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The Ipod Programme on Passive Continental Margins

J. R. Curray

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The IPOD programme on passive continental margins†

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During the past 200 Ma (1 Ma = 10^6 years) the arrangement of continents and ocean basins has been reorganized from a pattern of one supercontinent, with mainly plate edge, subduction, or active continental margins bordering one essentially contiguous ocean basin, to the present configuration of dispersed continents and several oceans. Most of the world's present continental margins which were formed during that 200 Ma period are 'passive' margins lying within the interiors of lithospheric plates. Several models of rifting and evolution of these passive margins have been proposed. The objectives of IPOD include testing of these models by learning as much as we can about the history of rifting of passive continental margins, their internal structure, distribution of facies, subsidence history, and the nature of the transition and modification of the crust at the margin. These objectives cannot be attained by drilling alone, and geophysical surveying and analysis of samples from the drilling are essential parts of the overall programme.

INTRODUCTION

About 200 Ma ago, all of the present continents were probably joined together into one supercontinent, Pangaea. There was only one small segment of passive margin which, in a reconstruction of Pangaea, extended from northern Africa to northern Australia. Subduction of oceanic crust characterized the tectonic style of the entire remainder of the margin of the supercontinent. Since that time, owing to a reorganization of the global pattern of plate tectonics, Pangaea has been breaking up, and rifted margins have been forming and undergoing a process of development. One of the foremost problems confronting earth scientists is understanding the geologic consequences of converting from a world with only one ocean and one continent into a world with several of each, and from a world with mainly active continental margins to a world with almost half active and half passive continental margins (figure 1). There were probably dramatic changes in the climates, affecting both the hydrosphere and the atmosphere, with concomitant major geologic and biologic effects.

Our principal interest has been to outline a programme of scientific ocean drilling which, with supporting geological and geophysical studies, will reveal the sequence of events in the development of a rifted continental margin from the earliest rifting stage to a mature stage. End members in this development process may be characterized by the rift system of eastern Africa and by the margins of the North Atlantic Ocean. We wish to understand the tectonic development of the margins, which we believe to be dominated by subsidence and down-to-

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† This is the 'White Paper' on passive continental margins prepared by the IPOD (International Programme of Ocean Drilling) Passive Margin Advisory Panel in response to a request by the IPOD/JOIDES (Joint Oceanographic Institutions Deep Earth Sampling) Planning Committee. It represents the work of the entire panel intermittently over a period of several years. Panel members who contributed to its preparation include: A. W. Bally, H. Beiersdorf, D. Bernoulli, H. Closs, J. I. Ewing, J. Grow, J. Hinz, J. Hunt, H. Kagami, L. Montadert, D. G. Moore, D. G. Roberts, E. Seibold, R. Sheridan, J. Thiede and J. R. Curray.

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basin faulting, possibly preceded by uplift and erosional stripping, and we also wish to understand the depositional style and environmental conditions at each stage in the development. It is unlikely that much of this knowledge can be gained without an ambitious programme of deep drilling. The potential scientific rewards are enormous, and the knowledge that can be acquired concerning the economic resource potential of continental margins could be of equal significance.

