

Hiatal shell concentrations, sequence analysis, and sealevel history of a Pleistocene coastal alluvial fan, Punta Chueca, Sonora

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Richly fossiliferous marine sediments exposed along the Sonoran coastline of the Gulf of California near Punta Chueca provide an excellent setting in which to test (a) the strength of the association of skeletal concentrations with sedimentary hiatuses, (b) the utility of taphonomic evidence for reconstructing detailed histories of those non-depositional episodes, and thus (c) the largely unexploited potential of skeletal concentrations in the identification and interpretation of lithologically obscure unconformities and condensed sequences in shallow marine deposits. Sequence analysis based on discontinuity surfaces is possible in the complex, alluvial fan-to-shallow marine transition at Punta Chueca despite rapid facies changes. Progradation of depositional sequences that contain cobbles reworked from older terrace deposits indicates accumulation during a fall in eustatic sea level. The supratidal to subtidal conglomerates and sands contain a variety of predominantly molluscan shell concentrations that, on the basis of post-mortem histories of shells, formed during periods of low net sedimentation (i.e. depositional hiatuses); the majority of these shell beds lie along discontinuity surfaces identified by independent physical stratigraphic evidence. Although not all discontinuity surfaces in the terrace are paved by shell material, and not all relative concentrations of shells indicate distinct discontinuities, the strength of the association between skeletal concentrations and stratigraphic hiatuses reveals the high degree of control on fossil occurrence by sedimentation rates, and indicates that skeletal concentrations can provide good clues to stratigraphically significant surfaces. Moreover, the detailed dynamics of non-depositional episodes are reliably revealed by taphonomic analysis of the associated fossil assemblages, improving interpretations of non-depositional episodes in local sedimentary history. □ *Taphonomy, marine paleoecology, hiatus, sealevel change, alluvial fan delta, Pleistocene, mollusks, Mexico.*

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Concentrations of skeletal material can be extremely useful in stratigraphic analysis. For example, shelly tempestites and concretionary mass mortality horizons can serve as marker beds for local correlation, and the distribution of different kinds of skeletal concentrations can distinguish facies and reveal paleobathymetric gradients (e.g. Waage 1964; K. A. Schäfer 1973; Aigner 1985; Norris 1986; Kidwell *et al.* 1986; Brett & Baird 1986). Skeletal concentrations formed during episodes of low net sedimentation can also provide keys to lithologically obscure hiatuses in the stratigraphic record. We refer to these skeletal concentrations, formed during brief or prolonged intervals of sediment starvation, dynamic bypassing, winnowing, or erosional reworking, as *hiatal shell concentrations*, a subset

of sedimentologic concentrations (*sensu* Kidwell *et al.* 1986). Although many examples of sediment-starved and erosionally-reworked skeletal deposits have been reported from marine depositional systems, and a variety of methods have been developed to infer conditions of their accumulation, they remain underexploited by modern stratigraphers.

Here, we characterize skeletal concentrations from a little studied but tectonically significant suite of ancient shallow marine environments, and evaluate the strength of the association of skeletal concentrations with independently verified discontinuity surfaces. The Pleistocene marine terrace along the Gulf of California near Punta Chueca, Sonora, records the complex intergradation and progradation of a coarse-grained

alluvial fan into adjacent low-energy shallow marine environments. Conglomeratic and sand facies all contain abundant, well-preserved aragonitic and calcitic shell material. Despite the rapidity of lateral facies changes and fine-scale vertical variability, we could identify several through-going discontinuity surfaces and thereby subdivide and interpret the section in terms of depositional sequences. Using standard taphonomic criteria, the detailed histories of periods of non-deposition can be reconstructed in as great a detail as periods of significant sediment deposition. Richly fossiliferous terraces similar to the one near Punta Chueca occur throughout the Plio-Pleistocene record of the Gulf (Durham 1950; Stump 1975) and its northern extension in southern California (Salton Trough; Kidwell 1988). This study demonstrates the value of taphonomic criteria in the stratigraphic analysis of complex shallow marine facies transitions. In addition, the features we describe may be of use in identifying comparable deposits and tectonic settings elsewhere.

Geologic setting

The Punta Chueca terrace is located opposite Tiburon Island on mainland Sonora, approximately 35 km north of Bahia Kino and 5 km north of the village of Punta Chueca, Mexico (Fig. 1). The 5–6 m thick terrace extends for 1.5 km along the shoreline in the modern supratidal zone,

except for a 100 m section at the southern end of the terrace which is covered at high tide. The strait separating Tiburon Island from mainland Sonora is extremely shallow, with a mean water depth of 5 m, a maximum water depth of 10 m, and a mean tidal range of 2 m (Parker 1964).

The sediments in the terrace were deposited during the last interglacial Pleistocene high stand of sea level (Malpica *et al.* 1978; Ortlieb & Malpica 1978; Bernat *et al.* 1980; Ortlieb 1982, 1984) along the seaward edge of a Sierra Seri coastal alluvial fan. Based on grain size, faunal composition, and stratigraphic context, three marine subenvironments were recognized: (1) shallow-subtidal to lower intertidal; (2) mid- to upper intertidal; and (3) supratidal (Beckvar 1986). Marine sediments are in gradational contact with overlying continental alluvium.

Thirty-two stratigraphic sections were measured at approximately 20–60 m intervals along the shoreline and were described in cm by cm detail. Observations included sediment size and sorting, physical and biogenic sedimentary structures, faunal composition, and skeletal abundance (% volume hardparts estimated visually using the charts of K. A. Schäfer 1969). Sediments range in size from silty clays to cobbles (average maximum size 22 cm) and are primarily unconsolidated. Grain sizes tend to coarsen upward throughout the terrace and many individual beds are reverse-graded. Finer-grained sediments are composed of angular to subangular arkosic particles derived from granitic bedrock in the adjacent

