Jeffrey A. May
Marathon Oil Company
P. O. Box 269
Littleton, Colorado 80160

John E. Warme
Department of Geology
Colorado School of Mines
Golden, Colorado 80401

2

SYNCHRONOUS DEPOSITIONAL PHASES IN WEST COAST BASINS: EUSTASY OR REGIONAL TECTONICS?

ABSTRACT

Numerous factors (e.g., sea level, tectonics, subsidence, climate, oceanography, sediment input) influence the timing and nature of deposition. From studies of reflection seismology, Vail and his colleagues assert that global fluctuations of sea level are the dominant control. Others argue about these eustatic changes, questioning their timing, magnitude, causes, effects on sedimentation, even their existence.

We address this controversy, relying primarily upon field study. We examine the controls on stratigraphic development along a tectonically active margin. In the San Diego Embayment, an asymmetric depositional cycle characterizes the Middle Eocene forearc stratigraphy. This cycle, hundreds of meters thick, is chronostratigraphically correlative with a sea-level supercycle. The thin, basal, retrogradational phase corresponds to worlwide sea-level rise. The overlying, thick, progradational sequence developed during a global highstand. Submarine-fan progradation punctuates the depositional cycle and correlates with a minor eustatic drop.

Coeval asymmetric cycles occur in coastal basins from Oregon to Baja California. In examining relative rates of tectonics and subsidence in forearc basins versus rates of sea-level change, eustasy appears to be the primary control on stratigraphic development in these numerous isolated basins. Field-based facies analysis thus supports utilizing sea-level and coastal-onlap curves in stratigraphic prediction.

INTRODUCTION

A lively controversy has been brewing even since Vail *et al.*'s (1977b) series of publications on seismic stratigraphy. Unquestionably, Vail and his Exxon colleagues started a revolution in geologic thinking. Their concept of "depositional sequence" (i.e., a genetically related sedimentary package having time-stratigraphic significance) provides a novel means for analyzing basin evolution. However, the cornerstone of this paradigm, that worldwide sea-level fluctuation is the primary agent controlling the development of globally synchronous depositional sequences, has come under intense scrutiny. Fundamentals of eustatic changes, including their timing, magnitude, causes, effects on sedimentation, even their existence, are at the focus of debate.

The principle of worldwide, cyclic development of sedimentary packages is well established in the geologic literature (cf. Suess, 1906; Barrell, 1917; Grabau, 1940; Kuenen, 1940, 1954; Umbgrove, 1942; Sloss, 1972). The utility of global cyclicity in interregional correlation and hence, stratigraphic prediction, is attractive, indeed. However, the controls on the formation of stratigraphic sequences are exceedingly complex. The nature and the timing of deposition and erosion within a single sedimentary basin are variably affected by worldwide and local tectonics, worldwide and local sea-level fluctuations, climate and oceanography, basin geometry, subsidence history, and sedimentary processes. Nevertheless, Vail and his colleagues contend that eustasy is *the* primary control on depositional development in basins worldwide and can be discerned from seismic-reflection data. Unfortunately, some of the evidence supporting the basic tenets of this seismic-stratigraphic method remains proprietary.

One purpose of our study was to test the "Vail model" of basin-margin sedimentation dominated by eustatic control. Rather than relying on remotely sensed seismic profiling, this analysis is based upon field study. We focused upon upper Lower to lower Upper Eocene units in the San Diego Embayment, a forearc basin along the tectonically active West Coast margin of the United States. Based upon outcrop examination, we identified various facies and delineated regional unconformities. Extensive nannoplankton and foraminiferal control aided precise dating and the recognition of depositional breaks, erosional surfaces, and abrupt bathymetric changes. Vertical and lateral stratigraphic patterns were arranged into depositional packages. Finally, we constructed a curve of relative sea level for the basin under study. Timing of our local sea-level changes correlates exceptionally well with those defined by others as global sea-level fluctuations. Furthermore, in comparing the local depositional phases with other isolated coastal basins from Oregon to Baja California, we can identify coeval stratigraphic development.

SEA-LEVEL CHANGES

Seismic stratigraphy has developed into a major interpretive device, whether on the scale of regional basin analysis or in the development of individual exploration prospects. However, arguments abound whether the limitations of seismic-sequence analysis, including our understanding of the controls on seismic-sequence development, preclude its usefulness in stratigraphic prediction. One area of contention concerns the cause(s) of eustasy. The magnitudes, rates, and frequency of worldwide sea-level fluctuations must all be accounted for. Vail *et al.* (1977b) defined short-term sea-level changes, "paracycles," of tens to 100 m on the order of 1–2 my in duration. "Supercycles," long-term variations of 100–400 m, occur over 15–20 my. Many workers (e.g., Pitman, 1978; Donovan and Jones, 1979; Watts, 1982; Watts *et al.*, 1982; Thorne and Watts, 1984) counter that mechanisms responsible for these numerous eustatic shifts are not known. Fleming and Roberts (1973), Donovan and Jones (1979), Morner (1980, 1981), and Pitman and Golovchenko (1983) list factors influencing ocean volume and (hence, sea level), and estimate rates and magnitudes attributable to each. They calculate that changes in oceanic-ridge volume may be the sole control on large eustatic shifts, potentially altering sea level by up to 500 m over a period of approximately 70 my. The duration of this mechanism, though, prevents its accounting for numerous rapid eustatic rises and falls. Instead, glaciation is most likely the dominant cause of rapid eustatic fluctuations, accounting for changes of 150–250 m at rates as high as 10 m/1000 y. However, glacial fluctuations are regarded by most workers to have been nonoperative over much of geologic time. Nonetheless, Vail and his colleagues portray numerous major sea-level shifts even during times of equable climates.

Another dispute entails the stratigraphic record of sea-level change. Sediment accumulation along a continental margin is dominantly a function of the interaction among basement subsidence, sediment supply, and eustasy. Simply equating stratigraphic progradation and retrogradation to sea-level fall and rise, respectively, may be fallacious in many cases. Sloss (1962), Pitman (1978, 1979), Pitman and Golovchenko (1983), and Parkinson and Summerhayes (1985) have demonstrated that simply altering the *rate* of a sea-level fall or rise may cause quite variable stratigraphic patterns. A stratigraphic stillstand or progradation can occur even during rising sea level if sediment input or basic-margin uplift is sufficiently rapid. Conversely, an apparent stillstand or retrogradation may ensue during dropping sea level given an equal or greater rate of subsidence. Thus, when a sea-level change is synchronous worldwide, nonsynchronous transgressive and regressive events may be recorded along various margins (Pitman and Golovchenko, 1983; Parkinson and Summerhayes, 1985).

Watts (1982) and Watts *et al.* (1982) further argue that these stratigraphic events are not responding to sea level at all, but in actuality record rifting and subsidence. They assert that coastal onlap is the depositional result of progressive lithospheric cooling and later flexural loading along passive continental margins. They assert that the apparently synchronous worldwide sea-level changes are fallacious; instead, rifting at similar times at several widely separated margins controls correlative stratigraphic development. Watts (1982) and Watts *et al.* (1982), however, only account for a few of the Vail *et al.* (1977b) eustatic events. They also fail to address Vail *et al.*'s (1977b) assertion that even along active margins, patterns of deposition and erosion are synchronous with those along passive margins.

Bally (1980), Watts (1982), and Watts *et al.* (1982) may actually strengthen the argument for a primary eustatic control on sedimentation. They demonstrated the close thing between tectonic episodes and synchronous worldwide deposition and erosion. These workers may have inadvertently revealed a cause-and-effect relationship between plate tectonics and eustasy (see Valentine and Moores, 1970). Global tectonics directly and indirectly plays some role in both ocean-water and ocean-basin volume (Fig. 2-1). As Kominz (1984) poionts out, the *interaction* of this multitude of secondary events may account for the many rapid and precipitous sea-level variations of Vail *et al.* (1977b). Major glacial and ocean-ridge fluctuations have undoubtably caused some eustatic changes, but the additive effects of (and interference among) other factors (Fig. 2-1) have played their part: plate reorganization (with collision, subduction, opening of seaways, and closing off or opening of basins), hotspot formation and cessation, orogeny, and epeirogeny with the concomitant change in sediment flux (input to *and* removal from the ocean basins), basin filling or desiccation, changing oceanic and atmospheric circulation or climatic patterns, waxing and waning of polar ice sheets, and possible variations in ocean-level distribution (geoidal eustasy). Until more is known about the interrelationships of these many components, it may be premature to discount the Vail *et al.* (1977b) concept of eustasy simply because the underlying causative mechanisms are not readily apparent.