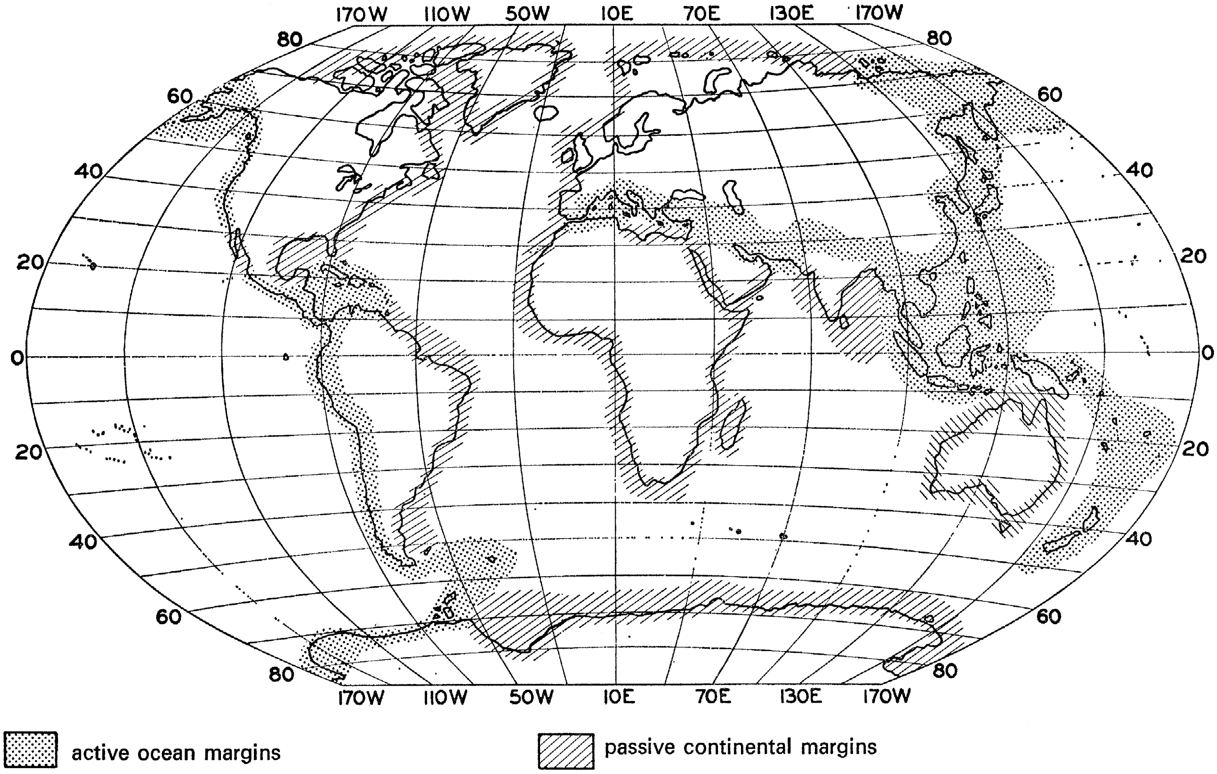

Figure 1. Distribution of passive, or intra-plate continental margins compared with active, or plate-edge continental margins.

Most of what we know of the physical history of the earth and the development of life on our planet is derived from studies on the composition and structure of the sediments and sedimentary rocks which veneer the crust of the earth. About 65% of all of the sediments younger than 200 Ma rest on the thin and relatively dense oceanic crust, which lies about 4 km deeper than the crust of the continents. Nearly 60 % of these oceanic sediments are contained in a few vast wedges of clastics, carbonates, and evaporites resting at the base of the slope joining these fundamental hypsographic levels. If we add to these the shelf and slope deposits resting mainly on adjacent continental crust, fully 60 % of the total world's sediments are contained in continental margins, and most of these lie along a few ancient passive margins, either the rifted or the sheared type. These great reservoirs of sediment are monuments to 200 Ma of slow subsidence and deposition on continental margins that originated with the fragmentation of the interior of Pangaea.

The ocean basins created during the drift of Pangaea's offspring have left us some parts of the record of their evolution, their environment, and their disappearance. However, the records of their birth are well hidden. Only along passive margins can these records be found, for only

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here is preserved the transitional boundary between continent and ocean basins. Elsewhere these two main geologic features of the Earth's surface are separated by a discontinuity where long ago the transition was destroyed, and with it the record of the oceans' birth.

Why are we so interested in the birth of oceans? For one reason, this is a period during which there is unique interaction between old continental rocks and new, hot oceanic rocks, and encroaching waters from the oceans. This interaction may be one of the most important processes of all in the accumulation of mineral deposits. Similarly, sedimentation in the juvenile ocean basins produces in many places a combination of evaporites, source beds, and reservoir beds that constitute a favourable framework for hydrocarbon accumulation.

Interesting and important as it is, the record of birth of an ocean is only part of the scientific treasure stored in passive margins. Sediment production and dynamics along continental margins result from the interaction of the oceans and continents and thus record the palaeoenvironmental conditions prevailing in each domain. Thus, deposits along some passive continental margins preserve a unique long term (150–200 Ma) record of the oceanic and continental palaeoenvironment which cannot be obtained anywhere else on this Earth.

Most previous work by geologists, geophysicists, oceanographers, and those exploring for hydrocarbons in the massive sediment wedges of the passive continental margins has been either directly mission-orientated or reconnaissance in nature. Most of our information is surficial or indirect, either from geophysical methods or by correlation with presumed analogous ancient deposits now uplifted into mountain ranges and exposed on land. These problems cannot be solved by drilling alone, any more than they could have been solved by surface studies and geophysics alone. Until relatively recently, only the grossest estimates of the structure of continental margins could be made with the technique of seismic refraction. Recently, the availability of multichannel seismic reflexion data has produced a quantum jump in our understanding of the structural framework of the margins. It opens the way for a widespread interpretation of the chronology and processes involved in the deposition of our greatest sediment reservoirs through drilling on the passive continental margins and the correlation of drilling results with structure revealed in multichannel reflexion records.

The JOIDES Deep Sea Drilling Project did not generally attack continental margin problems and only entered the broad continental margin zone in a few places. IPOD Phase I drilling has done only some shallow reconnaissance in the outer parts of a few margins as an aid to planning of possible later phases of IPOD drilling which will more directly face the task of solving the important geological and geophysical problems of passive continental margins. The results of these reconnaissance incursions into North Atlantic passive margins are the subject of the papers in this symposium.