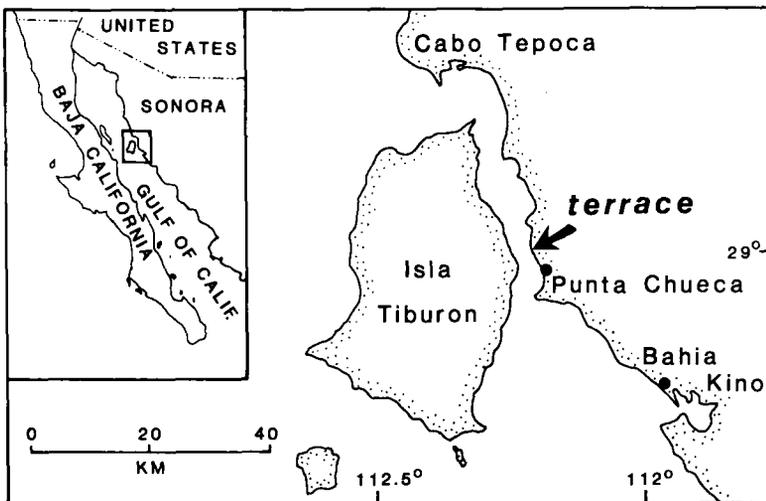


Fig. 1. Location of richly fossiliferous Pleistocene marine deposits near Punta Chueca, Sonora.

ent Sierra Seri. Well-rounded cobble conglomerates are almost exclusively gneissic and apparently recycled from older terrace deposits.

Well-preserved whole fossils are numerous (up to 55%) and range from dense concentrations of fossils rotated out of life position to sparsely dispersed shells in life position. The subtropical skeletalized fauna is predominantly molluscan (more than 100 species of bivalves and gastropods; Stump 1981) but includes locally abundant echinoids, barnacles, red algae, corals, hydrozoans, bryozoans, and serpulid worms.

Sequence analysis

The lithologically heterogeneous strata of the Punta Chueca terrace are subdivided into four depositional sequences by a series of laterally traceable discontinuity surfaces (Fig. 2). These surfaces are numbered successively PC-1, PC-2, etc. In individual measured sections, discontinuity

surfaces can be indicated by sharp lithologic contacts and can show disjunct grain sizes changes, burrowed horizons, and firmgrounds; individual features vary laterally. Depositional sequences are identified by the same number as their basal discontinuity surface. Each consists of a lateral array of sand, pebbly sand, and conglomeratic facies and records sediment accumulation along a water depth gradient.

The significance of the discontinuity surfaces as records of non-deposition is indicated by the onlap and downlap relations of overlying beds (arrows in Fig. 2) and by trace fossil evidence of sedimentary omission. Slight topographic relief on these discontinuity surfaces appears to be remnant depositional relief rather than erosional in origin. Each depositional sequence consists of a set of conformable beds. In the lower three sequences, these beds are flat-lying and largely parallel; the uppermost, PC-4 sequence consists of a series of large-scale (2 m) cliniform bed sets.

The distribution of hiatuses in the Punta

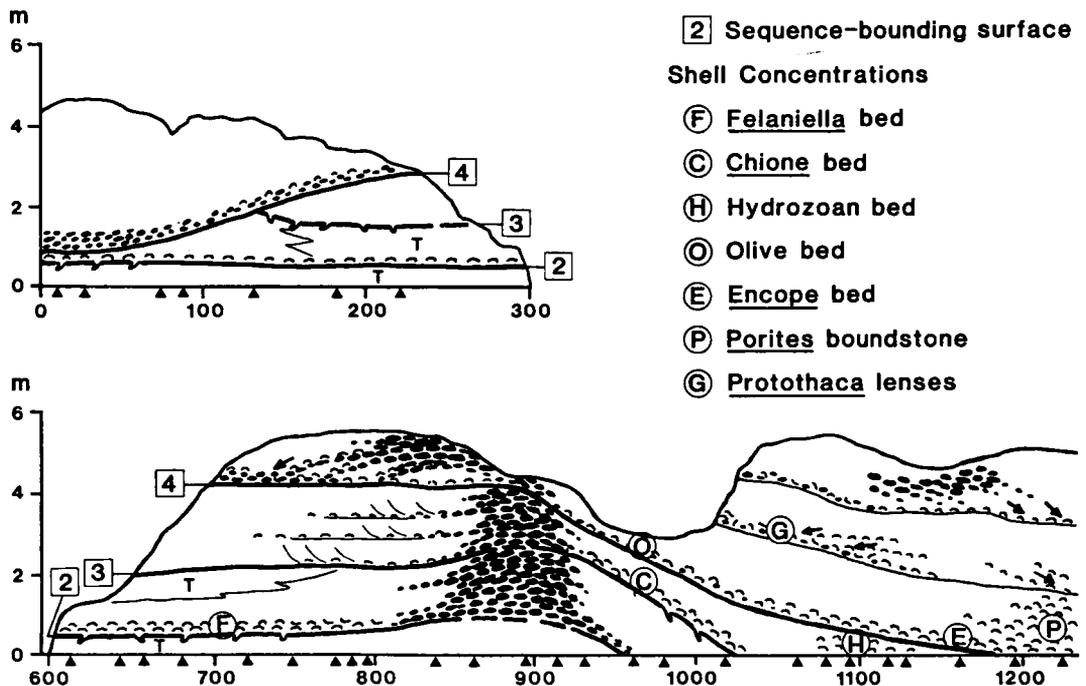


Fig. 2. Scaled cross-section of strata exposed in the Punta Chueca terrace, which cuts obliquely across the toe of the Sierra Seri alluvial fan. Distance along terrace measured from north to south in meters; black triangles indicate placement of measured sections; vertical exaggeration 25 \times . Each depositional sequence comprises a relatively symmetrical, lateral depth array of facies that can include upper-intertidal gneissic conglomerate (black coarse stipple), mid-intertidal pebbly to coarse arkosic sand, lower intertidal medium and fine arkosic sand, and shallow subtidal bioclastic sand and sandy boundstone (semicircle pattern). Only major skeletal concentrations are labeled (circled letter codes); T = *Tagelus* sand facies; arrows indicate lap out direction of beds.

Chueca record is clarified by transforming the vertical axis of the cross-section from thickness to time (Fig. 3). This replotting assumes that conformable bedding planes within each depositional sequence approximate isochronous events or time planes. A Wheeler diagram (Wheeler 1958) at such a fine stratigraphic scale is possible only because of the excellent and nearly continuous exposures along the modern shoreline. The hiatuses associated with the PC-2 and PC-3 discontinuities are of approximately the same magnitude when traced laterally and are each isochronous, whereas the PC-4 hiatus and hiatuses associated with clinoform set boundaries within the PC-4 sequence increase in magnitude and become younger in the direction of fan progradation.

