

PALEOBATHYMETRIC ANALYSES OF SEDIMENTARY BASINS DAVID BLOOM

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A number of outstanding examples of paleobathymetric analysis of Phanerozoic sedimentary sequences have appeared in the last decade with each study generally emphasizing one particular technique or fossil group including megafossil abundance and diversity (20, 27, 42), community analysis and trophic structure (1, 6, 8, 29, 46, 49), trace fossil assemblages (11, 12, 34), foraminiferal abundance and diversity (14, 41), and analysis of foraminiferal biofacies and associated microfaunal criteria (3, 4). Each of these studies provides a wealth of data and quantitative techniques leading to paleobathymetric interpretation and many stress sediment-fossil interrelationships (36) in various sedimentary and temporal settings. Rather than reviewing one or more of these paleobathymetric case histories in detail, this lecture will attempt to take an overview of megafossil, trace fossil, and microfossil evidence of major paleobathymetric boundaries with reference to figures presented in Lecture 8 of this series. Other lectures in this course scrutinize the characteristic lithofacies of various shallow to deep marine settings, thus only passing mention will be made of this evidence. However, special sedimentologic situations such as those associated with the oxygen minimum zone and calcium carbonate compensation depth will be singled out for special attention.

The title of this lecture stresses marine basins but in fact the overall focus is on continental margins including discrete basins. Basins *per se* are often marked by special water mass and faunal conditions, especially those characterized by well-defined sills within the oxygen minimum zone leading to bathymetric extension of parameters normally exhibiting much narrower bathymetric limits (22).

An effort has been made to avoid excess duplication of references in Lectures 8 and 11 but some duplication occurs; many references cited in Lecture 8 have obvious implications and import for topics and discussions in Lecture 11.

Megafaunal Analysis, Trace Fossil

Assemblages and Paleobathymetry

A recent review concerning the fidelity of the fossil record (48) notes that the primary and most basic data necessary for paleoecologic reconstructions involve numbers and diversity of invertebrate fossils present in a given sedimentary sequence, outcrop, or sample, and this view cannot be overemphasized. Quantitative estimates of abundance and diversity of all fossil evidence in stratigraphic columns of any age inevitably yield definitive general faunal trends similar to, if not identical, to modern trends (figs. 8-2, 8-10, etc.). Moreover, abundance *versus* diversity analysis (rarefaction analysis; fig. 8-4) allows recognition and definition of paleoecologically useful faunal units as well as general aspects of community structure (20, 39), comparable to modern analogs.

Quantitative analysis of megafossil assemblages is not always a logistically straightforward task compared with the relative ease with which quantitative microfaunal data are generated (2, 4, 22). However, a number of techniques exist with results generally reported in terms of number of specimens per square meter of outcrop, number of specimens per sample, number of genera and/or species per sample, etc., with resulting trends strikingly similar to those established with depth and latitude in modern marine environments (20, 27, 36, 46, 50, 51). A particularly useful semiquantitative method involves a four-unit logarithmic abundance scale used

to estimate total numbers of each taxon in terms of 1-10 specimens, 10-100 specimens, 100-1000 specimens, or more than 1000 specimens in a standard unit area of outcrop (44).

Littoral paleoenvironments (especially barred intertidal settings) generally display low diversity and high densities (individual abundance) whereas maximum diversities and abundance are associated with shelf-depth deposits with a decrease in density or abundance of shelled megafossils (not trace fossils) in bathyal paleoenvironments. Paleodiversities also display marked variation with latitude (40) similar to modern faunas in turn providing basic information for paleoclimatic interpretations.

Analysis of trophic structure through classification of feeding types (table 8-1) is now well-established as a major tool in paleoecology and paleobathymetric analysis with many examples confirming the notion that structure of most Paleozoic through Tertiary megafaunal communities is similar to their modern counterparts (1, 7, 47). The subjective definition of faunal associations or communities can be overcome to some degree by such statistical techniques as Q and R-mode Jaccard similarity coefficients (36), but associations of exclusively shelled invertebrates are not necessarily (in fact seldom) accurate representations of an entire community due to the general non-inclusion of trace fossil data representing abundances of members of the often dominant soft-bodied infaunal deposit and suspension feeders (50,51). However, some workers are now combining trace fossil and body fossil evidence (fig. 11-1) yielding a truer picture of natural faunal associations.

? Analysis of Upper Devonian progradational detaic-shelf-slope sequences within the Catskill Delta complex provide especially clear examples (fig. 11-1) of the similarity between Recent and ancient community structure. However, evidence of community evolution and hence variation through time is an important consideration in this sort of analysis. Early and Middle Paleozoic shelf communities were apparently dominated by brachiopods and other epifaunal suspension feeders whereas this same feeding group comprises only 17 per cent of Recent megafaunal assemblages inhabiting a comparable site adjacent to the Mississippi Delta (6). Moreover, a major reorganization of shelf megafaunas occurred in the Late Paleozoic with a decline in the relative importance of epifaunal suspension feeders even at this early date (table 11-1). In contrast, an infaunal linguloid-molluscan association indicative of highly stressed intertidal nearshore environments exhibits remarkable stability throughout the Paleozoic (table 11-1). Significant changes in the life-habits of marine bivalves have also occurred during the Paleozoic (38) thus evolutionary events must be integrated with paleoenvironmental interpretations.

Interestingly, megafaunal paleoecologic-paleobathymetric analyses have for the most part been concentrated on nearshore-shelf associations with little work on bathyal or "offshore" biofacies with the exception of references to graptolitic black shales (6, 9, 52). However, Paleozoic bathyal sequences composed of thick turbidite wedges and/or radiolarian-rich shales are not rare (33, 35) and occur commonly within mobile-belt settings (43) with three different graptolitic facies identified in Paleozoic proto-Atlantic sequences (52). Some of the thin bedded black graptolitic shales undoubtedly represent deposition on anaerobic slopes associated with the oxygen-minimum zone

What about swelling of deep forms?

