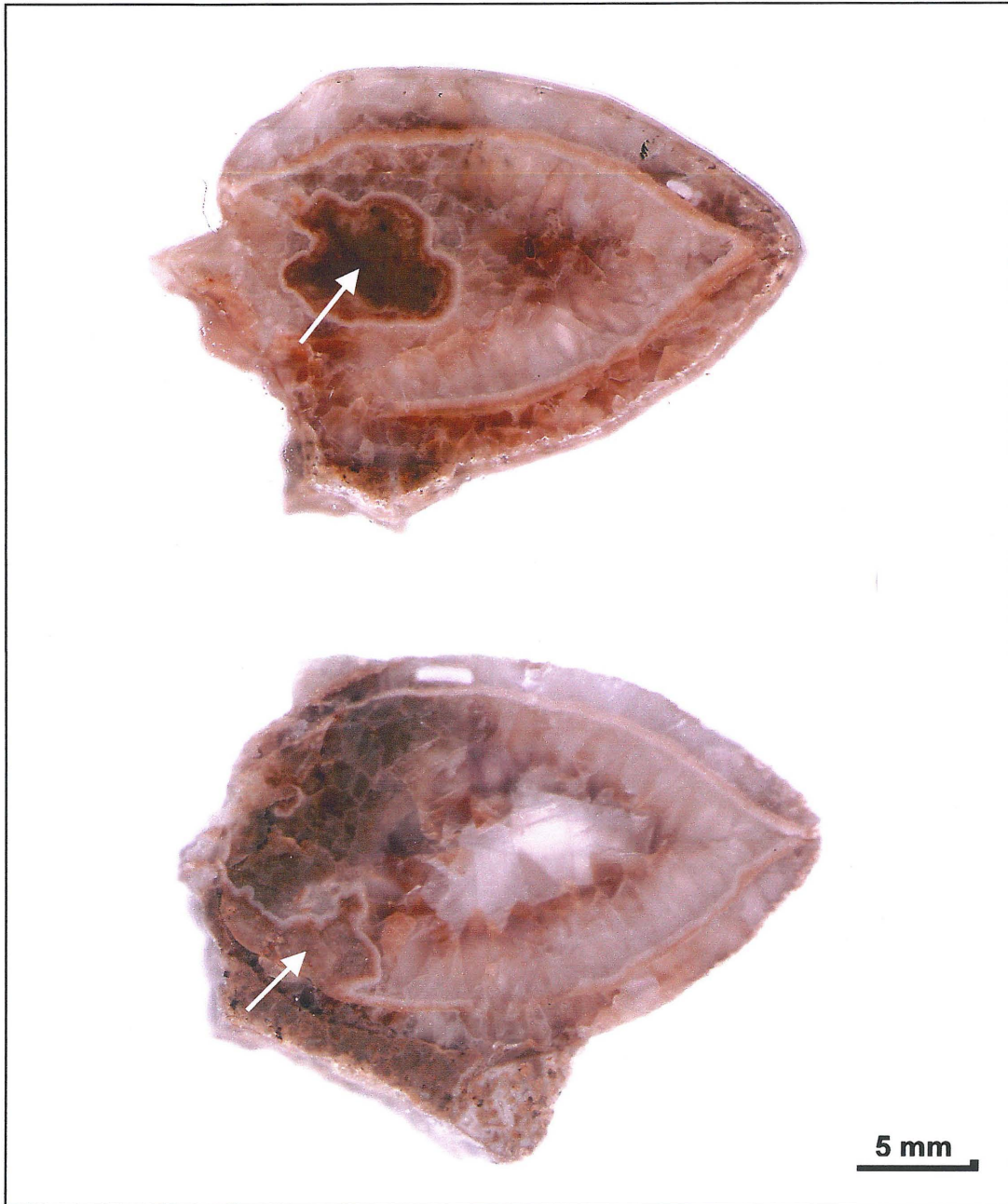
Figure 27. Irregular mud fill pattern in thinly-sliced articulated clam. White arrows indicate position of mud infill in pieces sliced approximately 3 mm apart. Notice thin white rim along sediment surface (early marine cement). Later void-filling calcite can be seen to have grown from inner shell surface.

characteristics would be to collect data at the slab level, then make thin-sections from that very slab surface. This study has avoided destructive methods where possible due to limited sample size of clam-rich facies. Thin-sections that were made revealed certain sedimentary characteristics, but could not be directly correlated to particular slab surfaces and fossil orientation data.

