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Sedimentological and geochemical trends resulting from the breakup of Pangaea

Global sedimentology
Formation of the oceans
Lake deposits
Evaporites

Sédimentologie globale
Formation des océans
Dépôts lacustres
Évaporites

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ABSTRACT

The breakup of Pangaea and formation of the Atlantic and Indian Oceans and the marginal seas has an important influence on the global geochemistry of sediments. The initial rifting phases may have resulted in deposition of extensive fresh water lake deposits with high organic carbon contents so that these sediments may contain as much as 1/8 of the earth's sedimentary organic carbon. Flooding of the developing rifts by the sea and extensive deposition of evaporites followed. The present estimate of a total of 10.5×10^6 km^3 of evaporite deposits beneath the floor of the Gulf of Mexico, Atlantic Ocean, Red Sea and Mediterranean Sea has doubled the known quantity of evaporites. Growth of extensive barrier reefs and associated carbonate platforms along the developing passive trailing margins persisted after the evaporite phase in the Atlantic and ended during the middle Cretaceous. Since then, the major site of carbonate deposition has shifted to the open seas in the form of the contribution of calcareous plankton to pelagic sediments. These are significant geochemical fractionations which have affected the composition of the major sedimentary reservoirs.

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RÉSUMÉ

Évolution géochimique et sédimentologique résultant du morcellement de la Pangée

Le morcellement de la Pangée et la formation de l'océan Atlantique, de l'océan Indien et des mers marginales qui l'a suivi, ont eu des répercussions importantes sur la géochimie sédimentaire.
Durant la phase initiale, au moment de la formation des fossés d'effondrement, il y a eu probablement dominance des dépôts lacustres à forte teneur en carbone organique. Le carbone organique de ces dépôts pourrait représenter jusqu'à 1/8e de la matière organique des formations sédimentaires.

L'envahissement par la mer de ces fossés d'effondrement s'est traduit par le développement extensif des formations évaporitiques. Le cubage de ces évaporites accumulées sous le fond du Golfe du Mexique, de l'Atlantique, de la mer Rouge et de la Méditerranée représente un total probable de $10{,}5 \times 10^6$ km^3. Ceci représente le double des estimations connues sur le volume des évaporites.

Après cette phase évaporitique dans l'Atlantique et jusqu'à la fin du Crétacé moyen, le développement extensif des barrières récifales et des plates-formes carbonatées a été prépondérant dans le « sillage » de ces marges passives.

La zone privilégiée de sédimentation calcaire a ensuite dérivé vers le large, en raison de la contribution prépondérante du plancton carbonaté à la formation des sédiments pélagiques.

Telles sont les grandes phases des fractionnements géochimiques qui ont affecté la composition des sédiments dans les principales zones d'accumulation.

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INTRODUCTION

The breakup of Pangaea and the formation of the Atlantic and Indian Oceans and their marginal seas has had an important influence on the global geochemistry of NaCl, $CaSO_4$, organic carbon, opaline silica and other elements associated with these phases. The rifts and small ocean basins which formed initially would have acted as sites of chemical fractionation of salts dissolved in the world ocean. The development of a great area of passive trailing margins which subside in a regular manner, and across which most of the continental area drains to the ocean has dominated the global sedimentation system of the past 200 MY. Superimposed on this grand pattern is the development of calcareous plankton which now fix large amounts of calcium carbonate in the open sea with the result that carbonate oozes are deposited over much of the deep sea.

Hsü (1965) recognized the sedimentological significance of the continental breakup process. Sleep (1971) related the thermal history associated with continental splitting to uplift, erosion, subsequent subsidence and sedimentation. Kinsman (1975) presented the outlines of the effects of rifting and continental breakup on sedimentation in terms of both rate of accumulation and changing sediment type. Southam and Hay (in press) have analyzed the sequence of events in a semiquantitative manner to gain an impression of the significance of these processes for global geochemical mass balance and cycling. This paper further develops these concepts making use of the significant new contributions resulting from analysis of Deep Sea Drilling Project data (Jansa *et al.*, 1979 ; Watkins, Hoppe, 1979 ; Thierstein, 1979 ; Arthur, Natland, 1979) and from the large body of new data produced by USGS and other investigations of the Atlantic margin of the US (Folger *et al.*, 1979 ; Buffler *et al.*, 1979 ; Klitgord, Behrendt, 1979 ; Grow *et al.*, 1979 ; Dillon *et al.*, 1979). These permit further development of a semiquantitative model of the sedimentological and geochemical effects of the breakup of Pangaea. In understanding the early development of a passive margin, the most important new information to consider is that which has been learned from intensive study of the western margin of the North Atlantic.

ANALYSIS OF SEDIMENT ACCUMULATION OFF THE EAST COAST OF THE UNITED STATES

Folger *et al.* (1979) recently presented their interpretation of cross sections of the shelf and slope/rise off the east coast of the United States based on multichannel seismic lines. Four of these were analyzed from measurement of the cross sectional area of sediment shown as Triassic, Jurassic, Cretaceous and Tertiary on the shelf and on the slope/rise, with the indicated "salt", an arbitrarily equivalent amount of anhydrite, and the carbonate bank or "reef" distinguished as discrete units. Two of the seismic lines, USGS CDP line 5 southeast of Cape Cod across the northeastern part of the Long Island platform and USGS/IPOD line across the margin southeast of Cape Hatteras, represent sections on arches. The other two cross sections analysed, based on USGS CDP line 2 and USGS CDP line 6, are both in the Baltimore Canyon trough and represent a basin. All of the cross sections extend to 300 km offshore in the original illustrations except that based on USGS CDP line 2, which ended at 240 km offshore, but was projected to 300 km for measurement. The results are shown in Figures 1 and 2. Figures 1A and B show the average areally integrated sedimentation rate and volume per kilometer of margin for the two cross sections on arches ; with A representing sediment on the shelf and B sediment on the slope/rise ; Figures 2A and B show the same information for the average of the two cross sections in the Baltimore Canyon trough, here considered a typical marginal basin. For the shelf, sedimentation increases from the Triassic to the Jurassic, and declines markedly during the Cretaceous and Tertiary. For the slope/rise, sedimentation is high in the Jurassic, declines in the Cretaceous and increases significantly in the Tertiary. The overall and detrital sedimentation rates for the Triassic shelf are nearly equal in arch and basin provinces. However, assuming that a volume of anhydrite equivalent to the volume of salt interpreted on the seismic sections is also present, and that half of the anhydrite is pre-salt Triassic and half early Jurassic, the basin accumulates more evaporite than the arches, and the amount of evaporite is approximately equal to the amount interpreted as detrital sediment. On both the shelf and the slope/rise,

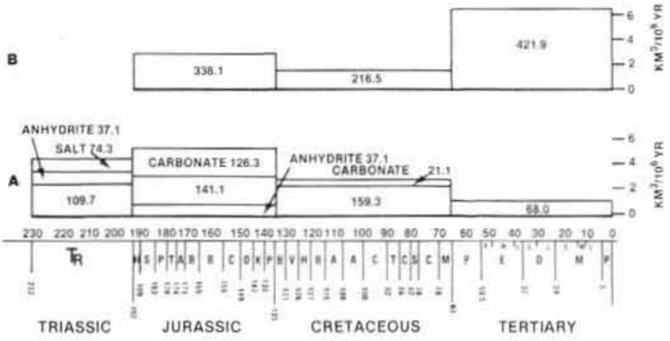

Figure 1

Volumes and areally integrated sedimentation rates for the average of USGS CDP line 5 southeast of Cape Cod and the USGS/IPOD line across the margin southeast of Cape Hatteras, representing sedimentation on arches. A is sediment on the shelf, B is sediment of the slope/rise. Numbers in columns are volumes in km² per km length of margin. Areally integrated sedimentation rates are km³ on shelf (A) or slope/rise (B) per km length of margin. Lithologies are unknown except as noted. Anhydrite equivalent in amount to the halite shown on the sections is inferred, but may not be present.

