

# TAPHONOMIC COMPARISON OF PASSIVE AND ACTIVE CONTINENTAL MARGINS: NEOGENE SHELL BEDS OF THE ATLANTIC COASTAL PLAIN AND NORTHERN GULF OF CALIFORNIA

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## Abstract

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To test for differences in the nature of the fossil record as a function of terrigenous sedimentation, macroinvertebrate concentrations in a recently rifted continental margin (Pliocene Imperial Formation, southeastern California) are compared with a mature passive margin (Miocene Calvert and Choptank Formations, Maryland coastal plain). Previous work suggested that shell beds are primarily a product of absolute low net sedimentation rather than high skeletal input; the duration and environment of low sedimentation (erosion, omission) determine the quality of paleontologic data through time-averaging and selective preservation of assemblages, and the frequency of low sedimentation episodes determine the stratigraphic density of richly fossiliferous horizons for sampling. Settings of rapid subsidence — and potentially high average sedimentation rates — such as active continental margins are thus expected to have fewer and taphonomically less complex skeletal concentrations than slowly subsiding passive margins, and, where steep bathymetric gradients co-occur with high subsidence, skeletal concentrations should be diachronous, patchy in development, and highly variable laterally. These predictions are largely borne out by the shallow marine Imperial Formation, whose average sedimentation rate is several orders of magnitude higher than the Maryland Miocene section. In both tectonic settings, major accumulations record relatively prolonged episodes of low terrigenous sedimentation, attesting to the predictive and explanatory power of a sedimentologic model for fossil accumulation. Major complex shell beds in the Imperial Formation (Latrania member) are exceptional deposits, formed under conditions of sediment starvation along the seaward edges of prograding coastal alluvial fans and fan-delta complexes and on bedrock highs; whereas major shell beds in passive margin deposits are stratigraphically condensed records of repeated marine transgressions. Although actualistic experiments suggest that rapid, deep burial is essential to the preservation of skeletal fossils, the stratigraphic record demonstrates that periods of sediment starvation and bypassing — and thus intermittent or retarded shallow burial of shells — are fundamental to the formation of many major skeletal concentrations.

## Introduction

Paleontologists collect fossils where they find them, both as sparsely dispersed specimens and from densely packed skeletal concentrations; practically all of these fossiliferous deposits reflect post-mortem, taphonomic mod-

ification of the original assemblages to some degree. Because most kinds of paleobiologic analysis require the comparison of data from different sampling horizons, the goals of taphonomic analysis have shifted from the evaluation of bias within single assemblages to (1) the identification of taphonomically compar-

able assemblages, regardless of level of bias, and (2) the search for systematic patterns in the distribution of fossiliferous deposits and their geological and biological controls. Thus from a paleobiological perspective, taphonomic analysis reflects a more positive approach, stressing what can be done with comparable but imperfect and irregularly spaced paleontological samples, rather than focussing on limits imposed by post-mortem modification of assemblages.

Previous analysis of a broad spectrum of molluscan shell beds from shallow marine Miocene strata of Maryland (Kidwell, 1982, 1985, 1986a, b; Kidwell and Jablonski, 1983; Kidwell and Aigner, 1985) indicated that episodes of low net sedimentation governed the formation of skeletal concentrations in that mature passive margin setting. Periods of erosion, sediment starvation, and bypassing determined the stratigraphic distribution of almost all skeletal concentrations, minor and major in scale, and strongly influenced the quality of shell preservation, time scales of skeletal accumulation (and thus time-averaging of assemblages), and patterns of benthic colonization through taphonomic feedback.

If patterns of sedimentation generally govern the formation of skeletal concentrations, then it should be possible to predict the distribution of fossiliferous deposits and their qualities, both as repositories of paleontological information as settings for biotic interactions. Moreover, the nature of the fossil record should differ quantitatively if not qualitatively among tectonic settings characterized by different patterns of sedimentation and subsidence, as well as among different depositional systems and paleolatitudes. If, on the other hand, skeletal concentrations are primarily the product of high skeletal input and preservation potential and are influenced only to a small degree by sedimentation rates, then patterns of skeletal accumulation should vary less predictably through the record.

To test the role of sedimentation in dictating skeletal accumulations, I examined biostratigraphic patterns in the Pliocene Imperial For-

mation of southeastern California, part of the thickest exposed Plio-Pleistocene section in North America. The Imperial Formation records marine inundation and deltaic progradation in the northern Gulf of California during a period of tectonic transition, from Miocene rifting to Quaternary oblique strike-slip faulting associated with the San Andreas fault system (Crowell, 1974; Moore and Curray, 1982; Winker and Kidwell, 1986). It thus provides a picture of shallow marine sedimentation and skeletal accumulation during rapid subsidence on a young divergent margin.

Of all active margin records available for study, the Imperial Formation was particularly attractive because it was reported (Mendenhall, 1910; Vaughan, 1917; Hanna, 1926; Woodring, 1932; Woodard, 1963) to contain skeletal concentrations similar in physical scale and faunal diversity to major shell deposits in the Maryland Miocene. The sedimentologic model would predict few major shell beds formed through prolonged episodes of low net sedimentation in active margins because of rapid burial of bedding surfaces; the great thickness of the Imperial Formation suggested that sediment supply probably had been sufficient to keep up with rapid subsidence. Large-scale skeletal concentrations should thus be primarily biogenic, the product of episodes or environments of high skeletal input rather than low terrigenous sedimentation. Unless the Imperial shell beds were biogenic in origin, they presented a possible contradiction to the sedimentologic model.

#### *California and Maryland Neogene settings compared*

The non-deltaic shallow marine facies of the Pliocene Imperial Formation (Latrania member) and the Miocene Calvert (Plum Point Member) and Choptank Formations are advantageous units for comparison (Fig.1). Both the active and passive continental margin records are characterized by terrigenous clastics deposited in a range of low-energy, intertidal to shallow subtidal marine environments out of

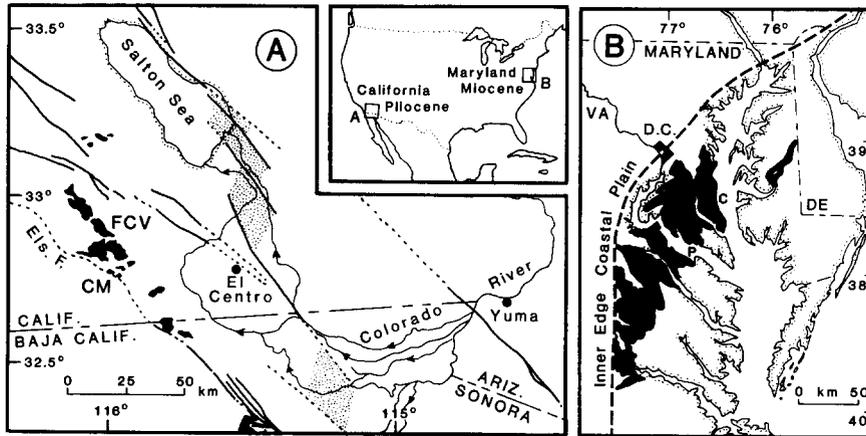


Fig.1. Outcrop belts (black) of Pliocene Imperial Formation in southeastern California and of Miocene Calvert and Choptank Formations in the Maryland-Virginia coastal plain. A. CM=Coyote Mountain study area on northeast side of Elsinore Fault; FCV= Fish Creek-Vallecito area; stippled pattern indicates active spreading centers; arrows indicate flow direction of northern distributaries of the Colorado River delta; NW-SE trending faults are part of San Andreas system. B. C= Calvert Cliffs; P= cliff exposures along Potomac River.

the direct influence of deltas. Both contain diverse mollusk-echinoid-coral faunas with many extant congeners.

The two records contrast strongly, however, in features related to tectonic setting.

(1) Net rates of sediment accumulation were more than an order of magnitude higher along the edges of the Pliocene Salton Trough. Johnson et al. (1983) estimated post-compaction accumulation rates of 4.0–5.5 mm/yr for the approximately 1 km thick marine deltaic part of the Imperial section from the Fish Creek-Vallecito area (Fig.1A) toward the center of the basin, as calibrated by magnetostratigraphy (4.0–4.3 Ma). These deltaic strata overlie and intertongue with the non-deltaic marine strata (Latrania member) that lap against the bedrock margins of the basin and are the focus of this study. Near pinchout against basement where the major shell beds are exposed, these strata (minimum thickness 0–70 m) have a minimum average sediment accumulation rate on the order of 0.1 mm/yr. In contrast, outcropping Miocene strata of Maryland (65 m thick section consisting of the Plum Point Member of the Calvert Formation and the entire Choptank and St. Marys Formations) accumulated at an average rate of ~0.007 to 0.009 mm/yr based on available

biostratigraphic control [Melillo, 1982; Kidwell, 1984; Schreiber, 1984; ~7.5 or 9.0 m.y. duration for exposed section (Langhian to mid-Tortonian) based on scales of Berggren et al., 1985 and Haq et al., 1987].