Sealevel history

The net trend within the Punta Chueca deposit is one of regression (i.e. seaward retreat of the shoreline): in local vertical sections, continental alluvium overlies upper intertidal deposits which overlie lower intertidal and subtidal deposits, and sediments coarsen upwards overall. Shallowing-up, regressive depositional sequences are usually attributed to a fall in relative sea level, but can be generated during sealevel rise, fall, or stillstand depending on the rate of sediment input along the strandline. Other lines of evidence are needed

to determine relative and absolute sealevel history.

In the following discussion, we explore three possible sealevel scenarios in light of (a) coarsening-up grain size trends and thickness of cobble conglomerates, and (b) the mixed provenance of the sedimentary deposits. In the terrace, arkosic sediments dominate the finer-grained deposits and are derived from the nearby Sierra Seri; modern fan deposits are composed of virtually identical arkosic sediments and also contain granitic cobble-sized clasts. In contrast, cobble conglomerates in the marine terrace deposit are composed almost exclusively of metamorphic (gneissic) clasts which could only have been reworked from older terrace deposits. There are no local metamorphic sources, underscored by the lack of metamorphic clasts in modern fan deposits. The nearest mapped gneissic source area is in the northeastern Sierra Bacha, more than 200 km north of Punta Chueca (Gastil & Krumenacher 1977).

(1) *Relative sealevel rise.* – During a rise in relative sea level, landward migration (transgression) of the shoreface would erode all or part of older terrace deposits and leave a lag of reworked gneissic cobbles as a pavement or relatively thin tabular unit. Successive depositional environments would either deepen or shallow upward, depending on the rate of arkosic sediment supply

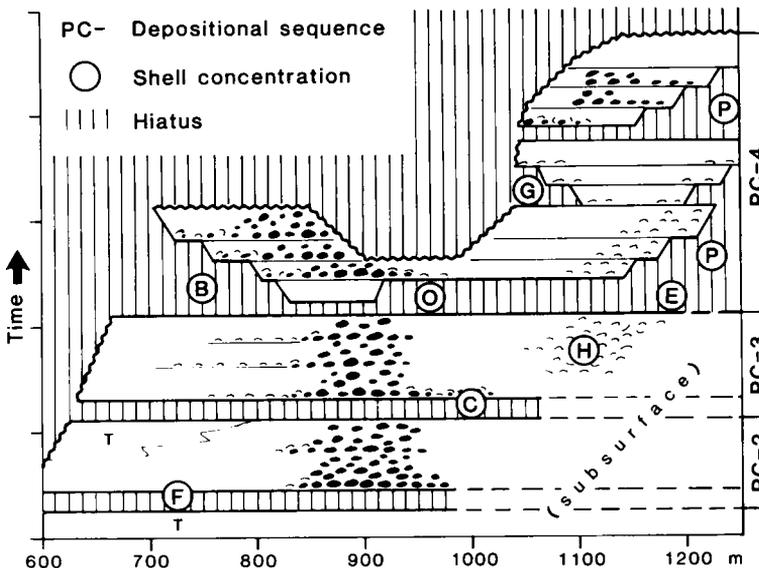


Fig. 3. Cross-section of southern part of Punta Chueca terrace scaled vertically to time. Lateral variation in duration of hiatuses is based on evidence of downlapping and onlapping beds. The occurrence of major skeletal concentrations is plotted for comparison. Hiatuses are not everywhere marked by skeletal concentrations (for example, northern trace of PC-3 surface), and not all skeletal concentrations lie along significant discontinuity surfaces (for example, hydrozoan bed in PC-3 sequence), but the association is extremely strong across all environments. Key to facies and skeletal concentrations as in Fig. 2; B = *Crucibulum* bed and foresets; wavy line = present day erosion surface.

relative to sealevel rise. However, because the potential source of gneissic cobbles is geographically limited to the eroding cliff-face and shifts landward with progressive shoreface erosion, conglomeratic units would decrease in thickness and in cobble size upward through the section regardless of whether the facies sequence was shallowing or deepening upward. Conglomeratic units developed higher within the sequence would be arkosic rather than gneissic in composition. These features are not observed in the Punta Chueca terrace.

(2) *Relative sealevel constant.* – If relative sea level does not change, and arkosic sediment input is low, the shoreface could erode landward and transgress older terrace deposits because of the concentration of high-energy waters along the shoreline. At any point offshore, sediments will fine upward as the source of cobbles becomes increasingly distant. The only way that gneissic cobble conglomerates could maintain or increase in abundance upward, such as observed in the Punta Chueca terrace, would be if, over time, cobbles could be transported for increasing distances offshore from the transgressive, erosional shoreface. This would require a change in conditions other than sealevel position alone. If relative sea level is constant and arkosic sediment input is moderate to high, the coastal alluvial fan shoreline would build outward (prograde and regress) and would have an exclusively arkosic composition.

(3) *Relative sealevel fall.* – Relative sealevel fall would cause downcutting of older fan deposits, supplying a constant and nearby source of reworked gneissic cobbles for accumulation in the currently-forming coastal alluvial fan. Progradation would generate a coarsening-up trend, with increasingly thick and coarse conglomerates of potentially gneissic, reworked composition. These features are observed in the Punta Chueca terrace.

A fall in relative sea level can result from several possible interactions between eustatic (absolute) sea level and local subsidence. However, if subsidence rates are assumed to have been constant, the regressive Punta Chueca deposits are best explained in terms of an acceleration in the rate of eustatic fall. During the initial period of still-stand or slow fall in eustatic sea level, at rates less than local subsidence, relative sea level was steady

or rose slightly, producing the fining-up arkosic sands of the PC-1 and PC-2 sequences. The *Felaniella* shell bed (described later in detail) that lies between these sequences probably does not signify any sealevel fluctuation, but simply the interruption of sediment accumulation by a series of major storm events. Acceleration in the rate of eustatic fall was characterized by cannibalization of older fan conglomerates and progradation of the PC-3 and PC-4 sequences, and, once the rate of eustatic fall exceeded local subsidence, by erosional incision of the entire Punta Chueca series yielding the modern terrace exposures.

