DAVID BLOOM

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FIGS. 1-6, DECEMBER, 1978

ANATOMY OF MARGIN BASINS

Presidential Address

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ABSTRACT: Sediments are delivered to basins or rises by a number of discrete processes or sets of processes working from several sources including terrigenous, biogenous, and hydrogenous which may deliver sediments continuously or discontinuously. The processes can be grouped in terms of the zone from which they move sediments directly to the deposition site. These include river and shore systems, shelf systems, canyon systems, slope systems, and the processes operating in the overlying water column. River and Canyon-centered processes work from point sources; shore, shelf and slope-centered processes deliver from linear sources; and the water mass-centered processes operate from area sources. These are the primary determinants of the patterns of sediments deposited from these sets.

Of these sets of processes and their resulting products, the river-shore system and the canyon system are easily the best known. A new surge of interest has begun for the slope system, but the water mass process system and the resulting hemipelagic and pelagic sediments and sedimentary rocks have been only narrowly studied although they produce the most complete records of environmental (climatic) changes and provide the best correlation data.

Another area of research yet to be broadly developed lies in the study of interactions between processes and process sets and in the factors that modulate process systems. How each of the major process groups work together and what synergistic effects come from those linkages offer productive areas of study. All of these should be examined to aid us in our primary goal of describing the Earth's history.

INTRODUCTION

Boundary Conditions

Anatomy is the study of a body to ascertain its component parts, their structures, relationships, and functions. This can be construed in several ways geologically, but I propose to use a sedimentological analogy taking a sedimentary prism as the "body." I will also discuss closed basin deposition specifically although I recognize that large (dimensions of 10's or 100's of km) sedimentary lenses can form without a closed depression catchment area. The continental rises are good examples. I use the closed basin as my model because I am most familiar with that form and because it is the form commonly studied for economic purposes. I will use examples from the contemporary ocean and specifically from the California Continental Borderland (Fig. 1) again because of my own experience. I will generally be discussing "deep" water sedimentary processes and products and to me this means water depths typical of continental margins and ranging from 100 m to 5000 m.

I must also define what scale I am using in a stratigraphic sense. The contemporary recognition of major lithosequences (Sloss, 1963) controlled by world-scale crustal motions (e.g., Vail, Mitchum, and Thompson, 1977a) which in turn can be subdivided into progressively smaller orders of sedimentary sequences has revolutionized our thinking about earth history and the major processes producing large sedimentary deposits. Another exciting area of research based on materials from world-wide piston coring programs and from the Deep Sea Drilling Program is the detailed analysis of world climatic changes which has now been extended back to Cretaceous time (Savin, Douglas, and Stehli, 1975). It seems to me that these two major stratigraphic advances provide a world framework into which smaller pieces of rock record can be fitted to provide large scale interbasin correlations.

My own work has been with the small

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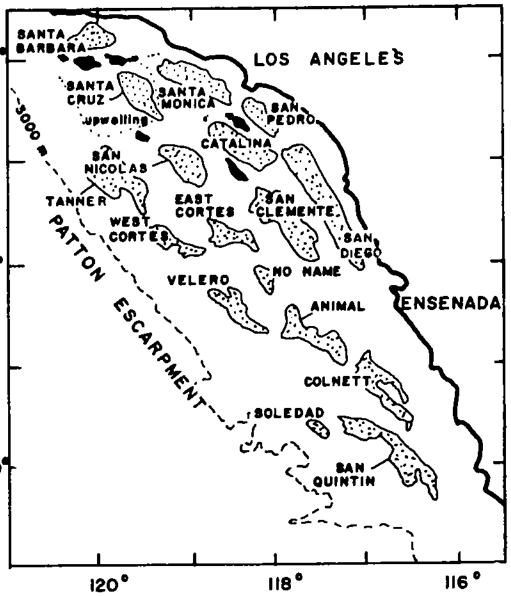

FIG. 1—The California Continental Borderland showing the outlines of the major basins. Upwelling is centered in the area south of the Northern Channel Islands and extends south to 33° N Latitude.

regional parts of the whole. For example, the history of the borderland evolution probably is no more than a very few millions of years in length and would be one of the smaller cycles as defined by Vail, Mitchum, and Thompson (1977b). Initiation of the Borderland began in late Miocene time (Doyle and Gorsline, 1977) and since that time tectonism, probably in pulses, has continued to alter the accumulating deposits. This can be minimized as a factor by looking at small units of the depositional record of essentially conformable nature. In most of the basins this conformable unit (see Fig. 2) has been defined by seismic data and estimates made of its age, which appears to be latest Pliocene and Pleistocene (Junger and Wagner, 1977). This unit is actually composed of many smaller cycles of the order of a few tens of thousands of years and which represent the deposits laid down during single sealevel cycles. Each of these is sufficiently short so that tectonism has little effect on the shape of the depression receiving the sediments although tectonic activity continues to be a major influence in some sedimentary processes at all times as in the example of mass movements initiated by earthquake shocks on a given slope (Ewing and Heezen, 1959; Haner and Gorsline, 1978). In a sense these small units are models of the world-wide sedimentary sequences whose scales are hundreds of millions of years just as the borderland basins are models of the conditions occurring in large oceanic basins. Thus my work has in great part been model studies of the latest cycle of accumulation (about 30,000 years) within small margin basins.