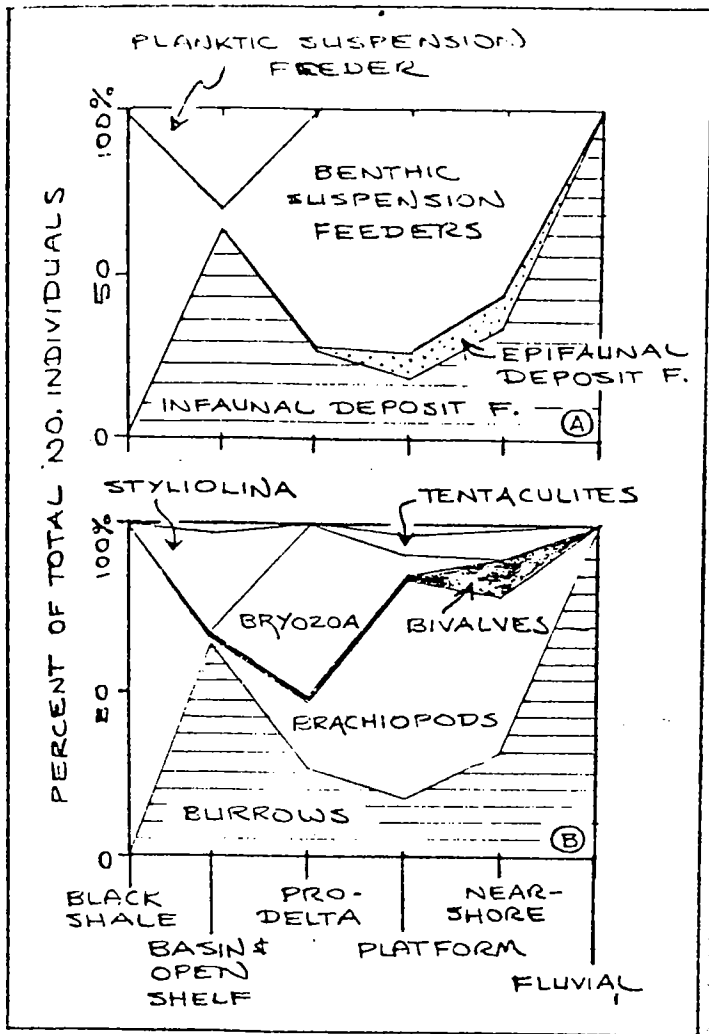


Fig. 11-1 A. Percentage (by abundance) of the four most common trophic-substrate groups (including all burrows) in the Upper Devonian Genesee Group, New York, representing an offshore to onshore paleoenvironmental gradient across the Catskill Delta complex. B. Percentage (by abundance) of major taxa across the same transect (46).

(fig. 8-1) or in silled basins controlled by this significant water mass (6, 10, 32) and varying rates of primary productivity along continental margins during the Paleozoic (45) tuned to Paleozoic climatic extremes (30).

Tertiary bathyal and abyssal megafaunal analyses are also relatively rare in the literature reflecting in part the generally low densities of shelled invertebrates and dominance of soft-bodied animals in these environments (fig. 8-7). However, a recent example of trophic analysis of molluscan communities within the Eocene Kreyenhagen Formation of California illustrates that paleoecologically significant variations in trophic structure are present in bathyal sediments (fig. 11-2).

In contrast to Paleozoic-Mesozoic megafaunal analysis, systematic study of trace fossils has not been primarily confined to shelf sequences. Indeed, the increasing importance of infaunal deposit feeding groups in bathyal through hadal environments portends an abundance of significant trace fossil evidence in these deeper deposits. This trend has been confirmed by abundant observations (37) leading to the recognition of a ubiquitous set of bathymetrically significant

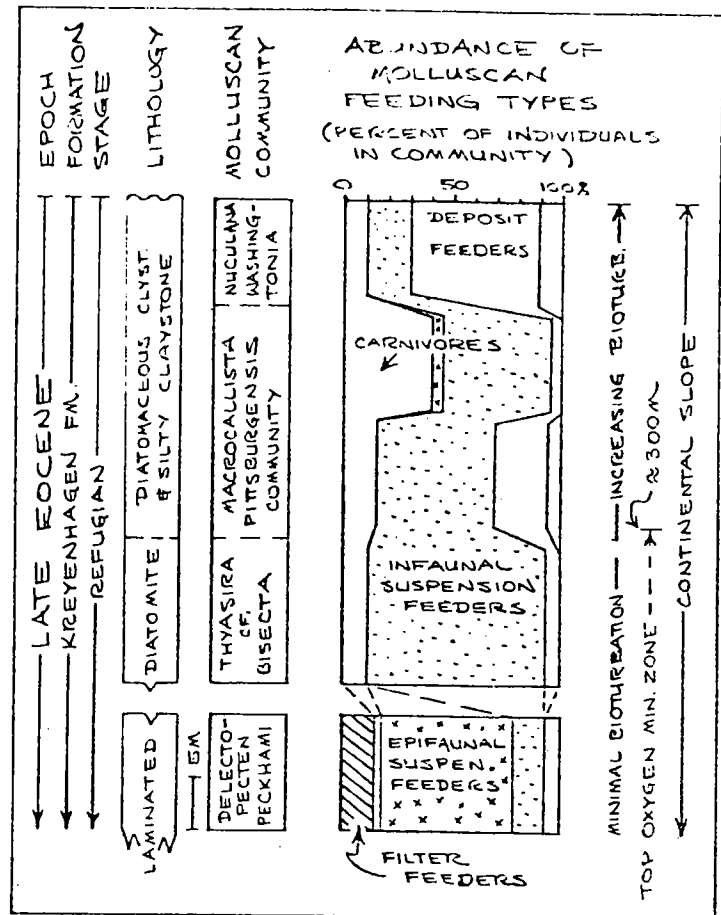


Fig. 11-2 Composition of Eocene molluscan communities according to numerical abundance and interpreted feeding types within the Kreyenhagen Formation, Arroyo Cero, California (replotted from reference 49) with interpretation of the oxygen-minimum zone boundary based on presence of laminated diatomites.

trace fossil assemblages (see ref. 8-47) which has been used extensively for paleobathymetric reconstructions (11, 12, 13, 21, 34) with several papers presenting general concepts of trace fossil use and identification (13, 17).

The general sequence of trace fossil assemblages associated with increasing water depth includes (a) the *Cruziana* facies composed of deep vertical burrows and crawling and resting traces (table 8-1) all characteristic of littoral-inner shelf depths with highly bioturbated sands and an abundance of infaunal suspension feeders, (b) the *Zoophycos* facies composed of shallow deposit feeding burrows of various orientations, deposit feeding trails, and common well-bioturbated sands characteristic of outer shelf-upper bathyal depths, (c) the *Chondrites* assemblage of rather exotic shallow-mining traces of deposit feeders representing bathyal depths, and (d) the *Nereites* facies of complex deposit-feeding trails representative of bathyal and abyssal depths (fig. 11-3). However, it must be noted that paleobathymetric interpretations based solely on trace fossils are suspect due to overlap of feeding types and traces; trace fossil evidence must be integrated with all other faunal and sedimentary evidence bearing on depth of deposition (28).