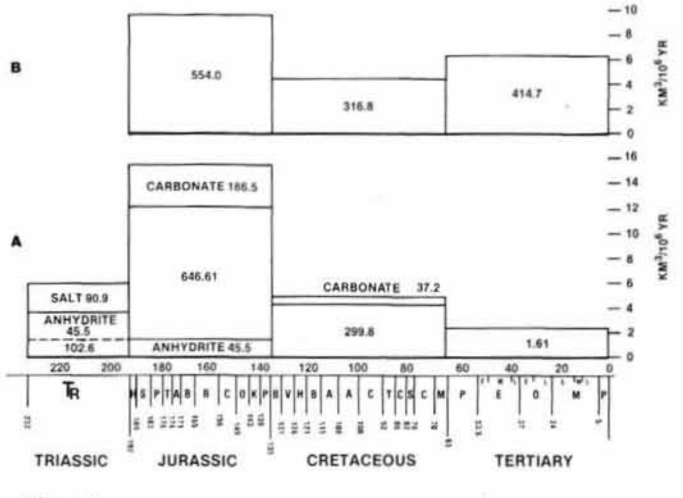

Figure 2

Volumes and areally integrated sedimentation rates for the average of USGS CDP Lines 2 and 6 southeast of Cape Cod representing sedimentation in a basin, Baltimore Canyon Trough. A is sediment on the shelf, B is sediment of the slope/rise. Numbers in columns are volumes in km³ per km length of margin. Areally integrated sedimentation rates are km³ on shelf (A) or slope/rise (B) per km length of margin. Lithologies are unknown except as noted. Anhydrite is equivalent in amount to the halite shown on the sections is inferred, but may not be present.

the basin and arches are best differentiated in the Jurassic, when sedimentation rates between them vary by factors of 1.5 to 4. Sedimentation rates for the basin and arches also differ for both shelf and slope/rise during the Cretaceous. On the shelf, the basin and arches are differentiated in the Tertiary, but on the slope/rise Tertiary sedimentation rates are equal for the former basin and arches.

SUMMARY OF A MODEL FOR DEVELOPMENT OF A PASSIVE MARGIN

The continental splitting process normally involves uplift, erosion, formation of rift grabens, attenuation of the continental crust, implacement of oceanic crust, separation of the continental fragments by sea floor spreading, and subsidence due to thermal contraction. The time constants associated with these processes are not known precisely ; the best estimate being for that associated with subsidence due to cooling of oceanic crust and mantle. The reference point for discussion of continental splitting is the time of separation, i.e. age of the oldest oceanic crust, but this is not a critical time as far as sedimentation processes are concerned. Because of the uncertainties in the time constants associated with uplift, erosion, rifting and attenuation, the model presented here describes the development of a passive margin in a schematic manner, recognizing an initial phase without sedimentation followed by four early sedimentation phases of equal length and a subsequent long period of maturity.

The sedimentological model for development of a passive margin is described in terms of the following phases, the first four involving sedimentation on the future passive margin are estimated to last about 20 MY each :

0) Uplift and erosion with the sediments deposited in a region distant from the site of future passive margin development.

1) Continuing uplift and erosion with lacustrine-fluvial sedimentation in a rift graben formed above sea level ; 20 MY required for the floor of the graben to subside to sea level. Delivery of sediment to distant areas continues.

2) Development of a deep narrow graben with maximum local relief and restricted connection to the ocean ; the high marginal walls tend to produce a local evaporative climatic regime, so that the sea in the graben is prone to development of unusually hypersaline conditions or evaporite deposition. This stage is also estimated to last 20 MY. Separation of the continental fragments occurs during the middle of this phase.

3) Development of a narrow seaway with marginal mountains and hills, but more open connection with the world ocean. The original slope of the adjacent borderlands is still away from the young ocean which has a less extreme local climate but is still prone to development of dense water masses with episodes of stratification alternating with turnover. This stage is also estimated to last 20 MY.

4) A period of very rapid detrital sedimentation, which occurs after subsidence to sea level of erosionally-thinned continental crust, marginal to the young ocean. This results in formation of the continental shelf proper and also causes reversal of regional slope and drainage into the young ocean basin. The bulk of the detrital sediment wedge produced by the initial uplift and deposited at a distance is re-eroded and re-sedimented on the newly developed continental shelf, slope and rise. This phase is initiated about 30 MY after separation, and is also thought to last about 20 MY.

5) Development of a mature margin with sediment supply becoming increasingly focused by large rivers at a few points ; shelf subsidence rate declines, and shelf and rise sedimentation patterns become strongly affected by sea level changes.

As discussed below, parts of this sequence seem to be well defined and constrained, other parts will remain highly speculative until deep drilling on the margins can verify or correct geophysical interpretations.

THE OVERALL LOSS OF SEDIMENT OFF PANGAEA

Hay *et al.* (in press) have discussed the size, shape, location, hypsography, nature of drainage and climate of Pangaea. The area of the ancient continent was probably slightly larger than the area of the present fragments because of attenuation and loss through subsidence of part of the marginal areas in the rifting process. Southam and Hay (in press) have discussed the volume and mass of sediment residing on the major tectonic units as shown in Table 1. About 2/3 of the sediment present today is of Mesozoic or Cenozoic age as shown in Table 2. Most of the post-Paleozoic sediment was derived from Pangaea and subsequently deposited in the Mesozoic-Cenozoic passive margins and in the deep sea. The deposits offloaded onto oceanic crust are equivalent to an additional layer of sediments about 2.25 km thick spread over all of the continental blocks. At the present, the average thickness of sediments on the continental blocks, including geosynclines is about 4 km (see Table 3), but only 2.4 km of this is Paleozoic or older. Thus the amount of sediment which has been lost from the continental blocks to the deep sea is

Table 1

Distribution of sediments on present tectonic units

Tectonic unit	Area $\times 10^6$ km²	%	Volume of sediment $\times 10^6$ km³	%	Mass of sediment $\times 10^{21}$ g	%
1. Craton (mostly Precambrian-Paleozoic)	96.3	19.1	165	14.8	356	14.3
2. Precambrian-Paleozoic Geosynclines	30.7	6.1	211	18.9	524	21.1
3. Mesozoic-Cenozoic Geosynclines	28.3	5.6	203	18.2	503	20.2
Total Geosynclines	59.0	11.7	414	37.1	1,027	41.3
4. Passive Margin Shelves (mostly Mesozoic-Cenozoic)	31.8	6.3	95	8.5	205	8.2
5. Passive Margin Slope and Rise (Mesozoic-Cenozoic)	27.5	5.4	280	25.1	607	24.4
Total Passive Margins	59.3	11.7	375	33.6	812	32.6
6. Active Margin (Mesozoic-Cenozoic)	6.3	1.2	19	1.7	41	1.6
7. Ocean Basins (Mesozoic-Cenozoic)	284.0	56.2	142	12.7	249	10.0
Total, All Tectonic Units	504.9	99.9	1,115	99.9	2,485	99.8

Table 2

Volumes and masses of sediment by age

Age	Volume 10^6 km³	%	Mass $\times 10^{21}$ g	%
Precambrian-Paleozoic	376	33.7	880	35.4
Mesozoic-Cenozoic	739	66.3	1,605	64.6
Total	1,115	100.0	2,485	100.0

Table 3

Average thicknesses, volumes, and masses of sediments on continental blocks and in ocean basins by age

	Average Thickness	Volume 10^6 km³	%	Mass 10^{21} g	%
Continental block Tectonic Units 1-4					
Precambrian-Paleozoic	2.4 km	376	33.7	880	35.4
Mesozoic-Cenozoic	1.6	317	28.4	749	30.1
Total	4.0	693		1,629	
Ocean basin Tectonic Units 5-7 Precambrian-Paleozoic	0	0	0.0	0	0.0
Mesozoic-Cenozoic	1.4	422	37.8	856	34.4
Total	1.4	422	99.9	856	99.9

about equal to the amount of Paleozoic sediment remaining on the continents, and an equal amount of Mesozoic-Cenozoic sediments resides in the continental shelves and younger geosynclines.