The limits of resolution of given sampling methods are also important boundary considerations. W. R. Normark (1978) has emphasized that what we see in marine continuous seismic profiles and piston cores may be highly biased as compared to the level of observation possible in a good surface outcrop. Similar caution has been given by the new seismic stratigraphers (Sheriff, 1977). This limitation causes much of the difficulty in meshing stratigraphic studies with studies of the contemporary ocean.

Different goals require different levels of resolution. On a world level, major cycles and relation of major sedimentary belts to crustal tectonic history can be examined with broad brush methods. Conversely, the definition of geologically important variations in climatic factors may require resolution almost at the annual level to be of value to specialists interested in modelling long term climatic changes. Perhaps because of my grounding in oceanography, my interests lean towards the fine comb rather than the coarse one; both are necessary elements in our ultimate understanding of earth processes.

Many marine geologists (e.g., Emery and Uchupi, 1975; Rona, 1973; Gorsline and Prensky, 1975) have also been impressed by the strong influence of sea level changes as a control on the delivery of sediments to basins or rises. Perhaps a better view of this is to speak of changes in shelf width. At high sea level, shelf width is maximum and acts either as a storage area for sediments or influences coastal processes that trap material in estuaries, coastal barriers, or inner shelf shoals (e.g., Emery, 1967; Swift, 1974; Allen et al., 1977). This control has operated to some degree during sea level cycles of all time scales.

I believe with most sedimentologists that the two primary controls of sedimentation are tectonic and climatic. All other factors

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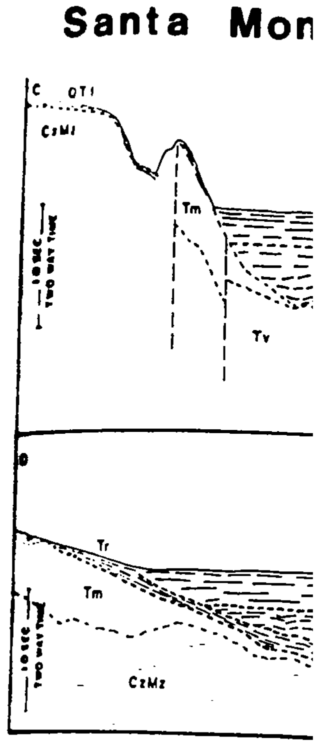

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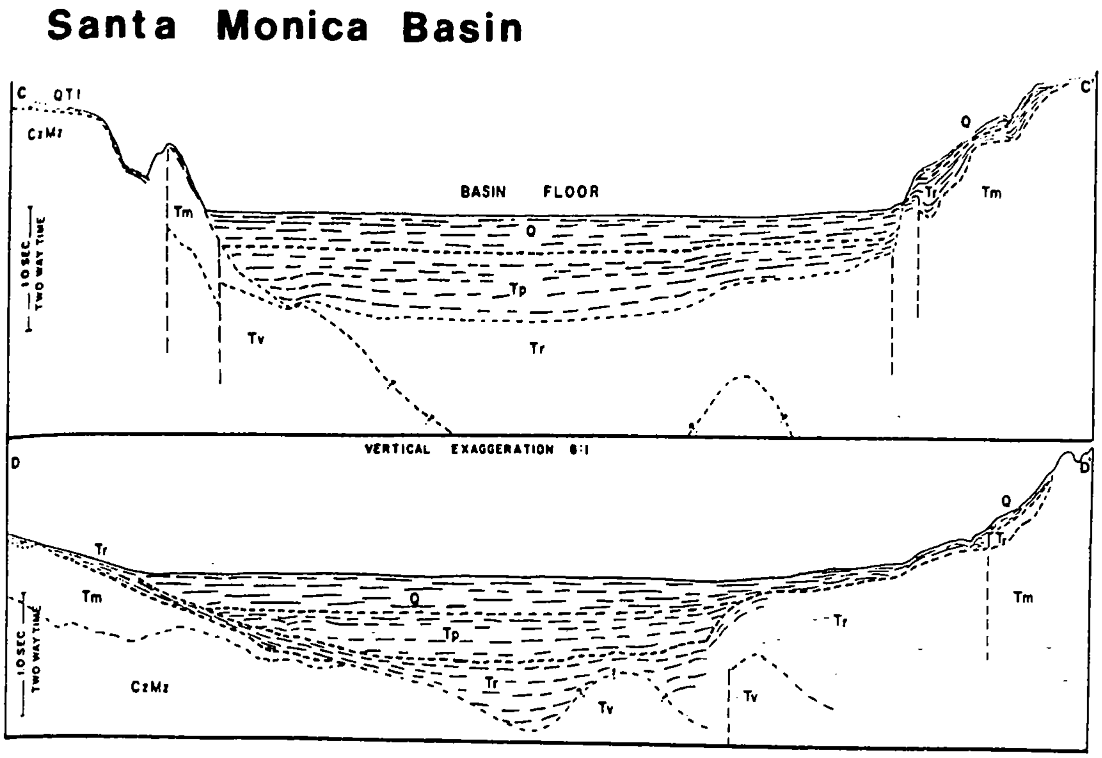