These time-averaged values of course say little about differences in short-term sedimentation rates or steadiness of sediment accumulation. However, the lack of significant unconformities in the Imperial section (Winker, 1987) and presence of numerous breaks in the Maryland Miocene section (Kidwell, 1984; 1986c) suggest major differences in the completeness of the two records.

(2) Initial dips (and thus the paleobathymetric gradient) were significantly steeper during Imperial deposition. In the highly faulted terrain of the modern Coyote Mountains, initial dips are estimated from the angular divergence of bed sets within small (<1 km) structurally coherent fault blocks, and range from a few degrees to more than 10° [Ruisaard (1979) cited 20° of local discordance between the Latrania member and basalt flows of the underlying Miocene Alverson Formation]. Steep paleobathymetric gradients for the bedrock-rimmed Pliocene basin can also be inferred from debris-flow and turbiditic deposits in laterally equivalent marine units to the

Latrania member in the Fish Creek-Vallecito area (Lycium and Wind Caves members of Winker, 1987). In the relatively undeformed Maryland Coastal Plain study area, initial dips are less than  $1^\circ$  (Kidwell, 1984).

(3) Unfortunately, there is little overlap in the grain size of terrigenous sediment, and thus some basic paleoecological and diagenetic differences should be expected owing to the coarser-grained substrata of the Imperial. The Latrania member is indurated and contains polymictic cobble conglomerates, pebbly sandstones, and medium to fine sandstones. Pre-Imperial erosion and faulting also provided basalt and metamorphic bedrock substrata as benthic habitats. Aragonitic hardparts are preserved as recrystallized calcite and as simple and composite molds. In contrast, Maryland Miocene strata are predominately unconsolidated, quartzose fine to very fine sands, silty sands, and clays with excellent preservation of aragonitic and bimineralic shells.

The relative benthic productivities of the two settings are difficult to assess. Bioclast production might have been higher in the Imperial because of its subtropical setting, notwithstanding the poor quality of aragonite preservation observed in outcrop. Paleoclimate evidence for the Miocene mid-Atlantic Coastal Plain suggests only temperate conditions (Gibson, 1967). On the other hand, approximately coeval diatomaceous sediments are associated with both the Pliocene Imperial strata (Boehm, 1984) and the Maryland Miocene (Palmer, 1986), indicating at least sporadic marine upwelling. If benthic production rates were higher during subtropical Imperial accumulation, this would act against the expectation of fewer large-scale concentrations of shell material, making the field study a conservative test of the sedimentologic model.

### Passive margin patterns: Miocene of Maryland

Shell material is distributed very unevenly through the fine-grained terrigenous clastics of the Maryland Miocene, which consists of a

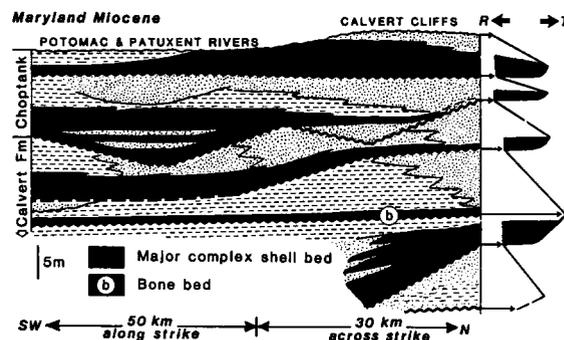


Fig. 2. Erosional disconformities subdivide the Maryland Miocene section into a series of cyclic depositional sequences that record successive transgressive-regressive migrations of shoreline. The four, laterally extensive major shell beds are stratigraphically condensed records of marine transgression and show great lateral and vertical variation in composition; they have complex taphonomic-ecologic histories related to repeated exhumation and reburial during prolonged (thousands, tens of thousands of years) low net sedimentation in shallow shelf environments. A similarly extensive bone bed records prolonged sediment starvation on the middle shelf at the time of maximum transgression. Regressive deposits (patterned areas) consist of less fossiliferous facies containing a variety of small-scale, physically and taphonomically simple shell beds formed over ecological time scales. Minor and major shell beds represent qualitatively different kinds of fossil repositories whose individual features and stratigraphic distributions are determined largely by geological controls on clastic sedimentation.

series of disconformity-bound transgressive-regressive cycles (Fig. 2). Shell-rich strata make up ~40% of the section by thickness, and comprise four relatively thick and laterally extensive shelly sands (major complex shell beds) and innumerable small-scale, localized shell concentrations (minor simple shell beds; Kidwell, 1982).

Regressive phases of the cycles consist of sparsely fossiliferous silty sand and sandy silts, and contain only scattered small-scale shell concentrations. Some of these minor simple shell beds were produced biogenically by gregarious species and molluscivorous predators, but most record storm and fair-weather winnowed concentrations of local death assemblages (Kidwell, 1982). The concentrated shell material was apparently locally derived and usually rapidly buried: the fauna of the minor

simple shell beds is similar in taxonomic composition to the surrounding dispersed assemblage, shells show little evidence of extended seafloor exposure, and shell-gravel-dwelling taxa are rarely represented in the assemblages. Minor shell beds in lithologically different facies differ in composition and mode of concentration, and reflect paleoenvironmental gradients across the preserved facies tracts (Kidwell et al., 1986, unpublished data).

In contrast, the major complex shell beds are tabular units that range up to 10 m thick and can be traced over areas of  $10^2$ – $10^3$  km<sup>2</sup> (Fig. 2). Taxonomic composition, bioclastic fabric, and sedimentary matrix vary considerably both laterally and vertically within each major shell bed. All four complex shell beds rest on unconformities along the margin of the basin and are stratigraphically condensed records of marine transgression (Kidwell, 1982, 1984). Evidence for in-situ accumulation during periods of low net sedimentation include: winnowed sediment matrix, hydraulically re-oriented and very densely packed parautochthonous infauna, encrusted and bored shells of exhumed infauna, multiple scoured and burrowed surfaces indicating repeated erosional reworking and physical amalgamation of minor shell concentrations, and condensation of discrete shell pavements into single, internally complex shell beds over paleohighs. The accumulation of dead shells on and just below the seafloor during these episodes of low net sedimentation is also reflected in the paleoecology of the subsidiary fossil assemblages, which show a strong correlation between sediment shelliness and the abundance of taxa that require or are tolerant of firm, shell gravel conditions (Kidwell, 1986b).

All of the minor simple shell beds record relatively brief episodes of concentration and rapid reburial; they are inferred to have formed over ecological time scales, with maximum durations of  $10^2$  years (Kidwell, 1982). In contrast, the major complex shell beds are composed of many individual minor simple shell beds telescoped into single complex deposits during prolonged regimes of low net

sedimentation. These "supra-ecologic" but sub-evolutionary (i.e., sub-biostratigraphic) time scales of skeletal accumulation have estimated durations of  $10^3$ – $10^4$  years each (Kidwell, 1982).

Biostratinomic patterns in this passive margin record reveal a strong control by terrigenous sedimentation — or, more precisely, by the failure of net terrigenous sedimentation. This sedimentologic influence is reflected in the post-mortem histories of individual shells, in the taphonomy of fossil assemblages within minor and major shell beds, and in the distribution of shell concentrations through the stratigraphic record. The net supply of molluscan hardparts to the seafloor may actually have been higher in absolute terms during prolonged periods of low net sedimentation for biological reasons, and thus fluctuations in skeletal input may have contributed to the striking alternation of shell-rich and shell-poor strata in the Miocene record. High skeletal input and favorable preservation conditions alone, however, could not have generated all of the observed features of individual shell beds, nor can they explain the systematic association of shell concentrations with bedding planes and unconformities. Instead, fluctuating rates of sedimentation on several hierarchical time scales can explain most of the physical and paleontologic features of the Maryland Miocene, as borne out by field tests and graphical modeling (Kidwell, 1985, 1986a, b).

Paleontologic samples from minor simple and major complex shell beds are not taphonomically comparable (Kidwell, 1982). The major complex shell beds are stratigraphically condensed and taphonomically complex records of prolonged, negligible rates of net sediment accumulation during marine transgression. Although composed of largely autochthonous specimens, fossil assemblages in the major shell beds contain species from a range of water depths and from both soft-bottom and shell-gravel habitats, and original species associations have been mixed by bioturbation and physical reworking. In contrast,

the minor simple shell beds are preserved in discrete regressive depositional facies, record geologically brief episodes of erosion, omission, and/or high hardpart input (mortality of gregarious species, predation–scavenging), are composed of predominantly autochthonous–parautochthonous shell material from single habitats, and thus are taphonomically less complex. Collectively, the minor simple shell beds provide a qualitatively different picture of benthic faunas than the major complex shell beds, even though both sets of shell beds sample bathymetrically similar suites of shallow marine environments. The minor simple shell beds provide higher resolution samples of fossil populations for evolutionary analysis, whereas the major complex shell beds preserve a higher diversity of species for analysis.