THE JOIDES/IPOD PASSIVE MARGIN PROGRAMME

With the reorganization of the JOIDES Deep Sea Drilling project into the IPOD Programme, the advisory structure of JOIDES and the emphasis of the programme were also reorganized. The former system of regional advisory panels was replaced by a system of four topical advisory panels: Ocean Crust, Ocean Palaeoenvironment, Active Ocean Margins, and Passive Continental Margins. This document, prepared by the Passive Margin Panel, evolved from a draft of a proposal written at the first meeting of the panel in October 1974, to a Proposal for a Passive Margin Drilling Programme, completed in December 1974, to the Panel's White Paper

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submitted to the IPOD–JOIDES Planning Committee in February 1977, and finally to this version revised for publication in this symposium.

At its first meeting the Panel adopted a philosophy of operation, which is outlined in a simplified form in figure 2. First, the various models and hypotheses of formation and evolution of passive margins were reviewed, and a favoured one was accepted as a working hypothesis.

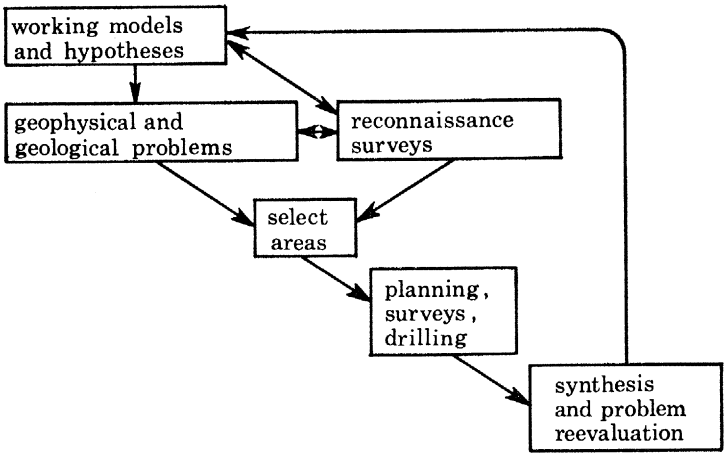

FIGURE 2. Flow chart of operating procedure and philosophy of the IPOD Passive Margin Advisory Panel.

Secondly, we have attempted to outline the most important and general geological and geophysical problems of passive margins. On the basis, then, of the reconnaissance surveys which have been conducted and on the basis of other published or unpublished information on the passive margins of the world, we have selected what we judged to be the best areas for attacking these problems and testing our working model of formation and evolution. Further surveys are then run, and if the area selected is still the optimum place in the world, drilling is proposed and conducted. After the drilling, results are evaluated and synthesized, and the problems and working hypotheses are re-evaluated. We are at the moment in this last stage. Some preliminary passive margin drilling has been completed in the northeast Atlantic. This symposium is devoted to reviewing and evaluating those results. The Passive Margin Panel and the IPOD/JOIDES Planning Committee are now planning the next phases of the programme.

FORMATION AND EVOLUTION OF PASSIVE MARGINS

Many models have been proposed for the formation of passive continental margins, but in recent years most of them have involved rifting and sea floor spreading. We have adopted such a model as our favoured working hypothesis.

It is difficult to attribute the various parts of this hypothesis to original sources. Certainly Seuss, Wegner, and Holmes envisaged some parts of this concept and the significance of the relationship between structural trends and continental margins of the North Atlantic Ocean. One of the early attempts to illustrate the geomorphic evolution of passive type continental margins was by Dietz (1952) (figure 3). At that time Dietz did not relate formation of the 'initial form' to rifting, sea floor spreading, and plate tectonics, but he did clearly demonstrate the relationship between subsidence, sedimentation, and evolution of geomorphic form. Some of this concept could also be attributed back to Cotton (1918), Kuenen (1950), and many others.

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One of the early clear statements on evolution of passive margins from the initial rift was Heezen (1960) as follow-up to his observation and correlation of the world-girdling mid-ocean ridges with rifts on land. He depicted (figure 4) essentially the model we have accepted here: evolution from an intracontinental rift such as the East African Rift System, to a young ocean basin floored in its central part by oceanic crust, to intermediate and older stages of passive (Atlantic-type) continental margins, modified by subsidence and sedimentation.

