Comparative Sedimentology and Paleontology of Waulsortian Mounds and Coeval Level-Bottom Sediments of the Lower Lake Valley Formation (Lower Mississippian) in the Sacramento Mountains (New Mexico, USA)

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With 4 Text-Figures, 2 Tables and 2 Plates

USA
New Mexico
Unteres Mississippian
Waulsortian Mounds
Sedimentologie
Riff-Lebensgemeinschaft

Contents

Vergleichende Sedimentologie und Paläontologie von Waulsortian Mounds und zeitgleichen Level-Bottom Sedimenten der Lower Lake Valley Formation (Unteres Mississippian) in den Sacramento Mountains (New Mexico, USA)

Zusammenfassung

Die Entstehung von Karbonat-Buildups und ihre Stellung in Zeit und Raum werden von der Interaktion biologischer und sedimentologischer Prozesse im Rahmen bestimmter Umweltbedingungen gesteuert. Die Rolle von Organismen in Waulsortian Mounds war infolge der Seltenheit von Skelettmaterial besonders schwierig zu erfassen. Waulsortian Mounds in den Sacramento Mountains wurden durch lokale Anhäufung von Schlamm (wahrscheinlich) mikrobiellen Ursprungs gebildet und durch frühe Zementationsprozesse verfestigt. Die Lebensgemeinschaft der Mounds fungierte überwiegend als Riffbewohner und seltener als constructors, bafflers oder Sedimenterzeuger. Sie stammt teilweise von „level-bottom"-Lebensgemeinschaften, aber unterscheidet sich deutlich davon in Zusammensetzung und relativer Häufigkeit, da bestimmte Habitate der Mounds für Einwanderung von Taxa geeignet sind und weil es Differenzen in den taphonomischen Prozessen und der daraus resultierenden Erhaltung gibt.

Abstract

The origin of carbonate buildups and their localization in time and space are determined by the interplay of biologic and sedimentologic processes within an environmental framework. The role of organisms in Waulsortian mounds has been particularly difficult to establish because of the scarcity of skeletal material in the mounds. Waulsortian mounds of the Sacramento Mountains formed by localized accumulation of mud of probable microbial origin, and became rigid structures as a result of early cementation. The mound biota functioned largely as dwellers rather than constructors, bafflers, or sediment producers. The mound biota was in part recruited from the level-bottom biota, but differs significantly from it in both composition and relative abundance because of distinctive mound habitats suitable for immigrant taxa, and because of differences in taphonomic processes and resulting preservation.

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1. Introduction

Carbonate buildups of Early Mississippian (Tournaisian to Visean) age occur worldwide as frameless, lime mud/cementstone mounds, although skeletal reefs of this age are also known (FANG & HOU, 1985; ADAMS, 1983; WEBB, 1993, pers. comm.). The frameless buildups in the Sacramento Mountains are referred to as Waulsortian because they are of similar age, consist of lime mud rich in spar-filled cavities, fenestellid sheets and crinoids, and contain many of the less abundant but diagnostic organisms that form the distinctive assemblages reflecting phases of deposition in progressively shallower water in the typical mounds of the Waulsort region of Belgium (LEES, 1988). Mounds of the Sacramento Mountains differ from these however in not containing the full array of assemblages present in the typical mounds, but only those of the deeper water phases (LEES & MILLER, 1985).

The origin of Waulsortian mounds is not yet fully understood. In particular the source of the lime mud and its localization, the origin of the abundant spar-filled cavities, and the role of the biota in mound formation continue to be primary topics of discussion. The present consensus, though with little clear evidence, is that the mounds are the result of microbially mediated sediment production, binding, and early cementation.

The role of the macrobiota, particularly the relatively abundant crinoids and fenestrate bryozoans, was, in earlier hypotheses as bafflers trapping mud produced on the mound surface by algae and other unpreserved organisms. In the presently-favored microbial model, macrobiota were not essential to mound formation as skeletal frame builders or sediment bafflers, although one could maintain that the combination of large fenestrate bryozoan sheets and the abundant early submarine radiaxial fibrous calcite cement formed a virtual framework. In any case, the macrobiota have been largely ignored in the ongoing discussion in spite of the fact that they may have played a positive part in mound formation, and may provide valuable information about conditions conducive to mound growth and about the mound habitat. One important source of information is the relationship between the mound biota and that of the coeval inter-mound level-bottom beds.

Questions investigated in this paper are:

① Did the biota function as constructors, bafflers or simply dwellers?
② What was the relation between mound and level-bottom biotas? Were the two biotas similar or different; if similar, did the mounds form simply because of greater localized productivity by the level-bottom community; if different, did the mounds form from initial patches of a distinctive mound community?
③ Do the differences reflect
   a) distinctive habitats that developed as the mounds grew, providing unique settings for taxa not present on the level-bottom, or
   b) distinctive preservational, taphonomic characteristics of the level-bottom and mound environments?

These questions are important because

1) biotic control on the development of Waulsortian mounds is poorly understood, though it has been considered to be low except for microbial activity (LEES, 1988) and passive baffling by macrofauna (PRAY, 1958; LEES, 1964; WILSON, 1975), and
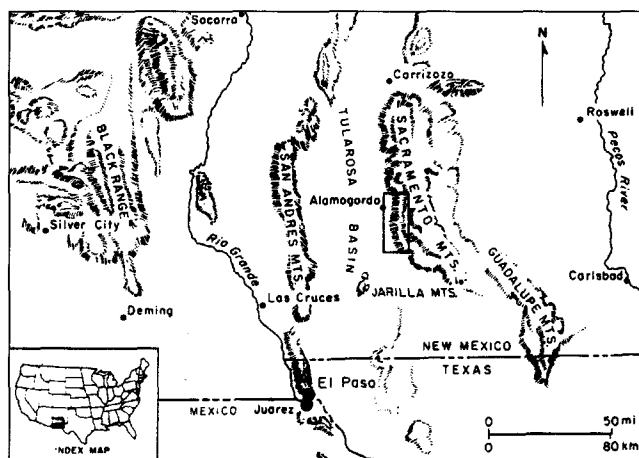
Text-Fig. 1.
Location map of the study area.
From AHR (1989).

2) comparative studies in general of mound or reef and contemporaneous level-bottom biotas are rare.

Waulsortian mounds form a distinct subclass of buildups characterized by a low density of skeletal components and an absence of skeletal framework. For this reason, in fact, they have been excluded from the discussion of reefs by some authors (e.g. FAGERSTROM, 1987). The spatial, temporal, and environmental distribution of Waulsortian mounds, however, is important to understand because it helps to more sharply define the limits of conventional, skeletal reefs. The role of the biota, as determinants or as passive inhabitants, is an important component of this understanding.

Data for this study are from the level-bottom beds of the Alamogordo Member of the Lake Valley Formation and from 8 coeval Waulsortian mounds. These are exposed within a continuous outcrop belt 29 km long on the west front of the Sacramento Mountains near the town of Alamogordo, New Mexico (Text-Figs. 1, 2, 3). Data on the microfacies and the relative abundances of constituent components are derived from 83 large (6 cm X 10 cm) thin sections from the level-bottom beds of the Alamogordo Member of the Lake Valley Formation and from 257 thin sections from mounds of Alamogordo, Nunn, and Tierra Blanca age in the study area.