Skeletal concentrations similar in scale and shell packing density to the Miocene major complex beds are common in the Tertiary record of the Coastal Plain. Whether all of these shell beds are transgressive and stratigraphically condensed is unknown, but asymmetrical transgressive–regressive cycles having fossil-rich transgressive lags and thick, progradational or aggradational regressive phases are a basic motif in terrigenous and carbonate sequences from both cratonic and mioclinal settings (e.g., Fischer, 1961; Ryer, 1977; James, 1979; Goodwin and Anderson, 1985). Pratt et al. (this issue) have found a strikingly similar pattern of sedimentologic control of both minor simple and condensed, major complex shell beds in Devonian marine strata of New York. Baselevel fluctuations and rates of terrigenous sediment supply thus appear to be fundamental and perhaps pervasive controls on skeletal accumulation in passive continental margin settings (Kidwell, 1985, 1986a).

### **Predictions for active continental margins**

Active continental margins here comprise settings characterized by higher average rates

of tectonic subsidence than mature passive margins over time scales of  $10^6$  to a few  $10^7$  years. Such active settings include rift and early drift phases of divergent margins, portions of foreland basins proximal to the tectonic load, subduction-related back-arc basins, and wrench or transtensional basins.

By virtue of their high subsidence rates, basins on active margins will accommodate greater volumes of sediment, and thus on average will record greater net rates of sediment accumulation than passive margins. Under such conditions, depositional hiatuses — including episodes of sediment starvation, sediment bypassing, and erosion — will be less common, briefer in duration, and have different origins than in passive margin settings. The basic predictions of a sedimentologic model for the formation of shell and bone beds, therefore, would be fewer and taphonomically less complex skeletal concentrations in active margins than in passive margins, and probably markedly different patterns of occurrence of those skeletal concentrations because of the different geological controls on regimes of terrigenous nondeposition. These predictions assume that sediment accumulation is essentially equilibrated — that is, aggradation of the seafloor largely keeps pace with the combined effects of tectonically and isostatically driven subsidence — and that the shallow shelf systems being compared have similar oceanographic facing and water energies.

Basins in some active margins, particularly bedrock-rimmed basins, will be characterized by steep bathymetric gradients and topographically complex seafloors as well as by rapid subsidence. Shallow subtidal environments of relatively high benthic skeletal production should therefore occupy narrow bands on the seafloor and will migrate over relatively short distances for any given rise in relative sealevel (baselevel), yielding shell-rich deposits that are areally less extensive, more strongly diachronous, and laterally more variable than passive margin shell beds. In addition, a given baselevel rise should produce fewer and smaller

estuaries to serve as temporary sediment sinks during marine transgression, thus reducing the likelihood of prolonged or widespread sediment starvation in open marine environments. Consequently, although transgressive lags of erosionally reworked skeletal material may develop along the margins of active basins, especially those rimmed by unconsolidated sediments, the stratigraphically condensed transgressive shell beds typical of passive settings should be rare. In general, transgressive-regressive cyclicity should be suppressed by high subsidence and steep bathymetric gradients in active settings. Transgressive and regressive phases that do develop are expected to exhibit appreciable rates of sediment accumulation and thus dispersed skeletal material and widely spaced minor skeletal concentrations.

The few major shell beds formed through low net sedimentation in an active margin should be limited to (1) submarine transport surfaces (sediment bypassed toplap surfaces) developed late within regressive phases, and (2) subtidal, upper surfaces of fault blocks perched above the seafloor and thus protected from ambient high rates of sediment aggradation. Such syndepositional faulting is expected in oblique strike-slip settings such as the Salton Trough (Crowell, 1974; Christie-Blick and Biddle, 1985). Under conditions of equilibrium sedimentation, however, most major shell beds in active margins should be primarily the product of high skeletal production and/or favorable preservation rather than low net terrigenous sedimentation.

Minor shell beds should be as abundant in active as in passive margin settings, all else being equal. The number and type should vary along onshore-offshore transects in ways comparable to patterns observed within regressive facies tracts of the Maryland Miocene. Among minor shell beds, biogenic concentrations might be more abundant than sedimentologic concentrations: not because they are more likely to form in active than in passive margin settings, but because they are more likely to enter the record unmodified by physical

reworking and other sedimentologic processes where burial rates (= sediment accumulation rates) are high. The effects of high sedimentation rate, of course, would have to be discriminated on the basis of sedimentary structures from the effects of a different, perhaps higher energy oceanographic facing.

### Patterns in active continental margins: California Pliocene

Along the western margin of the Salton Trough, the Imperial Formation includes non-deltaic strandline and subtidal marine facies that contain a great diversity and abundance of macroinvertebrates. These facies are composed of locally derived lithic sediments, and include the Lycium, Stone Wash, and Jackson Fork members in the Fish Creek-Vallecito area, and the Latrania (= Andrade) member in the Coyote Mountains (Winker, 1987) (Fig.1A). As examples of taphonomic patterns within active margin settings, this paper focuses on major skeletal concentrations in the Latrania member, which is the most accessible and fossiliferous of Imperial non-deltaic marine facies.

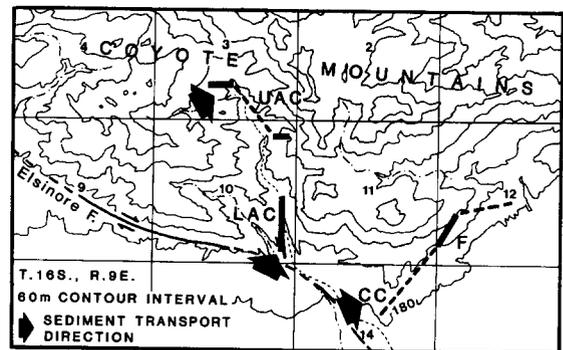


Fig.3. Locations (solid black lines) of stratigraphic cross-sections of Latrania member, Imperial Formation, in southern flank of Coyote Mountains, California: lower Alverson Canyon (LAC), upper Alverson Canyon (UAC), and Chuckwalla Canyon-Flatiron area (CC, F) are illustrated in Figs.5, 7, and 8 respectively. Grid units =  $1.6 \times 1.6$  km ( $1 \text{ mi}^2$  sections in township 16 south, range 9 east).

### Lower Alverson Canyon

Lower Alverson Canyon (=Shell Canyon, Fossil Canyon), a sinuous box-canyon in the south-central Coyote Mountains, is well known for a 7-m thick oyster-coral deposit (Figs.3 and 4). At the head of lower Alverson Canyon, the densely packed shell bed rests with slight angular discordance on indurated pebbly sands; down-canyon toward the south, the shell bed pinches out into cobble conglomerates (Fig.5). Although the shell bed has previously been described as a reef, there is no evidence for topographic build-up of the coral-rich skeletal carbonates at this locality. Instead, the shell bed lies in a distal and bottomset position relative to alluvial fan and shallow marine fan-delta deposits, which prograded north-northeast from a source area south of the present-day Coyote Mountains (Fig.3).

Vertical and lateral changes in faunal composition within the shell bed are correlated with the abundance and grain size of the terrigenous sediment fines

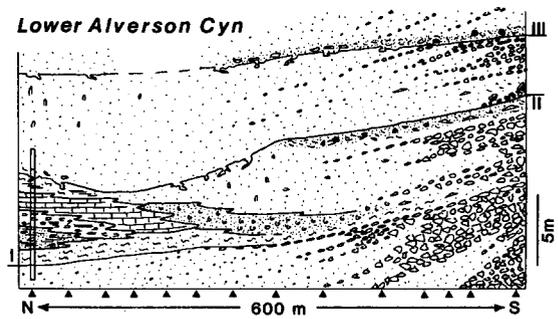


Fig.5. Major shell bed (I) in lower Alverson Canyon occupies a bottomset position relative to progradational-alluvial fan and marine fan delta deposits (source in south). Shell bed II occupies topset position within same depositional sequence; shell bed III is another down-lapped, bottomset shell concentration. Datum for cross-section is base of shell bed III; black triangles indicate location of detailed measured sections; faunal symbols as in Fig.8. Schematic column of Fig.4 located in extreme north of lower Alverson Canyon exposures (white box).

upward and decreases in abundance through the lower 1 m of the shell bed, culminating in an irregularly bedded, shell-supported impure limestone (biomicrudite) (Fig.4). The lower