Finally, Vail *et al.* (1977b) added more controversy by originally portraying

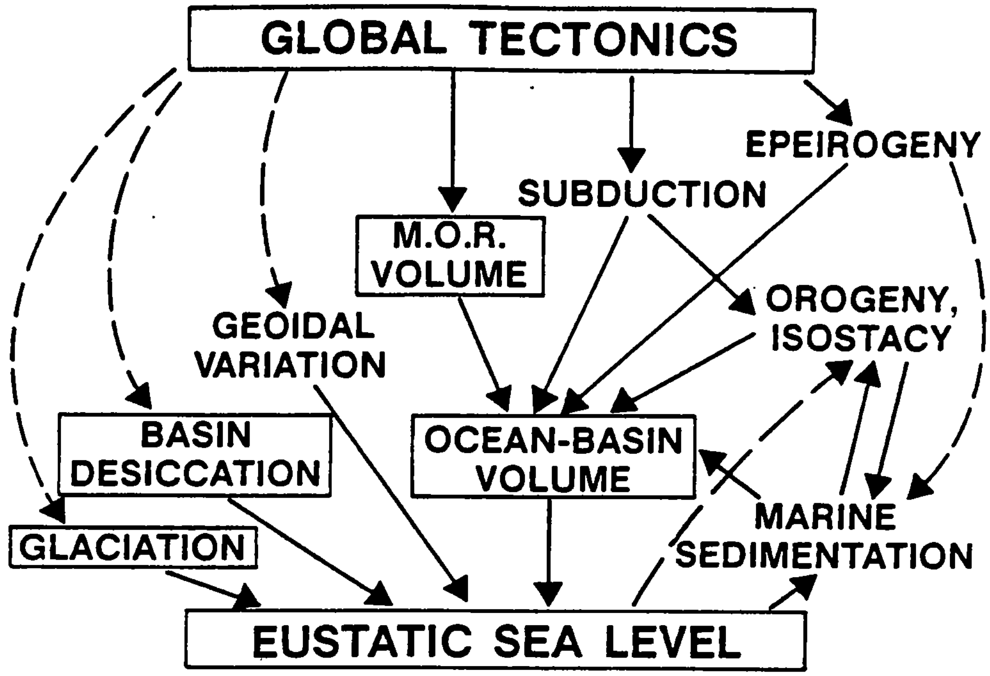

Fig. 2-1. Interrelationships of some probable factors leading to eustatic sea-level fluctuations. The major controls on the volume of ocean water and of ocean basins are enclosed in boxes. Global tectonics is the overriding influence, producing direct (solid lines) and indirect (dashed lines) events. M.O.R., mid-oceanic ridge.

"sea-level" curves which were asymmetric, with long-term transgressions and stillstands followed by apparently instantaneous regressions. These workers now recognize that the curve shape is an artifact of nearshore sedimentation. More recent publications (Vail and Todd, 1981; Vail *et al.*, 1981, 1984; Mitchum, 1984) have renamed these diagrams "coastal-onlap" curves. Upon sea-level fall, unconformable truncation of stratigraphic successions may occur. Utilizing this erosional surface as a eustatic time line produced the diagrammatically instantaneous "sea-level regressions" of Vail *et al.* (1977b). A true eustatic curve is probably more sinusoidal (e.g., Hallam, 1978, 1981; Matsumoto, 1980; Vail *et al.*, 1984). The asymmetric coastal-onlap curve, in contrast, portrays the nonuniform depositional response to eustatic rises and falls.

DEPOSITIONAL SIGNATURE

Regional Setting

Our study area comprises approximately 90 km^2 located north of San Diego, California, within the Del Mar and La Jolla Quadrangles (Fig. 2-2). Cretaceous and Cenozoic sedimentary deposition took place along the narrow, steep coastal plain and continental margin of a forearc basin (Kennedy and Moore, 1971). The

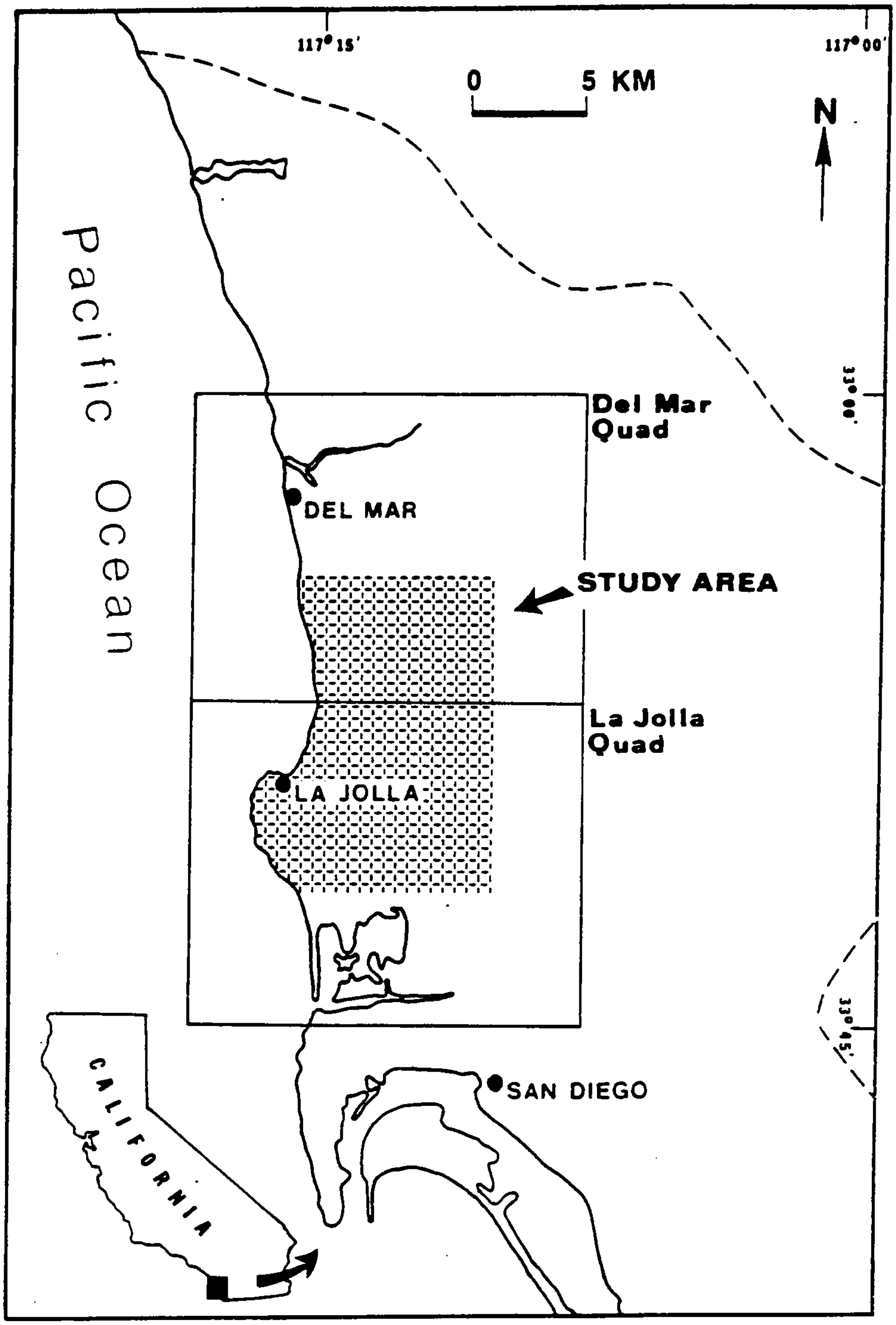

Fig. 2-2. Index map showing the area of field study within San Diego County. The inland limit of the San Diego Embayment is represented by the dashed line (Kennedy, 1975).

eastern limit, and source terrane of most of the detrital material shed into this complex, is the northwest-trending pre-batholithic Jurassic volcanics and Cretaceous batholith system of the Peninsular Ranges. K-Ar dates from granitic plutons in the Peninsular Ranges decrease eastward, from 112 to 75 my (Nilsen, 1977a), indicating the lack of active magmatism in source areas during the Eocene.

During the Eocene, oblique subduction of the Farallon plate occurred along the western coast of the present United States (Atwater, 1970; Dickinson, 1979). Remnants of the Farallon plate are still descending beneath North America, north of Cape Mendocino and along southern Mexico. During the Oligocene, the Pacific-Farallon Ridge impinged upon the North American plate, setting up transform motion along the West Coast (Atwater, 1970). The resulting strike-slip system progressively replaced convergence as two triple junctions, the Mendocino and Rivera, began migrating north and south, respectively, along the Pacific–Farallon–North American juncture. Even though the Cretaceous and Tertiary periods witnessed this active tectonic evolution, the San Diego area remained a relatively stable block (Nilsen, 1977b). However, the Paleogene east-to-west drainage system of this region was later dismembered by post-Oligocene oblique-slip faulting (Yeats, 1979a). The source terrane is now offset to the southeast in the Sonoran region of Mexico, and coeval distal (submarine-fan) facies crop out 300 km to the northwest of San Diego on the Channel Islands of the Southern California Borderland (Abbott and Smith, 1978; Howell and Link, 1979; Minch, 1979; Kies and Abbott, 1983).