FIG. 2—Sketches of seismic profiles taken from Junger and Wagner, 1977, which illustrate the dimensions and thicknesses of the latest conformable sequence of basin filling in Santa Monica Basin. Tp is latest Pliocene and Q is Quaternary. There is some question about these extrapolated ages and the entire conformable sequence may be Pleistocene.

derive from these as they work on the crustal material of the Earth. In the cycles which I have studied, the time scale reduces effects of tectonism and emphasizes climatic effects, as the dominant primary control. I doubt that I need detail the influence of these factors as they control weathering processes, sediment delivery, relief, base level, and so forth.

Measurement of sedimentation rates is a very useful tool in deciphering variation in sediment supply. In the simplest case, as sediment supply changes, sedimentation rates in the system respond directly. We sometimes forget that the presumption underlying this is that the receiving area for sediments remains constant. This is probably true in closed basins but is not true for basins filled to sill depth or for the slope-rise-abyssal plain system where the great size of the receiving region gives the effect of an infinitely large basin into which the sediment prism constantly expands with time. The general relation is as follows:

$$\text{Supply} = (\bar{S})X(\text{Ar})$$

where $\bar{S}$ is the mean sedimentation rate and Ar is the receiving area. Thus, if due to overtopping of a sill, receiving area doubles but supply remains constant, the mean rate must decrease by half. Therefore, variation in sedimentation rates with time in a single core is not unambiguous evidence for change in regional supply and does not require a climate change.

Modelling Sedimentary Deposits

Several years ago in an earlier SEPM Presidential Address, Sloss (1962) defined a model for quantitatively describing the shape (P) of sedimentary deposits:

$$P = f(Q, R, D)$$

In this general equation, Q represents the quantity and composition of the materials introduced, R is the rate of subsidence (uplift), and D is the dispersal rate of material through the system. Sloss then briefly described a few examples of the manipulation of the model illustrating that transgressive-regressive sequences can be produced by mechanisms other than the traditional sea level change.

This view of the development of sedimentary bodies impressed me and has been one of my guides to thoughts about the evolution of marine basin deposits. A later article by Allen (1964) expanded upon Sloss's examples and examined more complex synergistic interactions in the equation.

In discussion of the modes of filling marine basins I will use some very general terms to describe particular types of sediment input. Table 1 is a simple classification of marine sediment contributions which is based on the continuity of supply. The rain of pelagic and hemipelagic materials is essentially *continuous* although most commonly at varying rates; a turbidity current or a massive slide are examples of discrete geological *discontinuous* contributions that occur at widely varying intervals of time (Gorsline and Emery, 1959). I recognize that these two groups are much simplified but the concept is useful for general discussion.

Neocatastrophism

In recent years, a majority of marine geologists and sedimentologists have come to recognize the importance of the rare major event. Such events include the flood of the century, the rare train of long waves at sea, the major earthquake of a century. This neocatastrophism (on a human time scale) is actually geologically common and represents in many systems the moment during which large movement of material occurs separated by periods of relative quiet or equilibrium (Booth and Gorsline, 1973). In southern California, the major floods tend to come at decade or generation intervals (e.g., 1914, 1938, 1969) and in a few days deliver loads of sediment to the coast that exceed the cumulative delivery during all of the intervening years. These markedly disturb the equilibrium of the local shelves and produce much increased deposition rates in the associated basin deposits (see Drake, Kolpack, and Fischer, 1973). Several years may be required to return the system to equilibrium.

TABLE 1.—*Marine Sediment Contribution*

- A. Continuous
  - Terrigenous
    - nepheloid
    - wind borne
    - traction
  - Biogenous
    - pelagic
    - benthic
- B. Discontinuous
  - Mass Movement
    - slide
    - slump
    - high concentration flows
  - Turbidity Currents

CALIFORNIA CONTINENTAL BORDERLAND

Form and Origin

The continental margin off southern California and northern Baja California presents a different aspect as compared to the traditional picture of margins as (1) simple terraces forming the periphery of the craton and descending to abyssal plains that flank typical passive margins, or (2) into trench axial floors in tectonically active margins. The borderland form is typified by strike slip or shear margins of which southern California and northern Baja California are excellent examples (Junger, 1976; Crouch, 1978).

In the borderland province, roughly 1000 km long and up to 200 km wide, approximately 20 basins are arranged in three irregular rows to form a checkerboard pattern (Fig. 1) oriented northwest-southeast (Shepard and Emery, 1941; Moore, 1969; Doyle and Gorsline, 1977). The basins range in axial length from 50 to nearly 200 km and in width from 20 km to 100 km. All but one (San Diego Trough) are closed depressions and have sills that range in depth from 200 m to over 2000 m.

The borderland is unique in the present oceans because it provides a set of margin basins arranged at increasing distances from the sources of sediments. This is true both for terrigenous and pelagic supplies.