Most of the Waulsortian mounds in the Sacramento Mountains began to form during deposition of the Alamogordo Member, although antecedent lithologic and probable topographic controls on mound localization are evident in the underlying Andrecito Member (AHR, 1989). Continued mound growth during deposition of the Nunn and Tierra Blanca Members was common from Alamo Canyon southward and is reflected in distinct growth increments that correlate to the three members.

2. Previous Work

2.1. General Geology

A voluminous literature exists on Mississippian rocks of the Sacramento Mountains. The present state of knowledge on stratigraphy, structure, and paleontology can be summarized in terms of several contributions. Mississippian mounds of the Lake Valley Formation were first mentioned by LAUDON & BOWSHER (1941, 1949), and the parallel between the Sacramento Mountain and European Waul-

Waulsortian mounds was pointed out by PRAY (1958). Lithostratigraphic relationships used today were established by PRAY (1961; Fig. 3). The lower Carboniferous regional geology was summarized by ARMSTRONG (1962) and KOTTLOWSKI (1963, 1965), and described in more detail by ARMSTRONG & MAMET (1988). The Alamogordo Member in the Sacramento Mountains was deposited on a broad ramp sloping southward into the Pedregosa Basin; the mounds apparently grew in a deep outer-ramp setting on paleobathymetric highs of both tectonic and depositional origin (AHR, 1989). Terrigenous sediment was derived from a land area to the north and northeast, but very little was deposited in the study area during deposition of the Alamogordo Member. Because of post-Mississippian truncation to the north, the location of the strand line is unknown, but was at least 10's of kilometers away.

Following mound growth, and perhaps controlled in part by the location of the mounds, the ramp in the northern part of the study area evolved through localized sediment accumulation into a crinoid-rich shelf. This shelf graded abruptly southward into a starved basin that was filled subsequently by younger Mississippian, largely clastic, strata. The resulting wedge-on-wedge architecture of the Mississippian strata was described by LANE (1974). The cement stra-
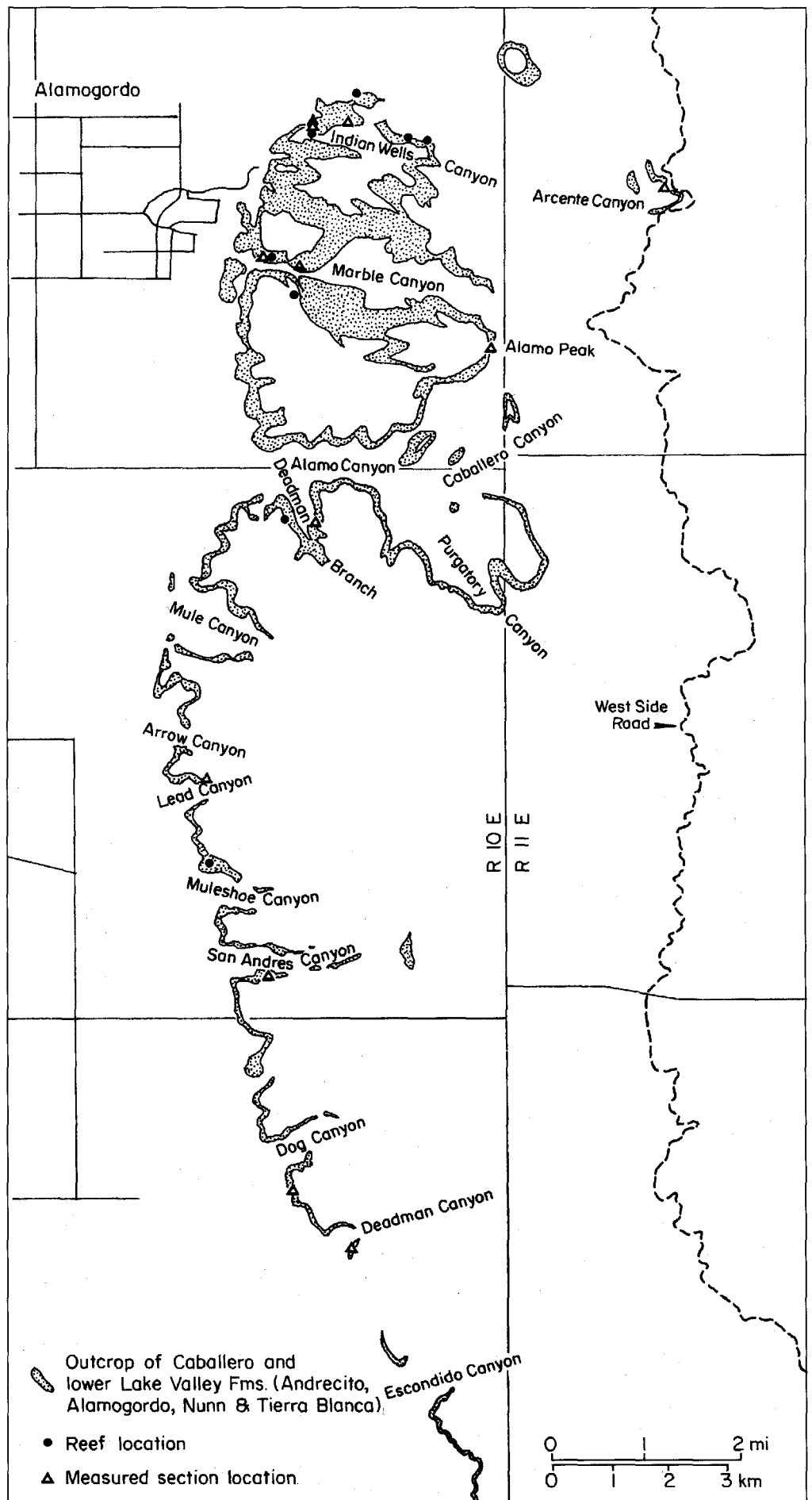
Text-Fig. 2.
Map of the Mississippian outcrop in the study area (adapted from PRAY, 1961) showing the locations of measured sections and Waulsortian reefs.

Outcrop of Caballero and lower Lake Valley Fms. (Andrecito, Alamogordo, Nunn & Tierra Blanca)