How much of the Mesozoic-Cenozoic sediment is recycled Paleozoic and older sediment and how much has been formed from the erosion of igneous rocks ? Holland (1978) has estimated that about 1/3 of the present load of rivers derives from weathering of igneous rocks. Because at the end of the Paleozoic the continental blocks had more sediment on them, which would tend to cover up igneous rocks, 1/3 can be considered a maximum value for the proportion of Mesozoic-Cenozoic sediment derived from weathering of igneous rocks. It is likely that the true value is much less. In any case, of the estimated total of $1{,}605 \times 10^{21}$ g of Mesozoic-Cenozoic sediment, at least $1{,}070 \times 10^{21}$ g was derived by recycling older sediment. Thus more than half of the sedimentary material present on Pangaea at the end of the Paleozoic has been recycled, and about half the recycled sediment has been lost off the continental block. This recycling rate is significantly higher than that suggested by Garrels and Mackenzie (1971) who assumed half of the total mass of sedimentary rocks to be 600 MY old or younger.

THE SEQUENCE OF BREAKUP OF PANGAEA

The sequence of separation of continental fragments presented in Figure 3 follows that presented and discussed in detail by Barron *et al.* (in press), but adds the Gulf of Mexico with continental separation at 150 million years ago, following Buffler *et al.* (1980). The values indicated on the ordinate are the length of passive margin resulting from continental separation ; on the left margin is the length of the rift prior to separation. Figure 4 shows the integrated effects of breakup of Pangaea in terms of the four phases of passive margin sedimentation, as discussed below.

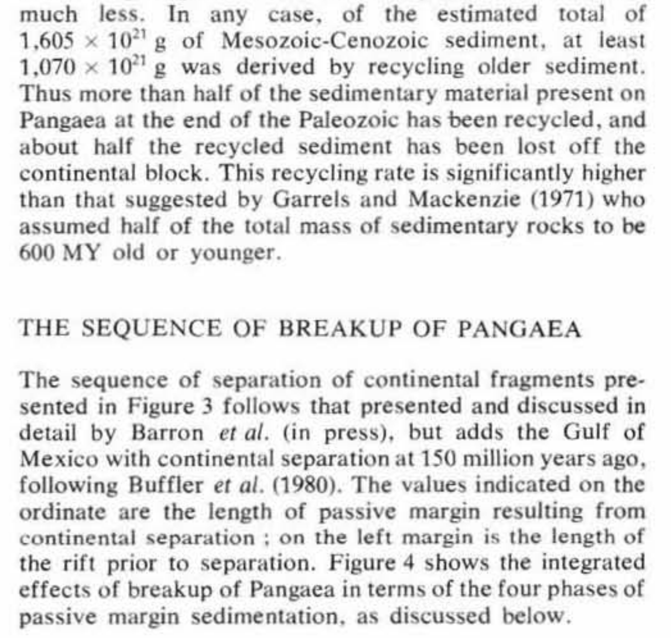

Figure 3

Length of rifts and passive margins resulting from the breakup of Pangaea plotted against time of separation of the fragments.

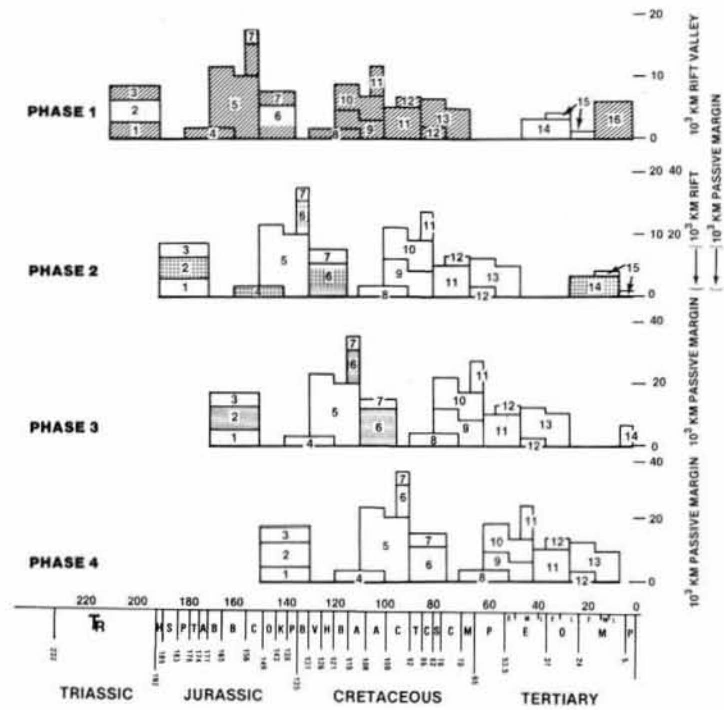

Figure 4

Synoptic schema of the development of rifts and passive margins showing phases 1-4. Numbers in columns refer to the rifts/passive margins indicated in Figure 3. In phase 1, diagonal lines indicate that the rift developed in a warm humid zone conducive to the development of stratified lakes, and hence likely to be sinks for organic carbon. Vertical scale is 10^3 km of length of rift. In phase 2, the quadrille pattern indicates deposition of evaporites, wavy lines indicate deposition of organic carbon-rich black shales. Vertical scales are 10^3 km of length of rift and 10^3 km of length of passive margin, because continental separation occurs in the middle of this phase.
In phase 3, the wavy line pattern indicates deposition of organic carbon-rich black shales. Vertical scale is 10^3 km of length of passive margin.
In phase 4, the vertical scale is 10^3 km of length of passive margin.

Phase 0 — Uplift and erosion prior to development of a central rift graben

Cloos (1939) described the process of uplift, rifting and associated volcanism using the Rhine graben and Red Sea Gulf of Aden areas as examples. From experiments, he determined that domal uplift was likely to produce three cracks at angles of approximately 60° to each other. McKenzie and Morgan (1969) discussed seafloor spreading at triple junctions as the result of upwelling mantle plumes. Burke and Whiteman (1973) have discussed uplift and rifting in Africa and use the terms *rrr* and *RRR* to distinguish between rift triple junctions and seafloor spreading triple junctions. Burke and Dewey (1973) ascribed development of a linear spreading center to coalescence of two arms of each adjacent *rrr* rift triple junction. The third arm fails to become a spreading center except in a few places where the *rrr* triple rift junction develops into a *RRR* spreading ridge triple junction. The early phase of uplift may be recognized by initiation of alkaline volcanic activity as suggested by Lebas (1971).