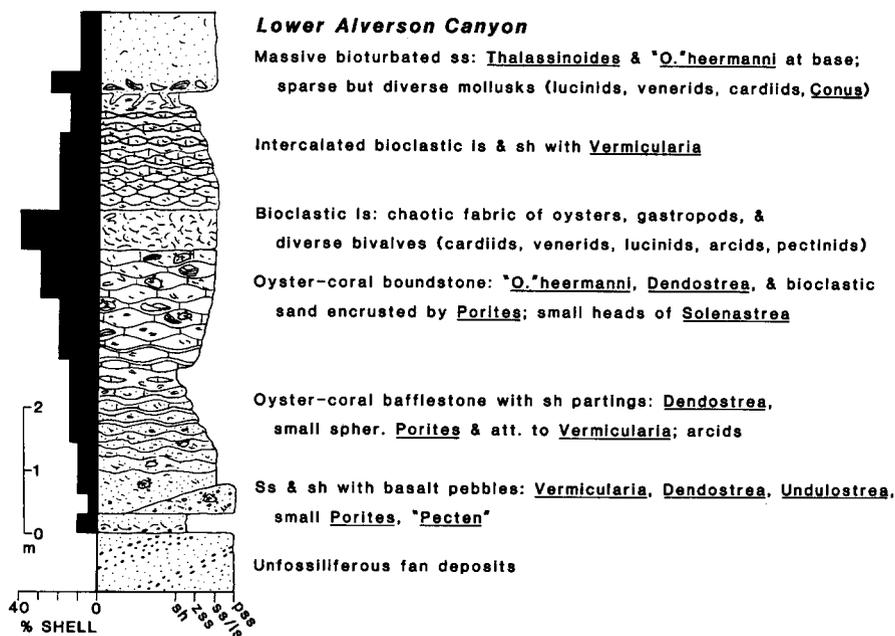


Fig.4. Schematic stratigraphic column of major shell bed in lower Alverson Canyon. Sedimentary matrix: *sh*=shale; *zss*=silty sandstone; *ss/ls*=sandstone (stipple) or irregularly bedded limestone (brick pattern); *pss*= pebbly sandstone. % shell=bioclastic carbonate by volume.

pebbly sands and muddy layers support assemblages dominated by sessile *Vermicularia* gastropods and two small species of oysters which are often attached to *Vermicularia* tubes. The major associated fossils are small (<2 cm) spherical colonies of the coral *Porites* and *Pecten*. Although some of the *Vermicularia* are intact and many of the oysters are articulated or still attached to various substrata, fragmentation is high and specimens are disoriented from life position within the basal pebbly sand bed and some portion of the assemblage may well be allochthonous.

These carbonate-poor *Vermicularia*-oyster assemblages grade upward into a bafflestone assemblage of large, disarticulated free-living oysters ("*Ostrea*" *heermani*), oblate colonies of *Porites*, and oyster-encrusting colonies of corals *Solenastrea* and rare *Siderastrea*. The circumrotary form of *Porites* suggests frequent overturning by waves or currents during growth. Shale interbeds reappear and are increasingly close-spaced in the upper half of the complex shell bed. Intercalated micritic beds contain whole *Vermicularia*, the small oyster *Dendostrea vespertina* (typically articulated and attached to conspecifics), a small species of *Pecten*, and bioclastic debris. Aragonitic bivalves and gastropods are relatively diverse but poorly preserved throughout the shell bed. The upper contact of the shell bed is characterized by *Thalassinoides* burrow systems and scattered disarticulated specimens of the large oyster "*O.*" *heermani*. The overlying massive sandstone contains sparsely disseminated steinkerns of lucinid and other infaunal bivalves.

The shell bed has been removed by erosion north of the head of the box canyon. However, the bed can be traced south (parallel to local structural strike) for approximately 600 m in the walls of the canyon and in another canyon immediately to the west (unnamed tributary to Ocotillo Canyon) (Fig.5). Over this distance, the "*O.*" *heermani*/*Solenastrea* and *Porites*/*Pecten*/bioclastic assemblages pinch out and are replaced by molluscan assemblages in a coarser grained terrigenous matrix. The most

distinctive of these proximal assemblages is dominated by molds of the small (<2 cm) gastropod *Bulla*. At the southern edge of the Lower Alverson exposures, the entire shell bed pinches out within polymictic conglomeratic sands and consists only of scattered mono-specific clusters of *Vermicularia* and small oysters in life positions, plus specimens and fragments of the sand dollar *Encope*. The massive, sparsely fossiliferous bioturbated sandstone above the shell bed also shows a proximity gradient in fossil assemblages, from a diverse fauna of infaunal and epifaunal bivalves and gastropods (*Miltha*, *Eucrasatella*, *Dosinia*, *Euvola*, *Malea*, *Strombus* preserved as molds) to an almost entirely epifaunal assemblage of the scallop *Euvola*, disarticulated *Dendostrea*, and *Encope*.

#### Origin

The shell bed occupies a "bottomset" position of a coastal alluvial fan that was fed from the southsouthwest and debouched into a shallow, low energy sea. The shell bed shows greatest thickness and species diversity most distal to the toe of the active fan, that is in exposures furthest north within Lower Alverson Canyon. In those sections, sediment starvation and very low net sedimentation are indicated by the predominantly sessile and attached (and, judging from growth rings, long-lived) epifauna, which would have been intolerant of significant sediment accumulation, and by the paucity of terrigenous sediment in the shell bed matrix. These conditions were probably interrupted by storm depositional pulses from the fan and episodic winnowing. Circumrotary *Porites* indicate at least episodically strong water motion; the zooxanthellate *Solenastrea* and *Siderastrea*, although turbidity tolerant, suggest relatively shallow and clear waters (Foster, 1979, 1980). The oyster-coral bafflestones, which show no evidence of biohermal growth above the level-bottom seafloor, accumulated on a substratum of epifaunal skeletal debris derived both from earlier colonists and from allochthonous, shallow-water habitats.

The shell bed shows a strong ecological gradient laterally toward the sediment source and vertically, reflecting progradation of the fan delta. The proximality gradient in assemblage composition probably reflects a combination of (1) increasing frequency and magnitude of disturbance by turbidity and depositional pulses from the fan, (2) increasing grain size of sediment (affecting penetrability by infauna and availability of appropriate substrata for epifaunal attachment), and (3) decreasing water depth (increasing water agitation and physical-chemical stress). The "regressive" sequence of lithologies and assemblages within the major shell bed tracks the progradation of the fan out over previously starved areas of the seafloor. The paleoecological and physical stratigraphic features demonstrate that the shell bed accumulated at a time when the fan complex was prograding actively.

Two other relatively extensive shell beds were discovered in toe-of-fan facies higher in the section beds (beds *II* and *III* in Fig.5). The uppermost shell bed (*III*) is clearly downlapped by clinofolds of gravel; fossils occur in a ~0.5 m thick highly indurated sandstone that rests with slight angular discordance on stratified gravelly sands. The shell bed can be traced for about 50 m before it is cut out by modern erosion. It contains an assemblage of *Vermicularia*, *Dendostrea*, and, toward the north, disarticulated specimens of "*O.*" *heermani*.

The middle shell bed (*II* in Fig.5) appears to occupy the topset position within a progradational sequence rather than the bottomset. It pinches out toward the south in conglomeratic sands of the fan but also thins away from the fan, possibly because of erosional beveling. The fossil assemblage shows lateral variation similar to the other major shell beds, from proximal *Encope-Vermicularia-Bulla*-dominated assemblages to distal *Dendostrea-Porites* assemblages over a distance of ~40 m. Skeletal material accounts for 10–30% of the bed and is largely disarticulated.

The remainder of the exposed *Latrania* member in lower Alverson Canyon contains

only sparsely disseminated shells. Small-scale concentrations comparable to the minor simple shell beds of the Maryland Miocene are rare.

#### *Time scale of accumulation*

The length of time represented by the complex bottomset shell beds is constrained by the rate of progradation of the fan deltas. This is difficult to pin down in absolute terms. From  $10^2$  to  $10^3$  yr might be required to build the fan laterally over distances of hundreds of meters. Fan deposition is typically episodic, and rate of fan progradation depends not only on the rate of sediment supply but on the size of the fan: the larger the fan, the greater the volume of sediment required for successive concentric increments.

Regardless of the absolute time scales of accumulation, the period of time represented by the major bottomset shell bed must have varied laterally, with the shell bed recording a relatively short period of skeletal accumulation in the most proximal area and a longer period in the distal areas. The spacing of the three shell beds through the section was governed by longer-term tectonic, climatic, or possibly eustatic cycles that determined the frequency of progradational packages. Four of these progradational sequences are depicted in Fig.5; only the upper three sequences (containing the numbered shell beds) contain skeletal or trace fossil evidence of marine deposition.

#### *Upper Alverson Canyon*

Spectacular exposures of oyster-coral bioherms occur further north in Alverson Canyon. The Upper Alverson shell bed also lies in a bottomset position to prograding alluvial facies and has a similar origin to the major shell bed in Lower Alverson Canyon. However, skeletal material accumulated on basalt bedrock rather than older alluvial deposits, and thus provides some paleoecological and taphonomic variation on patterns observed in Lower Alverson Canyon.

The bioherms occur along the base of 10-m high sandstone cliffs (south of jeep trail to

abandoned mine entrance) on the east side of the Canyon. The basalts, part of the Alverson Formation, are flows related to Miocene rifting of the Gulf of California (Ruisaard, 1979). The upper surface of the basalt is weathered into subangular to subrounded blocks and veneered by 30 cm of poorly sorted basaltic pebbly sand containing *Pecten* and the gastropod *Bulla*. Although the bioherms have been described as reefs attached directly to basalt, they are distributed through a 4.5 m stratigraphic interval and rest on the basal pectinid-rich pebbly sand and on inter-bioherm bioclastic sandstone (Fig.6).