● Reef location

△ Measured section location

tigraphy and diagenetic history of the Lake Valley limestones was described by MEYERS (1974).
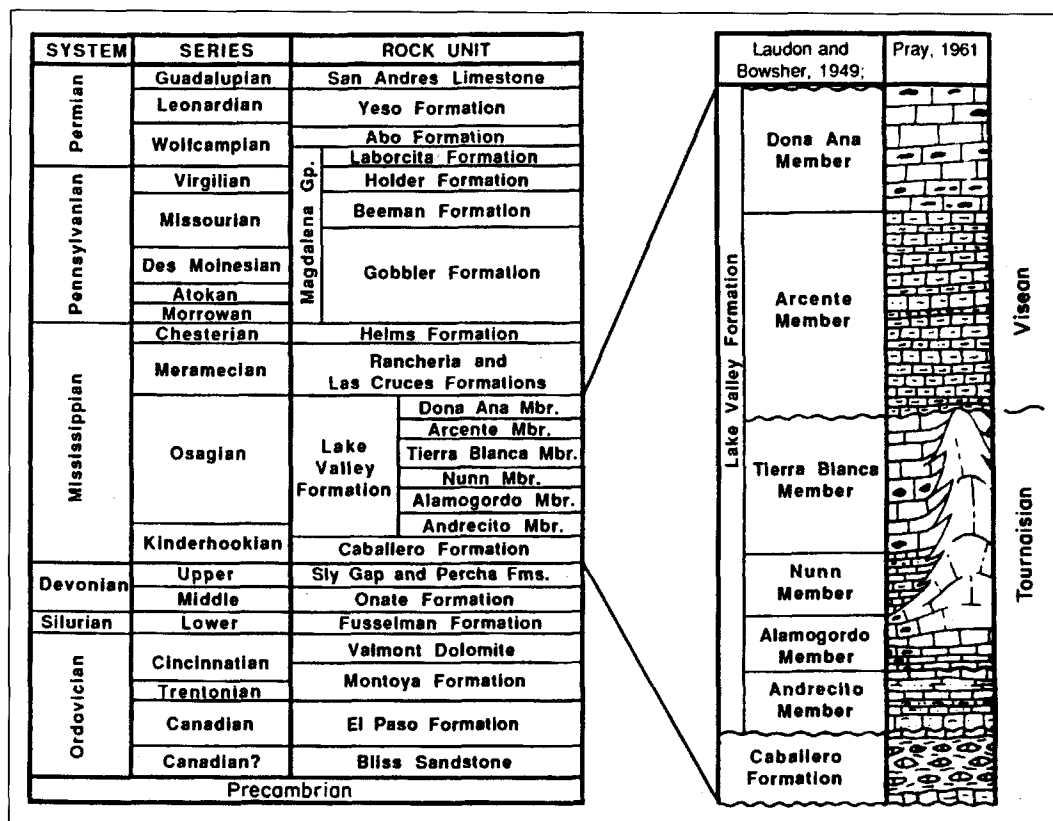
2.2. Mounds

The Waulsortian mounds in the Sacramento Mountains were described by PRAY (1958) as bioherms with a core facies of aphanitic and sparry calcite within a meshwork of intact and partially comminuted fenestrate bryozoans, grading

SYSTEM	SERIES	ROCK UNIT		Laudon and Bowsher, 1949;	Pray, 1961
Permian	Guadalupian	San Andres Limestone		Dona Ana Member	
Permian	Leonardian	Yeso Formation			
Permian	Wolfcampian	Abo Formation			
		Laborcita Formation			
Pennsylvanian	Virgilian	Holder Formation	Magdalena Gp.	Arcente Member	
Pennsylvanian	Missourian	Beeman Formation			
Pennsylvanian	Des Moinesian	Gobbler Formation		Tierra Blanca Member	
Pennsylvanian	Atokan / Morrowan				
Mississippian	Chesterian	Helms Formation			
Mississippian	Meramecian	Rancheria and Las Cruces Formations		Nunn Member	
Mississippian	Osagian	Lake Valley Formation — Dona Ana Mbr. / Arcente Mbr. / Tierra Blanca Mbr. / Nunn Mbr. / Alamogordo Mbr. / Andrecito Mbr.		Alamogordo Member	
Mississippian	Kinderhookian	Caballero Formation		Andrecito Member	
Devonian	Upper	Sly Gap and Percha Fms.			
Devonian	Middle	Onate Formation		Caballero Formation	
Silurian	Lower	Fusselman Formation			
Ordovician	Cincinnatian	Valmont Dolomite			
Ordovician	Trentonian	Montoya Formation			
Ordovician	Canadian	El Paso Formation			
Ordovician	Canadian?	Bliss Sandstone			
Precambrian					

(Right column labels: Visean, Tournaisian — Lake Valley Formation)

laterally and abruptly into a flank facies of coarse crinoidal debris. PRAY interpreted the lime mud ("aphanitic calcite") in the core facies to have been primary and autochthonous, probably derived from disintegrated algal sheaths or mats, but he also discussed the possible origin as transported mud concentrated by the baffling and trapping action of fenestrate bryozoans and crinoids, an hypothesis mentioned by LEES (1964) and given some prominence by WILSON (1975), but which is not now in favor.

PRAY also noted, from the geometric relationship between the core and flank facies at Muleshoe Mound, that water depth there may have been 100 m or more during at least the late stage of mound growth. This conclusion was reinforced by LEES & MILLER (1985) on the basis of their study of numerous Waulsortian mounds in northwestern Europe, and Muleshoe and Little Sugarloaf Mounds in the Sacramento Mountains.

Sparry calcite cements and lime mud of the mound core facies were studied in detail by SCHAEFER (1976) and COWAN (1980). They recognized several generations and types of cements, and suggested that many of the stromatactis-like cavities formed by erosion of uncemented sediment under and around patches of cemented mound substrate. They proposed that the mounds were stabilized during growth by patchy submarine cementation. Radiaxial-fibrous calcite cement and large fenestrate sheets are commonly associated with and fill these cavities.

The abundance of cement in the middle and late-stage, Nunn and Tierra Blanca, phases of mound growth is indicated by the estimate of SHINN et al. (1983) that nearly 90 % of a core through the upper 21 m of Muleshoe Mound consists of cement. From samples in the lower part of the Nunn and Tierra Blanca phases of Muleshoe Mound, up to about 6 m below the base of core taken by SHINN et al., JACKSON & DE KEYSER (1984) proposed a model of cyclical, shallowing-upward mound growth localized on growth centers ("point-sources") that shifted in position on the developing mound surface.

3. Procedure

The Alamogordo Member comprises the inter-mound or level-bottom beds coeval with the initiation and early growth of most of the mounds (Text-Fig. 3). In addition, it is the only one of the post-Andrecito members that exhibits little or no bedding discordance, erosional features, extensive or widespread evidence of resedimentation or variability in degree of paleoslope, or abrupt changes along dip in thickness, lithology, and biota. It is as close as one can get to a chronostratigraphic marker and is, therefore, a premier sequence with which to compare mounds and level-bottom beds. The Alamogordo member was measured, described, and sampled at 9 locations from north to south: Indian Wells, Arcente and Marble Canyons, Alamo Peak, Deadman Branch of Alamo Canyon, and Lead, San Andres, Dog, and Deadman Canyons (Text-Fig. 2).

Samples from the mounds are separated into two groups for analysis. The first group, consisting of samples from the Alamogordo phase of mound growth and thus correlative with the level-bottom samples, provides an opportunity to compare the mound community at the inception of mound growth with the adjacent level-bottom community. These samples, from the Alamogordo phase of Muleshoe Mound and the mound in Deadman Branch of Alamo Canyon, and from 6 mounds in Indian Wells and Marble Canyons, were collected at approximately 5-foot intervals from the base to the top of each mound. The second group of samples is from a nearly complete vertical transect through the middle and upper parts (Nunn and Tierra Blanca phases) of the core facies of Muleshoe Mound.

All thin sections were analyzed using the technique of LEES et al. (1985), in which the relative volumetric abundance of each constituent is estimated semiquantitatively within each thin section. In addition to allochems, depositional texture, presence or absence of cavities, peloids, geopetal fabrics, degree of component fragmentation, and grain orientation (fabric) are also recorded.