The Eocene units in the San Diego region formed within a broad embayment, and consist of intertonguing, eastward thinning strata deposited during two major transgressive-regressive events (Fig. 2-3). Kennedy and Moore (1971) summarized the distribution and lithostratigraphic relationships of these deposits (also, see Kennedy, 1975; Kennedy and Peterson, 1975). Howell and Link (1979) expanded upon earlier facies interpretations, developing a generalized model for the Eocene depositional system. More detailed paleoenvironmental studies include analyses of the shallow-marine Delmar Formation and Torrey Sandstone (Boyer and Warme, 1975; Clifton, 1979), of the deep-water complex present along coastal exposures (Lohmar and Warme, 1978, 1979; Lohmar *et al.*, 1979), and of the submarine-canyon complex (May, 1985). May (1982) mapped regional facies distributions, examined sediment transport through the San Diego Embayment, and investigated possible controls upon basin-margin stratigraphic development for the Middle Eocene.

In general, an integrated fan-delta/submarine-fan system dominated Eocene paleogeography (Fig. 2-4). A fluvial valley, the Ballena Channel, cut across the low-lying Peninsular Ranges and debouched onto a large alluvial fan, up to 20 km wide (Minch, 1973, 1979; Howell and Link, 1979). The alluvial deposits graded laterally into coastal-plain units and downdip into lagoonal and shoreline environments. A large submarine canyon, and Torrey Submarine Canyon (May *et al.*, 1983; May, 1985), was incised across the shelf, extending into the nearshore zone. This system provided a conduit for moving coarse-grained material onto the adjacent submarine fan (Fig. 2-4).

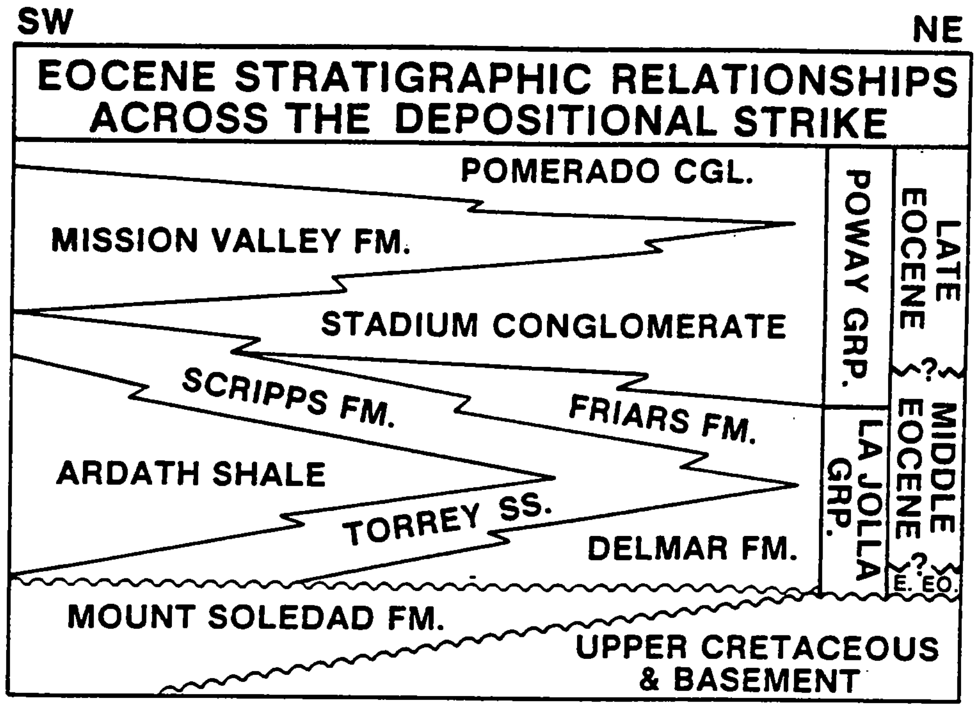

Fig. 2-3. Regional stratigraphic relationships of the Eocene units along a southweat-to-northeast transect across the San Diego Embayment (Kennedy and Moore, 1971). Note that the basin-margin succession is displayed as two symmetrical "depositional" wedges, the typical diagram for transgressive-regressive cycles of deposition.

Stratigraphic Record

Measured and interpreted stratigraphic sections are projected into two dip lines across the basin in Fig. 2-5. These cross sections provide insight into regional paleogeographic transitions with time. As previously identified (Fig. 2-3) by Kennedy and Moore (1971), a major retrogradational (transgressive)-progradational (regressive) cycle is indicated for the upper Lower to lower Upper Eocene. In addition, a smaller-scale retrogradational-progradational cycle. not diagrammed by Kennedy and Moore (1971), punctuates the large succession (Fig. 2-5). During periods of retrogradation, prevailing deposition consisted of finer-grained, basinal sediments encroaching onto more shoreward units. During progradations, coarser-grained nearshore and nonmarine detritus overstepped deeper-marine units.

Uppermost Lower Eocene strata are separated from underlying Lower Eocene clastics by a regional unconformity. At Locality 5, Dip Section I (Fig. 2-5), a soil horizon, representing subaerial erosion and exposure, caps a fan-delta sequence. Successive deposition then commenced with retrogradation. A lagoon and barrier system backstepped over the unconformity surface (Dip Section I, Fig. 2-5). Concurrently, a submarine-canyon system migrated headward, dissecting

BASIN-MARGIN ENVIRONMENTS

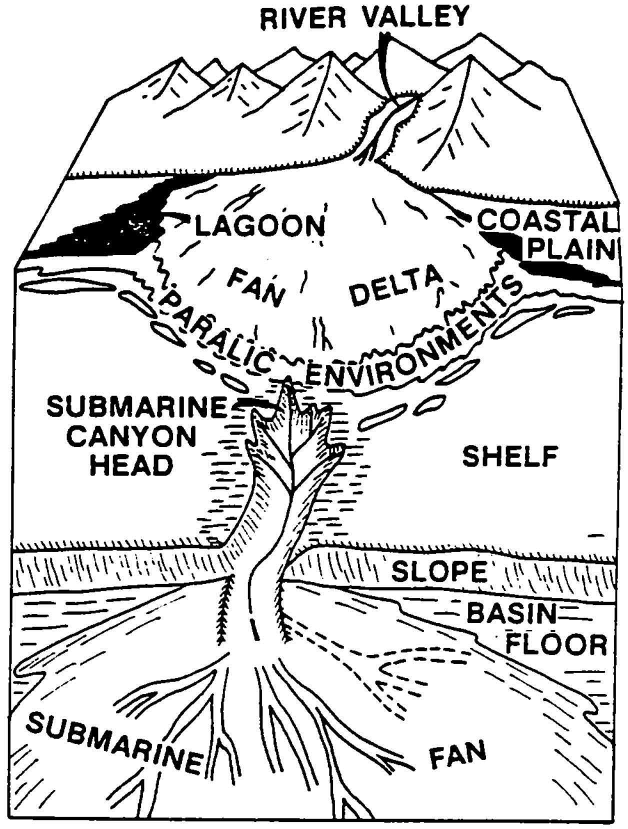

Fig. 2-4. Schematic diagram depicting the depositional environments defined within the Eocene San Diego Embayment (modified from Link *et al.*, 1979).

these nearshore deposits and creating a submarine unconformity. A modern analog is La Jolla Submarine Canyon cutting landward into slightly older beds during Holocene retrogradation (Shepard and Dill, 1966). Both the Eocene and modern submarine-canyon examples probably were initiated subaerially, during a sea-level lowstand.

The regional unconformity separating Lower Eocene from overlying deposits is entirely submarine where exposed to the southeast (more basinward) (e.g., Locality 15, Dip Section II, Fig. 2-5). The submarine-canyon system directly truncates the fan-delta sequence. Early Middle Eocene retrogradation led to partial filling of this canyon system. A tripartite, upward fining sequence of pebbly sandstones, sandstones, and mudstones represents progressive detachment of the canyon complex from nearshore sediment sources (May *et al.*, 1983).