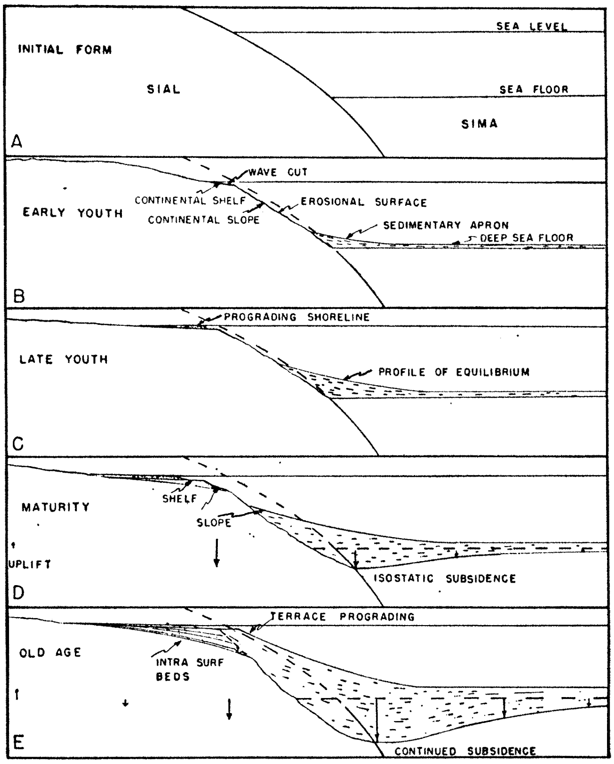

FIGURE 3. Geomorphic evolution of continental margins published by Dietz (1952). It is apparent now that this evolutionary sequence applies only to passive margins, and also that subsidence results from change in thermal regime and other factors as well as by isostatic loading by sediments.

Our favoured working model, based on general characteristics now observed by modern seismic surveying and deep drilling, is shown in an extremely simplified form in figure 5. Conceptually, the evolution includes the following phases: (1) doming, (2) rifting, (3) onset of drifting or sea floor spreading, (4) subsequent post-rift evolution.

(1) *Pre-rift doming*. Rifting is sometimes preceded or accompanied by a period of uplift or doming contemporaneous with volcanism. It has been presumed that the doming is caused by thermal expansion and/or phase change. Erosion of the uplifted region may then thin the crust, resulting in further isostatic uplift, while thermal metamorphism of the lower continental crust may cause additional thinning. The modern examples which have led to this part of the concept are regions of uplift surrounding the East African Rift Valleys and the Red Sea. Recent studies, however, suggest that in some rifted margins doming may not have occurred.

(2) *Rifting*. Evidence of the nature of the rifting process as constituting the initial stage of margin development depends heavily on the East African and other rift systems, because pre-rift and syn-rift sediments have been sampled in only a few places in the ocean basins. Rifting

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may follow a subparallel pattern, as exemplified by the Viking Graben of the North Sea and the continental margin of North Biscay, or as a trilete pattern, i.e., ridge–ridge–ridge triple junction, as exemplified by such segments of Atlantic margin as West Equatorial Africa and the Benue Trough. Commonly, one of the arms of the trilete pattern fails, leaving an aulacogen trending inland from the approximate 120° angle in the continental margin.