Data were analyzed with the Jaccard similarity coefficient program of HENNEBERT & LEES (1985), the correspondence analysis program of HENNEBERT & LEES (1991), and a commercial database program. No systematic trends in these biotic and lithic characteristics were detected with Jaccard or correspondence analysis programs, and systematic queries on the data base for each constituent did not produce significant correspondence between ranked abundance of individual constituents and sample location within or between measured sections. Consequently, our analysis is based on presence/absence data.

4. Data
4.1. Level-Bottom Lithology

The Alamogordo Member consists of resistant ledges up to 1 m thick of skeletal lime mudstone and wackestone separated by thin argillaceous beds 2–5 cm thick. It thins persistently to the south from a maximum thickness in the northern part of the study area of about 11 m and is absent in the southernmost Sacramento Mountains. The contacts with the underlying, shaly, silty Andrecito Member and the overlying, argillaceous lime packstone and grainy wackestone of the Nunn Member are mainly gradational.

Depositional fabric is characterized by the absence of geopetal structures and by mainly sand and silt-sized skeletal allochems aligned parallel to bedding (Pl. 1/1). Pore-filling cement is rare. Bioturbation that disrupted the original depositional alignment of skeletal allochems is present in nearly all thin sections, although it is not obvious in most hand specimens. Virtually all allochems except small ostracodes, spicules, and durable skeletons such as small corals are finely comminuted; evidence of grain solution is absent and bioerosion is rare, consisting only of 40μ borings in some skeletal allochems (Pl. 2/5). Multicomponent skeletons such as crinoids are largely disarticulated. Both because sedimentary structures such as ripples, flute casts, or crossbeds, indicative of hydraulic action and sediment transport, are absent, and because bioclasts are widely dispersed in the lime mud matrix, predation and scavenging are interpreted as the dominant mechanisms of skeletal breakage and disarticulation, and the preserved record is interpreted to be an in-place accumulation.

4.2. Level-Bottom Biota

Twenty-six constituents were logged for presence/absence within each thin section. Percentages of thin sections in which each constituent occurs, and the resulting rank order are listed in Table 1, Col. 1. The typical mudstone to wackestone texture of the level-bottom strata reflects the initial low productivity on the level bottom, the resulting sparse distribution of fossils in general, and the rarity of most individual taxa. The dominant and most commonly occurring constituents are crinoids, ostracodes, fenestrate bryozoans as small fragments, and sponge spicules. The low distribution density of most fossils is emphasized by the fact that 13 of the 23 taxa logged

in this study occur in less than 25 % of the samples. Of the more common and larger taxa, only ostracode valves and small corals generally occur as whole specimens.

4.3. Mound Lithology

As noted above, core and flank facies have been described in the Waulsortian mounds of the Sacramento Mountains. This is in contrast to the Waulsortian mounds of western Europe, in which thick encrinite flank facies are uncommon to absent. Mound samples analyzed in this study are only from the core facies. Also as noted above, mound initiation was predominantly during deposition of the Alamogordo Member, as was mound growth north of Alamo Canyon. In the area between Alamo Canyon and Dog Canyon, however, mound growth continued during deposition of the Nunn and Tierra Blanca Members. Differences in growth style during these time intervals resulted in distinct mound morphologies: Alamogordo mounds are relatively broad; overlying Nunn mound growth was more limited in lateral extent and resulted in a steep-sided, more conical form in cross-section; and Tierra Blanca growth was both aggradational and progradational outward from the nucleus of the Nunn mound. The tabular composite Alamogordo mounds are generally less than 10 m thick, and consist of small masses that may be only 2 to 3 m in diameter and thickness. In contrast, the combined Nunn/Tierra Blanca component of Muleshoe Mound is roughly hemispherical in plan, and nearly 100 m thick.

Our analysis is primarily of Alamogordo-age level-bottom and mound biotas; the samples from Muleshoe Mound of Nunn and Tierra Blanca age provide a glimpse of subsequent changes that occurred during later mound growth.

The Alamogordo mounds, in contrast to the level-bottom beds, consist of peloidal, clotted, and poorly bedded lime mud; poorly sorted, poorly aligned skeletal allochems, including lenticular concentrations of crinoidal debris. Radiaxial-fibrous and other forms of calcite cement occur as early cavity-lining and intergranular cement, and as later diagenetic pore-filling. Cavities in mound rocks are of diverse origin and contain geopetal fabrics consisting of peloids, multiple generations of internal micrite, and skeletal debris. Most of the peloids are uniform in size and appearance and are particularly common as geopetal fillings in shelter voids (Pl. 1/4) and large constructed cavities. The peloids are similar to the microbial peloids described by CHAFETZ (1986). PICKARD (1993) illustrated nearly identical peloids from Visean mounds in Scotland and argued for a microbial origin. Most of the skeletal allochems in the mounds, like those in level-bottom samples, are fragmented with the notable exception of large intact fenestrate sheets, corals, ostracodes, and spicules. Allochems are less well sorted, and the bryozoan and crinoid fragments in particular are much coarser on average (up to cms in size) than those observed in the level-bottom samples.

Mounds of Nunn and Tierra Blanca age also contain peloidal mudstone and wackestone, but they differ from Alamogordo mounds in that:

1) primary cavities, present mainly as small shelter voids, increase in size and abundance (Pl. 1/3,5);
2) submarine cements and fenestrate sheets are much more abundant (Pl. 1/6);
3) micrite and spicules are less abundant;

NAME of CONSTITUENT	1 Level bottom		2 Mounds of Alamogordo Age		3 Muleshoe Mound Nunn & Tierra Blanca Phases	
	%	Rank	%	Rank	%	Rank
Crinoid plates & spines	99	1	100	1	100	1
All ostracodes	98	2	96	3	97	3
Fenestrate hash	89	3	100	1	100	1
Sponge spicules	87	4	72	6	3	23
Echinoid spines	82	5	85	4	58	8
Mollusk & brachiopod shells	64	6	46	11	57	9
Trilobite fragments	53	7	27	15	23	16
Hyalosteliid spicules	46	8	47	9	14	17
Mametella	31	9	75	5	49	10
Earlandia	25	10	60	8	78	5
Fenestrate sheets	17	11	62	7	86	4
Ramose bryozoans	16	12	43	12	65	7
Calcispheres	13	13	42	13	24	15
Sphaerinvia	12	14	5	23	5	21
Moravamminids	11	15	35	14	5	21
Gastropods	7	16	10	21	9	18
Corals	6	17	12	20	7	20
Encrusting bryozoans	5	18	18	16	32	13
Geopetal peloids	4	19	9	22	37	12
Plurilocular forams	2	20	16	18	9	18
Micritized grains	2	20	1	26	1	25
Peloids	0	22	47	9	78	5
Filaments, undifferentiated	0	22	5	23	29	14
Cryptalgal coatings	0	22	4	25	0	26
Globochaetes	0	22	15	19	2	24
Girvanella	0	22	17	17	40	11
Thin sections	83		103		154	

4) skeletal allochems grade from poorly oriented to increasingly randomly oriented, and lenses of crinoidal debris are much less abundant.

This discrimination of the different phases of mound growth is important for two reasons:

1) In their comparison of European and North American Waulsortian mounds, LEES & MILLER (1985) relied on Muleshoe Mound and the probably similar Little Sugarloaf Mound for data from North America – thus their results are not representative of the Sacramento mounds in general;

2) The biotic composition in different mound phases is correlated with differences in lithology – the two aspects must be integrated in the analysis.