Because gneissic conglomerates must be reworked from older terrace deposits, the regressive series of depositional sequences are unlikely to record simple autocyclic progradation of alluvial fan complexes in response to sediment supply from the Sierra Seri: some change in erosional base level is indicated. The inferred lowering of base level and any coincident change in sediment supply are most probably broadly eustatic in origin, given the Pleistocene age of the Punta Chueca deposits and pluvial conditions that characterize this period in southwestern North America. Structural evidence for syndepositional faulting within the terrace deposits is lacking.

Distribution and origin of hiatal shell concentrations

The Punta Chueca terrace contains a wide variety of skeletal concentrations that range from small localized clumps and pavements of shells to laterally extensive concentrations associated with discontinuity surfaces. All of the concentrations associated with discontinuity surfaces, as well as many of the smaller-scale concentrations associated with bedding planes, show evidence of concentration during episodes of reduced net sedimentation. Paleoecologic, taphonomic, and sedimentologic features indicate concentration during brief or repeated events of erosional reworking by storm(s) and more prolonged accumulation during periods of low net sedimentation.

Modes of formation of shell beds were inferred from the following taphonomic evidence: percentages of articulated bivalves, frequency of shell encrustation, shell condition, and close-packing. Sediments in the terrace are typically

massive and oxidized, so that sedimentary structures and authigenic mineral evidence of depositional history and sedimentation rates could not be used. Valve orientations recorded for *Chione californiensis* were predominantly concave-up in the finer-grained beds and random in coarser-grained beds and so were of limited use in hydrodynamic interpretation.

Chione californiensis and *Tagelus* sp. were counted to determine the percentage of articulated valves. Disarticulation of infaunal bivalves results from their exhumation and/or subsequent seafloor exposure by currents, bioturbators, predators, and scavengers, whose actions separate valves loosened by ligamental decay. The tendency of valves to disarticulate varies greatly among bivalves owing to differences in ligament type and hinge mechanism, hence our census of only two of the many bivalve species in Punta Chueca assemblages.

C. californiensis was also used to calculate the percentage of shells infested by epi- and endobionts. These encrusters included boring sponges (*Cliona*), boring polychaetes (*Polydora*), encrusting serpulid polychaetes, encrusting gastropods (Vermetidae and *Vermicularia*), coral (*Porites*), red algae, balanid and other barnacles, and bryozoans. Encrustation frequencies provide a measure of the duration of post-mortem exposure of shells on the sea floor, especially encrustation of infaunal shells which are out of reach of most encrusters while the organisms are alive in their burrows. Many encrusters are sensitive to even temporary burial by sediment and to movement of sediment across the sea floor.

Paleoenvironmental interpretations also reflect paleoecologic data. This includes bathymetric tolerance or preference of modern congeners, but reflects primarily information on life habits such as depth of burrowing, substrate requirements, and tolerance to turbidity or physical disturbance of the sea floor.

PC-1 and PC-2 Sequences – FELANIELLA shell bed. – The PC-2 Sequence comprises an onshore-offshore facies tract from upper intertidal fossiliferous gneiss-cobble conglomerate in the south, through mid- to lower intertidal pebbly, coarse-, medium-, and fine-grained sands with sparsely disseminated shell debris in the north (Fig. 2). Cobble conglomerates contain well-preserved faunas dominated by epifaunal species, including *Crucibulum*, *Crepidula*, red algae, and

barnacles. Intercalated sands are less fossiliferous, with comminuted shell debris and abundant red algae fragments. Conglomeratic sediments grade northward into sparsely fossiliferous medium- to coarse-grained sands containing articulated specimens of the infaunal razor clam *Tagelus* in life position and shallow shell-filled pits formed by bottom-feeding rays. In the northernmost exposures of the PC-2 sequence, the *Tagelus* sand layer is overlain by an algal-rich, sparsely fossiliferous coarse-grained sand, which probably represents a low-tide strandline or shallow subtidal bar.

The most laterally extensive and densely packed fossil concentration within the sequence is the *Felaniella* bed, which lies along the basal PC-2 discontinuity (Fig. 2). The bed extends for 300 m and is 15–25 cm thick. Shells are densely



Fig. 4. *Felaniella* bed at the base of the PC-2 sequence, characterized by small *Felaniella* articulated *Tagelus* rotated out of life position, and clusters ofregarious tube forming *Vermicularia*; hammer head is 15 cm.

packed (55%) and dominated numerically by the small (1.5 cm) infaunal unguinid bivalve *Felaniella*. Visually, however, the assemblage is dominated by larger specimens of articulated *Tagelus* and other bivalves, and by the gastropods *Cerithium* and *Turritella*. *Tagelus* typically lie horizontally within the bed, rotated out of life position as are many other bivalves. Species composition is consistent along the length of the bed, although the relative abundance of individual species does vary. Locally, the basal contact of the shell bed (PC-2 discontinuity) is burrowed; *Tagelus* occupy some of these <20 cm unbranched tubes. Clusters of epifaunal vermiculariid gastropods occur in life position locally along the base of the *Felaniella* shell bed and indicate a period of omission or low sedimentation that preceded the major interval of shell accumulation.

The *Felaniella* bed (Fig. 4) records concentration by storm reworking, possibly by multiple events, as indicated by taphonomic evidence from shells within the bed. Forty-six percent of the *Tagelus* and 33% of the *Chione* valves are articulated (Table 1). These high percentages of articulation and the random azimuthal orientation of bivalves (as plotted on a stereonet) suggest exhumation, reorientation, and rapid reburial of the bivalves. Other evidence indicating relatively rapid reburial is the relatively low frequency of encrustation (29%) and the abundance of whole shells in good condition (unworn and unabraded). The tabular geometry of the bed is also consistent with an interpretation of shell concentration by storms, which repeatedly concentrated shells down to the same reference horizon.

The *Felaniella* bed overlies fine-grained, locally clayey sands of the PC-1 sequence. These sands contain articulated *Tagelus* preserved in life posi-

tion in their burrows. The lower surface of this layer is covered by modern beach sands.