Burke and Whiteman (1973) have tabulated the statistics for eleven *rrr* junctions in or at the margin of Africa, ascribing lengths of time ranging from 50 m.y. to 30 m.y. for the period of active rifting associated with these *rrr* junctions. On the Atlantic margin of North America, the basaltic sills and flows associated with Triassic graben development and deposition of the Newark Series (Sanders, 1963 ; de Boer, 1968) were dated at 220-230 m.y. (Armstrong, Besançon, 1970) or 40-50 m.y. prior to continental separation. However, the Newark Series exposed in the eastern US may have been deposited in a failed rift system antecedent to that along which continental separation occurred. For the development of the model, Kinsman's estimate of 30 m.y. has been considered appropriate for the time span between development of the rift and separation of the continental fragments. Clearly, this is a generalization because the time involved and complexity of the rifting process will vary from place to place. The North American-African rift was evidently a very complex process, producing not only the rift graben basins exposed at the surface in North America and Africa, but also a number of deeply buried basins, as suggested by van Houten (1977) and documented by Klitgord and Behrendt (1979). The splitting of Pangaea involved a continental thickness about 2.25 km greater and a seafloor spreading system less well organized than that of today. It is not unlikely that the intervals required from the processes of uplift and rifting leading to splitting were longer in the early Mesozoic and have tended to become shorter as the continents have been thinned by erosion and the global seafloor spreading system becomes more organized. The time span represented by this phase might be up to 30 MY.

The area involved in uplift and erosion was recognized by Closs (1939) to be extensive, but most modern authors have considered only the size of the central part of the uplift. The ratio of length to width for individual African uplifts, given by Burke and Whiteman (1973) varies from 2:1 to 3:1, with the smallest, Adamewa and Ngaoundere, being 50 × 150 km and the largest, Jos, being 200 × 500 km. Where uplifts have coalesced, Atakor-Ajjer (to form the Ahaggar) and Barmenda-Cameroun Mt., the length to width ratio is increased to 4:1 and 8:1. They suggest uplift of the basement of about one km for all of the eleven African uplifts analyzed.

Much larger areas may be affected by uplift. As Southam and Hay (in press) have shown, the profile of a typical midocean ridge suggests significant uplift extending to 800 km or more on either side of a rift. Viewed in the context of a continental area previously eroded to grade, such uplift has enormous sedimentological implications, involving the erosion of a vast volume of material. For North America, the regional uplift prior to separation from Africa may have extended west to near the site of the present Mississippi, with slopes similar to those presently existing between Denver and St. Louis. The amount of uplift of a continental area over an incipient spreading center can be estimated using the values for thickness and density of typical oceanic and continental crust sections given by Worzel (1974), but with the modification that the total continent is assumed to have an elevation of + 0.84 km, a sediment thickness of 4.0 km with an average density of 2.2, and an average density for the igneous and metamorphic crust of 2.84 down to − 33.0 km. Assuming that the weight of the columns must balance at − 100 km, taken to be the top of the asthenosphere, and that the difference between old seafloor (Worzel's ocean crust section) and a spreading ridge is that the latter lacks sediment and has the top of layer 2 raised to − 2.5 km because of warmer, less dense mantle material, the mantle beneath the spreading center can be calculated to have an average density of only 3.23 rather than the 3.30 assumed beneath old ocean crust and beneath the continent. Assuming that prior to rifting the density of the hot mantle material beneath the continent is 3.23 requires an additional 1.45 km of mantle beneath the continent and above − 100 km, elevating the surface of the continent by that amount. Kinsman (1975), using slightly different values for the thickness and density of the units, obtained an uplift value of 1.75 km. Taking into account the greater average sediment thickness on Pangaea (5.75 km) and its higher average elevation (+ 1.06 km) the uplift would be 1.42 km. These values neglect erosion which would remove material from the area of uplift and deposit it in unaffected regions. Isostatic adjustment as erosion removes material off the uplift would amplify the effect, so that to erode the crest of the uplift to the original grade and base level would require erosion of 5.3 km of material (4.0 km of sediment of density 2.2 and 1.3 km of igneous or metamorphics of density 2.84) from the present average continent. In the case of average Pangaea, 5.5 km of the average 5.7 km sediment cover would be eroded, leaving 0.2 km of sediment remaining on basement at the center of the uplift. If the uplift had the shape of the Mid-Atlantic Ridge, the total volume of sediment which could be eroded off each side would be 2,000 km^3 per kilometer of length if isostatic adjustment were complete and erosion proceeded to the original grade and base level. An estimate of half this amount is more realistic because erosion is unlikely to have reduced the surface to the original grade and base level before subsidence set in.

The material eroded off the uplift would be deposited in the distal part of the regional slope and beyond. In North America the sediments eroded off the uplift prior to splitting of North America from Africa, would have been deposited above the sea level in the continental interior. Simultaneous uplift in the Gulf of Mexico and Arctic regions and mountains in the west bordering the Pacific subduction zone would have acted to create a very large interior basin. Carbonate and other soluble rocks would bypass the basin which would accumulate only the detrital material. The Dockum, Chugwater, Spearfish, and other redbeds of the Triassic or early Jurassic of the eastern Rocky Mountains probably represent the clays and silts forming the distal portion of this great sediment wedge originating at the site of the future east coast, and would have overlain Permian rocks of the Great Plains and Midwest. The materials eroded off the uplift would have been largely the Permian and Pennsylvanian detrital sedimentary rocks produced as a result of the Appalachian orogeny. These sediments, probably in the order of 3.5×10^6 km^3, were recycled to the west, but are later recycled back to the east to be deposited on the developing slope and rise, following Garrels and Mackenzie's (1971) rule that the last rocks deposited are the first to be eroded.

Alkaline volcanism, uplift and erosion may precede continental separation by as much as 50 MY. The sedimentological model developed here assumes formation of a graben by rifting 30 MY prior to continental separation, allowing 20 MY for pre-rift doming and erosion. Because this interval does not directly contribute sediment to the future passive margin it may appropriately be termed phase 0, and precedes the phases of sedimentation on the future passive margin.

During this early period of uplift, the third arm of each *rrr* junction may become well developed causing thinning of the crust by uplift and erosion. The third arm would extend inland away from each obtuse angle developed along the rift trend. The importance of the third arm is that the thinning permits subsequent development of a marginal basin. Further, subsidence along the length of the failed third arm tends to guide reorganization of the drainage, as evidenced by the fact that many major rivers debouch in marginal reentrants. Figure 5 shows postulated major *rrr* junctions for Pangea and indicates the rivers associated with the failed third arms. The process of reorganization of drainage after uplift is long and complex but ultimately favors capture of other streams by those occupying the sites of failed third arms.

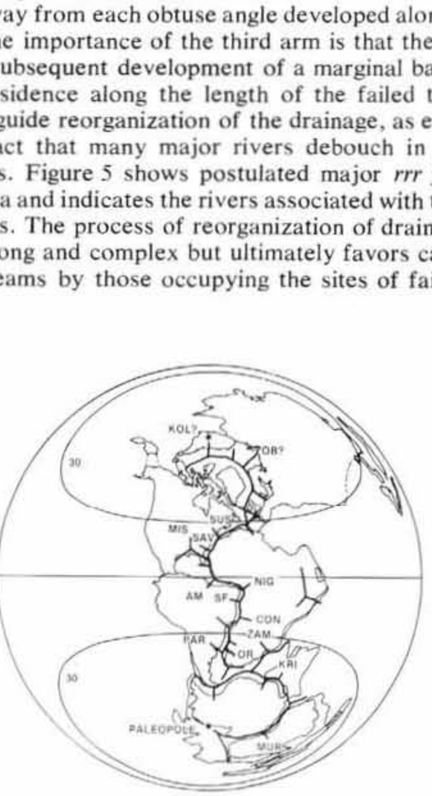

Figure 5

Map of Pangaea, showing major rifts and indicating rivers which may be associated with triple junctions KOL = Kolyma, LEN = Lena, OB = Ob, SUS = Susquehana, SAV = Savannah, MIS = Mississippi, RIO = Rio Grande, AM = Amazon, NIG = Niger, SF = San Francisco, CON = Congo, PAR = Parana, OR = Orange, ZAM = Zambesi, KRI = Krishna, MUR = Murray.