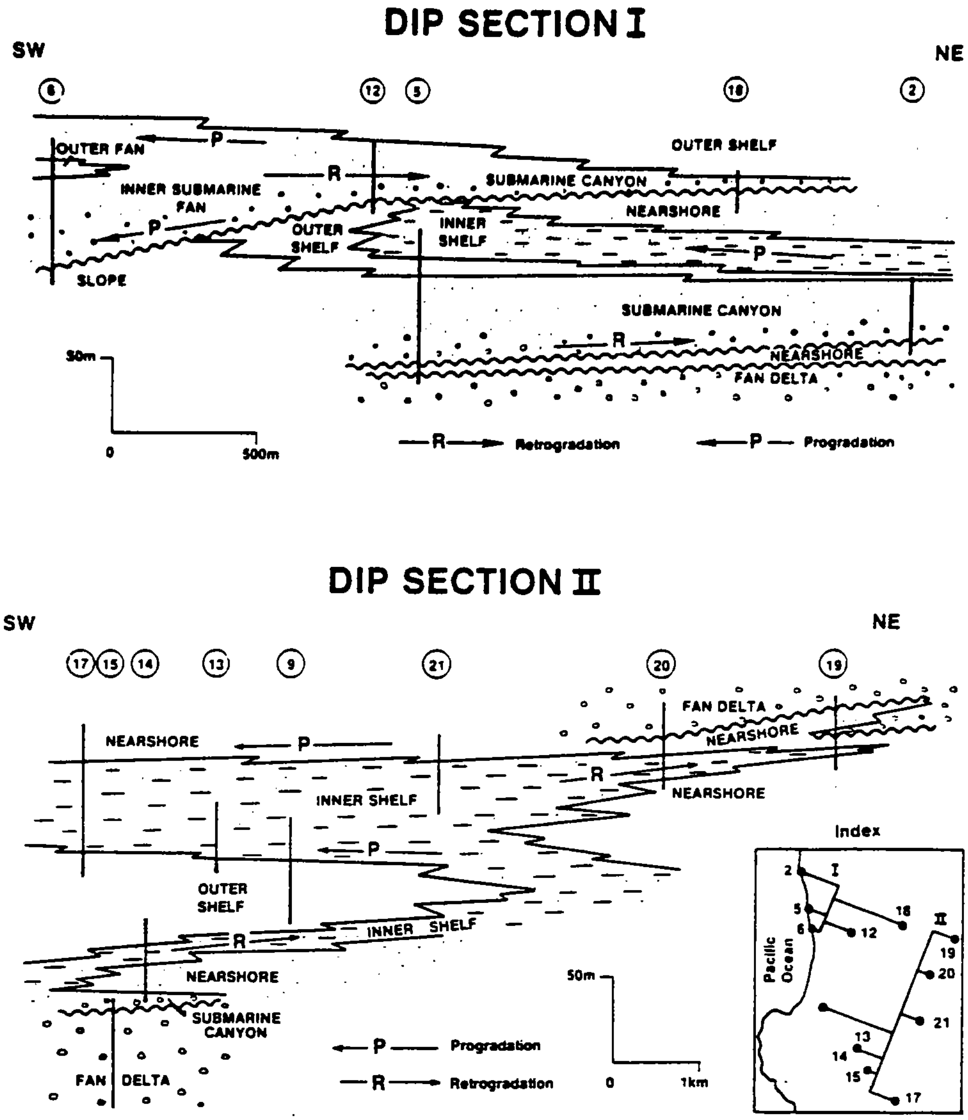

Fig. 2-5. Two dip-oriented cross sections displaying the facies relationships and stratigraphic development of the San Diego Embayment basin margin. The numbered stratigraphic sections are portrayed at their relative elevations and positions, projected into the dip sections. A major retrogradational (transgressive)-progradational (regressive) cycle is punctuated by a smaller-scale cycle. (Exact geographic locations of the numbered sections are given in May, 1982.)

Initial retrogradation was succeeded by basin-wide progradation. Inner-shelf and paralic sands built outward. Coarse-grained inner-shelf and nearshore units transitionally overlie outer-shelf and slope mudstones (Dip Sections I and II, Fig. 2-5). Coarse-grained sediments were also flushed into the deep basin. The submarine-canyon complex was rejuvenated, leading to submarine erosion (Localities

6 and 12, Dip Section I, Fig. 2-5). In outcrop, these submarine-canyon and inner-fan channels are incised into shelf and slope deposits. Submarine-fan growth resulted, represented by conglomerates and sandstones along coastal exposures north of La Jolla (Fig. 2-2).

Progradation was interrupted by a second retrogradational phase. Along the paleoshoreline, offshore facies blanketed the nearshore units (Dip Section II, Fig. 2-5). Toward the basin, hemipelagic mudstones backfilled channels on the submarine fan (Locality 6, Dip Section I, Fig. 2-5).

Finally, a late Middle to early Late Eocene regional progradation completed stratigraphic development. Landward, inner-shelf and paralic units again progressively spread over outer-shelf mudstones (Dip Section II, Fig. 2-5). This nearshore succession was truncated by another basin-wide unconformity; fluvial downcutting preceded regional expansion of a fan-delta complex (Localities 19 and 20, Dip Section II, Fig. 2-5). Submarine-fan development was also reactivated; alluvial and nearshore sediments were once again tapped by the submarine-canyon tributaries (Localty 6, Dep Section I, Fig. 2-5). Ultimately, outer-shelf strata marched over the canyon system, capping the succession (Locality 18, Dip Section I, Fig. 2-5).

Overprinted upon these depositional phases are small-scale pulses of sedimentation. Many fluctuations are areally restricted and too minor to portray. These lesser facies shifts are most easily recognized along the paleoshoreline. For example, at Locality 19 on Dip Section II, fan-delta conglomerates are portrayed as interfingering with paralic sandstones (Fig. 2-5).

Asymmetric Depositional Cycles and Sea Level

Based upon the stratigraphic patterns defined in Fig. 2-5, and from other measured exposures, a generalized cross section is extrapolated across the basin margin of the San Diego Embayment (Fig. 2-6). Facies shown in Fig. 2-5, for the Upper Lower Eocene to lower Upper Eocene interval, are assigned to their formations (as defined by Kennedy and Moore, 1971) in Fig. 2-6. The upper Lower Eocene regional unconformity truncates fan-delta units of the Mount Soledad Formation. The basal retrogradation includes nearshore strata of the Delmar Formation and Torrey Sandstone, and submarine-canyon and shelf deposits of the Torrey Sandstone and Ardath Shale. The Scripps Formation comprises coarse-grained nearshore, shelf, submarine-canyon, and submarine-fan units. These facies of the Scripps Formation form most of the small intervening progradational-retrogradational pulse and the larger-scale progradational cap seen in outcrop (Fig. 2-5). Finer-grained basin, slope, and outer-shelf deposits compose the Ardath Shale. The overall stratigraphic pattern for the upper Lower Eocene to lower Upper Eocene is a relatively ordered depositional "cycle" (Fig. 2-6). A smaller-scale, submarine-fan, progradational-retrogradational "cycle" punctuates this succession in the basinward portion.

A "cycle" may be thought of as a series of events that are arranged in a regular succession, then inversely repeated. If each facies in a stratigraphic sequence is represented by a letter, a complete "cycle" of deposition might be presented as "A-B-C-D-C-B-A" (see Duff *et al.*, 1967, p. 1-20; Bates and Jackson,

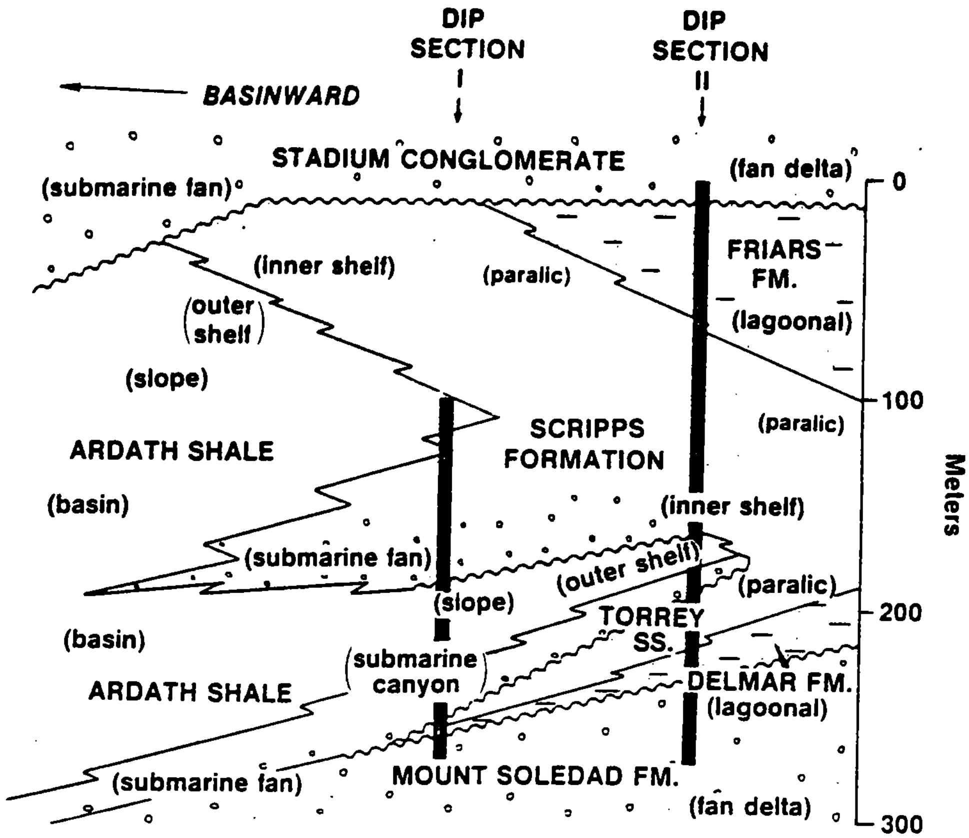

Fig. 2-6. Stratigraphic cross section through the Middle Eocene basin-margin units of the San Diego Embayment. Relative positions and stratigraphic intervals covered by the dip sections of Fig. 2-5 are shown. These strata define a large-scale retrogradational-progradational cycle of deposition bracketed by regional unconformities. Note the cycle's asymmetric thickness, with a relatively thin retrogradational (transgressive) base overlain by a thicker progradational (regressive) sequence. Facies are assigned to formations defined by Kennedy and More (1971).