TABLE 11-1 VARIATION OF PALEOZOIC LITTORAL AND SHELF BENTHONIC ASSOCIATIONS (BIOFACIES)¹

Association (Biofacies)	Dominant Forms	Variation with Time	Environment Setting	Duration
Linguloid-collescan	Infaunal detritus-feeding nuculoid bivalves and suspension feeding brachiopods; epifaunal bellerophonid gastropods.	Rhynchonellid brachiopods common in Early Paleozoic along with mussel-like mollusks. Replaced in Early Mississippian by spiriferid brachiopods and pectinoid and myalinid bivalve mollusks.	Sand and silt; nearshore zone including tidal flats	Ordovician-Permian
Strophomenoid-trilobite	Abundant and diverse brachiopods. Variety of strophemerid and orthid brachiopods, trilobites and crinoids.	Stable during Early Paleozoic.	Silt and mud. Inner shelf	Ordovician-Devonian
Atrypid-bryozoan	Abundant atrypid and pentamerid brachiopods and trepostomatous bryozoans.	Stable during Early Paleozoic	Mud; shelf (outer shelf?)	Ordovician-Devonian
Productid-chonetid	Abundant productid and chonetid brachiopods, crinoids, bryozoans, and bivalve mollusks.	Breakdown of pre-Mississippian two fold shelf associations to single productid-chonetid shelf association in later Paleozoic	Silt and mud; inner shelf	Devonian-Permian
Fusulinid-palaeotextularid	Abundant arenaceous Foraminifera with fusulinids, crinoids, bryozoans and some echinoderms.	Becomes significant outer shelf association in later Paleozoic	Mud; outer shelf	Pennsylvanian-Permian

¹Adapted from Bretsky (1968)

Microfaunal Trends and Paleobathymetry

Israelsky's early "oscillation chart" (26) still stands as an excellent example of how patterns of modern foraminiferal biofacies can be utilized in paleobathymetric interpretation of Tertiary biofacies of similar character with attendant evidence of the time-transgressive nature of these biofacies (and associated lithofacies) during transgressive and regressive cycles. More sophisticated methods of analysis and a massive increase in data concerning modern foraminiferal faunas have stimulated increased use of quantitative analysis of fossil foraminifera (2, 3, 22, 23, 24). Foraminiferal number, species diversity analysis (species number), etc., can be applied in a like manner to both fossil and Recent faunas (fig. 8-11 and 8-13).

Although most modern paleobathymetric analysis utilizing foraminifera have been carried out in Tertiary and Cretaceous deposits some successful quantitative studies have been made of this group in Late Paleozoic littoral-shelf sequences (41, 2). However, planktonic foraminifera do not appear until the mid-Mesozoic and other major differences exist between Paleozoic and Tertiary faunas reducing the effectiveness of direct analogy with modern distributions.

Significantly, radiolarians constitute one group of planktonic microfossils which appear to have maintained a stable environmental posture throughout the Phanerozoic, yet have been generally neglected in paleobathymetric analysis of Tertiary deposits. The increase in radiolarian number with depth has been demonstrated (fig. 8-10) with exceptionally

high numbers characteristic of lower bathyal and abyssal deposits. This same trend is extant in Paleozoic through Tertiary deposits (see ref. 8-30). Some workers early recognized the bathyal-abyssal significance of radiolarian-rich Paleozoic shales and cherts (35), but the controversy over the deep water origin of these deposits continued through the 1950's due to lack of definitive evidence from modern marine environments. In fact, only two papers dealing exclusively with Radiolaria appear in the *Journal of Paleontology* between 1927 and 1951, both of which concern the Arkansas novaculite; a 1964 paper on Paleozoic plankton (9) devotes only a sentence to their presence! At this point in time evidence of the deep bathyal-abyssal significance of radiolarian cherts is overwhelming as is the well-established relationship between increasing radiolarian number with increasing water depth. Significantly, former deep sea siliceous oozes in the form of radiolarites are now commonly recognized in association with isolated slabs of Paleozoic and Mesozoic oceanic crustal material incorporated into continental margins through plate collision processes (5, 15, 16, 18, 33). In addition, abundant to common radiolarians have been found in Mesozoic bathyal trench-apron and rise deposits (31), with particularly abundant and well-preserved radiolarians reported from bathyal Tertiary deposits around the Pacific rim including portions of the Monterey Formation of California, where they represent direct analogs of slope and basinal deposits common to the Recent Gulf of California.

Several well-studied Miocene through Pleistocene marine sequences in the southern San Joaquin Valley (3), Newport

ESTIMATED PALEOBATHYMETRY			
LITTORAL-INNER SHELF	SHELF-UPPER BATHYAL	BATHYAL (SLOPE)	BATHYAL-ABYSSAL
TRACE FOSSIL ASSEMBLAGES			
CRUZIANA	ZOOPHYCOS	CHONDRITES	NEREITES
DOMINANT BEHAVIORS			
Crustacean - feeding burrows Cobolite - resting traces Nereites - resting trails	Podochroa - deposit feeding Borella - fecal discharge	Poecochroa - deposit feeding trails, fecal discharge	Four Foraminifera
DOMINANT PRESERVATION			
Exposures, some sandstones massive bioturbation	Full relief, some sandstones massive bioturbation	hyporeites, mud casting found preserved by sand casting after scouring. Primary hyporeites and spiracles not preserved	

Summary and illustration of *Nereites*, *Chondrites*, *Zoophycos*, and *Cruziana* trace-fossil assemblages of Ouachita Miogenians of southeastern Oklahoma