Very much simplified, the borderland is downwarped regionally towards the seaward central portion lying off the international border. Emery (1960) and Doyle and Gorsline (1977) have shown that the depths to sills, bank tops, and islands increase to this portion of the borderland and shoal n
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Although there is still much controversy on the structural evolution of the borderland, most workers agree that the general form was initiated in Miocene time and the contemporary basins contain conformable, continuous, and relatively undisturbed deposits that date probably from late Pliocene time (note D. G. Moore's pre- and post-orogenic classification, 1969; Greene, 1975) and overlie increasingly deformed older late Tertiary sediment prisms.

The local basement formed by highly deformed rocks includes sedimentary rocks of Cretaceous age, volcanics of middle and late Tertiary age and basement complexes of Jurassic and Cretaceous age (Franciscan facies and batholithic units respectively) (Howell (*ed*), 1976). The contemporary sediments are derived from all of these lithologies and mainly from reworking of the Tertiary basin sediments that fill the inner basins such as Los Angeles and Ventura Basins to above sea level and also form the dissected flanking formations of the coastal mountains.

Sediment Sources and Rates Over Late Pleistocene Time

Borderland sediments are produced under a semiarid climate from sparsely vegetated surfaces and are sandy. Runoff is strongly seasonal and major floods of historic record come at intervals of decades to generations (e.g., 1862, 1883, 1905, 1914, 1938, 1969). During these major floods more sediment is delivered to the nearshore than in all of the intervening time and the shelves are abruptly overloaded beyond the available wave and current capacity to disperse the rapidly contributed load. These periodic geologically instantaneous pulses (1969 runoff delivered about 10^8 tons in 10 days of flow) throw the nearshore transport and depositional systems out of equilibirum (see Booth and Gorsline, 1973) and a period of a few years is required to restore equilibrium conditions (Drake, Kolpack, and Fischer, 1973). Scott and Williams (1978) have examined the erosion rates on land and their data show that the erosion is also concentrated during these exceptional events.

Work with sedimentary deposits laid down in the borderland over the last glacial cycle (roughly the past 30,000 years) (Gorsline and Prensky, 1975; Pao, 1977) shows that the rate of terrigenous contribution can increase as much as an order of magnitude during the cold, low sea level glacial epochs (Figs. 3, 4). Lowered sea levels increase stream gradient. Climates were probably wetter but still strongly seasonal and so runoff increased while the soil-holding factor of the vegetation remained low. Pollen evidence (Johnson, in press) suggests pine forest cover of coastal California during glacial times but this obviously did not inhibit delivery of large quantities of sediment. It is also possible that storm/flood frequency was higher. Numerous valleys that are much larger than the ephemeral streams that presently drain them are typical of Baja California and piston core data from the southern offshore basins are evidence that these regions contributed much more sediment than now at the times of lowered sea level perhaps 18,000 to 20,000 years before present.

The Borderland is located on the east side of an ocean basin in middle latitudes and so upwelling is a major process. Figure 5 illustrates the changes in biogenic sedimentation rates that take place during a glacial cycle. Just as terrigenous input markedly increases, biogenous rates (Fig. 3) more than

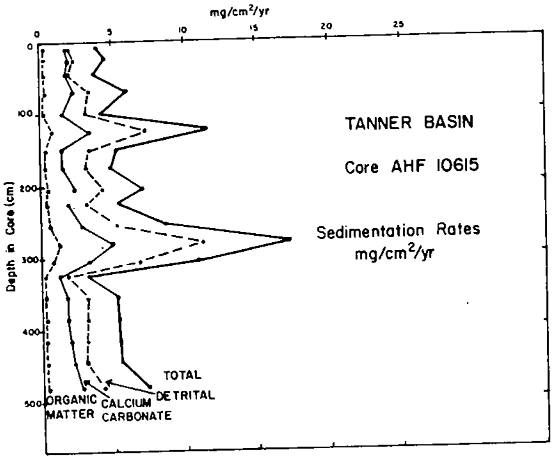

FIG. 3—Sedimentation rates of the various major sediment contributions in an outer basin piston core (Tanner Basin). The times of highest sedimentation rates correspond to times of cold water conditions based on foraminiferal data. Sedimentation rates are in amount of dry sediment per unit area per unit time.

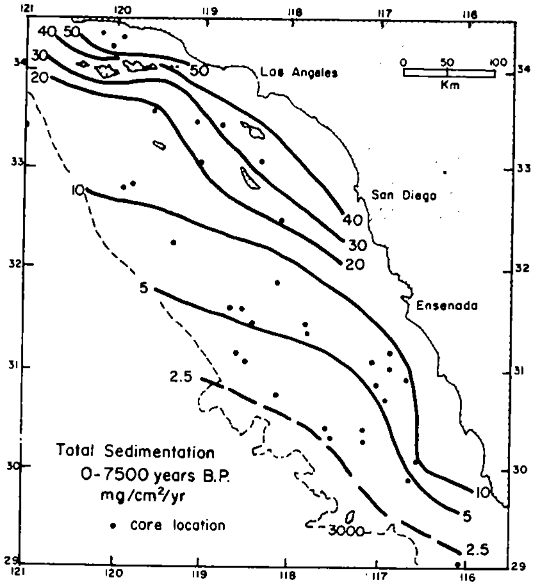

FIG. 4—The pattern of total sedimentation (mainly terrigenous) for the past period of warm water (high sea level) time shows the major source to be the northern rivers. In late Pleistocene time (ca. 18,000 yrs B.P.) the pattern shifted south and west and the magnitude increased (Gorsline and Prensky, 1975).