Individual bioherms range from 1.5 to 2.5 m thick and are approximately 10 m in breadth, although many coalesce with adjacent bioherms into larger skeletal bodies. Each has a complex microstratigraphy of faunal assemblages and fabrics (Fig.6). Typically, the lower third is a densely packed, subconcordant fabric of disarticulated and articulated specimens of "*O.*" *heermani* which are infested by *Cliona*, boring lithophagid bivalves, serpulids, and solitary *Astrangia*. Associated taxa include

small oblate spherical colonies of *Solenastrea* (<10 cm), *Porites* (<5 cm), and, toward the top, ramose and palmate colonies of an as yet unidentified coral. Disarticulated pectinids and *Bulla* occur in shell interstices.

This skeletal material provides a foundation for the middle part of the bioherm characterized by large (25 cm) spherical, conical, and bowl-shaped colonies of *Solenastrea* and mounds of *Siderastrea* as well as small heads of *Porites* and the solitary *Astrangia*. These corals are intergrown with, and sometimes overgrow, the large oysters ("*O.*" *heermani* and variants) which are almost all articulated and mutually attached. In the upper third of the bioherm, encrusting *Porites* colonies form a dense boundstone fabric with large articulated oysters, and create ~1 m of depositional relief on the upper surface of the bioherm. The only associated corals are small heads of *Solenastrea* and solitary *Astrangia* on *Porites*-overgrown oysters.

Bioclastic sands surrounding the bioherms have a chaotic fabric of articulated but detached large oysters, 15 cm heads of *Solenas-*

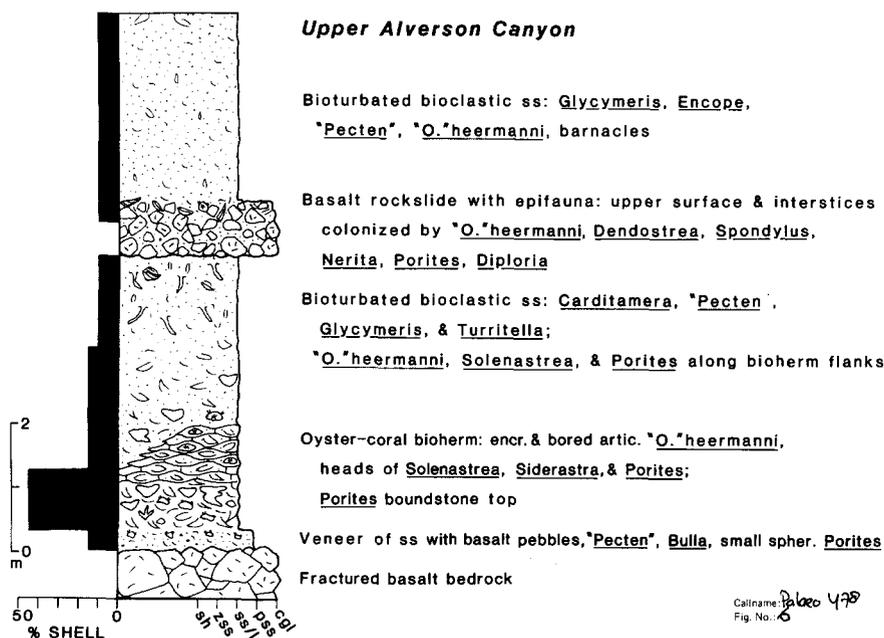


Fig.6. Schematic column of major skeletal concentrations exposed in east wall of upper Alverson Canyon. Symbols as in Fig.4; *cgl*= cobble conglomerate.

*trea*, and epifaunal *Carditamera* and *Pecten* (Fig.6). These grade laterally and vertically into a thick (6–7.5 m) interval of burrow-mottled, medium to coarse grained sandstone with 10–15% bioclastic debris. The fauna includes abundant *Glycymeris* bivalves and large *Turritella* gastropods, both of which characterize mobile coarse sands today. This sandstone is subdivided by a clast-supported conglomerate of basalt boulders, shed from the basalt escarpment that the sandstone laps against to the east (Fig.7). The basaltic rock-slide deposit was colonized by 20 cm “*O.*” *heermani*, small oysters, the rock-oyster *Spondylus*, and the coral *Diploria*.

Like the oyster–coral bafflestones of lower Alverson Canyon, the bioherms and bioclastic sands of Upper Alverson Canyon occupy a position distal to the local fan complex, which built out from the southwest. Owing to post-depositional faulting, this relationship has to be established using the provenance of the sedimentary matrix rather than by direct tracing of beds (Fig.7). Terrigenous sediment in the biohermal section is almost exclusively metamorphic, and thus could not have been

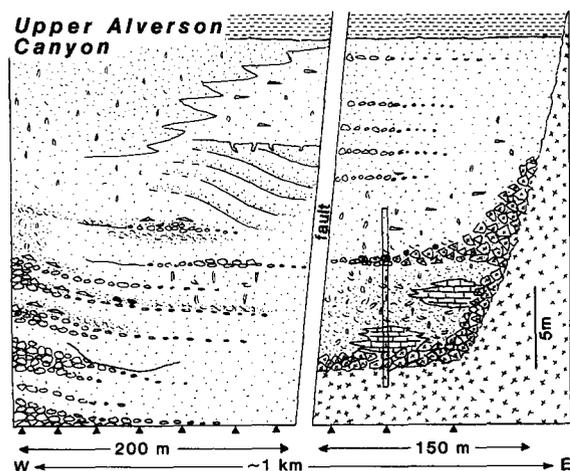


Fig.7. Bioherms and bioclastic facies (east fault block) occupy positions distal to coastal alluvial fan clastic sources in upper Alverson Canyon (west fault block). Datum for cross-section is the depositional contact of Latrania sandstones with overlying claystone member of the Imperial Fm; symbols as in Figs.4 and 8; x=basalt. Schematic column of Fig.6 located in east fault block (white box).

derived from the underlying Alverson basalts. Instead, the source must have been basement rocks to the west. Sandy fan-delta deposits exposed on the west side of Upper Alverson Canyon lap against basement, are predominantly metamorphic in composition, fine eastward toward the coral-oyster bioherms, and contain NE-dipping clinof orm bedsets.

Marine fossils are generally sparsely disseminated in fan-delta deposits on both fault blocks in Upper Alverson Canyon. Soft-bottom faunal assemblages vary in composition along paleobathymetric and sediment supply gradients much as observed Lower Alverson Canyon: *Encope* dominates thin sandstone layers in the proximal area; and *Clypeaster*, *Pinna*, *Euvola*, *Turritella*, and infaunal bivalves are dispersed through the thicker, more offshore sandstones of the fan-delta (massive, bioturbated; below fairweather wave base). Bivalves and echinoids are usually articulated and in life position; local concentrations of shell (up to 10% shell) in these sands evidently reflect aggregations of living organisms. Interspersed conglomeratic layers contain a variety of epifaunal taxa including *Dendostrea*, barnacles, encrusting bryozoans, rare *Vermicularia*, regular echinoids, and small *Solenastrea* heads. Attaching forms are found on either skeletal debris or lithic clasts. Many of these same species occur as allochthonous elements in very low abundance within sandstones, but, in general, fauna-substratum associations are very strong. Although sediment grain sizes are coarse, the lack of lateral mixing of faunas from different substrates argues for very low-energy conditions on the marine fan-delta during periods between high-energy events of sediment delivery. Low-energy marine conditions are further indicated by the pervasive bioturbation, which has obliterated almost all physical sedimentary structures.

### *The Flatiron*

The presence of sparsely fossiliferous, eastward-fining fan deposits in Chuckwalla Canyon led to the discovery of a major new

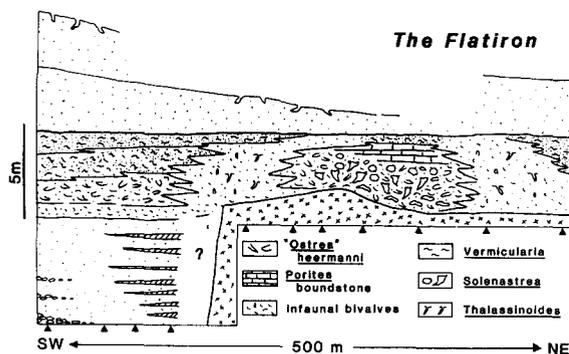


Fig.8. Lateral variation within newly discovered major shell bed on the Flatiron is related to (a) distance from active fans in Chuckwalla Canyon to southwest (Fig.3) and (b) variation in substratum type from old fan deposits in the southwest to basalt bedrock in the northeast.

fossil deposit in the Latrania member exposed further east in the Flatiron (Fig.3). The uppermost fan deposits in Chuckwalla Canyon lap out locally against the topographically irregular upper surface of the Alverson Basalt; a small ( $2 \times 2$  m) matrix-supported oyster accumulation, previously noted by Bell-Countryman (1984), is associated with one of these basalt paleohighs. However, a much more extensive and complex shell bed ( $4.3 \text{ m} \times 0.5 \text{ km}$ ) was encountered on the western edge of the Flatiron.