Index to Ichthyogenes

- | | |
|---|--|
| <p>Cruziana Assemblage</p> <ul style="list-style-type: none"> 1. <i>Bolonia</i> (x 1.0) 2. <i>Psaronichites</i> (x 0.7) 3. <i>Scalidus</i> (x 0.7), 4, 5 (x 1.0) 6. <i>Cruzalithus</i> (x 1.0) 7. <i>Micratulus</i> (x 1.0) 8. <i>Borella</i> (x 0.5) 9. <i>Pilichne</i> (x 0.2) 10. <i>Lindera</i> (x 0.5) 11. <i>Lamandichne</i> (x 0.2) 12. <i>Planolites</i> (x 0.5) <p>Zoophycos Assemblage</p> <ul style="list-style-type: none"> 13. <i>Cruentichne</i> (x 0.5) 14. <i>Aerolichne</i> (x 0.5) 15. <i>Zoophycos</i> (x 0.2) 16. <i>Laminites</i> (x 0.5) 17. <i>Helminthopus</i> (x 0.5) (clay filled) 18. <i>Asterisma</i> (0.4) | <p>Chondrites-Vereites Assemblage</p> <ul style="list-style-type: none"> 19. <i>Palaedon</i> (x 0.5) 20. <i>Synanodonta</i> (x 0.5) 21. <i>Lophosirenites</i>, 22*, 23*, 24* (x 0.5) 25. <i>Physosiphon</i>** (x 1.0) 26. <i>Helminthopus</i>** (smooth) (x 0.3) 27. <i>Parahelminthopus</i> (x 0.5) 28. <i>Schizoglyphus</i> (x 1.0) 29. <i>Mammillaria</i>** (x 1.0) 30. <i>Bifurcatus</i> (small) (x 1.0) 31. <i>Bifurcatus</i> (large) (x 0.7) 32. <i>Taraxacum</i> (x 0.3) 33. <i>Spiriferus</i> (x 0.1) 34. <i>Helminthopus</i> (fecal filled) (x 0.6) 35. <i>Susterglyphus</i> (x 0.6) 36. <i>Scalidus</i>, 37* (x 0.6) 38. <i>Asterisma</i>** (x 0.6) 39. <i>Scalarintha</i>** (<i>Phyllodoites</i> form) (x 0.5) 40. <i>Scalarintha</i>** (x 0.5) 41. <i>Scalarintha</i>** (<i>Neonereites</i> form) (x 0.5) 42. <i>Chondrites</i>** (x 1.0), 43 (x 0.5) |
|---|--|

Fig. 11-3 Summary and illustration of *Nereites*, *Chondrites*, *Zoophycos* and *Cruziana* trace fossil assemblages (facies) in Mississippian - Pennsylvanian rocks of the Ouachita Mountains, southeast Oklahoma (11); estimated paleobathymetry not from reference 11.

Bay (23), and Imperial Valley, California (24) offer good examples of how quantitative analysis of foraminiferans and radiolarians can yield meaningful paleobathymetric patterns (fig. 11-4, 11-5, 11-6, 11-7, 11-8, and 11-9) and enhance direct analogy with modern microfaunal biofacies. Discussion of important foraminiferal and microfaunal parameters will not be repeated here (see Lecture 8). However, attention will be focused on a comparison of modern microfaunal trends established in the southern California offshore area (fig. 8-12) and across Guaymas Basin in the Gulf of California (figs. 8-11, 8-13 and 8-14) with similar trends established both horizontally (fig. 11-4) and vertically with time (figs. 11-5,

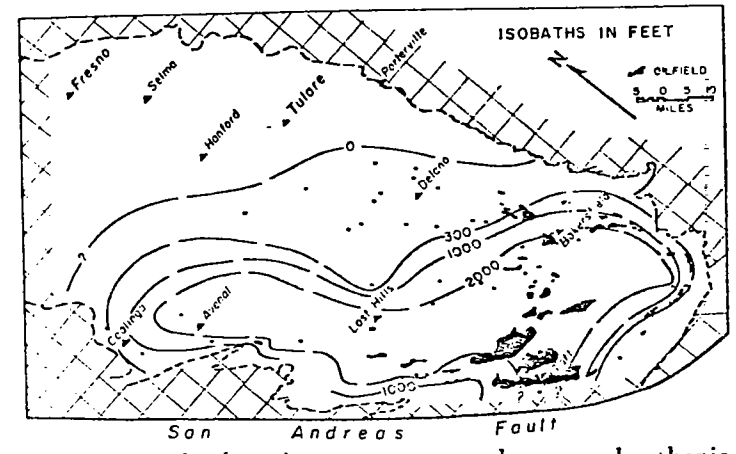
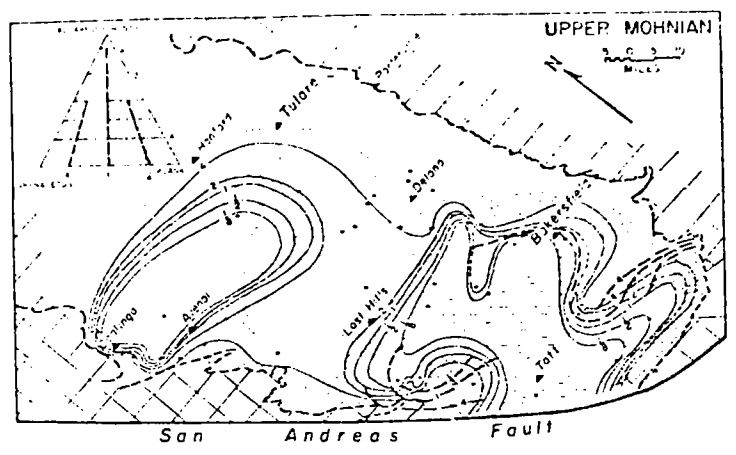


Fig. 11-4 Planktonic-arenaceous-calcareous benthonic foraminiferal relationships and estimated paleobathymetry in Late Miocene (Upper Mohnian) time, southern San Joaquin Valley, California (3). Paleobathymetry based on analysis of benthonic foraminiferal biofacies analysis.

11-6, 11-7, 11-8, and 11-9) in analogous late Tertiary deposits of southern California.

Paleobathymetric curves accompanying the Tertiary sections are based on interpretations of deepest dwelling foraminiferal species and biofacies in any given sample with members of shallower biofacies in the same sample assumed to represent displaced and redeposited specimens. The magnitude of faunal displacement was previously demonstrated in Lecture 8 (fig. 8-14). An example from a bathyal Pliocene turbidite deposit (fig. 11-8) and trends within the Newport Bay section (fig. 11-7) indicate that downslope transport of shallow material is equally massive in Tertiary deposits and for that matter in off-shelf continental margin settings of all ages (43).

Use of ratios between various foraminiferal groups is an effective tool in modern and ancient marine deposits (fig. 8-12; fig. 11-8). Arenaceous species commonly occur in shallow environments with an increase in relative planktonic number, clearly marking the shelf edge in the southern portion of the Late Miocene San Joaquin Basin (fig. 11-8), Late Pliocene and Middle Miocene shelf-slope transitions in the southeastern Los Angeles Basin (figs 11-5 and 11-6), as well as the Pliocene shelf-edge in the northern portion of the Gulf of California (fig. 11-9). Planktonic foraminifera are also abundant within Miocene laminated diatomites representing slope and basin-plain deposition beneath an oxygen deficient water mass