1980). For the Eocene interval of San Diego (Fig. 2-6), the basal nonmarine units are successively overlain by lagoonal, paralic, shelf, slope, and basinal facies. A submarine fan punctuates the deep-marine mudstones. Then the cycle reverses in a mirror image: basinal mudstones are progressively capped by slope, shelf, paralic, lagoon, and finally, nonmarine strata.

Apparent is the asymmetric nature of this stratigraphic cycle (Fig. 2-6). Approximate thicknesses are shown for the deposits across the basin. Facies tracts developed during retrogradation are markedly thinner than equivalent facies produced during progradation. The basal retrogradational sequence is also much compressed compared to the capping progradational sequence (less than 50 m thick versus over 150 m).

Utilizing absolute ages assigned from nannoplankton, foraminiferan, and, in rare cases, molluscan zonations, the stratigraphic cross section of Fig. 2-6 has been converted to a chronostratigraphic diagram in Fig. 2-7. In comparing the timing and sense of local sea-level fluctuations to global variations, a fairly close correspondence becomes obvious, as discussed below. Bracketing of the complete Early to Late Eocene retrogradational-progradational cycle between nannoplankton subzones 11 and 15b (Okada and Bukry, 1980) correlates exceptionally well to the timing of an onlap "supercycle" of Vail and Hardenbol (1979). Individual stratification sequences predicted as a response to relative changes in sea level are likewise correlative with specific eustatic events (Fig. 2-7).

Vail and Hardenbol (1979) show a rapid global sea-level rise during latest Early Eocene through earliest Middle Eocene. Apparently in response, deeper-water units impinged upon shallow-marine and nonmarine strata in the San Diego Embayment. As global sea level approached a stillstand approximately 47 m B.P. (Vail and Hardenbol, 1979), the shelf and nearshore deposits of the San Diego Embayment began to prograde. Widespread slumping also occurred in the basin, as detached masses of the continental slope sloughed into deeper waters. Next, active submarine-canyon erosion and submarine-fan progradation punctuated the overall depositional cycle. Probably related to the small-scale eustatic drop 45 my B.P. (Vail and Hardenbol, 1979), coarse-grained detritus, previously concentrated in the shallow-marine setting, was tapped and flushed basinward (also, see Howell, 1980; Howell and Vedder, 1984). As global sea level again resumed its rise, basinal fine-grained deposits blanketed the fan system. This medial Middle Eocene sea-level fluctuation did not obviously affect the landward portions of the San Diego Embayment; shoreline progradation was unabated. Shelf-to-lagoonal facies continued outbuilding through the late Middle to early Late Eocene, coincident to a worldwide sea-level stillstand, dated as 43 to 40 my B.P. by Vail and Hardenbol (1979).

This latest Early Eocene through early Late Eocene, stratigraphically asymmetric, retrogradational-progradational depositional cycle present in the San Diego Embayment is bracketed by two regional unconformities (Fig. 2-7). The exact ages of these unconformities are difficult to define; nonmarine deposits underlie the basal truncation surface and cap the uppermost one. Approximate dating is based on the first and last nannoplankton subzones present in marine strata on either side of these surfaces. Thus, the basal regional unconformity is assigned an age of approximately 49–49.5 my; the uppermost unconformity falls somewhere between 38 and 41 my. These ages approximate the timing of Vail and Hardenbol's (1979) eustatic falls (Fig. 2-7), and a cause-and-effect relationship is assumed. Exact absolute ages and exact correlations are difficult to assign because, whereas neither sea-level fall nor unconformity development are instantaneous, the rock record and the onlap curve of Vail and Hardenbol (1979) do not provide precise estimates of the duration of these events.

Thus, within the constraints of the data, there does appear to be a concurrence between the timing of the overall cycle of stratigraphic development in the San Diego Embayment and a global "supercycle," as well as a tie of specific depositional events to individual trends in sea level. Eustasy appears, therefore, to be the primary control on changes in paleoenvironmental and stratigraphic patterns, even in this tectonically active basin (also, see Howell and Vedder, 1984).

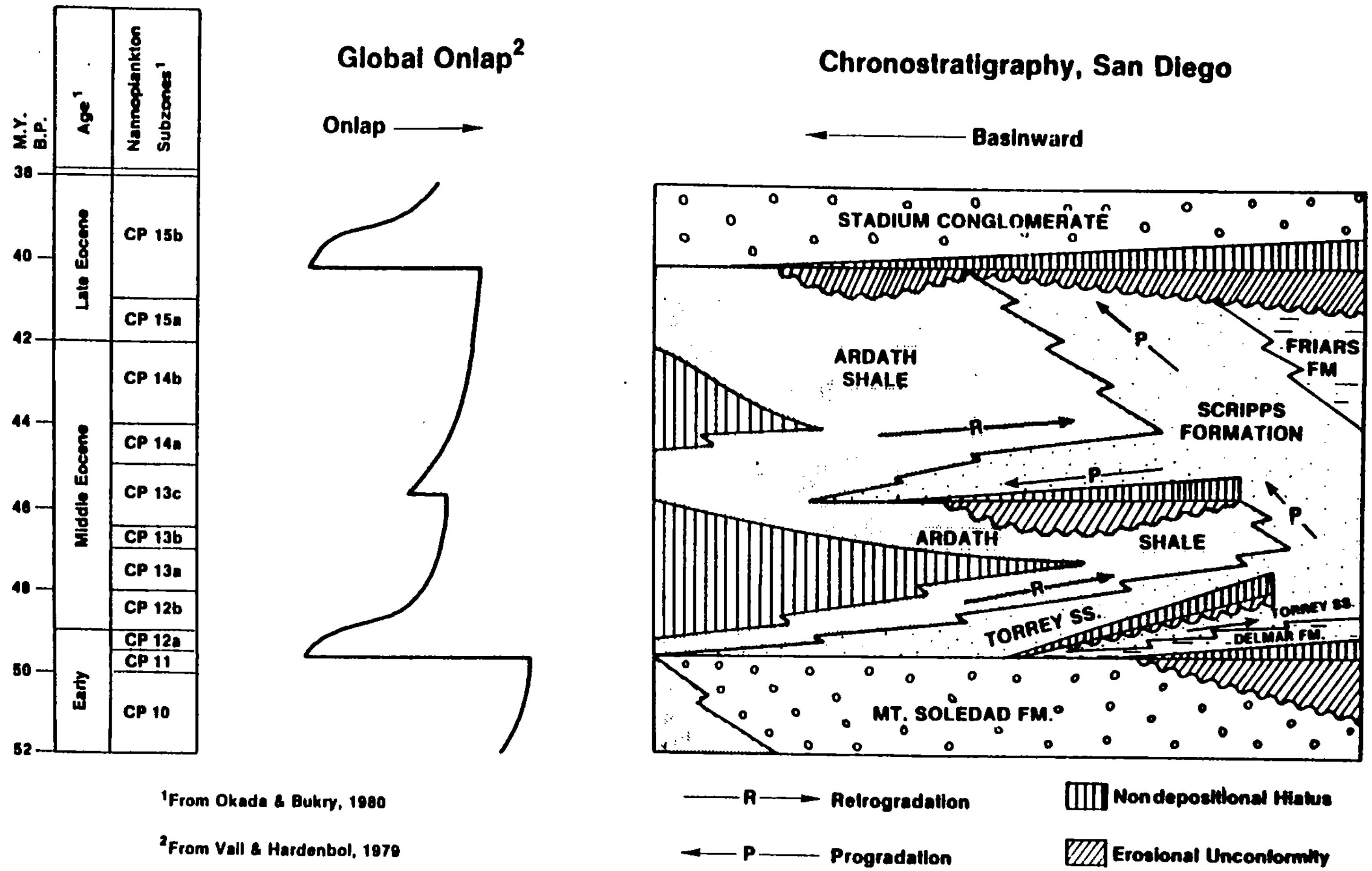

Fig. 2-7. Chronostratigraphic diagram of the Middle Eocene San Diego Embayment compared to the globe coastal-onlap curve of Vail and Hardenbol (1979). Local relative changes in sea level, defined from stratigraphic retrogradation, progradation, unconformity development, and paleontologic control, correlate with the timing of worldwide fluctuations in sea level. Specific depositional events include: (1) a basal unconformity related to a eustatic sea-level drop; (2) a thin basal retrogradational sequence and the headward erosion of a submarine-canyon system during global sea-level rise; (3) basinward flushing of nearshore detritus, producing submarine-canyon erosion and submarine-fan progradation, caused by a slight eustatic fall; (4) backfilling of submarine channels by Mudstone during a slight global sea-level rise; and (5) shallow-marine and subaerial progradation during a worldwide highstand. The medial Middle Eocene eustatic fluctuation only affected basinward deposition; progradation was apparently unaffected in the shoreward position

[QUERY: CAN THIS CAPTION BE RESET BY A WIDER LINE LENGTH TO FIT IT ON THE PAGE?]