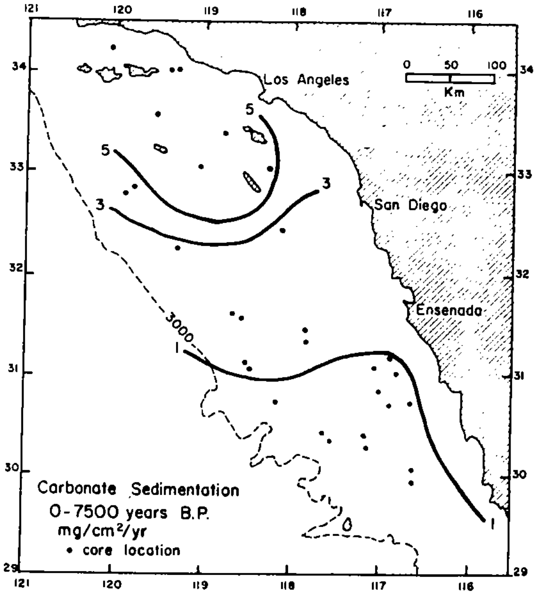

FIG. 5—Biogenic contribution during the current warm water episode matches the area of present upwelling. In late Pleistocene time (ca. 18,000 yrs B.P.) the pattern shifted south, enlarged, and the rate markedly increased.

double during the cold periods due to the increased rate of ocean and atmosphere circulation at those times of strong thermal contrast between equator and high latitudes. Note that on a world scale, larger scale oscillations of ocean temperature have occurred over Tertiary time and are documented by Deep Sea Drilling Program data (Savin and Douglas, in press). With increased planktonic productivity, the water chemistry of the water column in areas of upwelling alters and increased carbonate solution occurs (Berger, 1970; 1974) and so the real changes in bioproductivity in the upwelling areas of the northern Borderland were probably larger than the roughly two-fold increase seen in carbonate sedimentation rates in the basin sediments during the cold water low sea level cycles (Fig. 4).

Water Motion and Sediment Dispersal

Water circulation is the major factor influencing the disposition of suspended sediment and where it strongly affects the bottom can also determine the patterns of traction load distribution. Water motion in the Borderland involves several scales of dimension and rate. Surface layer circulation (uppermost few hundreds of meters of the water column) is driven by the major wind stress circulation of the north Pacific and is dominated by the slow relatively shallow and broad California Current, a typical eastern boundary current. This is deflected by effects of topography, winds, and Coriolis effect (see Emery, 1960) to form a large gyral over the northern Borderland centered on the areas of large scale upwelling south of the northern islands (Figs. 1, 5). The currents then swing south past the northern Baja California coast, and to the equatorial covergence. Suspended fines are thus carried into the Borderland from far distant sources (Fleischer, 1970).

Seasonally when the offshore atmospheric pressure cells shift and weaken, the California Current shifts seaward and a deeper flow moves to the surface along the inner margin forming the Davidson Current. Thus during some parts of each year coastal turbid waters will move north rather than south with the major surface drift. Over shelves, gyrals form as boundary cells to the major currents. These may move suspended load to one basin
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Deep circulation is controlled by the deeper gaps in the Patton Escarpment and enters the outer central Borderland and moves north over progressively shallower sills. Basin water below sill depth is uniform in density (Emery, 1960) and so the succeeding northern basins are filled by progressively shallower levels of the entering deep water flow. This flow at the present is from North Pacific Intermediate Water with very low oxygen content. Therefore, the basin floors are all covered by waters with initially low oxygen content which is further decreased, as the deep waters move north, by oxygen demand of the organic matter contributed from the upwelling process. In Santa Monica and Santa Barbara Basins (Fig. 1) the bottom waters over the central basin floors are anoxic and cannot support a benthic macrofauna. Therefore, reworking of primary sedimentary structures is excluded, preserving varve-like laminae in hemipelagic sediments (Hulseman and Emery, 1961; Soutar and Crill, 1977). During the cycles from warm to cold climates and associated variation in general oceanic circulation rates the position of the oxygen deficient intermediate water masses and the intensity of the minimum varies. There are suggestions in the sedimentary record of the central borderland basins that the oxygen minimum increases in thickness and that oxygen is further decreased during cold cycles although much documentation is needed (Gorsline, 1977). Geologically the importance lies in the preservation of annual laminae which can yield annual resolution of sediment contribution which in turn is primarily related to annual runoff (Soutar and Crill, 1977). Sill depth controls the microfauna assemblages of each basin regardless of maximum basin depth.