BONITA CANYON SECTION

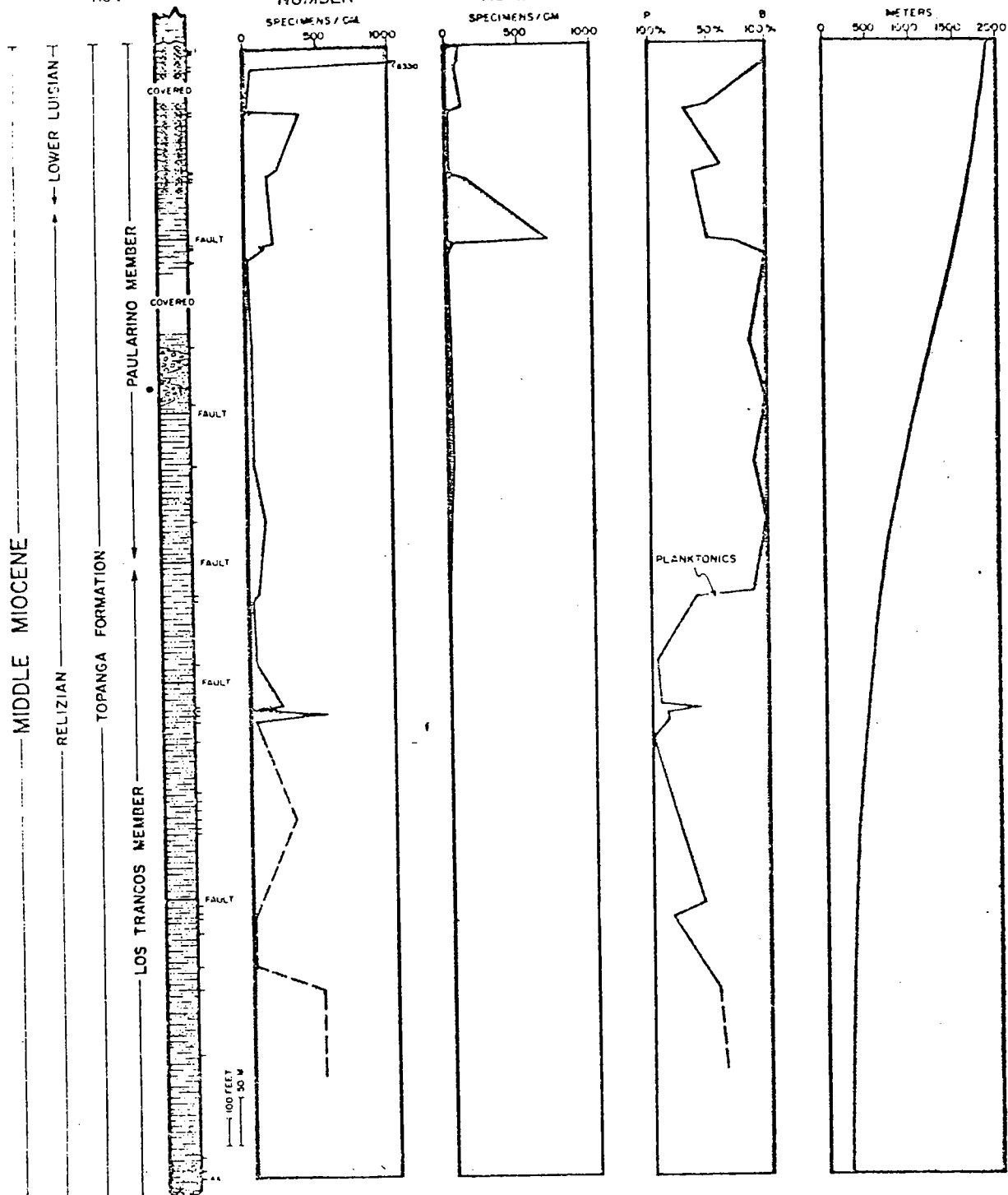
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FORAMINIFERAL NUMBER

RADIOLARIAN NUMBER

PERCENT PLANKTONIC & BENTHONIC SPECIMENS

ESTIMATED PALEOBATHYMETRY

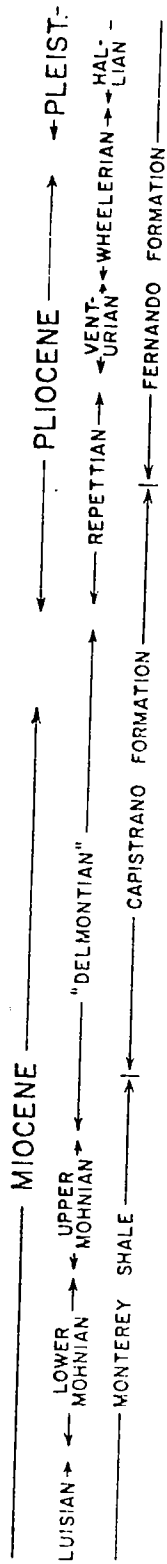


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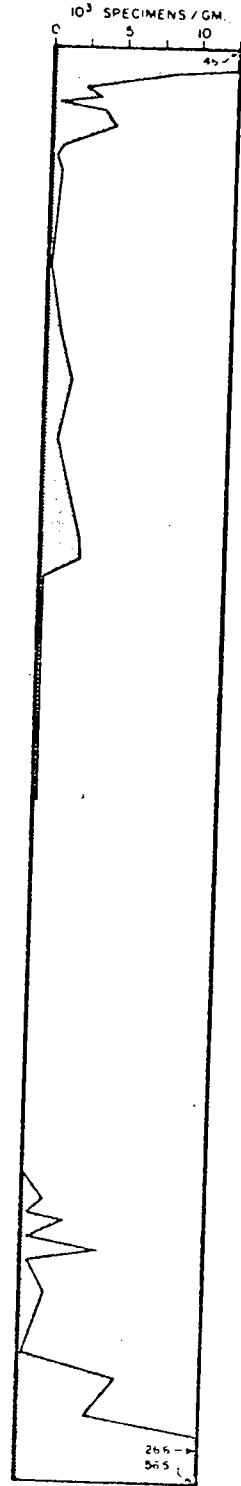
Fig. 11-5 Foraminiferal and radiolarian trends and estimated paleobathymetry within the Topanga Formation, Bonita Canyon, Orange County, California (23). This section represents a Middle Miocene shelf-to-slope transition continued in Newport Bay section (figs. 11-6 and 11-7).