The faunal composition and fabric of the shell bed changes laterally both with increasing distance from the fan complex and with a shift from old fan to basalt bedrock substratum (Fig.8). Nearest to the fan, the shell bed rests on older non-marine strata (Fig.8). Disarticulated pectinids and clumps of attached *Dendostrea* characterize the upper 0.8 m of the sandstone ( $\sim 10\%$  shell) at the base of the shell bed. The undulatory upper surface of this pectinid sand is marked by bioeroded "*O.*" *heermanni* (both articulated and disarticulated). The shell bed itself grades from irregularly parted sandy limestone to increasingly thin-bedded fossiliferous fine sandstone with shale partings. *Spondylus* and *Vermicularia* dominate the assemblage, with unbroken *Vermicularia* and small oysters becoming more abundant upward.

Throughout the shell bed, endo- and epi-

bionts are abundant on both live and dead skeletal material (including steinkerns of *Vermicularia*), and include *Cliona*, bryozoa, barnacles, oyster spat, and, less commonly, *Porites*. Associated fauna include pectinids, lucinids, *Carditamera*, and large *Turritella*. This shell gravel is overlain abruptly by a thick ( $> 1.2$  m) bioturbated sandstone characterized by *Thalassinoides* and infaunal bivalves in life positions. The increasing proportion of infauna relative to epifauna, diminishing frequency of bioerosion, upward coarsening of matrix, and downlapping relationship of sandstone beds that fine eastward indicate that the shell bed accumulated contemporaneously with the prograding fan deposits of Chuckwalla Canyon.

Further east on the Flatiron and even more distant from fan deposits, the shell bed rests on basalt. Shell material is more densely packed, especially in the lower part of the shell bed ( $> 70\%$  shell versus  $\sim 45\%$ ), and the bed contains a much greater abundance and diversity of corals. These features are consistent with a more distal position relative to the fan complex in Chuckwalla Canyon. The basic "regressive" stratigraphy of the shell bed is the same: an "*O.*" *heermanni*-dominated assemblage grades up into bioclastic sand, which is replaced by a *Vermicularia* bed. The shell bed is topped by a massive coarse sandstone with *Thalassinoides*. Locally, this uppermost sand shows graded bedding and low-angle cross-sets.

Oyster-coral bioherms, similar to those in upper Alverson Canyon but not damaged by extensive collecting, are developed locally at the base of the shell bed along the northeast edge of the Flatiron, furthest from the fan complex. The bioherms range up to 2 m thick and can be traced for more than 8 m. Small colonies of *Porites*, *Solenastrea*, *Siderastrea*, and *Diploria* are attached to weathered basalt boulders at the base. "*O.*" *heermanni* provides the substratum for attachment throughout the rest of the bioherm. Large conical (40 cm high), mounded, and palmate slabs ( $> 30$  cm) of *Solenastrea* are attached to the upper valves of articulated oysters in life position. The less

common, mounding *Siderastrea* shows the same habit. In contrast, *Porites* typically utilized disarticulated oysters and other smaller skeletal debris. Coral colony size and number decreases upward with the exception of *Porites*, which creates a boundstone fabric in the top 1–1.5 m of most bioherms.

### *Paleogeographic implications*

These interpretations agree in broad outline with the paleoenvironmental results of previous workers. Foster's (1979, 1980) analysis of ecological morphology in Imperial corals indicated that the "reef" buildup [her quotes] in lower Alverson Canyon reflected low sedimentation on the muddy seafloor but high water turbidity and organic influx. A sedimentologic study by Bell-Countryman (1984) suggested a range of intertidal to subtidal environments, with coral growth seaward of a very shallow subtidal sand flat or on basalt rock platforms. Both authors cite the context of the Alverson Canyon shell beds in a regressive shallow marine sequence.

It is unnecessary to invoke a series of local depositional basins in this small area to account for lateral variability in the Latrania member (e.g., Bell-Countryman, 1984). Skeletal material accumulated on several older rock units and depositional topography was clearly complex, but the complex shell deposits in the three study areas may well be the fault-splintered remnants of a single laterally extensive shell accumulation. Much of the spread in sediment transport directions reflects radial fan patterns and, probably, a complexly dissected source area. Paleoecological trends reflect differences in substratum type and other proximality gradients related to the fans. The record has subsequently been complicated by post-depositional faulting and fault-block rotation associated with right-lateral shear along the Elsinore Fault (Fig.3).

Although portions of the modern Coyote Mountains were emergent during deposition of the Latrania member, the taphonomic analysis presented here indicates that it is misleading

to depict the Coyote Mountains as an isolated bedrock island surrounded by a concentric depth-array of benthic communities (e.g., Stump, 1972; Bell-Countryman, 1984). Instead, the regional paleodip and sediment transport directions were to the northnortheast, even for Latrania deposits on the southern flank of the Coyote Mountains. Based on grain size trends, paleocurrent indicators, and taphonomic evidence, sediment transport was from a polymictic source located southsouthwest of the Coyote Mountains (Fig.3), rather than entirely from basement and basalt exposures within the remnant modern Coyotes. This southern upland has subsequently been sheared and down-dropped from the Coyote Mountain block along the right-lateral Elsinore Fault.

The apparent episodes of sediment starvation during this early, rift-to-drift phase in the northern Gulf of California were probably tectonic in origin and related to extremely rapid subsidence. Pitman and Andrews (1985), for example, have calculated that subsidence due to heat loss in the early formation of small pull-apart basins can outstrip even continuously high rates of sediment supply, such that deep water conditions prevail for several million years. Under such circumstances, many shallow-water environments along the margins of the basin should be starved of terrigenous sediment as well and would provide settings for the accumulation of potentially large scale and internally complex skeletal concentrations.

The origin of cycles of fan progradation are more ambiguous. They may record (1) episodic fault uplift or offset of source areas, with climatically determined lag times in the development of new drainage systems, supply of conglomerates, and later delivery of sands, or (2) eustatic or relative sealevel controls on depositional baselevel. In the latter situation, starved episodes would coincide with periods of relatively rapid baselevel rise, and alluvial progradation with periods of relatively slow rise, steadiness, or slow lowering of baselevel. The taphonomic evidence as yet do not provide a solution.

### *Taphonomic implications*

Skeletal concentrations in the Pliocene Imperial Formation reflect strong control by patterns of terrigenous sediment accumulation. The thick (4–7 m), internally complex skeletal deposits of the marine non-deltaic Latrania member are bottomset strata of coastal alluvial fan and fan-delta complexes, and accumulated on distal, shallow subtidal seafloors that were locally starved of terrigenous sediment. Progradation of fan complexes determined the duration of periods of skeletal accumulation under starved conditions — and thus scales of time-averaging in fossil assemblages — and governed microstratigraphic trends in species composition and quality of preservation. Longer-term alternations between fan progradation and fan retreat or inactivity controlled the stratigraphic spacing of the major shell beds; the distribution of fan complexes along the complexly embayed coastline determined the geographic and bathymetric location of major skeletal accumulations.

Minor shell concentrations (decimeter thick, one to ten meter lateral extent) are present in fan-delta clinofolds but are rare; these marine sandstones and conglomerates usually contain only sparsely disseminated fossils. Most of the minor shell beds reflect single colonization events of epifaunal species, which form aggregations by attaching to conspecifics and to cobbles and boulders. The sand dollar *Encope* is found in life position in low-density aggregations within proximal sandstones; these minor concentrations reflect gregarious adult behavior and thus, like almost all of the other minor concentrations in the Latrania, are biogenic.

In addition to reflecting absolute low rates of terrigenous sedimentation, the distal thickening of the major shell beds probably also reflects a positive feedback between skeletal production and low sediment accumulation. In the Lower Alverson Canyon shell bed, for example, the faunal assemblage is most diverse at locations most distal to the fan, and these

assemblages also include species with the largest body sizes (e.g., "*O*". *heermani* up to 17 cm, corals to 35 cm). Growth rates may also have been relatively high in these distal areas of low net sedimentation: Foster (1980) cites thin corallite walls and septae in *Siderastrea* as indicators of rapid growth. In contrast, the largest species in assemblages from proximal areas of higher sediment accumulation are *Encope* (to 10 cm), thin-shelled *Euvola* and other pectinids, and small clusters of *Vermicularia*. The combined production of skeletal material in these proximal communities was thus quite likely lower than in the distal coral-oyster communities.

Not all of the major complex shell beds of the Latrania member are demonstrably condensed<sup>1</sup>, further suggesting that skeletal production probably was higher in the distal, sediment-starved areas. In lower Alverson Canyon, where stratigraphic relations can be determined in greatest detail (Fig.4), the maximum thickness of the lower shell bed (7 m in northern end of canyon) is comparable to coeval facies of sparsely fossiliferous fan-delta deposits. This suggests that skeletal carbonate production in sediment starved areas was sufficient to keep pace with terrigenous sediment aggradation in the fan areas. Thickness and diversity trends in the major shell beds are thus consistent with a positive feedback between benthic production of skeletal carbonate and low terrigenous sedimentation.