The course of eustatic rises and falls is relatively sinusoidal (e.g., Hallam. 1978, 1981; Matsumoto, 1980; Vail *et al.*, 1984), but the resulting deposition, as demonstrated in our example, is asymmetric.

This principle of asymmetric cycles of deposition along a basin margin becomes important when used in both stratigraphic prediction and correlation. Traditionally, a wedge of "transgressive," then "regressive" strata is diagrammed; many authors depict this typical progression of upward deepening, then upward shoaling facies as uniform and equally thick (e.g., Fig. 2-3; Vail *et al.*, 1977b, p. 67; Weser, 1977, p. 28; Kingston *et al.*, 1985). Others have attempted to portray the actual stratigraphic relationships (e.g., Kauffman, 1977; May *et al.*, 1984; also, see Sabins, 1964). When estimating the lateral and vertical extent of a facies belt, whether on outcrop or in the subsurface, the conceptual model of asymmetric patterns of sedimentation provides a basis for prediction.

This asymmetric sedimentologic evolution is due largely to the combined effect of basin-margin subsidence and a symmetrically fluctuating sea level (see Barrel, 1917). Rates of sediment supply and autocyclic processes play a lesser role, except in specific cases. Even a symmetrical sea-level fluctuation, acting upon a stationary basin, should produce an asymmetric stratigraphic cycle. During a sea-level rise, detrital influx to the basin is greatly diminished. Fluvial gradients and, hence, transport capacity are reduced. Sediment becomes trapped upstream as fluvial valleys aggrade (Plint, 1983; Golovchenko and Pitman, 1984). Any detritus reaching the shoreline remains in the nearshore zone. The continental shelf becomes progressively starved. Thus, the retrogradational phase of the depositional cycle, when facies bands migrate landward, is characterized by a low sediment supply and a thinned stratigraphic section.

Given enough time during a sea-level highstand, streams will come to grade after having aggraded their valleys. Clastic input to the shoreline then resumes and begins building basinward. Progradation occurs (Vail *et al.*, 1984).

Progradation intensifies as sea level drops. Stream valleys are flushed of sediments and their gradients increase (Plint, 1983). Continental shelves also become narrower. If sea-level fall is very rapid, sediments may bypass and even erode the shelf. During this scenario, submarine-fan progradation takes place.

Superimposed upon a symmetric cycle of sea-level rise, stillstand, and fall are the quite variable rates of subsidence in the various tectonic regimes. Basin-margin subsidence can greatly modify the effects of sea-level fluctuation. Subsidence causes a relative sea-level rise even when global sea level is static; during global sea-level rise, subsidence adds to the eustatic effect. The dropping basin margin helps yield starved and thinned retrogradational packages. Conversely, subsidence can also aid in the development of thick progradational packages. When the rate of subsidence approaches the rate of sea-level fall, vertical aggradation and stacked stratigraphic sequences result. Thickened progradational phases can thus occur during both a sea-level highstand and during the fall, depending on the rate of basin-margin subsidence. Progradation can even take place during a sea-level rise if the rate of sedimentation is even greater.

Primary Eustatic Control

Many authors have correlated eustatic fluctuations to alterations in sedimentation and erosion, climate and temperature, biological diversity, production and preservation of organics, and various geochemical signatures. The recent literature is replete with examples of unconformity development and local facies changes related to variations in worldwide sea level (e.g., Loutit and Kennett, 1981a; Beard *et al.*, 1982; Cotter, 1982; Shanmugam and Moiola, 1982; Mullins, 1983; Plint, 1983; Weimer, 1983; Busch and Rollins, 1984; Howell and Vedder, 1984; Kidwell, 1984; May *et al.*, 1984; Poag and Schlee, 1984; Aubry, 1985; Ross and Ross, 1985). As discussed above, sea level obviously affects terrestrial erosion. During highstands, the terrigenous influx decreases; the continental shelf may become a sediment sink for both clastic detritus and organic carbon (Rona, 1973a,b; Worsley and Davies, 1979; Loutit and Kennett, 1981b). The restricted supply of dissolved material causes increased deep-basinal carbonate dissolution; a deep-sea hiatus appears and/or siliceous sediments replace the carbonates (Davies and Worsley, 1981; Loutit and Kennett, 1981b; Steinberg, 1981). During lowered sea levels, not only do exposed continental shelves serve as sources for increased clastic input, but also, the production of pelagic carbonates in the deep ocean intensifies (Worsley and Davies, 1979; Davies and Worsley, 1981).

Eustasy influences the niches available for shallow-marine organisms (Valentine and Moores, 1970; Hays and Pitman, 1973; Fischer and Arthur, 1977). Concurrently, upwelling and primary production along continental margins are highly altered. During raised sea levels, faunal diversity and deposition of organic-rich sediments both may increase (Hays and Pitman, 1973; Fischer and Arthur, 1977; Arthur and Schlanger, 1979; Worsley and Davies, 1979; Woodruff and Savin, 1985).

Furthermore, changes in circulation and climate occur. During cooling periods, sea level drops as the glacial cover increases; deep-marine hiatuses may develop as bottom-water flow intensifies in response to the greater production of cold polar waters and the increase in latitudinal temperature gradient (Moore *et al.*, 1978; Barron and Keller, 1982). Temperature changes corresponding to alterations in eutasy are also registered in carbon- and oxygen-isotope values (Arthur and Schlanger, 1979; Matthews and Poore, 1980; Dodge *et al.*, 1983; Williams, D. F., 1984).

Thus, ample evidence exists that eustasy can govern sedimentologic, biologic, and chemical events along passive continental margins and in the open ocean. In addition, we demonstrate herein that global sea-level changes may also be the primary control on sedimentation in tectonically active areas. Stratigraphic development in the San Diego Embayment was dominantly a response to worldwide sea-level fluctuations. Further support for this concept is the synchronous evolution of similar asymmetric depositional cycles in other isolated coastal basins along the tectonically active Pacific margin.

Coeval Stratigraphy

Nilsen and McKee (1979) reconstructed the Eocene paleogeography for the West Coast, showing a series of small, isolated coastal basins (Fig. 2-8). In order to compare the stratigraphic development in these individual depocenters, a correlation chart is presented for the late Early to early Late Eocene (Fig. 2-9). Numerous problems arose in attempting this correlation. Relative dating of sedimentary packages is based upon diverse fossil groups, whose biostratigraphic zonations are not easily compared. Ideally, each zonal scheme should be related to an absolute time scale. But many zonations are not chronostratigraphically fixed. Zonal schemes for vertebrates, mollusks, benthic foraminifera, planktic foraminifera, nannofossils, and palynormorphs are also commonly not comparable at equal levels of resolution.

A further complication is that many biostratigraphic zonations are based upon environmentally controlled fauna and flora rather than upon forms truly representative of distinct time-stratigraphic intervals. Land mammals and molluscs

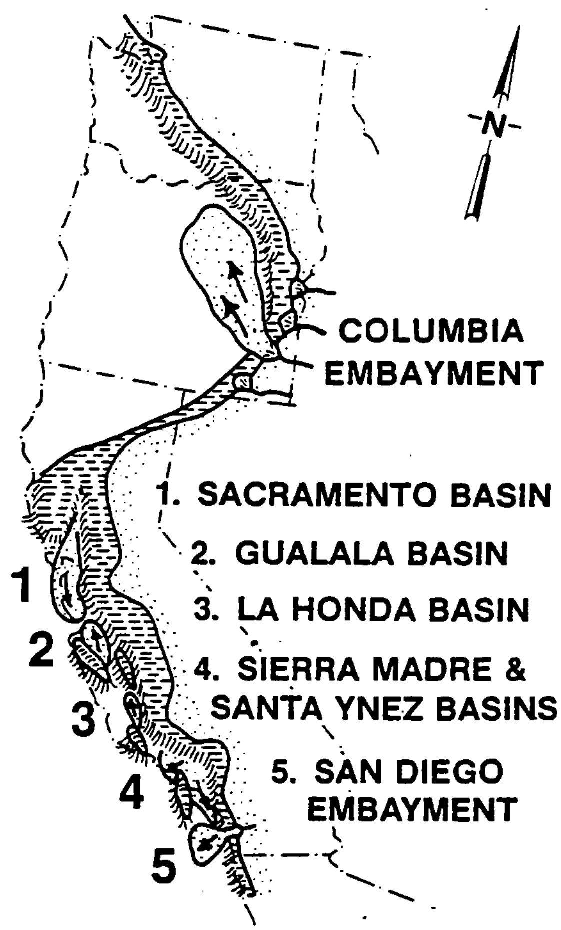

Fig. 2-8. Simplified paleogeographic reconstruction for the Middle Eocene of the western United States (modified from Nilsen and McKee, 1979). Submarine-fan development occurred concurrently in these small, isolated coastal basins, probably due to the slight global fall of sea level in the medial Middle Eocene.