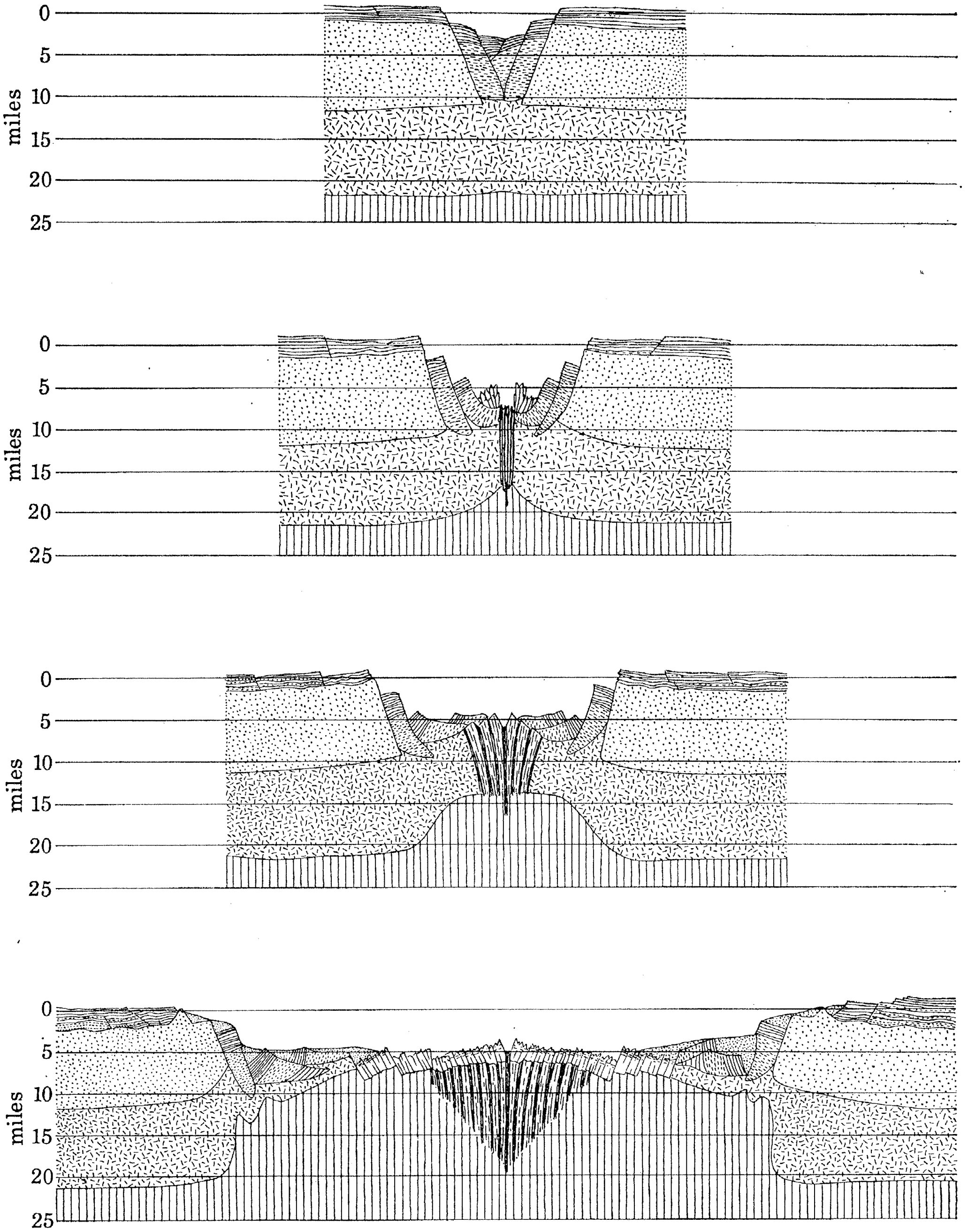

Figure 4. Rift origin of passive continental margins published by Heezen (1960), showing an East African Rift Valley stage, an incipient oceanic stage, a Red Sea stage, and a present Atlantic Ocean stage. Top layer sedimentary rock of continents, underlain by continental crust. Below that is the 'type of material that makes up the crust of the oceans', and the bottom layer is Earth's mantle.

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During this rifting stage, the basic structural framework of the margin is determined by the pattern of rifting and pre-existing zones of structural weakness, which may show evidence of palimpsest structural control. Within the rift, basic and alkaline intrusive rocks may be intercalated with and thickly covered by contemporaneous coarse clastic continental sediments. Depending on the altitude of the rift valley and climate, repeated transgressions and regressions may result in evaporite deposition on the extending continental crust and perhaps also on some of the oceanic crust formed early in the next stage. During this rifting stage, if uplift or doming preceded rifting, drainage is directed away from the rift valley, thus restricting the clastic sediment supply. If doming did not precede or accompany the rifting, or if access to an abundant terrestrial sediment supply is provided at one end of the rift or by the drainage gap, the rift, and sometimes the subsequent early stages of formation of the resulting elongate young ocean basin, may be filled with terrigenous sediments as rapidly as opening occurs. Examples are the northern ends of the Gulf of California and the Andaman Sea. Finally, if no prerift uplift occurs, the rifting process may be submarine in an older epicontinental sea, and accompanying volcanism may not be widespread.

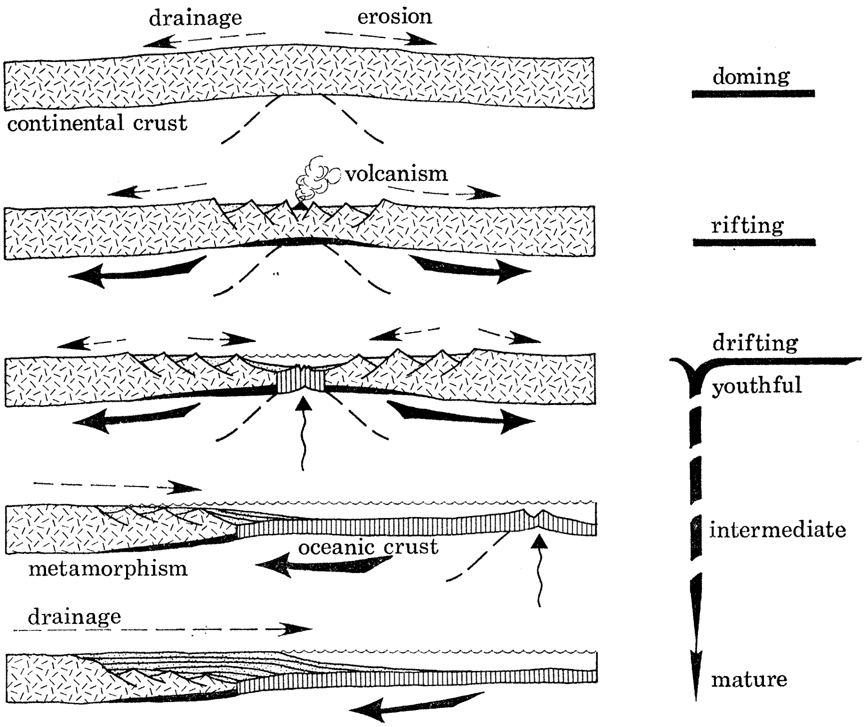

FIGURE 5. Model of formation and evolution of rift segments of passive continental margins, as adapted from many published sources. See text for full explanation of each stage.