Tides influence the entire water body of the borderland and where topographic constrictions are present, the currents may reach velocities sufficient to scour the sills. Measurements at depths of 1800 m in one such constriction in the San Clemente Rift area show strong tidal cycles with maximum currents of 25 to 30 cm/sec within 3 m of the bottom (J. E. Warme, pers. comm.), which are adequate to move sand. Profiling reveals scour of the sills between Santa Monica and San Pedro Basins which has since been mantled by recent sediments suggesting that lowered sea levels and the resulting decrease in cross section produce conditions for the maximum concentration of tidal currents. Major scour has occured in the shallow (about 200 m) sill between Santa Barbara and Santa Monica Basins (Fig. 1) and this may date from the last rise of sea level and strong currents are presently active in the channel. In the geologic record similar effects must have occurred over sills between basins and between margin basins and the open ocean.

Deeper sills may well be sites of residual deposits that can contain paleontologic records of the shift of depth of water masses with changing climate. In the oceanic realm interesting data have been interpreted for major changes in the depth of the top of the Antarctic Bottom Water as deduced from sediments deposited in the Vema Gap (e.g., Auffret, et al., 1975; Ledbetter and Johnson, 1976).

Shepard and his associates (1969, 1973, 1977) have documented that tidal forces operating in canyons incised in slopes produce oscillating flows within these canyons that have tidal periods in deeper water and progressively shorter periods as one progresses shoreward up the canyon axis. These forces also generate internal wave trains which will progress shoreward except where strong seaward surface flows occur as off the mouths of rivers. In those regions the internal wave trains are apparently propagated seaward. Southard and Cacchione (1973) and Cacchione (1977) have shown that interaction of internal waves with different slope gradients in canyons or over shelves and across shelf edges can produce either internal surf at the point of intersection of the wave train with the bottom, surges either shoreward or seaward, or a damping and absorption of the wave trains. These must strongly influence suspended sediment movement and resuspension (Drake and Gorsline, 1975).

Submarine canyons influence surface wave trains because of the refraction caused by the contrast in depth between shelf and canyon and these effects work on the shore zones.

Surface waves work over the shelf surface and the shore and provide the main driving force for sediments entering the coast from rivers and shore erosion. Very long waves (periods of 20 seconds or more) can generate sand transporting surges over the full range of shelf depth and are probably geologically common (say one such train per decade) and can resuspend fines and move sands by traction processes either seaward or shoreward depending on the shelf configuration and wind directions (Cook and Gorsline, 1972).

PROCESSES

Table 2 lists the major process sets that can act to distribute basin sediments. Much research has been done on canyon-centered processes of the fan-canyon-turbidite plain system (e.g., Mutti and Ricci-Lucchi, 1972; Haner, 1971; Normark, 1970, 1973). Relatively little work has been done on slope and water-centered processes. When I describe a system as slope-centered, for example, I mean that the initial sediment input from shore and shelf transport systems is centered on the slope. Once deposited on the slope the sediment may be stable, may move by creep or in slides, slumps, or by other gravity processes or as turbidity currents. In some instances currents flowing along the slope may rework sediments by traction or by resuspension (Heezen et al., 1963). Slides may progressively evolve to turbidity currents. In all of the above, the processes act along a front over a plane surface and the sediment distributions derive from a *linear source*. Contrast this with canyon-centered processes which generally are initiated from the canyon head region as slides, slumps, debris flows, etc., but can be considered to originate essentially from a *point source* as they debouch from the canyon mouth. To complete this sequence, water-centered processes deliver sediments from an *area source* as in the pelagic rain of planktonic tests from the surface waters. Process oriented research has generally been concentrated on one of these process sets and even more commonly on a single process within a set.

TABLE 2.—*Process Sets*

I. River-Shore-Centered Processes
II. Shelf-Centered Processes
III. Canyon-Centered Processes
IV. Slope-Centered Processes
V. Water-layer-Centered Processes

At this point let me say that it seems to me that we need work on two large problems: (1) process linkage, and (2) process modulation. By *linkage,* I mean the interactions between processes or between process sets and also between such pairs as process and environment, or process and deposit (see Hampton, 1972; Carter, 1975). In the canyon-centered system, most workers agree that chains of processes occur. Mass failure by liquefaction leads to slurry flow then to high density fluid flow and finally to low density fluid flow (also see Allen, 1971). Process sets link, as in the case of river and surf zone systems with canyon centered systems. Because these linkages are present, we must then recognize that synergistic effects can occur. A given process may have a potential dispersal capacity which is limited by the "upstream" linked process or, conversely, may be amplified by the upstream process. One can, for example, then wonder what happens if a process overloads the next process "downstream" in the system?

By *modulation,* I mean the start and stop conditions for a process, the critical thresholds for various levels of transport or deposition, and, in general, the factors that control the process. One can envision "run away" models and closed feedback process-response models (K. S. Rodolfo pers. comm.). What are the "capacities" of the various processes?