PC-3 Sequence - CRUCIBULUM pavements, hydrozoan bed, CHIONE bed. - The PC-3 sequence contains a nearly symmetrical north-south tract of upper intertidal to shallow subtidal conglomerate, sand, and bioclastic sand facies. The PC-3 sequence boundary is fairly indistinct. In the south and extreme north, it is characterized by burrows; in the central terrace by a pavement of *Crucibulum*; also in the north by worn spheroidal clusters of serpulid worm tubes; and in most outcrops, by a sharp lithologic change. The upper-intertidal cobble facies contains a similar fossil assemblage to that of the PC-2 conglomeratic facies, and grades both to the north and south into algal-rich mid-intertidal, sparsely fossiliferous pebbly coarse-grained sands. The proximal sands to the north are characterized by large-scale (30 cm), south-dipping cross-sets, and by pavements of concave-down and randomly oriented *Crucibulum*, two beds of which are lateral extensions of gravel tongues from the conglomeratic facies. The southern proximal sand facies also contains *Crucibulum* pavements which pinch-out against the conglomeratic facies. These sands grade laterally into extremely fossiliferous low- to subtidal medium- to coarse-grained sands (hydrozoan bed).

The hydrozoan bed is the thickest concentration (45-55 cm) of shell material within the PC-3 sequence and extends for 160 m along the southern part of the terrace. Well-preserved, uniformly dispersed whole fossils constitute about 45% of the bed; comminuted shells comprise 50% of the matrix. The diverse molluscan assemblage includes (in numerical rank order) *Chione*, *Fel-*

Table 1. Summary of taphonomic features. Sample sizes range from 84 to 244 specimens per bed except for asterisked beds, which lack sufficient numbers of *Chione* for quantitative comparison.

Inferred origin Shell bed	% Articulated (<i>Chione</i>)	% Encrusted (<i>Chione</i>)	Shell condition	Thickness (cm)
Single or multiple storm events				
<i>Felaniella</i> bed	33	29	good	15-25
<i>Chione</i> bed	53	16	excellent	15-30
Hydrozoan bed	44	31	good	50-55
<i>Encope</i> bed	18	20	good	25-30
Starved or bypassed				
Olivid bed	19-22	45-60	worn	15-20
<i>Protothaca lenses</i> *	very low	high	very worn	25-45 max.
<i>Porites</i> boundstone*	very low	high	very worn	35-75

aniella, *Tellina*, Olivid gastropods, *Trachycardium*, and conspicuous *Laevicardium*, plus red algae clumps, hydrozoans, and bryozoans. The shell bed has a high percentage of articulated *Chione* valves (44%), relatively low levels of encrustation (31%), and most shells are in good condition (Table 1). These features and the thickness of the bed suggest concentration and amalgamation of multiple shell layers by successive storm events. Post-event bioturbation, as evidenced by the presence of deep-burrowing bivalves, may explain the absence of scour surfaces within the shell bed.

A thinner and less laterally extensive shell bed within this sequence is the *Chione* bed, which lies along the PC-3 discontinuity and pinches out to the north in the conglomeratic facies. The *Chione* bed is 15–30 cm thick and extends for 70 m before disappearing beneath modern beach sands. Shell material is densely packed (45%) – the bed is bioclast-supported – and bivalves are randomly oriented. Articulated and disarticulated specimens of *Chione* dominate the concentration; *Conus*, *Cerithium*, *Crucibulum*, and *Tellina* are associated. Rare cobbles in the pebbly, poorly sorted coarse-grained sand matrix are encrusted by red algae, bryozoans, and barnacles. The *Chione* bed is interpreted as the record of storm activity based on a very high percentage of articulated valves (53%), very low frequency of encrustation of shells (16%), and excellent physical condition of shells (Table 1). The dense packing of shells and their rotation out of life position is evidence that the concentration did not accumu-

late passively but involved reworking and selective redeposition of skeletal material. Horizontally-oriented, apparently in-situ vermiculariid aggregations are locally very common along the top of the bed, where they almost bind the shell material together. These aggregations indicate a period of omission or very low net sedimentation following the concentration of other molluscan shell material and before the resumption of significant net terrigenous sedimentation.

PC-4 Sequence – CRUCIBULUM foresets, PROTO-THACA-gravel lenses, Olivid-ENCOPE bed, PORITES biostrome. – The PC-4 sequence comprises a diverse facies tract of upper-intertidal cobble conglomerates, mid- and lower-intertidal sparsely fossiliferous coarse-grained sands, and shallow subtidal boundstones formed by the encrusting coral *Porites*. These facies are repeated in each of a series of laterally amalgamated, large-scale (1–2 m) clinofolds, which prograde south of the main conglomerate body. On the north side of the conglomerate body, spectacular large-scale (2 m) foresets of gravel and *Crucibulum* shells lap onto the continuation of the PC-4 surface (Fig. 5). The lithology and faunas of all of the upper- to mid-intertidal conglomerates and sands are similar to those described in the other sequences.

Major clinofold boundaries south of the main conglomerate body are lagged by thin, anastomosing lenses (maximum 30 cm thick and 100 m long) of fossiliferous gravels encrusted by barnacles and red algae. The fossil assemblage



Fig. 5. Large-scale foresets of gravel and convex-up limpets (*Crucibulum*) in the PC-4 sequence. These foreset shell pavements lap down onto the PC-4 discontinuity surface (arrow) and converge into a bottomset gravel bed, whose interstices are packed with worn and randomly oriented *Crucibulum* (B concentration in Fig. 3). Cliff height above beach is 7–8 m.

includes broken, worn, and encrusted disarticulated specimens of the bivalve *Protothaca* and the gastropods *Crucibulum*, *Crepidula*, and *Tegula*, all of which characterize gravel and hard-bottom substrata. The gravel lenses lap down onto the PC-4 discontinuity surface. The low frequency of articulation and poor condition of shells indicate prolonged exposure and gradual accumulation of shells on the sea floor.