Phase 1 — The elevated rift valley graben : sedimentation in swamps, fresh water lakes, and streams

When rifting first occurs the graben is a shallow feature on the regional uplift. The regional uplift is likely to be the highest area in the vicinity, and as such will act to modify the local climate to serve as a trap for rain. By analogy with the East African Rift systems, it can be expected that paludal, lacustrine, and fluvial environments will dominate in the rift, with marginal alluvial fans developed along the graben walls. The source area for detrital sediments is restricted to the immediately adjacent parts of the uplift.

For the model, initiation of sedimentation in the rift is considered to start 30 MY before separation, and this fresh water phase is expected to last about 20 MY. At 10 MY before separation the floor of the rift graben reaches sea level and subsequently the rift can be filled with marine water or form dessicated basins below sea level, such as the Dead Sea graben and Afar at the present time.

The narrow growing rift is prone to great irregularity in development with longitudinal basins and arches resulting from dilation and compression due to minor changes in the strike of the walls as the central block subsides. In the eastern United States it is evident that the rift did not develop as a single longitudinal feature, but as a series of quasi-parallel troughs, each no more than several hundred km in length (van Houten, 1977 ; Klitgord, Behrendt, 1979). The trend of the rifts follows pre-existing structures, and suggests reactivation of zones of weakness in the crust.

The volume of sediment which accumulated in the developing rift was, by comparison, a small fraction of that eroded off the uplift. Based on analogy with the Dead Sea Rift, Southam and Hay (in press) cited 40 km as the average width and 5 km as the average depth of sediment fill before floor of the graben reaches sea level and marine invasion can take place. Hence, the sediment volume is 200 km^3 per km of length of the rift. Subsequent longitudinal splitting of the graben as continental separation takes place would leave each passive margin with 100 km^3 of phase 1 rift sediment per kilometer of length. This estimate agrees well with the pre-salt Triassic detrital sediment volume of 106 km^3 per km length of rift obtained by measuring both the salt and the sediment below the salt on the cross sections of Folger *et al.* (1979), and assuming an amount of anhydrite equivalent to half of the salt to be included in the sediment below. However, the cross sections of Folger *et al.* terminate at the shore line, so that the estimates of volume based on them do not include the onshore Triassic grabens with exposures of the Newark Series. In Figures 6-7 the « Triassic » detritus of the cross sections of Folger *et al.* has been shown as deposited during phase 1, in this case between 210 and 190 MY ago, which is younger than the 220-230 MY dates on the basaltic sills and flows of the Newark Series obtained by Armstrong and Besancon (1970), but corresponds with their dates for the dikes and may be more appropriate for the age of grabens buried beneath younger shelf sediments.

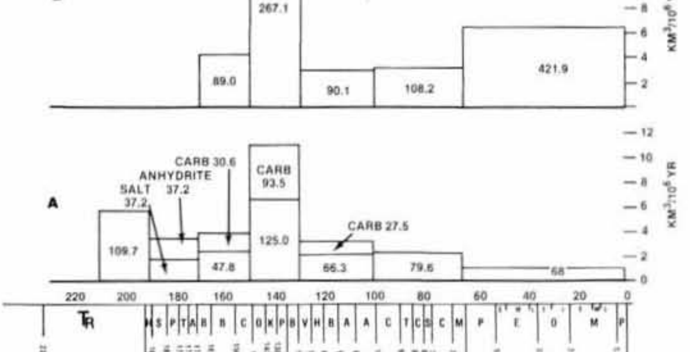

Figure 6

Volumes and areally integrated sedimentation rates for the average of USGS CDP line 5 southeast of Cape Cod and the USGS/IPOD line across the margin southeast of Cape Hatteras, representing sedimentation on the arches in terms of the phases of passive margin development presented in the text. A is sediment on the shelf, B is sediment of the slope/rise. Numbers in columns are volumes in km^3 per km length of margin. Areally integrated sedimentation rates are km^3 on shelf (A) or slope/rise (B) per km length of margin.

Southam and Hay (in press) have suggested that the elevated rift grabens may be an important sink for organic carbon. Degens *et al.'s* (1971 ; 1973) and Degens and Stoffers' (1976) accounts of Lakes Tanganyika, Malawi and Kivu in the East African Rift System demonstrate that these tropical lakes are stratified, with a well developed thermocline separating oxygenated surface waters from anoxic bottom waters. Bottom sediments of these lakes may have very high contents of organic carbon, up to 10 % in the sediments of Lake Tanganyika. Southam and Hay assumed an average carbon content of 5 % in all rift sediments formed over the past 180 m.y. to estimate a total of up to 7.36×10^{20} grams of organic carbon in rift sediments. Using a new estimate based on the additional rifts included in Figure 3, but counting only those rifts which developed in humid zones, assuming an average organic carbon content of 5 % and assuming an average of 20 % lacustrine sediments in the graben fill, the estimate of the total of organic carbon is reduced to $2{,}18 \times 10^{20}$ g of organic carbon. This still amounts to a ten-fold enrichment over the average in sediments.

In constructing Figure 4 the attribution of the site of formation of a rift to a humid or arid environment was based on its paleolatitude on the paleogeographic maps of Barron *et al.* (in press). The rift is assumed to have been humid and to have had lakes if it developed outside the bands 12-30° N and S. The lakes are assumed to have been thermally stratified and to have accumulated sediments rich in organic carbon unless the rift developed after the late Eocene and occupied a latitude higher than 30°. The only Mesozoic rift which developed exclusively in the assumed arid band is that between North America and Africa ; a part of the rift between South America and Africa also developed in the arid band. Lake development within the arid band cannot be excluded if parts of the rift also extended into more humid regions and could serve as sources for rivers, such as the Jordan, flowing along the length of the rift. Definition of the bands between 12-30° N and S as arid zones relies on the assumption that the Hadley cells governing atmospheric circulation were in the same position in the Mesozoic as suggested by the atmospheric models studied by Barron (1980) and the paleoclimate-paleolatitude analyses of Habicht (1979), and that they did not occupy different latitudes in the Mesozoic as suggested by Frakes (1979). If large continental areas affect climatic zonation as suggested by Robinson (1973) and as used by Ziegler *et al.* (1979) and Bambach *et al.* (1980) in their Paleozoic reconstructions, then the arid zones would extend obliquely across the continent, starting at higher latitudes on the east and expanding in width to reach lower latitudes to the west. Application of this paleogeographic paleoclimatic model to the Pangea of 180 m.y. ago produced the interesting result that the North American-African rift would have developed in a humid region (see Hay *et al.*, in press, Figure 5). This is in agreement with the presence of extensive lacustrine deposits in the older beds of the Newark Series. Analysis of the paleoposition of rifts with Robinson climatic belts would be an interesting exercise and might suggest modification of Figure 5. It would also be useful to seek additional evidence to determine whether climatic boundaries can be significantly deflected by large land areas.