I will not attempt a review of process literature but suggest that interested readers begin with the short course notes by Middleton et al. (1973) and Southard and Middleton (1977), the papers of Hampton (1972), Lowe (1972; in review), McCave (1972), Walker (1973), Carter (1975), Coleman (1977), and Moore (1977). All of the above have extensive bibliographies. Many of these deal with turbidity currents and some look at the mechanics of mass movement and pelagic biogenic processes.

In order to keep the discussions of basin filling process systems brief, I shall omit discussion of the river-shore centered systems and the shelf systems although these are necessary parts of the whole and govern the flow of material to the deep depositional sites. Obviously they must
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sites. Obviously they must operate on all terrigenous supply. In this regard, the paper presented at the 10th International Sedimentologic Congress by Karl and Gardner (1978) is particularly interesting. They describe three cases of canyon-shore arrangements. In the first case the canyon is attached to the surf zone. As sea level rises, the erosion of the canyon head may not keep up with the rate of rise of sea level (passive wide shelf margins for example) and the shore outraces the canyon. Wave refraction and internal wave interactions may continue to link shore and canyon but eventually the umbilical cord breaks and the canyon suddenly becomes detached with consequent immediate effects on the fan-plain system it serves. This model would suggest that modified sedimentary activity of canyon and fan continue after sea level rise is well advanced and then abruptly cuts off. The model can be applied to river fed canyons as well and the Mississippi submarine canyon may provide a model for a detached river fed canyon.

CANYON-CENTERED SYSTEM

The best known system is the canyon-fan-turbidite plain model. With the publication of Kuenen and Migliorini's paper (1950) the turbidite current has dominated the marine sedimentologic scene although its history is much older (see Walker, 1973). It is now recognized that a variety of processes are involved ranging from mass movement to low concentration flows. I will summarize the very detailed model by saying that sediments accumulate in canyons attached to either long-shore drift or to river discharge and then move down canyon periodically either because of overloading, shock, or decrease in bulk density (in situ gas formation as an example). These accumulations move initially by mass movement processes (Shepard and Dill, 1966; Hampton, 1972) and then, as they become increasingly mixed with fluid and with possible inclusion of clay from erosion of the canyon floor or canyon slope slides, become classic turbidity currents. Flows are initially channelized but become sheet flows.

Modifying traction processes such as slope currents (Heezen et al., 1963), or tide-driven currents (Shepard and Marshall, 1969) can rework these deposits and changes in gradient, channel configuration, sediment concentration, and shifts from channelized to unconfined flow produce sedimentary structure assemblages that can be identified with particular environments; as for example, canyon, inner fan channel, inter-distributary fan, distributary mouth, suprafan, lobe, etc. (Haner, 1971; Mutti and Ricci-Lucchi, 1972; Normark, 1978).

Seismic signatures have been defined for may of these environments (Payton, 1977) and numerous ancient examples reported (see references above). We probably now know enough to establish boundary conditions for hydrodynamicists and can with their assistance determine quantitatively what happens when sediment input is varied. A major problem is the difficulty of sampling adequate sections of contemporary fans and to establish the necessary volumetric characteristics of the ancient sections. Most of the present debate stems from the above problems.

At this point, I would like to emphasize the problem of mass budgets and volumetric measurements. A 10 cm thick turbidite covering 1000 km^2 (20 × 50 km) contains $10^{11}\,\mathrm{m}^3$ or about 0.1 km^3. This is an awesome volume of sediment to pile up and corresponds to a century of discharge by the Amazon River (Gibbs, 1967; Strakhov, 1962). In outcrop, turbidites a meter thick are common, and in a small basin (1000 km^2) involve very large masses of input if they are basin-wide events. This leads us to consider the question of the dominant contributor for turbidity currents. Is it the canyon or the slope?

SLOPE-CENTERED SYSTEM

I am impressed that the slope system has been neglected so long. The effects of mass movement were noted in the 1950's and 1960's (e.g., Ewing and Heezen, 1952; Moore, 1961; Dott, 1963) but have received little attention until very recently. Curray and Moore (1963) reported evidence of mass movement on continental slopes from early seismic profiling surveys. Emery and Uchupi (1975) and Seibold (1974) for example have shown the many large scale mass movements along the slope on both sides of the Atlantic. Lewis (1971) reported low gradient slides, and Almagor and Wiseman (1977) have shown some excellent examples from eastern Mediterranean slopes. A number of papers (e.g., Jacobi, 1976; Embley, 1976; Haner and Gorsline, 1978) have recently appeared and an SEPM special publication on slope processes (Pilkey and Doyle, in press) indicates a wave of interest is beginning.

It is evident that mass movements including slides, slumps, and debris flow are common, are of many scales, and can move km^3 of sediment to basins. Figure 6 shows a tentative estimate of relative areas of influence of the major delivery systems in three borderland basins over late Pleistocene and Holocene time.

Much of the structure mapped in subsurface and at surface in older basins is probably large scale mass movement of ancient slope material. Reference to the profile sketches of Emery and Uchupi (1975) of the Atlantic slopes will show that slides 10's of km in dimension are common. Many megabreccias ascribed to ancient margin thrusts may in fact be large slope slides similar to those of the present Atlantic margins. Shearman (1976) has presented field evidence that the melanges of the Zagros Mountains of southern Iran are in fact large scale debris flows or slides. Some of these appear to occupy very large channels cut into the ancient slope. It is evident that the margins of ancient basins may typically include such features which in many instances have probably been inferred to be fault zones of more classic form.