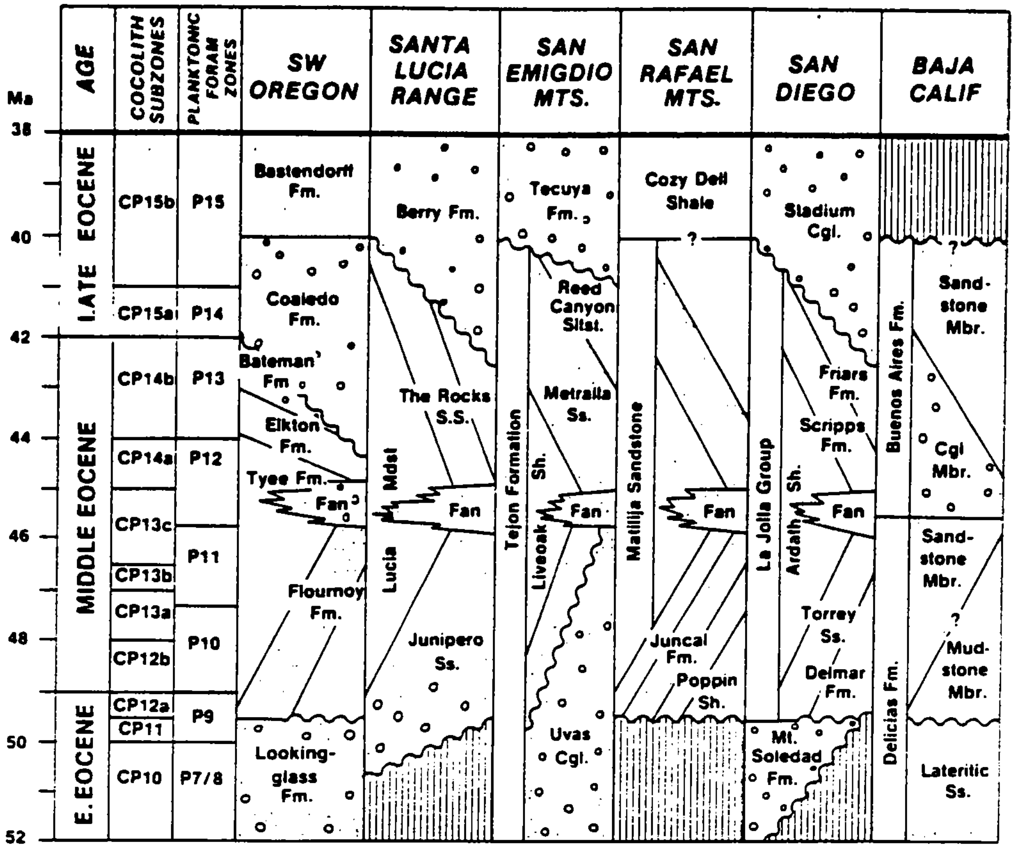

Fig. 2-9. Possible correlation of basin-margin stratigraphy for some coastal basins of the western United States and Baja California during the Middle Eocene. Coeval depositional patterns support a primary eustatic control on development. Soil horizons and unconformities of latest Early Eocene age correspond to global sea-level fall. During the ensuing rise, shallow-to-deep-marine retrogradational deposits dominated. Submarine-fan progradation in the medial Middle Eocene was an apparent response to a slight eustatic drop, with the basinward flushing of coarse-grained, nearshore clastics which had accumulated during the previous highstand. Progradational deposition, with conglomeratic fan-delta formation, coincided with a late Middle to early Late Eocene worldwide highstand. Local variations in these patterns were caused by differences in relative paleogeographic position, the effects of basin shape and gradient, differences in sediment supply, local tectonic and subsidence events, and later erosion. [The chart is based upon data from Troxel (1954), Baldwin (1975, 1976), Clarke *et al.* (1975), Gastil *et al.* (1975), Howell (1975b), Link (1975a,b), Nilsen and Clarke (1975), and Nilsen and Link (1975). Recent studies by Armentrout (1981) restrict the Flournoy through Elkton Formations to the lower Middle Eocene, perhaps evidence of a primary tectonic control on stratigraphic development in southwest Oregon.]

provided the earliest subdivisions for the West Coast Tertiary (see Weaver. 1916; Wood *et al.*, 1941; Addicott, 1981); these fossils are of limited use, occurring predominantly in nonmarine and shallow-marine strata. Kleinpell (1938) and Mallory (1959) constructed schemes based upon benthic foraminifera. However, extension of their work outside type areas gave rise to correlation problems. Studies of planktic foraminifera and nannofossils (Steineck and Gibson, 1971; Poore, 1976; Bukry *et al.*, 1977) demonstrated that some benthic foraminiferal "stages" are time-transgressive. Recent research shows that many planktic forms are also environmentally restricted. Because these faunas and floras are variously climatically distributed and depth-stratified, climatic oscillations have differentially affected low-latitude and high-latitude assemblages (Hay and Mohler, 1967; Hay *et al.*, 1967; Fairbanks *et al.*, 1982; Keller, 1983a,b; Barron *et al.*, 1984; Siesser, 1984).

Data for Fig. 2-9 are drawn from numerous sources. Clarke *et al.* (1975) and Howell (1975b) made major contributions to correlating sections from California. Bishop and Davis (1984a, 1984b, 1984c) updated and revised work in this region as part of the COSUNA project (see Childs, 1985; Salvador, 1985). Data on Baja California were obtained from Troxel (1954) and Gastil *et al.* (1975). The most problematic area is the Pacific Northwest, with major discrepancies between Baldwin (1975) and Armentrout (1981) (also, see Heller and Dickinson, 1985). Therefore, our correlation chart (Fig. 2-9) should be considered tentative, meant as a forum for discussion and further analysis. The overall pattern that emerges, however, is one of concurrent, large-scale, retrogradational-progradational cycles punctuated by medial Middle Eocene submarine-fan growth.

Lower eocene The upper Lower Eocene stratigraphy of the West Coast is characterized by locally derived conglomerates and sandstones (Fig. 2-9). In southwest Oregon, the massive, conglomeratic, basal Lookingglass Formation rapidly thickens southward against the Klamath Mountains. This grades upward into the Tenmile Member, a more distal facies of rhythmically bedded sandstone and siltstone marking the beginning of a marine transgression. Overlying the Tenmile Member is a minor pebbly sandstone and conglomerate, the Olalla Creek Member, reflecting active rising of the Klamaths as the Lookingglass Sea transgressed (Baldwin, 1975).

In the southern San Joaquin basin (San Emigdio Mountains), the basal conglomerate and sandstone (the Uvas Conglomerate Member of the Tejon Formation) rests unconformably upon the basement complex. Nearshore marine facies of this unit indicate the beginning of a major transgression (Nilsen and Clarke, 1975). The shallow-marine Junipero Sandstone of the Coast Ranges (Santa Lucia Range) may have been contiguous with the Uvas Conglomerate (Nilsen and Link, 1975).

Further south, a broad embayment of the Sierra Madre basin was bordered by the San Rafael High. Red and green mudstones of the Poppin Shale indicate nearshore (deltaic?) deposition (Howell, 1975b) along this crystalline complex.

In Baja California, the Delicias Formation is marked by a subaerially weathered, lateritic sandstone (Howell, 1975b; Gastil *et al.*, 1975). This surface is probably equivalent to the regional paleosol found in San Diego (Peterson and Nordstrom, 1970).

Middle Eocene The lower Middle Eocene is marked by onlapping stratigraphic sequences and rapid basinward deepening along these marginal basins (Fig. 2-9). Basal sandstone of the Flourney Formation is overlain by siltstone and sandstone, then deeper-marine units of the Tyee Formation in southwest Oregon (Baldwin, 1975). In the San Emigdio Mountains, the Liveoak Shale Member similarly contains a basal sandstone unit overlain by bioturbated marine shales, mudstones, and some siltstones (Nilsen and Link, 1975). Analogous patterns include the deep-marine Lucia Mudstone, which transgressed shallow-water sands in the Santa Lucia Range, and the Anita Shale of the Santa Rafael Mountains (Howell, 1975b; Nilsen and Link, 1975).

In Baja California, the lower mudstone member interfingers with, and is capped by, a thick sandstone sequence in the Delicias Formation. Fossils indicate a transgressive brackish-water to shallow-marine succession, analogous to the Delmar Mudstone and Torrey Sandstone sequence farther north (Gastil *et al.*, 1975).

Of special note is major submarine-fan development within the Middle Eocene; this fan development appears to be time-equivalent throughout most of these West Coast basins (Fig. 2-9). In San Diego, deep-water conglomerates occur just above the medial Middle Eocene nannofossil subzone (*Chiasmolithus gigas*). Fans of the other West Coast examples occur in similar stratigraphic positions and are tentatively correlated. These similar regressive fan sequences include the Tyee Formation (Dott and Bird, 1979), The Rocks Sandstone (Thorup, 1941; Link, 1975a; Link and Nilsen, 1980), Metralla Sandstone Member of the Tejon Formation (Nilsen and Link, 1975), and Matilija Formation (Link, 1975b; Link and Welton, 1982). Other coeval fan units of the West Coast include the Butano Sandstone, Point of Rocks Sandstone, and Markley Formation (Clark and Campbell, 1942; Clarke, 1973; Clarke and Nilsen, 1973; Nilsen and Simoni, 1973).