The PC-4 discontinuity surface is identified by the downlapping termination of overlying strata, especially the gravel lenses. In the southern part of the terrace, the surface is marked by a thin (15–30 cm) concentration of gravel and shell material (Olivid shell bed) which grades laterally into a gravel-poor, slightly thicker (25–30 cm) and denser concentration of shell material (*Encope* bed). Maximum size of gravel decreases to the south along this layer, and faunal composition varies accordingly.

The Olivid shell bed extends 140 m to the south beyond which it pinches out in the main conglomerate body (Fig. 2). Shell abundance increases from 5–10% in the north to 35% in the south concomitant with decreasing size and close-

packing of gravel. Shells are randomly oriented in the interstices of the gravelly matrix. *Protothaca* and *Chione* are the most abundant species, but shells of the gastropods *Oliva* and *Olivella* are also common and distinctive. Encrustation is very common (45–60%), relatively few *Chione* are articulated (20%), and shells are worn and abraded (Table 1). These taphonomic features indicate that shell material was exposed on the sea floor either continuously or episodically after death, and that permanent burial was delayed. The Olivid shell bed formed gradually as a result of sediment starvation or bypassing.

The Olivid shell bed persists downdip into the more densely fossiliferous *Encope* bed, which can be traced an additional 160 m in the terrace. The *Encope* bed contains densely packed whole fossils (55%) in a matrix of fine-grained sand and 50% comminuted shell (Fig. 6); disarticulated bivalves are predominantly concave-up. The molluscan assemblage includes *Chione*, *Tellina*, *Felaniella*, Olivid gastropods, *Conus*, and *Trachycardium*; the sand dollars *Encope grandis* and *E. micropora*, typically flat-lying or slightly oblique in orientation, occur throughout this bed and form



Fig. 6. Densely packed bioclastic fabric of the *Encope* bed, base of PC-4 sequence. Pencil is 14 cm long.

a distinct layer where they are particularly abundant. Encrustation frequency is low (20% maximum) indicating rapid burial, but articulation frequency is also low (18%) suggesting multiple reworking events (Table 1). This difference in exposure time of shell material at the sea floor probably reflects the difference in substratum between the stable gravels of the Olivid shell bed and easily-entrained sands of the *Encope* bed.

The *Porites* boundstone facies is present only in the most downdip, southern reaches of the PC-4 sequence, and rests on the *Encope* bed. It is 35–75 cm thick and can be traced for 80–100 m before dipping below modern beach sands. *Porites* dominates the bed, occurring as low mounds which encrust both cobbles and shells (Fig. 7). Whole and broken specimens of *Chione*, *Turritella*, *Conus*, *Trachycardium*, and *Ostrea* are common; bryozoans, *Encope*, and small colonies of the coral *Astrangia* also occur. The matrix is composed of pebbly coarse-grained sand, abundant red algae fragments, and comminuted shell. A similar *Porites*-rich facies recurs in southernmost exposures of each of the clinoform bed sets of the PC-4 sequence (Fig. 3). The extremely high frequency of encrustation by sediment-sensitive corals as well as other endo- and epibionts in these facies and the very low articulation frequency for infaunal bivalves indicate accumulation under prolonged conditions of low net sedimentation.

Implications for analysis of stratigraphic hiatuses

Owing to the excellent exposure of downlapping and onlapping beds and discontinuity surfaces, and thus independent physical stratigraphic evidence for hiatuses in terrigenous sediment accumulation, Punta Chueca deposits provide an excellent setting in which to test (1) the strength of the association of skeletal concentrations with episodes of non-deposition, and (2) the utility of taphonomic evidence for reconstructing detailed histories of non-depositional episodes.

Not all discontinuity surfaces were marked by skeletal material, and not all shell beds record low net sedimentation (for example, shell-filled ray pits in the PC-2 sequence are biogenic in origin). However, the majority of concentrations did form during breaks in 'normal' deposition, ranging from brief events of storm reworking to repeated cycles of storm exhumation to burial and prolonged conditions of very low net terrigenous sedimentation (Table 1). These concentrations are associated with relatively obvious sequence boundaries (Figs. 2 & 3) as well as with lithologically obscure bedding surfaces. Although not all hiatuses can be detected, shell concentrations, when present, provide good clues to the stratigraphically most significant surfaces.

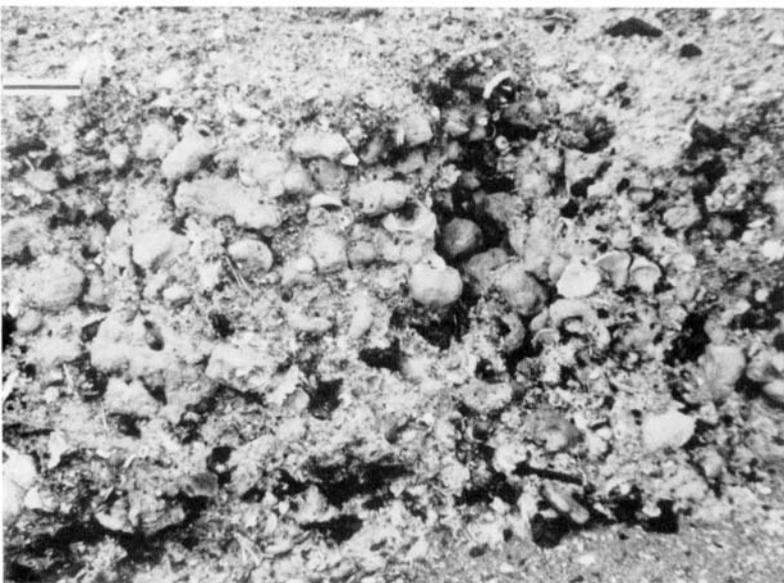


Fig. 7. Boundstone facies of the PC-4 sequence, produced by low-mounding colonies of the coral *Porites*. Scale is 10 cm.

Shell bed thickness can be a function of many factors other than the period of bioclast accumulation, and so is probably an unreliable criterion for the duration of associated hiatuses. For example, the most impressive and thickest shell beds are associated with downlap and onlap evidence of non-deposition (*Crucibulum* bed B along PC-4 discontinuity; *Chione* bed C, *Olivid-Encope* bed O & E), or are developed in the most offshore reaches of depositional sequences (hydrozoan bed H and *Porites* bed P) (Fig. 3). However, concentrations associated with concordant sequence boundaries (*Felaniella* bed F, *Crucibulum* pavements within PC-3 sequence; Fig. 3) can be but are not always thinner, suggesting that any correlation between shell bed thickness and estimated period of non-deposition is weak.