Much work is needed in the identification of the form of mass movement and boundary conditions and the energy sources to start the motion. As has been done for fans and canyons, slope systems need work on the identifying sedimentary structure assemblages and geomorphic units comparable to the Bouma series, Mutti-Walker classifications, etc. Identification of these deposits has been strongly accelerated by the need for knowledge about sea floor hazards and it is probably this need that has generated the rapidly rising interest of the marine geologic community.

WATER LAYER-CENTERED SYSTEMS

The hemipelagic contributions are the forgotten orphans of margin sedimentology. These sediments by reason of their continuous or near-continuous deposition carry the record of changing environmental conditions. Such programs as CLIMAP sponsored by the Office for the International Decade of

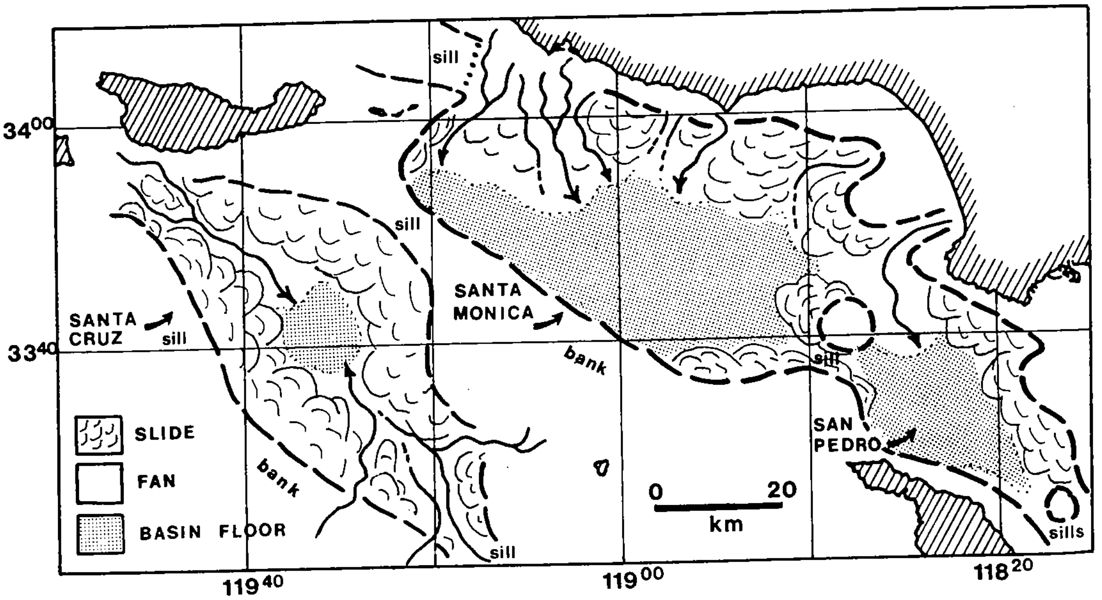

FIG. 6—Schematic representation of the zones of influence of turbidity current, mass movement, and location of sills in three California Borderland Basins, based on seismic profiling and echo sounding data. Active canyons are shown as arrows; inactive canyons as lines terminating in dashes. Sill positions are indicated.

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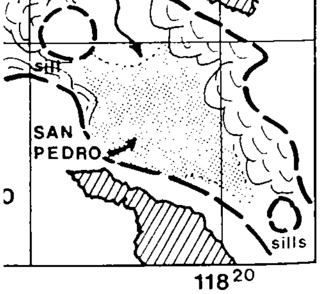

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Ocean Exploration of the National Science Foundation have shown the wealth of historical data enclosed in these sediments (e.g., Hays et al., 1976). The record of sea water surface and bottom water temperature change since Cretaceous constructed from DSDP data is an excellent example. Clay mineralogy (Fleischer, 1970), carbonate content (Broecker, Turedian, Heezen, 1958; Gorsline and Barnes, 1972) and isotopic studies of planktonic and benthonic foraminiferal tests (Shackleton, 1967; Shackleton and Opdyke, 1973) are examples of studies that can be very profitable as means of correlation and indicators of paleoclimatic changes that in turn influence sediment supply.

This is a wide open area for sedimentologic research and the proportion of hemipelagic deposits is large. In great part, the marine sedimentologists have forgotten about earth history over the past couple of decades and have concentrated on process. To my mind, a geologists's main goal is describing the history of the earth. Because the main record of such change is recorded in sediments and sedimentary rocks, we should be in the best position to further that objective, yet we have been passed by our paleoecology and geochemical colleagues in this regard. Basin synthesis showing change with time in the proportion of the influence of the major delivery systems and the correlation of the changes with tectonic and climatic change deduced from the hemipelagics and sediment-structural relationships is an area of research that promises many useful applications, of which more fine scale time correlations will perhaps be of greatest application to energy resources studies.

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