To some degree, these thickness and diversity trends must also reflect the greater water depths and greater time-averaging or faunal condensation (*sensu* Fürsich, 1978) in the sediment-starved habitats. Because the quality of skeletal preservation is virtually identical throughout the entire extent of the

<sup>1</sup>*Condensed* is used here in its strict stratigraphic sense, that is, of a local section that is thin relative to coeval deposits elsewhere because of low net sedimentation (Jenkyns 1971). Evidence for repeated events of seafloor reworking and amalgamation or mixing of successive benthic communities within a single section is suggestive of stratigraphic condensation, but is not sufficient to demonstrate it.

major shell beds, lateral variation in thickness and diversity are unlikely to be artifacts of selective diagenesis.

### **Taphonomic comparison of tectonic settings**

As predicted by the sedimentologic model, skeletal concentrations are more localized and lateral ecological and taphonomic gradients within concentrations are steeper in the active margin record (Table I). These features were governed most directly by the steep bathymetric gradients and topographic complexity of the bedrock-rimmed basin. Even if the major skeletal concentrations exposed in the three study areas of the southern Coyote Mountains are part of a single laterally continuous deposit, the areal extent is still only on the order 10 km<sup>2</sup>, as contrasted with major shell beds in the Maryland Miocene that can be traced over 1000's km<sup>2</sup>. In lower Alverson Canyon (Fig.5), species composition changes from the distal oyster-coral bafflestone to the proximal *Bulla* shelly sand facies over a distance of only a few hundred meters. In contrast, detection of far less dramatic changes in species composition within major shell beds of the Maryland Miocene requires onshore-offshore transects of 1-10 km.

Evidence for post-mortem transport of hard-parts (strong size-sorting of shells, hydraulic equivalence of shells and matrix, high-energy sedimentary structures, preservation of shells in exotic matrix) is scarce in the Latrania member. Fossil assemblages are largely autochthonous or parautochthonous in origin and little biased by the addition of transported elements despite rapid lateral changes in water depth and substratum type. Assemblages that contain a mixture of soft-bottom and shell- or hard-bottom species are rare and can be attributed to (a) faunal condensation of a series of local but paleoecologically unrelated assemblages by sediment starvation, or (b) ecological response of benthos to the in-situ accumulation of skeletal debris (taphonomic feedback).

Post-mortem bias from skeletal transport is also minimal in Maryland Miocene shell beds. However, in contrast to the active margin record, ecologically mixed assemblages are very common owing to faunal condensation and taphonomic feedback (Kidwell, 1982, 1986b). This difference probably reflects the different nondepositional regimes in the two settings of skeletal accumulation. Numerous scoured and burrowed surfaces within the Maryland Miocene major shell beds indicate condensation through repeated cycles of sediment deposition and erosional reworking (Kidwell and Jablonski, 1983; Kidwell, 1986a), and is consistent with physical stratigraphic evidence for transgressive ravinement. The California Pliocene major shell beds, on the other hand, show relatively little evidence of even temporary deposition of terrigenous sediment or of significant seafloor winnowing; the inferred regime of sediment starvation is consistent with skeletal accumulation in the context of stratigraphic downlap. The taphonomy and paleoecology of major shell beds in passive margins is thus more complex than for shell beds in active margins, even when the effects of shell transport are constant.

The sedimentologic model predicts that skeletal concentrations in active margin settings will be more strongly diachronous along their lateral extent, in part because it was expected that they would track migrating environments of high skeletal productivity rather than environments of low net sedimentation. Latrania shell beds are not demonstrably diachronous, but the amount of elapsed time recorded does vary along the lateral extent of individual skeletal concentrations. The downlapped shell beds record minimum elapsed time — and thus minimum amounts of overall time-averaging — where they pinch-out in fan deposits, and maximum time scales of accumulation in their distal, deeper water reaches. Absolute time scales of accumulation are difficult to estimate because of inadequate biostratigraphic control within the Latrania member and poor information on rates of progradation of modern coastal alluvial fans. However, the Latrania shell beds

TABLE I

Comparison of skeletal concentrations in active and passive continental margins. Descriptive categories of shell beds (Kidwell, 1982) are based on two independent features: (1) physical scale relative to shell-poor stratigraphic facies (major = equivalent or greater in dimensions than most associated facies); (2) internal complexity or variability in composition, fabric, matrix, etc., observed laterally and/or vertically within shell bed (simple = homogeneous in features or monotonic variation)

	California Pliocene "Imperial Fm", Latrania Mbr	Maryland Miocene <sup>a</sup> Calvert (Plum Point Mbr) and Choptank Fms
<i>Geologic Setting</i>		
Average rate of sediment accumulation	4.5–5.5 mm/yr entire Fm <sup>b</sup> , > 0.1 mm/yr Latrania mbr	0.007–0.009 mm/yr
Depositional gradient	few degrees to >10°	<1° original dip
<i>Major complex shell beds</i>		
Stratigraphic frequency	1–3/~70 m marine section <sup>c</sup>	4/~40 m open marine record <sup>d</sup>
Maximum thickness	2–7 m	1.5–10 m
Lateral extent	<10 km <sup>2</sup>	500–3500 km <sup>2</sup>
Geometry	tabular to wedge-shaped over hundreds of meters; pinches out onshore in fan delta; laps out "offshore" against bedrock paleohighs or faulted out	tabular to wedge-shaped over tens of kilometers; pinches out onshore; offshore, intertongues with less fossiliferous strata
Shell packing density (by volume)	10–45% calcitic shells and molds of aragonitic shells	20–70% aragonitic and calcitic shells
Time for accumulation	10 <sup>2</sup> –10 <sup>3</sup> yr?	10 <sup>3</sup> –10 <sup>4</sup> yr
Origin	sediment starved, shallow subtidal; distal edge of prograding coastal alluvial fans	sediment starved and bypassed, shallow subtidal; condensation during marine transgression
<i>Minor simple shell beds</i>		
Stratigraphic frequency	<5 shell beds/5 m	4–30 shell beds/5 m
Maximum thickness	<10 cm	<10 cm
Lateral extent	<1 m <sup>2</sup> , usually <30 cm <sup>2</sup>	30 cm <sup>2</sup> –1 km <sup>2</sup>
Geometry	clumps, lenses, thin beds	pods, clumps, lenses, pavements, thin beds
Shell packing density	5–30% calcitic shells	20–50% calcitic and aragonitic shells
Time for accumulation	<10 <sup>2</sup> yr	<10 <sup>2</sup> yr
Origin <sup>e</sup>	predominantly biogenic; rare sedimentologically-overprinted biogenic	few biogenic; most are sedimentologic and sediment.-overprinted biogenic

<sup>a</sup>Data largely from Kidwell (1982).

<sup>b</sup>Johnson et al. (1983).

<sup>c</sup>Uncertainty reflects possibility of fault splintering of a single major shell bed.

<sup>d</sup>In addition to four major shell beds, section includes a stratigraphically condensed bone bed.

<sup>e</sup>Categories follow Kidwell et al. (1986).

may record shorter periods of accumulation than those in the Maryland Miocene by an order of magnitude (Table I).

The generality of the Imperial pattern for rifted and strike-slip basins is not yet known. Fossiliferous, coarse-grained marine clastics are found throughout the Tertiary record of California, but few reports of these deposits note significant concentrations of macroinvertebrates and coastal-fan facies may be lacking. However, richly fossiliferous Pleistocene coastal fan deposits are known from the Sonoran coast of the Gulf of California [at Punta Chueca (Beckvar and Kidwell, 1988) and possibly Puerto Libertad (Stump, 1975)], and Neogene faunas in Latrania-type sediments are common along the entire margin of the Gulf (see review in Anderson, 1950; Durham, 1950). The major shell beds of the lower Imperial Formation are probably not unique examples of this pattern of skeletal accumulation.

One of the major predictions of the sedimentologic model (i.e., that the features and origin of skeletal concentrations are governed primarily by low absolute terrigenous sedimentation rather than by high absolute skeletal input) is that active continental margins will contain fewer and less complex skeletal accumulations than mature passive margins. The major complex shell beds of the Latrania member, formed during episodes of sediment starvation, provide an exception that proves the rule. Along the bedrock-rimmed margins of the Pliocene Imperial basin, taphonomic and paleoecologic patterns were governed by the local episodicity of sediment accumulation in time and space, rather than by high rates of sediment accumulation for the Pliocene basin as a whole. In this situation, source area and baselevel controls on sediment supply — expressed through the fan-delta depositional system — figured larger than subsidence controls in determining rates and patterns of sediment and skeletal accumulation. These conditions are not independent of tectonic setting, and will typify the early post-rift marine phase of basin development when subsidence can outstrip terrigenous supply.