Observations of the normal faults formed during the rifting stage indicate that they are of the listric type, steep-dipping at the surface and soling out against deep crustal discontinuities. The mechanism of development of such faults is surficial stretching and propagation of the faults downward.

(3) *Drifting, or the onset of sea floor spreading.* After rifting, oceanic crust begins to accrete at the edges of the separating blocks of attenuated continental lithosphere. The nature of the change from rifting to drifting, and the geology of the continent–ocean boundary zone formed at this

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time are not fully understood. Overlaps and underlaps between reconstructed continents suggest variations in the width of the continent–ocean boundary zone that may reflect differing amounts of extension of continental crust in the rifting stage, pervasive jointing and injection of the continental crust by dikes, and local variations in geology. In other areas, however, oceanic magnetic anomalies and a characteristic isostatic gravity anomaly suggest that the continent–ocean boundary may be a narrow zone, linear over hundreds of kilometers. An important factor that may influence the geology of the boundary may be the altitude of the continent at this time, and whether rifting starts in a thermal region uplift or in an epicontinental sea.

The change from rifting to sea floor spreading marks a major change in the thermal regime of the margin. During rifting, the heat source remains fixed beneath the rift axis, but on spreading moves away from the continent–ocean boundary, allowing it to cool. It has been suggested that secondary heating and thermal expansion at the onset of spreading may produce a second short period of uplift.

The subsidence curves derived from various margins are closely similar to each other and to empirical cooling curves constructed for the oceanic crust, indicating that the subsidence rates are apparently largely independent of both the structure and initial altitude of the continent. One effect of the subsidence is to allow wide transgression of the margin, often revealed as an important unconformity with onlap separating the faulted syn-rift section from the unfaulted post-rift section. Another important effect of subsidence is to tilt the margin gently oceanward, reversing the drainage pattern. During the early spreading stage, fracture zones and aseismic ridges in the young ocean may strongly influence continental margin structure and sedimentation, locally causing continuation of restricted evaporite or anoxic environments before open oceanic circulation is established. These ridges may locally segment the passive margins and the young ocean into independent structural basins separated along strike.

(4) *Post-rift evolution.* The subsequent evolution of the margin is a function both of age and the poorly understood interplay between regional and local differential subsidence, sedimentation, eustatic sea level fluctuations, climate, and ocean circulation. Two end members of rifted margins appear to exist: starved and mature margins. The starved margins are characterized by a thin prograding sedimentary cover and may be chronologically old or young. Examples include the northeastern Atlantic Ocean. Only starved margins have been drilled during IPOD, owing to the limited drilling capability of *Glomar Challenger*. Mature margins are characterized by prograding wedges of sediments 10 km or more in thickness, and are exemplified by the eastern margin of North America. A full study of mature margins will be possible only with increased drilling capability.

One effect of subsidence due to cooling and sediment loading on the margin is to bury the earlier sediments deeply as the margin progrades seaward. This may be manifested as a time transition upward in any location (or drill site) from continental sediment, to neritic and shelf sediments, to progressively deeper water, and finally pelagic facies. Alternatively, reef growth on fracture zones or marginal basin highs may keep pace with subsidence, resulting in the accumulation of thick sequences of shallow-water carbonates (such as the Blake Plateau) that may later be deeply buried. In contrast, the sediment section in any location (or drill site) on a mature margin, i.e., one with a higher rate of input of terrigenous sediments, may grade upward from continental sediments to neritic and shelf or slope sediments all the way to the sea floor, without deposition of pelagic or deep-water facies overlying the shallow-water terrigenous facies.

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The lithology and volume of the sediments that comprise the post-rift sequence on starved and mature margins clearly depend on oceanic palaeo-environment, climate, sea level fluctuations, and geology of the continental hinterland. The ocean basin margins distort the largely wind-driven latitudinal surface water circulation to produce eastern and western boundary currents and major divergences. These boundary currents separate the stable central water masses and the highly variable coastal water masses over the margin. Changes in ocean basin circulation may profoundly influence the sediment dynamics along continental margins and produce large hiatuses in the record. Fluctuations in the carbonate content of the sediments may be related to worldwide changes in calcite compensation depth during the Mesozoic and Cainozoic. These changes also seem to correlate with the sequence of transgressions and regressions observed on land.

Eustatic changes in sea level may also reflect changes in spreading rate which alter the cross-sectional area of mid-ocean ridges, and hence ocean–basin volume and circulation. The spreading rate changes and hiatuses in the margins may also correlate with regional warping of the margin, indicating that the continent may respond to spreading rate changes in a way not yet understood. Apparently such changes do not involve extensive renewed faulting on the margin, but minor faulting occurs by reactivation of older rift structure and transform fault trends.