Some shell beds (for example, the *Porites* bed) may reflect elevated levels of shell production and/or enhanced shell preservation in addition to low net terrigenous sedimentation. Such a correlation and possible feedback (Kidwell 1986) between high skeletal input (from either local or distant sources) and sedimentary hiatuses (erosional or omissional) would increase the likelihood that skeletal material will be associated with discontinuity surfaces. These shell beds would still be referred to as hiatal shell concentrations.

In the Punta Chueca deposits, paleoecological

and taphonomic evidence in addition to stratigraphic context indicate that shell-rich beds were not produced by high rates of skeletal input alone. Hard-bottom epifauna (both free-living and attached) and soft-bottom infauna are strongly correlated with the conglomeratic and fine sand sediment types they prefer, and the ecologically unrelated faunas are rarely found in mixed assemblages even though substratum type changes laterally very rapidly. The strength of the correlation between preferred substratum and embedding matrix for the skeletized fauna indicates that shell transport between adjacent habitats was minimal and that shell concentrations were formed from essentially local death assemblages rather than by the episodic injection of abundant, exotic bioclasts (Beckvar, 1988).

Taphonomic and paleoecologic analysis of concentrated skeletal material also reveals the detailed histories of non-depositional episodes in the record, histories that are compatible with independent evidence based on physical stratigraphic relations of shell-rich and shell-poor beds (Table 2). The *Felaniella* and *Chione* shell beds, for example, are both storm concentrations, but have qualitatively different histories in detail (Figs. 8F & C). In the former, a period of omission, evidenced by firmground burrow systems and large clusters of in-situ vermiculariid gastropods, preceded the main period of storm reworking of infaunal death assemblages. Each

Table 2. Taphonomic and paleoecologic evidence from skeletal concentrations for the short-term sedimentary dynamics of hiatuses.

Attribute	Interpretation
Typical burrowing depth, rate of growth, and opportunism of infaunal assemblage	Thickness and relative permanence of depositional increments
Typical burrowing depth of those infauna preserved articulated but reoriented	Sediment thickness reworked during erosional event
Draft-filling of articulated shells; encrusted interiors of shells	Exhumation (reworking) and post-mortem exposure of shells, in contrast to reorientation of buried shells by bioturbators
Recurrent assemblages of reoriented infauna within single skeletal concentration, many shells disarticulated; minor scour surfaces within concentration	Multiple events of erosional reworking, i.e. dynamic bypassing
<i>Glossifungites</i> (firmground) trace assemblage; high disarticulation and encrustation of paving shells	Duration of omissional events of sediment starvation or bypassing
Relative abundance of benthos requiring or tolerating shell gravel conditions	Ecological persistence of dead shells on or just below sediment surface, i.e. bypassing or shallow-water starvation

episode or at least the final episode of erosion and shell concentration was followed immediately by deposition of a relatively thick increment of sediment, which sequestered shells from encrusters and mechanical destruction on the sea floor and favored resumed colonization by deep-burrowing *Tagelus* and other infauna. In contrast, storm-concentrated shells of the *Chione* bed (Fig. 8C) were buried only under a thin and patchy layer of sediment that protected shells from disarticulation and encrustation but allowed settlement of vermiculariid gastropods, which effectively sealed off the shell bed and made it less susceptible to erosional reworking.

The laterally intergradational *Encope* and Olivid shell beds also make an interesting comparison (Figs. 8E & O). Low articulation frequencies indicate shell exhumation and reworking of both the shallower-water Olivid assemblage and deeper-water *Encope* assemblage. However, sedimentary increments were thinner and more temporary during accumulation of the Olivid shell bed: shells are worn and extensively encrusted

(Table 1), and species are primarily epifauna and very shallow-burrowing infauna adapted to shell gravel conditions (e.g. *Chione*, *Protothaca*). The lower encrustation frequencies and better preserved shells of the *Encope* bed, on the other hand, suggest more continuous protection of dead shells by sediment, and the representation of deeper-burrowing and soft-substratal infaunal species in the assemblage (including *Encope*) suggests that temporary sedimentary increments were also relatively thick. This gradient in the thickness and relative persistence of temporary depositional increments parallels the gradient in water depth and energy.

In other beds it is possible to estimate depths of erosional reworking of the substratum. For example, deep-burrowing *Panopea* are preserved in life position in the hydrozoan bed, indicating that erosional events worked less than c. 20 cm of sediment. Incorporation of rotated *Tagelus* in the *Felaniella* bed suggests erosional reworking (and intervening deposition of sedimentary increments) of perhaps 20–30 cm of sediment per