4.4. Mound Biota

Biotic constituents in mounds of Alamogordo age and in the Nunn and Tierra Blanca parts of Muleshoe mound are listed in Table 1. Cols. 2 and 3. The value for each constituent in each column is the percent of thin sections in which it occurs. Differences in the biota parallel the much greater abundance of cementstone in Nunn and Tierra Blanca mounds as compared to Alamogordo mounds. However considerable differences among the Alamogordo mounds in time of initiation, in duration of growth, and in lithologic and biotic characteristics indicate that more detailed and comprehensive work will add important details about their growth history.

The mound biota is dominated in general by crinoidal skeletal components, fenestrate hash, and ostracodes. The most marked biotic differences between the two sets of mound samples are:

1) the much greater abundance in the Alamogordo mounds of hyalosteliid spicules (Pl. 1/2), calcispheres, Mametella (Pl. 2/9), moravamminids, plurilocular foraminifers (Pl. 2/3), globochaetes (Pl. 2/7) and the greater density within thin sections of fenestrate hash; and

2) the greater relative abundance in the cement-rich microfacies of the Nunn and Tierra Blanca mounds of

large fenestrate bryozoan sheets (Pl. 1/6), ramose bryozoans, encrusting bryozoans (Pl. 2/8), *Girvanella*, and filaments. The greater relative abundance of these groups reflects their constructional sheltering and encrusting roles in cavity, and probable hardground, formation.

5. Discussion

The overall abundance of organisms was low in both level-bottom and mound settings, as indicated by the mudstone to wackestone lithology. However, it was approximately 50 % greater on the mounds than in the intermound level-bottom, as demonstrated by the density of fossils in the thin sections.

Diversity (richness) was greater on the mounds (23 taxa) than on the level bottom (19 taxa). In general terms, the greater richness is explained by the wider range of habitats on the mounds – in topography and slope, in soft and hardground substrates, and by the presence of fissures and cavities. The greater richness may also be explained in part by the greater abundance of fossils in the mound thin sections, because the number of species tends to increase as the sample size (in this case, number of specimens observed) increases.

The relative frequency of occurrence of taxa within the three sets of samples is indicated in Text-Figure 4. In all settings, a relatively small number of taxa are widely distributed in the thin sections, many taxa are rare, and fewer taxa are moderately common, although this is less the case for mound than for level-bottom taxa. The most notable biotic difference between mound and level-bottom settings is that 57 % of the taxa occur in 20 % or less of level-bottom thin sections as compared to 39 % of the taxa occurring in 20 % or less of either set of mound thin sections. On the other hand, a slightly greater proportion of level-bottom than mound taxa are cosmopolitan (22 % vs. 17 % occurring in more than 80 % of thin sections). To explain these differences in frequency of occurrence, sedimentation rate, environmental heterogeneity, and skeletal productivity must all be considered. Fossils are volumetrically more abundant in the mounds than in the level-bottom beds even though the sediment accumulation rate was an order of magnitude greater on the mounds. Thus, even though the fossils are a minor component of the mounds in volumetric terms, production was much greater there than on the level bottom.

The simplest explanation for the greater percentage of level-bottom species that are present in only a small percentage of thin sections is that fewer taxa should be found in each level-bottom thin section than in each mound thin section because of the 33 % fewer total fossils per level-bottom thin section. This sample-size effect is greatest for rare constituents, and reflects the lower density of life on the level-bottom sea floor.

The slightly greater proportion of cosmopolitan species on the level bottom is explained by:

1) the environmental uniformity of the level bottom, suggesting that through time, as sediment accumulated, any of the organisms present might have been living throughout the area even though density would have been lower;

2) the relatively slow sedimentation rate; and

3) the effect of bioturbation that mixed the slowly accumulating sediments to produce a strongly homogenized, time-averaged record.

Both habitat preferences and preservational or taphonomic processes must be considered in analyzing the differences in biota between the level-bottom and contemporaneous Alamogordo mounds and between the mound subsets, as summarized in Tables 1 and 2. The effect of taphonomy is exemplified by the relative abundances of fenestrate bryozoan sheets and hash in mound and level-bottom samples. Fenestrate hash is ubiquitous and, in the absence of evidence of transportation, indicates that fenestrate bryozoans lived in both mound and level-bottom settings. The greater abundance of fenestrate sheets in the mounds, however, suggests that preservation there was better. Probable reasons for this are:

1) more rapid burial because the sedimentation rate was an order of magnitude greater than on the level-bottom,

2) substrate cementation, which held the sheets in fixed positions,

3) less predation and scavenging by crustaceans, as suggested by the lower frequency of occurrence of trilobites on the mounds, and

4) less bioturbation.

In general, however, taphonomic processes appear to have been similar in the mound and level-bottom settings: grain solution, sediment transport, and mechanical abrasion are absent in both settings, and individuals of specific microfossils are equally well preserved in the different
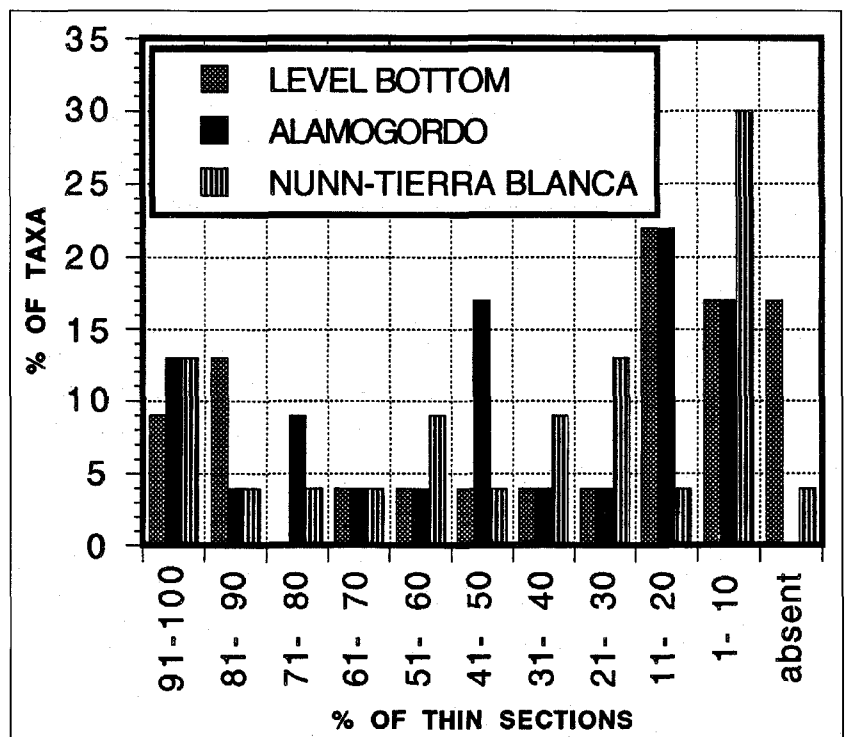
Text-Fig. 4.
Frequency distributions of biotic constituents within thin sections from the level-bottom and mound units.

Table 2.
Relative abundances of constituents in:
(Col. 1) Alamogordo age level-bottom beds and mounds;
(Col. 2) mounds of Alamogordo age and mound phases of Nunn and Tierra Blanca age in Muleshoe Mound.