NEWPORT BAY SECTION

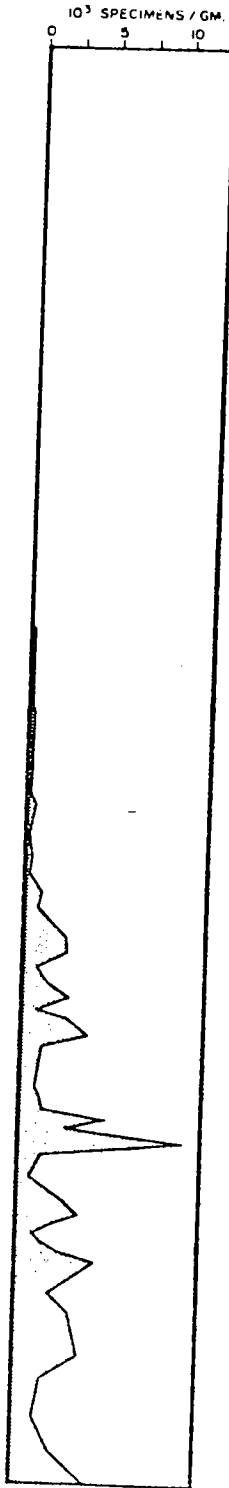
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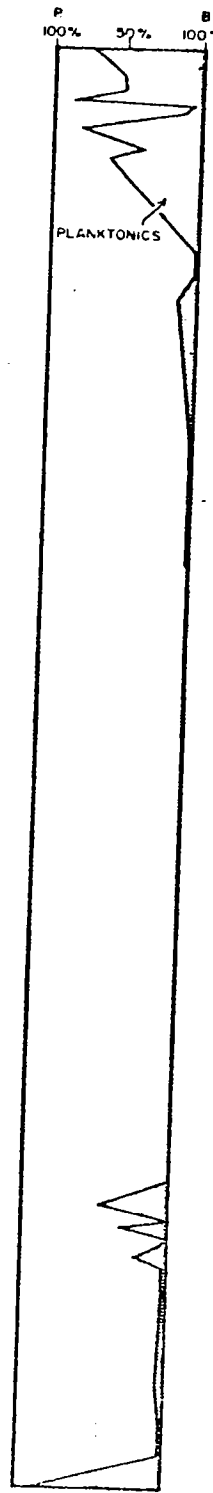
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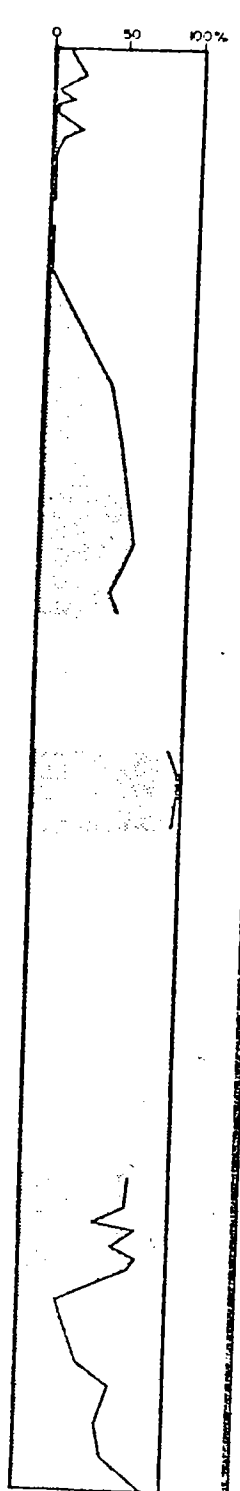
RADIOLARIAN NUMBER



PERCENT PLANKTONIC & BENTHONIC SPECIMENS



PERCENT DISPLACED SPECIMENS



LITHOLOGIC CODE

- [] SAND
- [/] SILT / SILTST
- [.] CONGLOMERATE
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Fig. 11-6 Foraminiferal and radiolarian trends, Newport Bay section, Orange County, California (25).

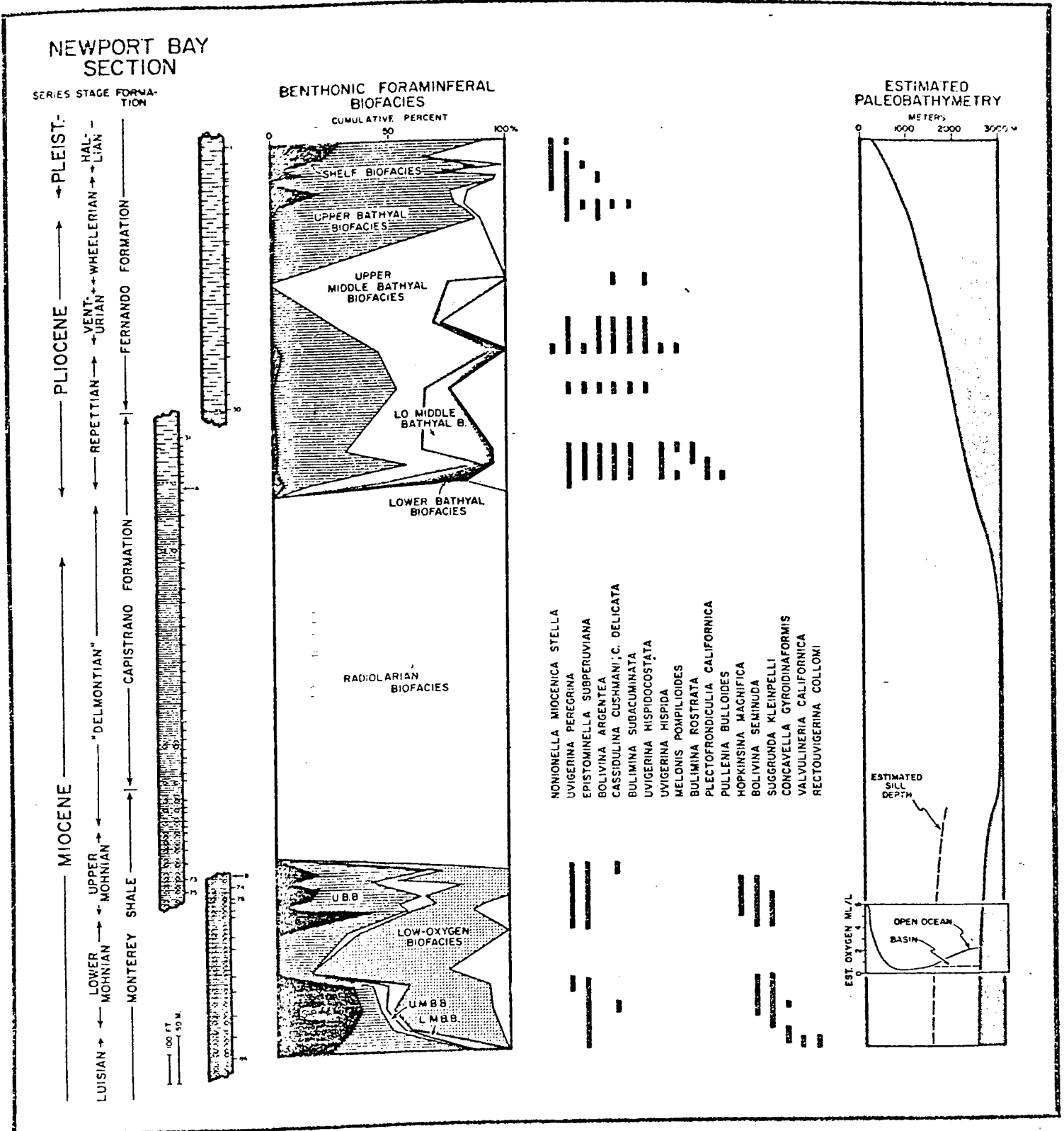


Fig. 11-7 Foraminiferal biofacies trends, ranges of significant species of benthonic foraminifera, and estimated paleobathymetry, Newport Bay section, Orange County, California (23).

patterns of displaced species all present strikingly similar patterns.