Preliminary results on skeletal concentrations from other outcropping members of the Imperial Formation, away from the direct influence of bedrock shorelines and fan-deltas, are consistent with predictions of the sedimentologic model. These strata comprise Colorado River-derived quartz-rich sandstones, siltstones, and claystones in a progradational sequence of subtidal to intertidal marine deltaic facies that are largely barren of macroinvertebrate fossils (Kidwell, 1987; Winker, 1987). Major facies-scale concentrations of shell material represent <1% of the section by thickness, and are the product of high skeletal input (both allochthonous and autochthonous) not always associated with low terrigenous sedimentation. These concentrations include: (1) large, diachronous, cross-bedded lenticular bodies of oyster coquina from delta-front sequences in the Deguynos member, with one unusually large coquina body that attains 16 m thickness and can be traced 4 km; (2) a variety of small-scale biohermal (5 m maximum buildup) and channel lag concentrations of epifauna (oysters, pectinid and anomiid bivalves, circumrotary bryozoan and serpulid colonies) from delta front and transitional-intertidal facies in the Deguynos and Camels Head members; and (3) thin sheets (to 2 m) of reworked oysters produced during transgressive phases of delta reworking and colonized by open marine benthos in the Deguynos member; these latter accumulations are clearly mixed sedimentologic-biogenic in origin. Other rare skeletal concentrations are much smaller in scale and primarily biogenic in origin. These include patchy, low-density assemblages of deposit-feeding bivalves from prodeltaic claystones in the Mudhills and Deguynos members.

An active margin record with finer-grained sediments than the Imperial Formation would have been more comparable to the Maryland Miocene, both paleoecologically and diagenetically. The Pliocene Purisima Formation of the central California coast, for example, is strikingly similar to the Maryland Miocene in grain size, fossil preservation, quality of outcrops, and range of subtidal paleoenvironments, a

consequence of the basin being rimmed by unconsolidated sediments rather than bedrock. Depositional gradient and subsidence rate are intermediate between the Maryland Miocene and Pliocene Imperial Fm.

Taphonomic analysis of Purisima shell beds by Norris (1986) bears out the predictions of the sedimentation rate model. In 219 m of foreshore to mid-shelf deposits measured by Norris throughout the Purisima outcrop belt, shell beds account for only 10 to ~30% of section thickness (contrasted to ~40% in the Maryland Miocene). Norris found that almost all Purisima shell beds are minor in scale, and formed through a variety of storm and fairweather winnowing processes and benthic colonization events. Internally complex concentrations several meters thick are restricted to shoreface and inner shelf facies and, despite evidence of small-scale scour features, are not demonstrably condensed relative to coeval deeper-water strata. Instead, they appear to be more like the diachronous fossil-rich facies predicted by the sedimentologic model, produced through the lateral migration of coquinid shoals across a shelf undergoing relatively high average rates of sediment accumulation.

## Conclusions

(1) Major shell beds in non-deltaic shallow marine strata of the Imperial Formation (Latrania member) of southeastern California formed under conditions of sediment starvation along the distal edges of prograding coastal alluvial fans and fan delta complexes. Despite steep depositional slopes and an abundance of easily-transported epifauna, paleoecological gradients are preserved laterally within the shell beds; the shell beds also provide microstratigraphic records of coastal fan progradation. Different time scales of accumulation are recorded at different points along each major shell bed, and thus bulk samples for paleoecological and morphometric or evolutionary study will not be equivalent in time-averaging or in the nature of post-mortem bias. Moreover, the development of major shell

beds is very localized owing to control by fan progradation. Within the Latrania member, minor shell beds are rare and almost all are biogenic; they occur within the broadly clinoform deposits of coastal fan deltas.

(2) Sediment accumulation in the active margin California Pliocene exceeded that of the passive margin Maryland Miocene by several orders of magnitude, and is reflected in the heterogeneity of the fossil record. As predicted, relative to passive margin shell beds, major shell beds in the active margin setting are patchier and show sharper gradients in thickness, faunal composition, and time scale (duration) of accumulation. Major shell beds in both settings formed during relatively prolonged episodes of low net sedimentation, although these conditions were engendered by different local processes. In the passive margin, erosional reworking, dynamic bypassing, and sediment starvation characterized shallow subtidal environments during rapid, probably eustatic baselevel rise and marine transgression; in the active margin, sediment starvation characterized shallow subtidal environments between phases of fan progradation driven by tectonics or eustasy. The major shell beds in the two settings are comparable in that they accumulated during episodes of low net sedimentation, but they are taphonomically and paleoecologically complex in different ways.

(3) Minor shell beds — which, among shell beds, provide the highest resolution and taphonomically simplest paleontologic samples (Kidwell, 1982) — are extremely rare in the active margin, perhaps because they have a relatively low potential for preservation during diagenesis and weathering in coarse-grained clastics. The few minor concentrations are almost exclusively biogenic, whereas minor shell beds of the passive margin are common and predominantly sedimentologic in origin (shelly storm beds, channel lags, bedding plane pavements; plus hydraulically reworked biogenic concentrations). The reasons for these differences in minor shell beds are obscure, but the relative abundances in the two tectonic settings reduce opportunities for

TABLE II

## Controls on major skeletal accumulations

<i>Feature governed by</i>	In California Pliocene	In Maryland Miocene
<i>Lateral variation<sup>a</sup></i>		
sedimentation rate	proximity to fan delta	paleotopographic relief on seafloor
substratum type	coarse-grained fan deposits, bedrock, skeletal material	fine-grained clastics, skeletal material
average bathymetric gradient; seafloor irregularity	steep; great	gentle; slight
<i>Microstratigraphic complexity</i>		
at 10 cm scale	taphonomic feedback, faunal condensation, chance	taphonomic feedback, faunal condensation, chance
at 20–30 cm scale	fan pulses	storm reworking and deposition
at 1–10 m scale	change in water depth: fan progradation	change in water depth: marine transgression
<i>Lateral extent</i>		
dimension of marine basin	Salton Trough < 100 km length	Salisbury Embayment ~250 km inner margin
range of water depths with appreciable skeletal input	intertidal below fairweather wave base	intertidal to ~average storm wave base
area of low clastic input	relative extent of rocky and inactive fan shoreline; rate of active fan progradation	relative extent transgressive shoreline; distance of marine transgression per event
<i>Thickness, stratigraphic frequency and proportion</i>		
duration of each interval of sediment starvation	length of hiatus between successive phases of fan progradation	duration of each transgressive event, time lag before regressive deposition
rate of skeletal accumulation during starved intervals <sup>b</sup>	greatest production during starvation, greatest preservation potential within concentrations; overall higher net input than in Maryland Miocene?	greatest production during starvation, greatest preservation within concentrations; moderate absolute rates of net input?
recurrence of starved conditions	climatic or tectonic control of progradational cycles ("periodicity" < 1 m.y.)	eustatic control of transgressive-regressive cycles ("periodicity" < 1 m.y.)
long-term average rate of stratigraphic accumulation	rapid subsidence; initially low, discontinuous supply of clastics controlled by bedrock source area; locally low net accumulation for few m.y.	slow subsidence; eustatically controlled variation in clastic supply; very low net accumulation for ~10 m.y.

<sup>a</sup>Variation observed in species composition and preservation of assemblages, bioclastic fabric, clastic matrix, bedding and sedimentary structures.

<sup>b</sup>Product of benthic skeletal production, shell transport, bioerosion, mechanical reduction, early diagenetic destruction; broad correlate of water depth.

paleobiologic comparisons of taphonomically equivalent accumulations.

(4) Although major shell beds formed through low net sedimentation were unexpected in active margins, the *Latrania* shell beds corroborate rather than contradict a sedimentologic model for fossil accumulation (Kidwell, 1986a). The California–Maryland comparison indicates that geological controls on episodes of low net sedimentation structure the fossil record of shallow marine settings in both active and passive margins, determining the locus, time scale, and detailed history of skeletal accumulation (Table II) and thus the quality and comparability of paleontologic samples. Dependent and independent fluctuations in the supply of skeletal hardparts appear to play a minor or secondary role, and their reciprocity — high when sedimentation is low, low when sedimentation is high — accentuates the contrast between shell-rich and shell-poor strata.

For the purposes of predicting skeletal accumulations, simplifying assumptions of equilibrium sedimentation should be avoided. In both settings, the interbedding of shell-rich and shell-poor strata reflects the alternation of *disequilibrium* phases of sedimentation. The major skeletal accumulations, which contain the most diverse but taphonomically and paleoecologically most complex benthic assemblages, record periods when the seafloor was stranded below depositional baselevel by sediment starvation; whereas minor and taphonomically more simple skeletal concentrations are distributed in variable density through the thicker records of seafloor aggradation or progradation. The immediate controls on episodic sediment accumulation differ between the two settings — fan progradation in California versus eustatically-driven transgression-regression in Maryland — but the fundamental controls on the two fossil records are the same. When high rates of sediment accumulation are maintained more continuously, as in the marine deltaic portion of the Imperial Formation, biostratigraphic patterns are in good agreement with those of the equilibrium model.

(5) Although conventional wisdom and actualistic experiments suggest that calcareous hardparts require rapid permanent burial for preservation, the stratigraphic record of rich skeletal deposits in Maryland, California, and elsewhere (see Parsons et al., this issue) indicate accumulation during prolonged conditions of low net sedimentation and retarded permanent burial. Shallow, intermittent burial of hardparts is apparently sufficient to protect hardparts from destruction during prolonged regimes of sediment starvation or bypassing. Sedimentologic models thus have not only heuristic value in framing hypotheses, but considerable explanatory power for the nature of the fossil record.

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