	1	2
	Level bottom vs. Alamogordo	Alamogordo Mounds vs. Nunn / Tierra Blanca
	Mounds	Phases
Crinoid plates & spines	=	=
All ostracodes	=	=
Fenestrate hash	=	>>
Sponge spicules	>	>
Echinoid spines	=	>
Mollusk & brachiopod shells	>	<
Trilobite fragments	>	=
Hyalosteliid spicules	=	>>
Mametella	<<	>
Earlandia	<<	<
Fenestrate sheets	<<	<
Ramose bryozoans	<<	<
Calcispheres	<<	>
Sphaerinvia	>>	=
Moravamminids	<<	>>
Gastropods	<	=
Corals	<	>
Encrusting bryozoans	<<	<
Geopetal peloids	<<	<<
Plurilocular forams	<<	>
Micritized grain	*	*
Peloids	<<	<
Filament, undifferentiated	<<	<<
Cryptalgal coating	<<	>>
Globochaete	<<	>>
Girvanella	<<	<<
Thin sections		

>>, <<: values in Table 1 differ by more than 100%
>, <: values in Table 1 differ by more than 20%, but less than 100%
= values in Table 1 differ by less than 20%
* values too small to be significant

settings. Consequently, differences in assemblages are interpreted in large part in terms of habitat differences.

In examining Tables 1 and 2, crinoid plates and spines, ostracodes, and fenestrate hash are the dominant and ubiquitous taxa in all rock types and depositional settings. Thus, they are not as diagnostic of habitat-correlated environmental and preservational differences as are the less common taxa.

Sponge spicules, mollusk and brachiopod shells, trilobite fragments and Sphaerinvia (Pl. 2/2) are significantly more common in level-bottom beds than in the Alamogordo mounds. These taxa found the level-bottom environment more desirable than the initial mound surfaces and are diagnostic of that setting. In contrast, Mametella, Earlandia (Pl. 2/1), fenestrate sheets, ramose bryozoans, calcispheres, moravamminids, encrusting bryozoans, plurilocular foraminifers, filaments, globochaetes, and Girvanella are much more abundant in the Alamogordo mounds. In addition, crinoids, ostracodes, and fenestrate hash, although present in essentially all thin sections from both the level-bottom and Alamogordo mounds, are more abundant in the mounds.

Differences in Col. 2, Table 2 highlight the effect of habitat/guild differences that developed as mound growth continued into Nunn and Tierra Blanca time. Particularly diagnostic of the increasing volumetric abundance of cement-filled cavities and fissures are the encrusting sheet and ramose bryozoans, filaments and Girvanella, that would have been important in hardground and cavity formation. Geopetal peloids are largely restricted to this microfacies, having accumulated in cavities. Concentrations of hyalosteliid spicules (Pl. 1/2) and the ostracode Kirkbya (Pl. 2/4) are largely restricted to cavities, suggesting that cavities were their preferred life site.

Most of the biotic differences in these three settings are in relative abundances rather than presence or absence, and thus provide minimal estimates of biotic and environmental differences. Because the taxonomic categories we have been able to use are broad (mostly at levels higher than the genus), more subtle differences will no doubt be recognized with finer levels of taxonomic resolution.

Water depth on the Alamogordo ramp and on the tops of the growing Waulsortian mounds has been a major and continuing topic of discussion. The paucity of algal fossils, cryptalgal coatings and micritized grains in all samples suggests that the level bottom and mound tops were uniformly below the photic zone. Our data provide little insight into this question except that cryptalgal coatings occur only in the Alamogordo mounds, and that calcispheres, perhaps of algal affinity, and Mametella, a putative red alga, are significantly more abundant in the Alamogordo mounds than in the other settings. These observations suggest that water was shallower on the Alamogordo

mounds than on the adjacent sea floor or than during subsequent Nunn and Tierra Blanca mound growth. In parallel with this, transported crinoidal accumulations are also more common in Alamogordo mounds than in the other two settings, suggesting more turbulence (higher water energy) at that time.

6. Conclusions

Dominance of crinoids and bryozoans in both the level-bottom beds and the mounds suggests at first glance that the mounds resulted from localized intensified growth of these two groups of organisms that were already present in the area. Evidence contrary to that supposition, however, is:

1) these organisms did not create a skeletal structural framework;

2) the absence of diagnostic sedimentary structures, such as bedded mud and skeletal debris among crinoid stem segments and erect fenestrate bryozoans, indicates that these organisms did not function as bafflers; and

3) perhaps most importantly, although these organisms occur in greater density on the mounds than on the level-bottom, they nevertheless make up a small part of the mass of the mounds.

The organism community on the inter-mound sea floor was apparently of low density at any time but spatially homogeneous when time-averaged. It and the contemporaneous community of the Alamogordo mounds are similar in composition, but strikingly different in relative proportions. A few taxa preferred the level bottom; most, the mounds; only a few that were present on mounds but absent on the level-bottom were presumably immigrants to the mound setting. A hard-ground/cavity community, which became particularly common during the later stages of mound growth, contains taxa that were absent on the soft substrate of the level bottom, and represents a unique guild that developed within the mound habitat.

There is little evidence of direct involvement of the Waulsortian skeletal biota in mound construction except for some encrusters, abundant intact fenestellid sheets, and some hyalosteliid spicule concentrations. The fenestellid sheets, multi-cm-scale in size, and in growth position, formed shelter or constructional voids subsequently lined with radiaxial-fibrous calcite and partly filled with internal sediment.

Differences in the biota of the Alamogordo-age mounds and level-bottom beds indicate that the environment in the two settings was very different. The site at which a mound would develop has been correlated with differences in thickness and lithology of the underlying Andrecito Formation, interpreted as representing coarser grained substrate on topographic highs on the initial Alamogordo sea floor (AHR, 1989). We infer that the Alamogordo mounds formed mainly as the result of localized microbial mud/peloid production and submarine cementation. Differences in biota, sedimentary structures, depositional fabrics, volume and types of cements, and micrite/peloid characteristics between the mounds and level-bottom beds in the Alamogordo Member indicate that the mound biota was apparently recruited only in part from the level-bottom assemblage, and that the mounds were not formed by local intensification of the sedimentologic and biotic processes characteristic of the level-bottom. Instead, the mounds developed as deep-water (marginally subphotic?) microbial(?) mud accumulations and cementstone with unique micro-habitats. The later mound phases, unlike the level-bottom beds and the Alamogordo mounds, are characterized by primary cavities that may attain meter-scale size, the multiple generations of cement, micrite, and peloids. These features indicate distinctly different sedimentary processes on mounds and level-bottom.

We conclude therefore that the narrow time span of Waulsortian mounds is not a consequence of limitations on skeletal biota available to construct mounds. Rather, it was related to availability of environmental characteristics conducive to microbial mud/peloid production and submarine cementation, suitable substrate, and antecedent topography. These conditions were characteristic of deep water ramps in the Lower Carboniferous, where skeletal buildups were limited in occurrence (AHR, 1989; WRIGHT & FAULKNER,1990). More specifically, however, the problem remains to explain the localized and relatively great concentration in this environment of both microbial activity to produce the peloidal sediment and the much greater volume of both macro-organisms and microorganisms that were growing on and contributing to the mound. This will require unique energy sources, which by analogy are exceedingly rare on the modern sea floor (CALLENDER & POWELL, in press).