Upper Middle Eocene to Upper Eocene In most areas, a minor transgression followed submarine-fan growth (Fig. 2-9). In San Diego, this phase is characterized by submarine-fan retrogradation (Locality 6, Dip Section I, Fig. 2-5). A similar example is the transition from the Tyee to the Elkton Formation; interbedded sandstones and siltstones pass upward to dark-gray siltstone. These units, in turn, grade upward to shallow-marine, cross-bedded sandstone of the Bateman Formation (Baldwin, 1975). Nilsen and Link (1975) also noted a minor transgression followed by a regression in the San Emigdio Mountains. In the more basinward setting, the Metralla turbidite sequence is overlain by bathyal marine shales of the San Emigdio Formation. The Matilija Sandstone similarly records a minor transgression. Overlying the submarine-fan units is a mudstone sequence followed by a shoaling section (Howell, 1975b; Link and Welton, 1982).

Finally, fan-delta outbuilding took place in many of these basins (Fig. 2-9); the bordering batholithic mountain ranges provided a source throughout the Pacific West Coast. The Stadium Conglomerate in San Diego, Coaledo Formation in southwest Oregon, Berry Formation in the Santa Lucias, and Tecuya Formation in the San Emigdio Mountains all reflect continental alluvial-fan units prograding over regressive nearshore sequences (Baldwin, 1975; Nilsen and Link, 1975). In contrast, shallow-marine and continental sandstones represent coeval regression in Baja California, but are truncated by a major erosional surface which removed Upper Eocene units (Gastil *et al.*, 1975). Massive shale and siltstone of the Cozy Dell Shale in the San Rafael Mountains is the only major indication of local overprinting of the regional patterns. This fine-grained, deep-marine unit caps the regressive succession (Howell, 1975b).

Tectonism versus Eustasy

Compact, isolated forearc basins were strung along the Eocene West Coast from (present-day) Oregon to Baja California. Individual depositional events and large-scale stratigraphic development were apparently chronologically coincident in many of these depocenters. Such synchronism demands that some regionally extensive mechanism exerted a dominant control on sedimentation.

As already described, the timing of global fluctuations in sea level corresponds to these depositional episodes. The complete asymmetric cycle of stratigraphic retrogradation and progradation correlates with a "supercycle" of sea level. Punctuating this large-scale pattern was a period of major submarine-fan outbuilding, likewise correlative to a eustatic event. These interrelations argue that eustasy was the primary control on sedimentation along this tectonically active margin. However, the possibility exists that tectonism, acting in concert along the entire North American West Coast, produced these synchronous patterns.

In contrast to passive margins, and even small pull-apart basins, little work has been conducted on subsidence rates in forearc basins (e.g., Bandy and Arnal, 1969; McKenzie, 1978; Jarvis and McKenzie, 1980; Royden and Keen, 1980; Steckler and Watts, 1980; Watts *et al.*, 1982; Cochran, 1983; Andrews and Pitman, 1984). Available studies show that subsidence in such settings is quite variable (see Dickinson *et al.*, this volume). The angle of plate impingement, angle of subduction, development of an accretionary wedge, and sediment input related to volcanism all play parts. Yeats (1978), ignoring the effects of compaction, determined Paleogene subsidence in the Santa Ynez basin (precursor to the Ventura basin) to range from 110 m/my in the south to 700 m/my in the north. Beaudry (1983) calculated Neogene subsidence in a modern forearc system along the Western Sunda Arc. Linear rates of 50–125 m/my resulted from subduction and tectonic accretion. By adding sediment loading, these rates increase, ranging from 117 to 300 m/my.

Along the Eocene West Coast, subsidence due to oblique subduction, therefore, probably was quite variable. Each basin, even distinct portions within the same basin, could have a unique subsidence curve. Oblique subduction also probably yielded wrench faulting and locally accelerated uplift and/or subsidence. Yeats (1978) reports subsidence rates in the Ventura basin ranging from 40 m to 2 km per million years related to strike-slip movement. Uplift of marine terraces along the California coastline has occurred at rates to 5 m/1000 y. (5 km/my)

(Lajoie *et al.*, 1982a). In the Imperial Valley, tectonic subsidence to 1.5 mm/y (1.5 km/my) and uplift of 5.9 mm/y (5.9 km/my) have been measured (Johnson *et al.*, 1983).

These examples of extremely high and variable rates of uplift and subsidence in wrench-faulted and convergent settings indicate that a regional tectonic control on synchronous stratigraphic development was unlikely. Eustasy is the simplest explanation for the coeval depositional patterns. Tectonism did, however, produce local overprints, for instance, uplift and erosion in Baja California (Beal, 1948) and variations in lithofacies during the Middle to Late Eocene progradation.

CONCLUSIONS

The Eocene forearc basin of the San Diego region was compact and bathymetrically steep, with high sediment input and rapid lateral and vertical facies changes. This depocenter was very responsive sedimentologically to changes in sea level. High subsidence rates preserved the resultant depositional signature.

The large-scale depositional signature is an asymmetric cycle, hundreds of meters thick, with a thin retrogradational base and thick progradational cap. This asymmetric cycle is different from the traditional wedge of "transgressive" and "regressive" strata typically portrayed for basin-margin sequences. Comparing the timing and duration of cycle development to global sea level indicates a primary eustatic control. The asymmetric depositional cycle corresponds to a "supercycle," a succession of relative sea-level rises, stillstands, and minor falls. A small eustatic drop interrupted the late Early to early Late Eocene supercycle (Vail and Hardenbol, 1979). This drop was probably responsible for submarine-fan progradation, which punctuated the overall depositional cycle. Small-scale depositional pulses, produced by local factors which affected sediment supply, overprint the overall cycle (Figs. 2-5 to 2-7).

Further support for eustatic control on sedimentation is the synchronous development of depositional cycles and submarine-fan growth in other isolated coastal basins of the tectonically active Pacific margin. A late Early Eocene erosional surface corresponds to a global sea-level lowstand. Facies retrogradation then followed during a worldwide sea-level rise and general transgression. Basinal muds encroached upon shelf to nearshore sands which, in turn, overlie coastal and lagoonal fine-grained units. In many of the basins, a medial Middle Eocene drop in sea level produced a pulse of submarine-fan progradation. This fan deposition was followed by progradation during the late Middle Eocene highstand. Shelf and nearshore units built seaward and are themselves capped, in many basins, by fan-delta deposits. The variability in rates and duration of uplift and subsidence in forearc basins argues against tectonism as the dominant control on regionally extensive stratigraphic development.

Our field work, with stratigraphic and paleontologic resolution generally greater than that of remotely sensed seismic stratigraphy, indicates that global sea-level curves may be utilized in stratigraphic prediction. Even in tectonically active areas, knowledge of eustatic changes can be combined with models of sedimentation to indicate regional stratigraphic patterns, namely, the presence and extent of specific rock types. Such cycles may also be used in stratigraphic correlation (Sabins, 1964).

However, there are obviously many instances where local conditions override the eustatic control on deposition and affect the stratigraphic cycle. For example, in Baja California, there is no recognized submarine-fan sequence within the Middle Eocene. In this case, the exposed Eocene units are relatively more landward than those cropping out in the other examples. In another case, rather than a conglomeratic fan delta developing during the late Middle to early Late Eocene in the vicinity of the San Rafael Mountains, fine-grained delta and shelf units indicate overprinting due to a difference in sediment source and/or local tectonic factors. Tectonism clearly affected southwest Oregon. Based on previous work (Baldwin, 1976), Dott and Chan (1981) and May (1982) believed the Tyee submarine fan to be equivalent in time to the California examples and the progradational sequences to be synchronous. However, recent compilations by Armentrout (1981) and Armentrout and Franz (1983) indicate that the depositional cycle of southwest Oregon may be much more compressed in time. The lack of a coarse-grained progradational facies in Baja California emphasizes an obvious final important factor. Erosion at any time after deposition can alter or eliminate a depositional cycle.

Such variations in the patterns expected from a dominant eustatic control may aid in the analysis of a basin. Understanding each factor causing deviations can help refine knowledge of the structure and evolution of a basin. The resulting improvements include a better interpretation of basin shape and gradient. Identification of the timing and magnitudes of previously unrecognized local events of subsidence or uplift can be significant. Improved stratigraphic analyses include perceiving erosional unconformities, discerning variations in sediment supply, and developing more precise paleogeographic reconstructions. Finally, recognizing and understanding variations in expected stratigraphic patterns may indicate the causes and/or magnitude of specific transgressions and regressions.

ACKNOWLEDGMENTS

J. A. May's dissertation research was funded by grants from Amoco Production Company, Marathon Oil Company, Shell Development Company, Union Oil Company, the American Association of Petroleum Geologists, and the Geological Society of America. Jack Welch, Department of Parks and Recreation, was instrumental in permitting access for field work in Torrey Pines State Reserve. This paper was aided by discussions with X. Golovchenko, W. C. Ross, and J. M. Lohmar. C. Pedde, P. Roberts, and D. Arteaga provided technical assistance.