The rates and cause of subsidence have not been previously understood. Dietz (1952) attributed the subsidence accompanying evolution of passive margins entirely to isostatic loading by sediments, but he apparently did not realize that starved margins also undergo considerable subsidence. From recent studies, it appears that the subsidence rates from effects other than sediment loading are similar to those of the adjacent oceanic crust, due to thermal ageing. This exponential subsidence starts at the time of onset of drifting.

IDENTIFICATION OF IMPORTANT GEOLOGICAL AND GEOPHYSICAL PROBLEMS

Introduction

Problem definition is a most important aspect of planning. We have, therefore, tried to identify significant problems of passive continental margins, differentiating the more general problems from regional and local problems.

Before preparation of the scientific narrative of the original IPOD proposal in mid-1973, a large number of earth scientists submitted lists of geological and geophysical problems to be considered in planning a drilling programme. We took these suggestions and selected from them these general problems that we considered to be important enough for investigation. Our present list has evolved from that original 1973 questionnaire and our first compilation of 1974 into its present form.

Repetition and overlap in the description of passive margin problems are difficult to avoid, because the evolution and genesis of structure are closely linked with genesis and evolution of the sedimentary sequences. Fortunately, this means that a well planned transect-type drilling and survey program will contribute to the solutions of both major problem areas.

Problems related to structural evolution

(*a*) *Ocean–continent transition*

(i) *Ocean–continent crustal boundary*. Precise definition and description of the boundary between continental and oceanic crust are still eluding us. So far, the drilling programme has not penetrated oceanic crust adjacent to continental crust, and attempts to delineate the boundary by

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geophysical methods remain controversial. It is important to identify the nature of this boundary, which probably manifests itself in different ways in different places. This should be done first in youthful or starved margins, and ultimately in mature older margins, by calibrating and confirming geophysics by means of deep drilling. The boundary of transform fault segments of passive margins probably differs from the more common rift segments and should be tested separately. This problem will be discussed later.

(ii) *Attenuation of the crust and/or lithosphere*. Geophysical data suggest that many passive margins are underlain by an attenuated continental crust. Attenuation may occur early in the development of the margin, i.e. during rifting or early drifting, or some attenuation may occur later during stages of rapid subsidence. Different styles of attenuation may depend on initial tectonic setting and mode of opening. Three types which may be significantly different are: first, continental crust of normal thickness, representing evolution from an East African or Rhinetal rift type into a Red Sea type; secondly, previously attenuated crust associated with oceanic, or continental back-arc-spreading, such as the Japan Sea, Andaman Sea, and the Pannonian, West Mediterranean type; thirdly, margins dominated by transform faulting and oblique opening, such as the Gulf of California.

Differing mechanisms for attenuation have been proposed:

(*a*) thermal expansion, uplift, and supracrustal erosion,
(*b*) flow of the lower crust accompanying subsidence,
(*c*) extension by rotational block faulting along listric normal faults,
(*d*) subcrustal erosion,
(*e*) ductile thinning,
(*f*) metamorphism of the lower crust during any of these processes.

It can be anticipated that many additional models will be conceived, but the only real tests which will allow some tighter constraints to be put on the problem include drill penetrations into the crust underlying continental margins.

(iii) *Nature of the upper mantle near the continent–ocean boundary*. Subsidence of the continental margin may occur because of density changes in the mantle, rather than, or in addition to, the possible reasons listed above for thinning of the continental crust. It has been suggested that density differences exist in the mantle to as deep as 400 km beneath passive continental margins, much deeper than the usually accepted thickness of lithospheric plates. These problems will have to be attacked by deep seismic experiments and other geophysical studies, rather than by drilling.

(*b*) *Vertical tectonics*

(i) *Doming*. Although doming before or during the rifting stage is a part of the working model we have accepted, we do not know whether this event is common in the early formation of rifted margins or whether it is the exception or rare event.

(ii) *Subsidence*. Massive subsidence follows the rifting phase of passive margins. The history of subsidence remains to be unravelled, but it appears to be linked to the various hypotheses explaining crustal and lithospheric attenuation. While a substantial amount of subsidence is due to sediment loading, the subsidence of sediment-starved continental margins indicates that sediment-loading is not the only factor to be considered.

Are differences in the subsidence history related to different types of passive margins? Do block-faulted margins have a subsidence history differing significantly from flexured margins?

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Only continuously cored sections, with environmental determinations and dating by all geologic methods, will allow us to measure subsidence rates. Preliminary studies suggest that outer passive margins subside at the same rates, or at least along the same types of exponential curves as ageing oceanic crust, starting from the time of onset of spreading. Worldwide changes in subsidence rates may be related to tectonic and/or eustatic cycles, and local and regional changes are related to sediment loading. Accurate age–depth measurements obtained by drilling will allow us to evaluate these fascinating possibilities.