Microfacies characteristic of level-bottom strata (Fig. 1)
and associated Waulsortian mounds (Figs. 2–6).

Fig. 1: Sparsely skeletal lime mudstone with sponge spicules generally aligned parallel to bedding.

Fig. 2: Hyalosteliid spicule bundle.

Fig. 3: Peloidal geopetal mud with cluster of spicules, suggesting sponge may have been influential in forming cavity or may have lived in it.

Fig. 4: Peloidal lime wackestone with diverse skeletal allochems including *Mametella*, and shell with geopetal fill.

Fig. 5: Geopetal peloids.

Fig. 6: Fenestrate bryozoan-radiaxial calcite cementstone, most common in Nunn and Tierra Blanca phases of mound growth.

Bar length for all figures is 0.5 mm.
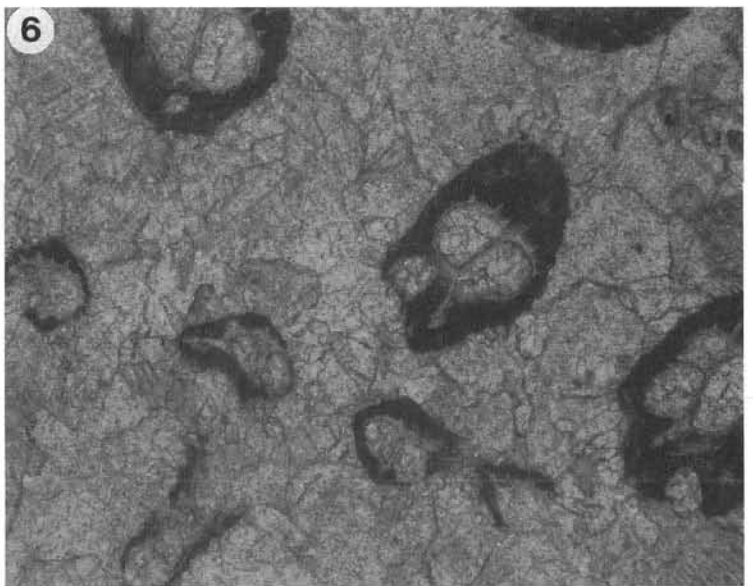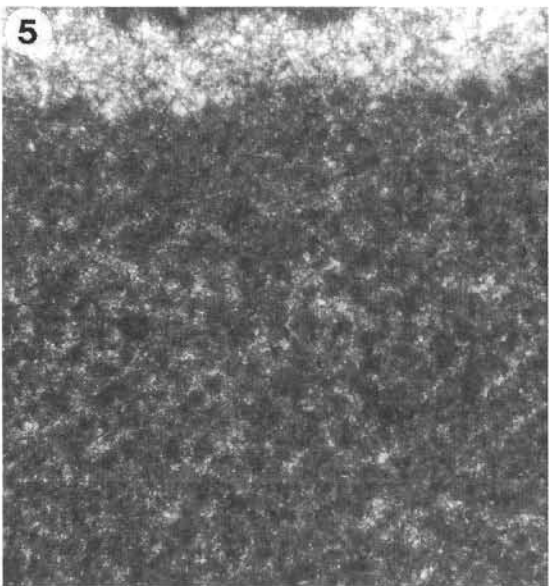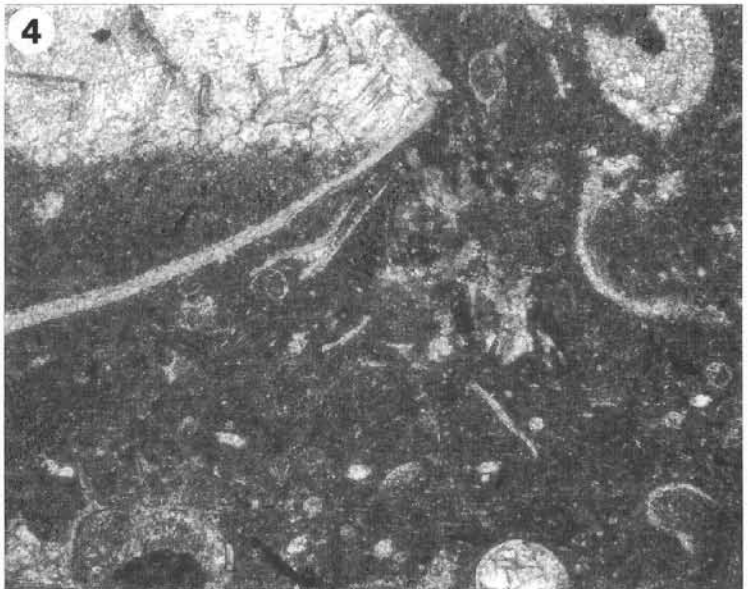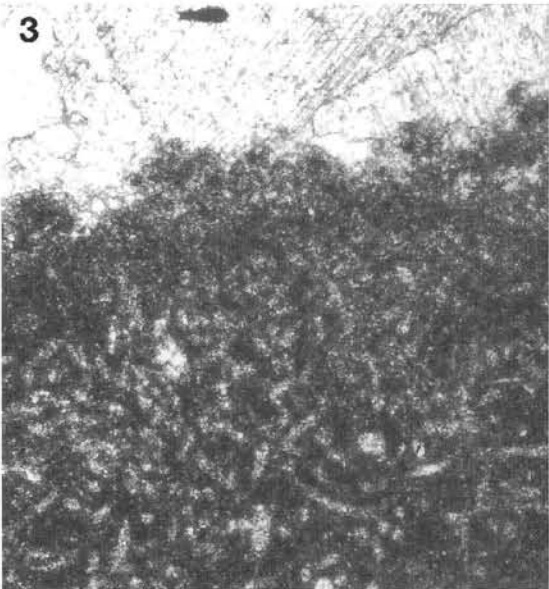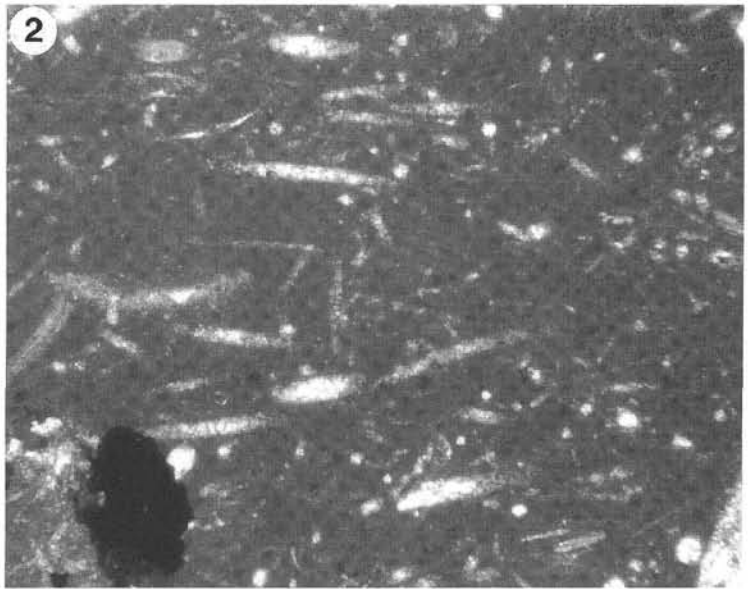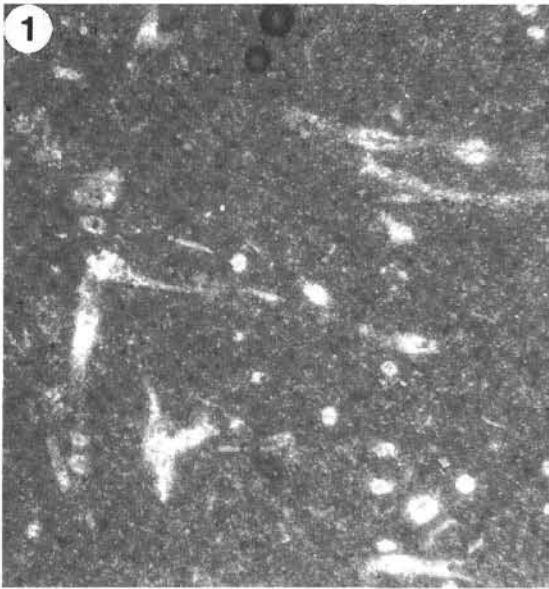
Plate 2