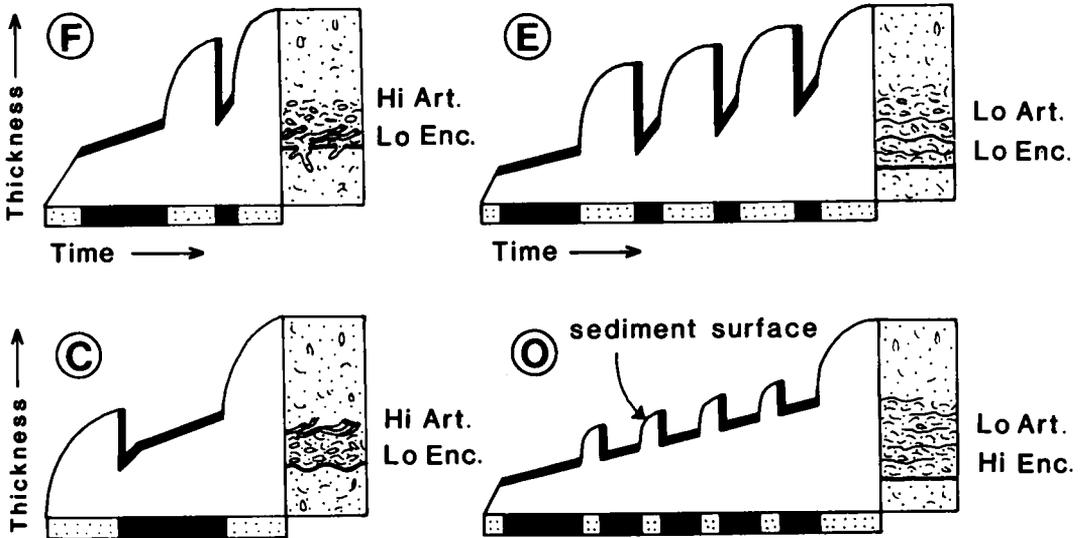


Fig. 8. Detailed histories of accumulation for major skeletal concentrations in the Punta Chueca deposits. Vertical axis of each graph is thickness of accumulated sediment; schematic column along right edge depicts resultant stratigraphic record. Horizontal axis is elapsed time; black segments are hiatal periods of terrigenous omission (sediment starvation or bypassing) or erosion during which skeletal material is concentrated; stippled segments of time bar are periods during which terrigenous sediment accumulates, at least temporarily, allowing colonization by infauna. Note in schematic columns that not all of these depositional increments are preserved. In the *Felaniella* bed (F), an interval of sedimentary omission precedes erosional reworking and concentration of infaunal shell material, whereas in the *Chione* bed (C), omission follows erosional reworking. Fossil assemblages in both skeletal concentrations are characterized by high articulation and low encrustation frequencies. *Encope* (E) and Olivid (O) shell beds both record multiple reworking events (low articulation frequencies); depositional increments were thinner and more ephemeral during hiatal accumulation of the Olivid bed than during accumulation of the deeper subtidal *Encope* bed.

event. Geopetal, draft fillings of articulated shells indicate that shells were exhumed and filled while lying on the sediment surface, and that they were not simply rotated within the sediment by bioturbating organisms. Bryozoan-encrusted interiors of sediment-filled articulated *Chione* also indicate exhumation and exposure of shells on the sea floor before final burial.

Conclusions

(1) Sequence analysis, based on the identification of through-going discontinuity surfaces, is a practical approach to stratigraphic analysis in the complex marine-to-nonmarine transitions of coastal alluvial fans. However, successful sequence subdivision and correlation using physical stratigraphic relations requires excellent exposure. Individual discontinuity surfaces vary greatly in features over short distances on the order of 100's of meters; depositional sequences are similarly variable in facies.

(2) Based on the provenance of conglomerates derived from older fans and the progradation of depositional sequences, the regressive Punta Chueca deposits accumulated during a period of accelerating fall in eustatic sea level. Without compositional evidence for the incorporation of reworked cobbles in the modern terrace, the regressive stratigraphic record would have been ambiguous in terms of sealevel history.

(3) The regressive Punta Chueca deposits contain abundant shells in a variety of concentration types, ranging from small-scale biogenic shell lenses produced by bottom-feeding rays, to laterally more extensive hiatal shell concentrations formed during periods of low and negative sedimentation rates. Hiatal concentrations range up to 75 cm thick and formed under conditions of sediment starvation, erosional reworking, and winnowing of the sea floor, as indicated by the relative frequencies of articulated, encrusted, and worn infaunal bivalves. Although coarse-grained deposits may seem to be diagenetically and taphonomically unlikely settings for the preservation of abundant skeletal material, the Punta Chueca example demonstrates that when low-energy conditions prevail in the shallow marine environment, coastal alluvial fan deposits can provide excellent sources for paleobiologically significant macroinvertebrates.

(4) Not all discontinuity surfaces in the Punta Chueca terrace are marked by hiatal shell concentrations, nor do all shell concentrations indicate major discontinuities. For example, although marked by a significant shell concentration in the southern part of the terrace (*Chione* shell bed), in northern exposures the PC-3 surface is characterized by only a sparse pavement of *Crucibulum* that is indistinguishable from *Crucibulum* pavements on bedding planes higher within the sequence (Fig. 3). Those bedding plane concentrations mark only diastemic hiatuses in the record. Consequently, although the association of skeletal concentrations with stratigraphically significant discontinuity surfaces is not perfect it is extremely strong, sufficiently strong to argue that skeletal concentrations provide excellent clues to the possible presence of discontinuities and good corroboration where other evidence for discontinuities is ambiguous.

(5) Taphonomic and paleoecologic analysis of hiatal skeletal concentrations can provide useful insights into the dynamics of non-depositional episodes, that is, of the relative frequency and magnitude of erosional, depositional, and omission events during the period of low terrigenous accumulation. In the Punta Chueca deposits, inferred dynamics were in all instances consistent with the physical stratigraphic context of the shell concentration and provided additional paleo-environmental insights. For example, concentrations associated with stratigraphic downlap (*Porites* boundstone, *Protothaca* gravel lenses, and *Crucibulum* bed, all of the PC-4 sequence) indicate accumulation under conditions of sediment starvation; concentrations associated with stratigraphic onlap and concordance (along PC-2 and PC-3 surfaces) reveal repeated minor events of erosional reworking and winnowing; and laterally intergradational shell beds (e.g. *Olivid* and *Encope* shell beds along the PC-4 discontinuity) show differences in frequency and magnitude of depositional increments consistent with the paleobathymetric gradient in water energy, as indicated by the change in elevation and terrigenous grain size (Fig. 8). Relatively few and simple taphonomic criteria are required to reconstruct sedimentary dynamics in detail from hiatal skeletal concentrations (Table 2, and Kidwell & Aigner 1985), and yield information comparable to that derived from taphonomic and diagenetic analysis of hardgrounds. In contrast to

earlier work (Kidwell & Aigner 1985), this study demonstrates more directly through independent physical stratigraphic evidence that taphonomic criteria are reliable for the interpretation of depositional hiatuses, and that they pertain to a broader variety of shallow marine environments.

These results suggest that shell concentrations can provide excellent criteria for the identification and interpretation of hiatuses in shallow marine records. In situations where exposures are few or small, highly visible skeletal concentrations would provide good clues to discontinuity surfaces of potential stratigraphic value. Moreover, in combination with conventional physical stratigraphy, taphonomic analysis provides a powerful means of reconstructing the sedimentary dynamics and origin of unconformities and condensed sequences.

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