One further detail that could completely negate the results of any shell orientation survey is the uncertainty in the original life position of *N. occidentalis*. If, for example, ancient lucinids actually were epifaunal, shallower infaunal, or infaunal with anterior-up, any measurements of orientation would have to be reinterpreted. However, features observed in this study, such as strong symmetricality and limited ornamentation of lucinid shells, do support the initial assumption that *N. occidentalis* was an infaunal burrower, aligned umbo-up in life. Furthermore, since modern lucinids are known to be fairly deep infaunal burrowers living with umbo up, the simplest interpretation is to consider this life habit as consistent with ancient lucinids.

Finally, the formulation of the GCSD and the SCSD and derivative estimates of size and size uniformity seemed to work well as a rough estimate of these features. The resulting data became most significant in taphofacies (3) – disarticulated shell hash – as controlling features were a high shell density, small shell pieces, and high uniformity of size. These data work well only as an estimate, and could best be applied in further studies involving assemblages of mostly one species and consistent levels of fragmentation (as shell fragments and small, whole shell pieces become indistinguishable in this measure).

Conclusions

It is clear that much previous work on the Tepee Buttes has assumed such vital aspects of paleoenvironment as original topography. Most studies have cited only a high percentage of articulated lucinids as evidence of life position in certain places on the buttes. Aligned geopetal features can help us determine, however, that life-position shells are the rarest lucinid constituent in almost all of the slabs examined. In addition, the only generalizations about facies distribution that can be made from the results of this study largely contradict those generalizations made by previous studies. From our observations, a correlation of fossils across the present sloping surface cannot be considered indicative of original distribution. The present topography of the Tepee Buttes could be an entirely erosional feature, a possibility that often goes unmentioned.

Taphonomic features show a fine-scale variability that may be characteristic of seep settings, perhaps because of shifting hydrocarbon escape patterns and taphonomic feedback amongst live and redistributed shells. Shell orientation data unequivocally point to some mode of reworking, probably some combination of currents, bioturbation, and perhaps shallow-slope-controlled deposition.

Though individual geopetal surfaces can be quite irregular, a set of closely-aligned geopetal structures within a slab most likely does represent original horizontality; mud infill probably occurred soon after deposition, as early marine cements often appear as later features. When the geopetal does not match with life position (as often), this sequence of shell filling probably indicates a clam killed during or soon after a reworking event; the opposite sequence, if seen, might indicate a number of depositional scenarios. On an individual basis, any given clam could potentially have also been pushed out of life position by burrowers like themselves, worms, or shrimp, and this scenario is surely quite possible in many of the less-aligned shell

beds. However, consistent alignment of shells is not likely the result of bioturbators. As there is no conclusive evidence for slope-controlled reworking of shells and sediment, or for large scale diagenetic compression, such aligned beds probably were reworked hydraulically, with currents being more likely than storm deposits. Presence of currents implies a depth probably too shallow for methane hydrates. Frequent current reworking could also have played a role in keeping topography low, spreading out the abundant seep carbonate over a broader area and keeping the seep mound from growing very much faster than the surrounding seafloor accumulation.

There are doubtlessly many more sources for error and complication in the Tepee Buttes setting, possibly so much that a positive identification of dominant depositional controls could never be established. This study has hoped simply to highlight some of the depositional data overlooked by previous work in order to lessen possible erroneous assumptions from further work on the Tepee Buttes as well as from seep studies that hope to use this setting as a point of comparison.

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