Summary of Significant Paleobathymetric Indices

Figure 11-10 presents a synthesis of a number of the more significant megafaunal, microfaunal and trace fossil trends with depth documented and discussed in Lectures 8 and 11 along with associated major physical (water mass) and lithologic boundaries across the littoral-to-abyssal gradient. With few exceptions, the majority of these various faunal and lithologic boundaries (fig. 11-10) can be readily identified in Mesozoic and Tertiary marine sequences with many of the boundaries or faunal gradients applicable to Paleozoic sequences. Multiple combinations of depth-diagnostic ratios are possible between key parameters and most of the faunal and lithologic boundaries can be analyzed in a quantitative way (either in terms of absolute numbers or relative percentages) both horizontally in terms of various biofacies or lithofacies modes, trace-fossil facies, or vertically (with time). There are a total of more than 50 faunal and lithologic boundaries (or sharp gradients) of paleobathymetric significance represented on figure 11-10; use of such devices as triangular plots (fig. 11-4) further increases the number of significant ratios possible, with one triangular plot generating 4 to more than 25 parameters which can be mapped vertically or horizontally. With the exception of foraminiferal biofacies the parameters presented on figure 11-10 can be utilized without detailed paleontologic analysis or alternately can utilize already existing data regarding species presence, absence, or relative abundance.

Many substitutions of parameters illustrated (fig. 11-10) are possible. For example, percentage of graptolites (out of total megafaunal assemblage) can be substituted for percentage of planktonic foraminifera in Paleozoic sediments, or ratios of fusulinid to arenaceous foraminifers could replace ratios between calcareous and arenaceous foraminifera... the possibilities for recombination and extension of these parameters are infinite. Furthermore, faunal and sedimentologic parameters such as mean grain diameter, relative abundance of significant sedimentary structures, etc., can be interrelated with direct implications for paleobathymetric interpretation.

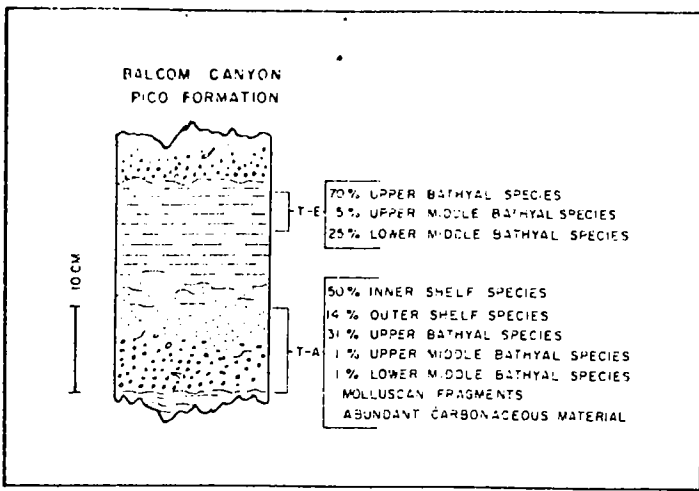


Fig. 11-8 Percentage (by relative abundance) of bathymetrically significant benthonic foraminifera within a single turbidite unit, Pliocene Pico Formation, Balcom Canyon, Ventura County, California (22); note marginal percentages of *in situ* middle bathyal species in lower portion of turbidite.

produced by an effective sill-depth within the oxygen minimum zone similar to basin and slope conditions off southern California and Gulf of California today (fig. 8-13). Increasing radiolarian number within the Bonita Canyon - Newport Bay sequence (figs. 11-5 and 11-7) is also indicative of increasing water depth, with a peak in radiolarian abundance occurring in red-brown mudstones of the Upper Miocene Capistrano Formation, analogous to sediments deposited at depths in excess of 3000 m in the Gulf of California today. This unit represents the point of greatest subsidence during evolution of this portion of the Los Angeles Basin with associated sediments devoid of calcareous benthonic foraminifers suggesting deposition near the base of the local lysocline or calcium carbonate compensation depth (fig. 8-1; fig. 11-7). In fact, an instructive exercise involves turning figures 8-11 and 8-13 on end and comparing them directly with figures 11-6 and 11-7 with obvious implications for both lithologic and faunal trends in these two sequences; foraminiferal numbers, benthonic foraminiferal biofacies, and