Microfossils characteristic of level-bottom strata and associated Waulsortian mounds.

Fig. 1: *Earlandia*.
Fig. 2: *Sphaerinvia*.
Fig. 3: Plurilocular foraminifer.
Fig. 4: Fragment of the ostracode *Kirkbya*.
Fig. 5: Thick walled ostracodes and borings in shell fragments.
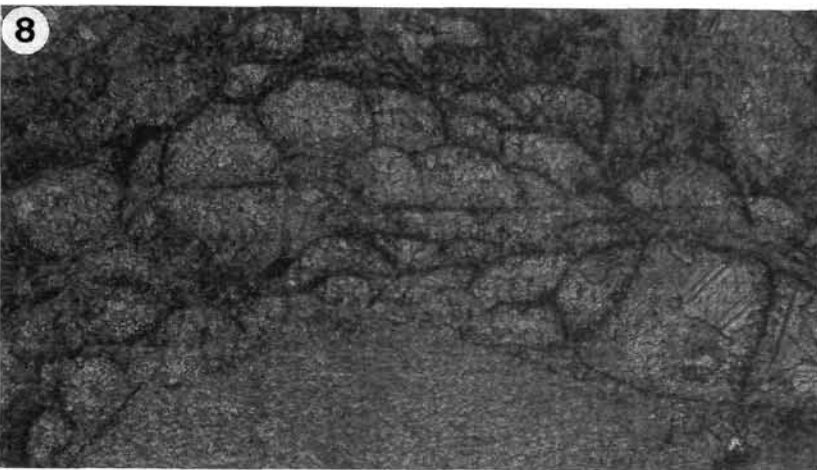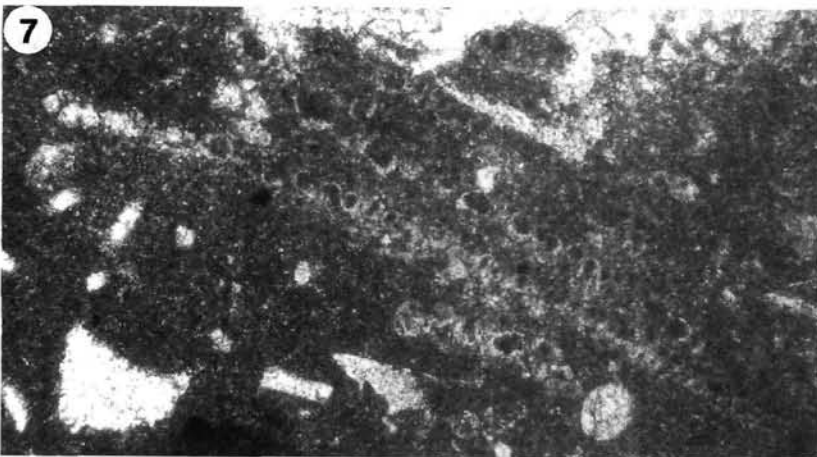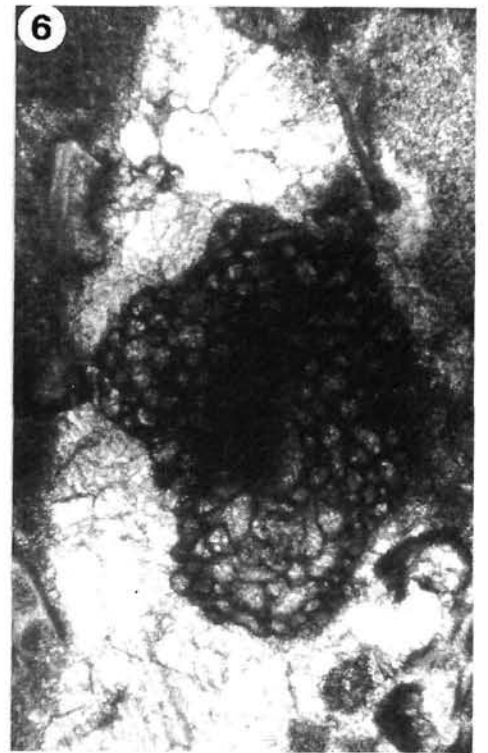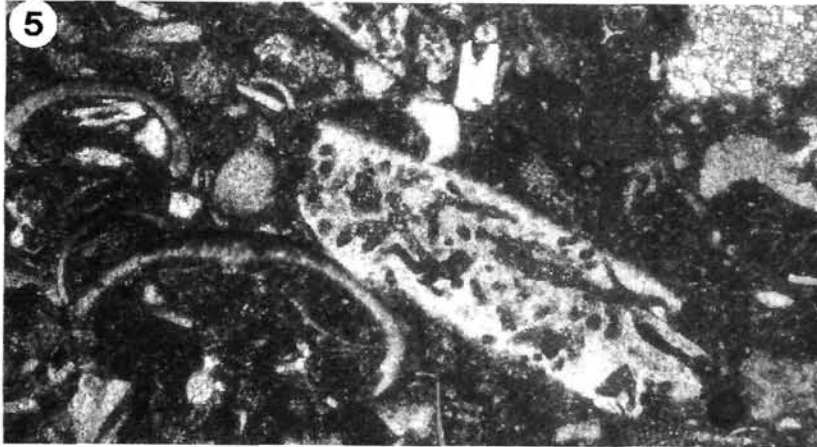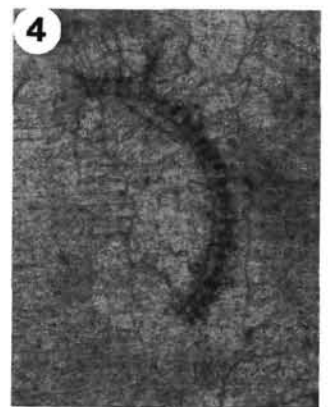   Both are distinctive of level-bottom beds.
Fig. 6: *Salebra*.
Fig. 7: Globochaetes.
Fig. 8: Encrusting bryozoan on crinoid fragment.
Fig. 9: *Mametella*.

Bar length for all figures is 0.5 mm.

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