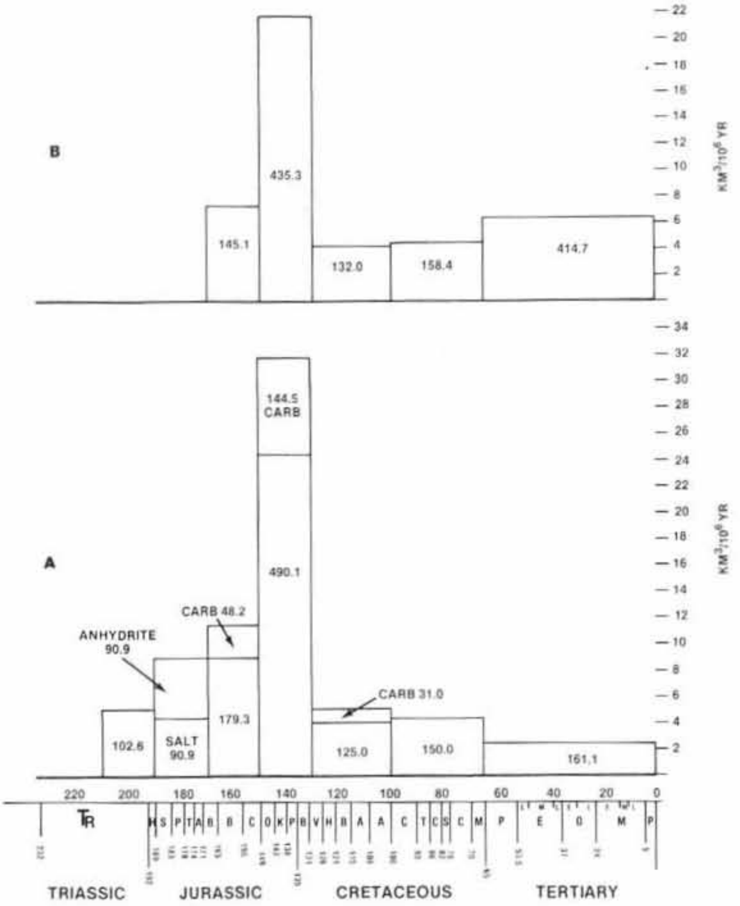

Figure 7

Volumes and areally integrated sedimentation rates for the average of USGS CDP lines 2 and 6 southeast of Cape Cod representing sedmentation in a basin, Baltimore Canyon Trough in terms of the phases of passive margin development presented in the text. A is sediment on the shelf, B is sediment of the slope/rise. Numbers in columns are volumes in km³ on shelf (A) or slope/rise (B) per km length of margin.

Phase 2 — The narrow sea between high walls : hypersalinity and evaporites

During this phase the floor of the rift graben has sunk below sea level while the uplift has attained its maximum elevation. The relief is at a maximum both because the greatest elevation of the basement is reached during this phase and because erosion must attack older rocks which had been more deeply buried and had become more lithified. The walls of the graben may be expected to average between two and three kilometers elevation above sea level, and the width of the graben may increase to 100-200 km. The local climate of the graben is likely to be arid even if it is located in a relatively humid region. The marginal mountains formed by the uplift bordering the graben walls extract moisture from the air of the prevailing winds, which must rise over them and cool in order to pass. As the dry air flows down into the graben it is adiabatically heated and develops a high evaporative capacity. During this phase, the regional drainage away from the graben becomes best developed.

The length of this phase can be estimated from the extent of salt deposits known on Atlantic margins. Salt deposition can take place before the appearance of oceanic crust, so that no salt occurs on oceanic crust, or may take place before and after separation, so that salt overlies both continental and oceanic crust as indicated by studies of the Angola and Brazil basins (Cande, Rabinowitz, 1978) and of the North American margin (Folger *et al.*, 1979). It is evident that the time of separation is in the middle of this phase. A total of 20 MY spanning 10 MY on either side of the time of separation is an appropriate estimate for the length of this phase. It takes place while the thinning of continental crust by faulting is most active.

Whether the evaporative tendency of the basin will result in actual deposition of evaporites depends on the nature of the connections with the open ocean. If these are through lateral offsets in the developing margin, it is likely that restricted circulation will result and evaporite basins may form. If the connection is open, as in the case of the Gulf of California, the narrow sea may act as a site of formation of warm saline water masses and these may lead to enhanced turnover, both downwelling and upwelling in the narrow sea. Spreading rate and widening of the basin probably increase after separation.

The volume of sediment which accumulates during this phase is highly variable depending to a large extent on the degree of restriction of basins within the rift. In Figures 7-9 only the salt shown on the cross sections of Folger and an equivalent amount of anhydrite subtracted equally from the preceeding and succeeding sediments is shown as the deposit of phase 2. An amount of anhydrite equivalent to the amount of salt shown on the cross sections is used for lack of a more accurate estimate of the relative proportions of halite and anhydrite in these ancient evaporite deposits. Jansa *et al.* (1980) have shown that off eastern Canada, the evaporites are almost exclusively halite, and have suggested that anhydrite was deposited in basins originally more proximal to the Tethys and presently on the eastern side of the Atlantic. If the salt off the eastern US is an extension of that off eastern Canada, no anhydrite may be present. If the evaporites off the eastern US belong to a different depositional episode, materials other than halite may be expected. The halite off the eastern US is postulated on the basis of diapiric structures seen in seismic sections. Anhydrite is not as readily recognized on seismic sections as is salt, and cannot usually be distinguished from carbonates. The average volume of salt (halite) is 64 km^3 per kilometer of length of the margin, but it may be assumed that only half of the original width remains with North America and that an equivalent amount exists off North Africa as suggested by the discussion of Manspeizer *et al.* (1978). In the case of the cross sections off North America, the salt is distributed over a width of 60-100 km so that the average thickness is between 0,6 and 1,0 km. Diapir formation is thought to require a minimum thickness of salt of about 1 km.

If evaporite deposition takes place during phase 2, significant extraction of $CaSO_4$ and NaCl from the ocean may occur. Estimates of the amount of salt removed and deposited in the North America-Africa narrow sea are about $1{,}5 \times 10^6$ km^3, that in the Gulf of Mexico about $2{,}1 \times 10^6$ km^3 and in the South Atlantic about 2×10^6 km^3. As noted by Southam and Hay (in press), these extractions are sufficient to have had a significant effect on oceanic salinity, and may have resulted in a reduction of the salinity by 20 % during the early and middle Cretaceous. If equal amounts of $CaSO_4$ were removed, precipitating out as gypsum to be later transformed by diagenetic metamorphism into anhydrite, the ionic balance would have changed during the Cretaceous. However, composition would have remained within the limits determined by Holland (1974) and would not have allowed deposition of unusual evaporite minerals.

Evaporite deposition including 1 km or more of halite during this phase may strongly affect the later development of the margin. If subsequent sediment loading produces diapirism, the margin may be one in which continuous deformation takes place, with the rate of deformation varying with the rate of subsequent sedimentation, as in the case of the northern margin of the Gulf of Mexico.

If the rift is open to the ocean, evaporite formation may be excluded, but high organic productivity may result from rapid cycling of nutrients in the unstable water masses. The modern Gulf of California has high productivity and an associated accumulation of diatomaceous sediments. Rates of sedimentation of 250 tp 500 m m.y. have been reported for the diatomaceous sediments of the Gyaymas slope by Curray *et al.* (1979) and Lewis *et al.* (1979). Even if the average content of diatom remains only 1/3 of the sediment, diatom frustules are sedimenting at rates of 80-160 m/MY, averaging 130 m/MY. Applied over the 20 MY length of phase 2 this would amount to a thickness of 1,6 to 3,2 km, averaging 2,6 km of diatom frustules, or forming a volume of 260 km^3 per kilometer of length along the 100 km width of the phase 2 half graben attached to each continental margin. This is a volume greater than that of the salt which accumulated in basins off the US East coast. It is unlikely that the high productivity of the Pleistocene-late Pliocene in the Gulf of California would persist throughout the entire span of phase 2. The diatomaceous sedimentation in the Gulf of California also coincides with the development of an oxygen minimum zone, so that the sediments are enriched in organic carbon.