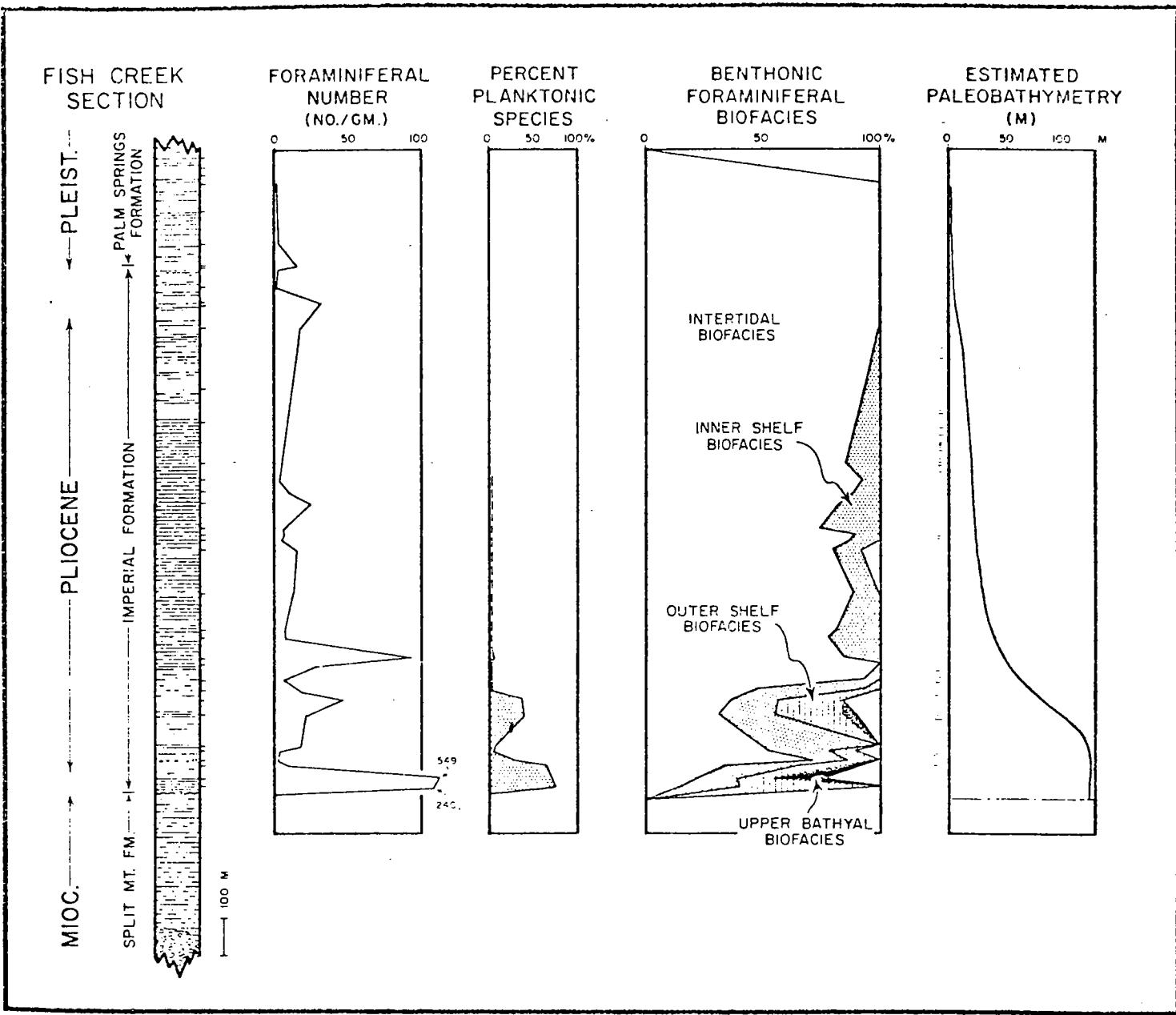


Fig. 11-9 Foraminiferal trends, benthonic foraminiferal biofacies, and estimated paleobathymetry in Fish Creek section of the Imperial Formation, Imperial County, California (24).

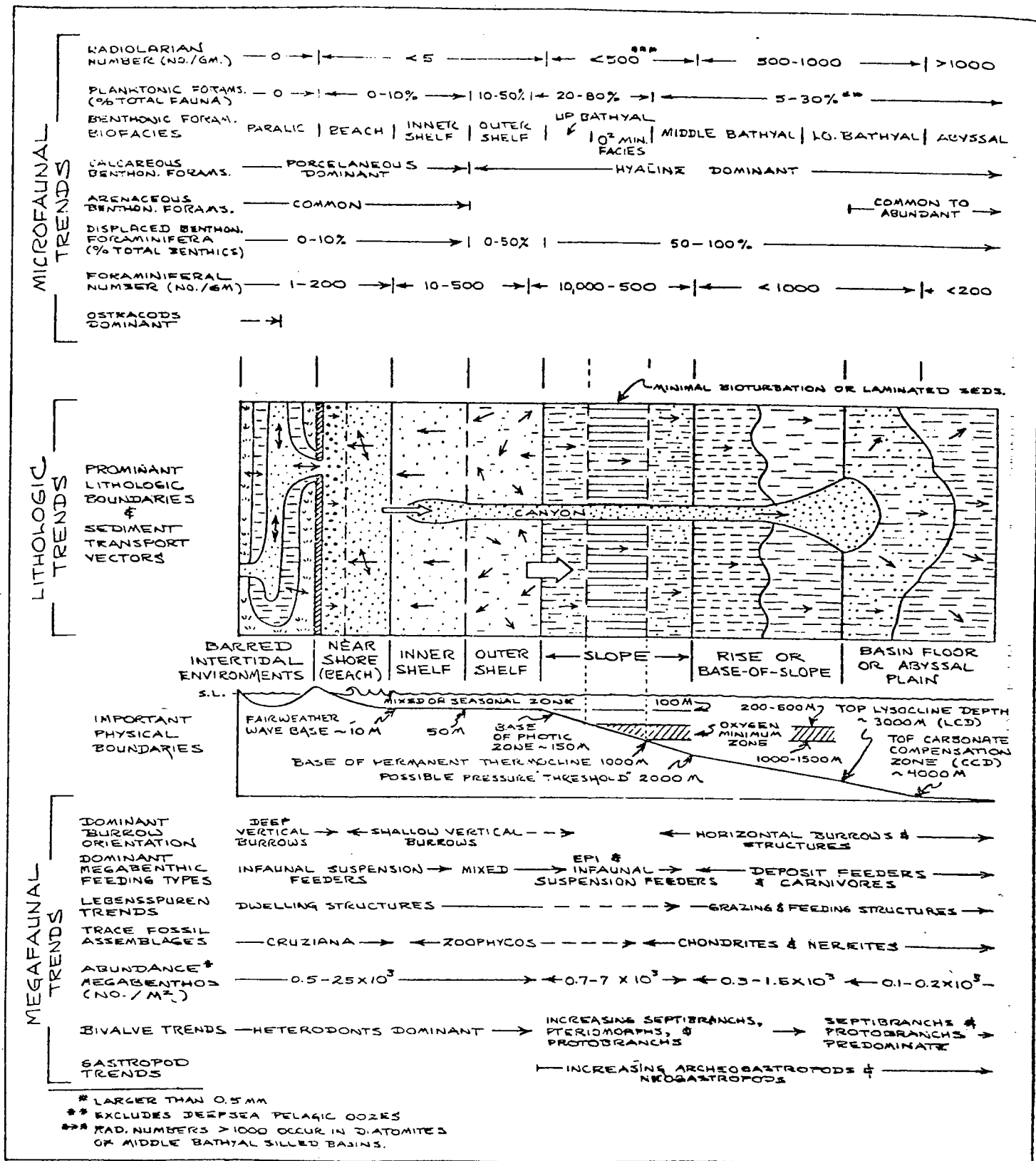


Fig. 11-10 Summary of significant megafaunal, trace-fossil, lithologic and microfossils trends across a schematic littoral-to-abyssal gradient with associated major physical (water mass) boundaries. Arrows indicate general direction of sediment transport with open arrow indicating transport of suspensates. See Lecture 8 (fig. 8-1) for classification of marine environments. Foraminiferal trends based on Late Tertiary and Recent distributional patterns and abundances.

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