The fixation of SiO_2 by diatoms as amorphous silica in the Gulf of California is a geochemically significant sink for silica on the global scale (Calvert, 1966). The rates of sedimentation of diatom frustules reported by Curray *et al.* (1979) and Lewis *et al.* (1979) are about an order of magnitude greater than the rates of deposition of diatomaceous ooze around the Antarctic, which range up to 22 m/MY but average about 7,4 m/MY.

The significance of removal of organic carbon in the Gulf of California cannot be estimated until the detailed results of DSDP Legs 64 and 65 have published. However, organic carbon values are unusually high in the diatomaceous deposits accumulating within the oxygen minimum zone so that this is probably an important site of accumulation of organics.

The fate of different narrow seas during this phase is indicated in Figure 4. Evaporite deposition is indicated only along passive margin segments for which undoubted evidence from drilling or seismics exists. Because seismic interpretation of an area as underlain by salt often relies on the presence of diapirs, regions with thin salt or with only anhydrite deposits would not be recognized.

In the Cape Basin of the South Atlantic, this phase resulted in deposition of « black shales » (Supko, Perch-Nielsen, 1977), as a result of episodic salinity stratification and development of anoxic bottom waters (Natland, 1978 ; Arthur, Natland, 1979).

The situation in the Gulf of California, with deposition of diatomaceous deposits, may be unique. Diatoms are unknown prior to the Campanian, so that strictly analogous deposits could only be expected in the narrow oceans associated with the breakup of the Lord Howe Rise, Campbell Plateau, Australia and Antarctica, the separation of the Seychelles from India, and in the Red Sea-Gulf of Aden. High productivity of other organisms may have introduced organic carbon into the bottom sediments in areas occupying the proper paleolatitude. Only the India-Seychelles separation appears to have taken place in a latitude similar to that of the modern Gulf of California.

Phase 3 — The narrow ocean

During this phase the ocean widens from 200 to 600 km or more, and the marginal mountains and hills subside to sea level. Local climatic conditions become less severe, but still distinguish the narrow ocean from the world ocean. The tendency toward hypersaline conditions decreases but the narrow ocean with developing marginal shallow water embayments may serve as a source of warm salty bottom water. Major streams and rivers are still deflected and flow away from the ocean in this phase, but the source areas for sediment begin to expand as the marginal uplift subsides.

This phase occurs during the interval from 10 to 30 MY after separation. At 30 MY after separation, heat loss beneath the original uplift has proceeded until the former uplift reaches sea level (Kinsman, 1975). During this phase, the density of the mantle beneath the continental margin increases from 3,25 to 3,28 due to the thermal contraction.

During this phase, the differential relief in the spreading ocean floor due to fracture zones related to marginal offsets is important in dividing the narrow ocean into a series of basins. Although the surface water connections may be well established, deep water connections are not, and dense water introduced into one basin may not be able to spread into the adjacent depressions. The importance of these sills between basins will decrease as the ocean becomes wider and further subsidence occurs.

The volume of sediment which accumulates during this phase is a matter of speculation. The area draining to the narrow ocean will increase gradually, hence the source area for detrital sediments will increase, but there is presently no way to estimate how much sediment will be delivered to the basin. In applying the model to the east coast of the United States (Fig. 6-7), it has been arbitrarily assumed that the great wedge of sediments shown as Jurassic on the cross sections is middle and late Jurassic, and that only the salt is early Jurassic. A volume of Jurassic sediment equal to half the volume of salt was considered to be anhydrite and unrecognized on the seismic sections, and deducted from the total of Jurassic sediment and placed in phase 2. It has then been arbitrarily assumed that one fourth of the remaining Jurassic sediment belongs to phase 3. The true amount could easily be half or double that arbitrarily chosen, but this will not alter the general pattern of the sedimentation model.

Phase 3 sediments are assumed to be largely terrigenous detritus and reef or bank carbonates. During this phase, shallow marginal seas may become sources of downwelling plumes of warm salty bottom water (WSBW) which can fill individual basins in the young narrow ocean. As Brass *et al.* (in press) have discussed, WSBW promotes anoxic conditions in the bottom waters both by having low initial oxygen content and by producing stratification. Episodic anoxic conditions seem to have occurred in the Angola/Brazil basin of the South Atlantic during the interval Aptian-Cenomanian (Perch-Nielsen *et al.*, 1977 ; Bolli *et al.*, 1978). The anoxic events are recognized by the presence of organic carbon-rich black shale layers in otherwise normal sediments.

Their paleolatitude during this phase suggests that the North Atlantic and Gulf of Mexico would also be appropriate regions where analogous deposition of organic carbon could be expected, but drilling has not yet penetrated into sediments which would correspond to this phase.

Phase 4 — First flooding of the shelf-reversal of drainage

When the margin of the ocean subsides below sea level, it becomes a site of sediment accumulation. The regional slope reverses and drainage begins to reorganize and to return the vast volumes of sediment which had been deposited on the distal reaches of the uplift and beyond. Initially, drainage is through many rivers and streams reaching the coast ; integration into large drainage basins feeding through a single river does not develop until later during the mature phase. The sediment source area suddenly enlarges to become an order of magnitude or more larger than that supplying the phase 3 narrow ocean.

This phase begins as the uplifted margin subsides to sea level, about 30 MY after separation of the continental fragments. The USGS cross sections suggest that a flood of sediment followed deposition of the salt, but subsidence of the shelf to sea level so that drainage could reverse and rivers could deliver their loads is a prerequisite. The duration of this phase is indeterminate, but the 20 MY assumed is a reasonable estimate.

The volume of sediments accumulating during this phase is very large ; about 40 % of the entire sediment wedge on the outer shelf and 30 % of the sediment of the slope and rise belong to this phase.

This large volume of sediment must be mostly detrital material. If it is derived chiefly from the sediments eroded off the uplift 50 MY earlier it can be expected to be mostly the sands and coarse silts which accumulated on the flanks of the uplift. The younger part of the sequence would be the finer grained deposits recycled from more distant regions. The very high sedimentation rates would promote preservation of organic carbon, and an overall organic carbon content significantly higher than that of the average sediment can be expected.

The USGS cross sections off the US east coast show a large carbonate bank or reef complex at the Jurassic-Cretaceous shelf margin. Apparently, as in the case of the Permian basin of west Texas, the carbonate edge to the margin is not a barrier to the seaward transport of detritus, because large volumes of sediment also accumulated on the slope/rise. Differential sedimentation between basins and arches is pronounced both on the shelf and on the slope/rise.

Paleolatitudinal position determines whether or not a marginal carbonate bank is likely to develop during this phase. The Apulia-Anatolia/North Africa, Atlantic/North Africa, Gulf of Mexico, South America/Africa, and India/Seychelles/Madagascar margins are most likely to have carbonate bank complexes associated with massive detrital sedimentation during this phase of development.

Phase 5 — Maturity

The mature passive margin borders an ocean wide enough to dominate the climate of the marginal landmass. The coastal plain, shelf, and slope/rise become stabilized and sedimentation depends less on the declining rate of thermal subsidence, and increasingly on sea level changes and sediment supply. The rate at which detritus is delivered from the continental interior and the rate at which biogenic carbonate and opal are secreted by organisms is also a function of climate and sea level changes (Hay, Southam, 1977).

The margin reaches maturity about 50 m.y. after continental separation and continues in this phase until ultimately reorganization of sea floor spreading transforms the passive margin into an active margin.

In the mature phase, differentiation of the passive margin shelves into detritus and carbonate dominated areas becomes significant. The detrital shelves depend on river mouths which act as concentrated point sources for sediment supply ; the carbonate shelves draw on the oceanic carbonate supply available throughout their length and thus have a diffuse supply.

The source area for the sediments of the mature margin expands to include most of the area of the continent, but deposition of detrital sediment becomes more and more concentrated at the mouths of a few rivers which have captured portions of neighboring drainage basins and focus the sediment supply. Wave and current activity on the shelf are unable to distribute large point source sediment inputs so that the shelf becomes oversupplied near the large river mouths and a delta prograding onto the slope/rise at rates up to 5 km/my may result. The undersupplied areas of the shelf may experience significant landward retreat of the shelf break.

Coarse grained detrital sediments are most likely to remain on the shelf. Entrainment in the shore zone causes longshore drift of quartz sand to form a narrow band of beach, barrier bar and island deposits. Finer particulates are deposited further offshore or are bypassed to the slope/rise. The overall effect is a tendency to segregate silica (quartz) from the aluminosilicates (clays) with the effect that the detrital regime forms two reservoirs with differing compositions, porosities, permiabilities and pore water characteristics.

In tropical and subtropical regions the supply of sediment to the shelf is chiefly carbonate, fixed by benthic organisms. Because the supply is the open ocean reservoir of dissolved carbonate and only secondarily depends on river input, the shelf break in the tropics-subtropics builds up close to sea level during transgressions. The carbonate shelf edge can prograde only slowly because large scale carbonate production by benthic organisms is restricted to shallow water. Conversely, as long as the shelf edge is carbonate and in a warm climate it is unlikely to recede landward because of the large oceanic supply available throughout its length.

Sedimentation on the slope/rise tends to be much more homogenous. The sorting of detritus which occurs on the shelf due to wave and current action does not take place so effectively on the slope and rise where the major modes of sediment transport are by slumping and turbidity flows.

The break in slope at the edge of the shelf, which by definition separates the shelf from the slope/rise, can migrate significant distances seaward or landward during maturity ; the vertical stratigraphic section at any given point may include deposits representing very different sedimentation regimes. Most commonly the shelf break recedes, so that upper slope sediments can be expected to be underlain by shelf sediments. Only where detrital sediment supply has been very large, as in the Gulf coast of Texas and Louisiana, the shelf is underlain by slope and rise sediments.

Marginal basins with very thick sediments may or may not be directly related to the modern shelf, slope and rise. The erosion of the continental margin which takes place during phases 0-2 cannot thin the continental block to the extent that more than about 2,5 km of sediment can accumulate on the shelf. Much thicker accumulations can occur in the narrow strip of the continental margins which is tectonically attenuated by lystric faulting and plastic flow as separation takes place (Bott, 1979). As Le Pichon and Sibuet (in press) have noted, the oceanic crust may not appear until the continental crust has been thinned so that its elevation approximates that of the mid-ocean ridge, ie. is about 2,5 km below sea level. Tectonically attenuated continental crust can accomodate a sediment thickness of about 11,3 km of sediment if the separation occurred about 150 million years ago and if the top of the sediment is at present day sea level. Sediment loaded onto oceanic crust may be able to accumulate to a depth of about 11,8 km under the same conditions. The differences in thickness of sediment which can accumulate are due to the assumption that the oceanic crust formed without a veneer of attenuated continental crust is slightly less dense than that formed beneath a veneer of continental crust and hence will undergo slightly more compaction and contraction with time.

Differentiation of basins and arches on the shelf will become less pronounced with time as the thermal subsidence slows and other processes, such as changes of sea level and sediment supply, become dominant in controlling the sedimentation patterns. On the slope/rise, the differentiation of basins and arches ceases about 100 MY after continental separation because the differential subsidence becomes insignificant.

The volume of sediment which can accumulate on the shelf decreases with time, so that more and more material bypasses the shelf and is deposited on the slope/rise. During the mature phase, sea level changes provide the major control over whether deposition is on the shelf or on the slope/rise.

The basement of the continental margin subsides following an exponential decay curve as described by Sleep (1971), Rona (1974), Parsons and Sclater (1977), and McKenzie (1978). Most of the subsidence has already occurred before the passive margin reaches maturity, but thermal subsidence is still simportant as a factor affecting sedimentation until about 200 MY after separation.

A PRIMARY OVERRIDING INFLUENCE. THE CRETACEOUS TRANSGRESSION

Superimposed on the general pattern of passive margin development resulting from the breakup of Pangaea is a secondary effect, the rise in sea level to a maximum in the mid-Cretaceous, caused by the formation of new spreading centers and young oceans. The rise in sea level to about 300 m above that of today modified the development of passive margins, and was particularly important in the development of those margins which reached phases 4 and 5 during the middle and late Cretaceous. The high sea level tended to restrict supply and to spread shelf sedimentation over much larger inland seas, and as a result, reduced the sediment deposited on the shelves and slope/rise system. As sea level fell during the Cenozoic, many of the Cretaceous deposits were re-eroded and have served as a source of material for Cenozoic sedimentation on the shelf, slope and rise, and in the deep sea.

A SECONDARY OVERRIDING INFLUENCE. THE RISE OF CALCAREOUS PLANKTON

At present, most of the ocean floor is covered by carbonate oozes made of the tests (shells) and skeletal elements produced by planktonic foraminifera and coccolithophores. The coccolithophores are calcareous algae and had their origin during the late Triassic or earliest Jurassic. The planktonic foraminifera are protozoans and had their origin in the Jurassic. Neither of these groups produced widespread deep sea oozes before the middle Cretaceous, but they have dominated the pelagic sedimentation system since that time. Southam and Hay (in press) proposed that the salinity of the world ocean may have been significantly reduced by extraction of salt during the early breakup of Pangaea, and it may be that the changing nature of ocean water provided conditions necessary for the flourishing of calcareous plankton.

Southam and Hay (1977) have suggested that prior to the mid-Cretaceous, $CaCO_3$ was only a minor component of deep sea deposits, and was largely restricted to deposition on the shelves and in epicontinental seas. During the late Cretaceous, with the high stand of sea level, the coccolith-planktonic foraminiferal oozes were deposited widely on the shelves and epeiric seas as well as in the deep sea. With the lowering of sea level during the Cenozoic, the calcareous oozes have come to be deposited almost exclusively in the deep sea. On the continental/slope rise, the coccoliths and tests of planktonic foraminifera are mixed with terrigenous detritus to form hemi-pelagic sediments.

SUMMARY

The breakup of Pangaea had an important influence on the global geochemistry of sediments. A simple model tracing the development of passive margins assumes uplift and erosion, deposition in fresh water lakes in the initial rift basins, potential for salt extraction as the rift graben reaches sea level, and episodic development of stagnant conditions in the narrow ocean after separation of the continental fragment. For about 80 million years after continental separation, processes on the passive margin are dominated by the effects of thermal subsidence as the continental blocks move apart. As the margins of the narrow ocean subside to sea level, sediment originally eroded off the uplift can be returned to the developing continental margin.

As the margin becomes more mature, sea level changes and organization of drainage of the adjacent continent become the most important process, dominating sedimentation patterns.

Superimposed on these general trends are the effects of the Cretaceous transgression which is an indirect effect of the breakup of Pangaea, and the rise of oceanic calcareous plankton which may be related indirectly to the breakup of Pangaea as salt extractions of the Gulf of Mexico, North Atlantic and South Atlantic altered the salinity and composition of ocean water.

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