(*c*) *Styles of deformation*

(i) *Block faulting*. Modern multichannel seismic reflexion records commonly reveal substantial block faulting underlying relatively undisturbed sediments, as already explained in the description of the rifting and drifting stages of margin evolution. The formation of fault blocks is presumed to be associated with the early rifting. In detail, the shape of the faults is not clear (listric faults as against vertical or inclined non-curved faults), and the subsidence history of the intervening grabens differs from place to place.

(ii) *Marginal ridges*. Ridges of presumed igneous or metamorphic origin have been postulated on the basis of geophysics as existing under some passive margins. These ridges apparently act as barriers or dams and cause ponding of sediments in shelf or plateau basins. They may result from rifting and erosion, transform or transcurrent faulting, differential subsidence, or reactivation and subsequent uplift, or a combination of these. In some cases the ridges may be large carbonate buildups, which may or may not be associated with underlying deeper basement structures.

The classical example of a marginal ridge is the eastern margin of the U.S.A. Deep penetration into the ridge would prove or disprove the geophysical interpolations and lay a longlasting debate to rest. Samples of the sediments immediately above the ridge would help considerably to explain the stratigraphic evolution of the sequences on the landward side of the ridge, and thus provide most meaningful background for evaluation of the hydrocarbon potential of this continental margin and other analogous margins.

(iii) *Diapirism*. Diapiric ridges, anticlines, and domes dominate the structure of some passive margins. Some of these are known to result from salt, while others appear to be generated by overpressured shales and mudstones.

The slope of the Gulf of Mexico is underlain by numerous salt and some shale diapirs. In several cases it has been reported that this salt is underlain by reflectors, suggesting that some, if not all, the salt in the Gulf is no longer rooted. Others postulate two ages of salt (e.g. mid-Jurassic and Cretaceous). Moreover, limited refraction studies suggest that a refractor with substantial relief underlies the wedge of Tertiary sediments. Whether or not this refractor underlies the salt source layer is unknown and is of considerable regional importance.

(iv) *Gravity sliding*. Mass movements are known to be common phenomena of continental margins. Stability of any sedimentary accumulation on a continental slope is, in simplest terms, a function of slope gradient, sediment type, rate of accumulation, and tectonic or oceanographic disturbances. Previous JOIDES and IPOD drilling, other marine geologic survey work, and surface mapping of ancient equivalents have shown that displaced sediments are common in outer continental margin deposits. As a byproduct of drilling into other major targets, information on disturbed slumped sequences would be most helpful in the interpretation of seismic reflexion lines.

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Major deltaic shelves such as the Gulf of Mexico and the Niger Delta are underlain and deformed by complex systems of listric growth faults in the sediment section. Whether or not these systems have one or more common sole faults is not demonstrated, although seismic data suggest that this may be the case. This could be tested by further geophysical surveying and deep drilling in the Gulf of Mexico shelf.

(*d*) *Continental fragments and marginal plateaus*

During the rifting of continents, complex rift patterns may evolve as in the present east African rift system. If subparallel rifts all proceed into the rifting and sea floor spreading stage, continental fragments or microcontinents may be separated by oceanic crust. Microcontinents are especially common in the western Indian Ocean, apparently having been produced by rift patterns not unlike the present system in east Africa.

A somewhat related problem is the formation and crustal structure of marginal plateaus. Most are presumed to be underlain by thinned or attenuated continental crust, but some may represent microcontinents separated from the main continental mass by a narrow aborted zone of oceanic crust filled with sediments.

Elevation of microcontinents and marginal plateaus is presumably related both to amount of attenuation of the original continental crust and the age of the onset of drifting.

(*e*) *Transform fault segments*

While our models of formation of rifted or passive continental margins are generally drawn as two-dimensional cross-sections, we fully appreciate that passive margins are complex mixtures of rift and transform segments. The structure and evolution of the transform segments are probably quite different from the rifted segments. Although some descriptions of these segments have resulted from hydrocarbon exploration campaigns, we do not yet have sufficient information to understand them, especially their subsidence histories. Furthermore, most attempts at precision matching of conjugate segments of margins across oceans have not been entirely satisfactory, and gaps and overlaps are common. Part of the reason for these mismatches is probably the attenuation of the continental crust previously discussed, but part must also be due to complex pattern changes in the early evolution of rift-transform systems.

Detailed studies of two young ocean basins, the Gulf of California and the Andaman Sea, and studies on wax models, have suggested an evolutionary sequence from initial rifts to mature rift-transform patterns. Initial rifts are irregular and are probably controlled in part by pre-existing lines of structural weakness. These irregular rifts evolve early in the drifting and sea floor spreading stage into rectilinear patterns of short segments of spreading rifts and transform faults. As spreading continues, the pattern tends to simplify itself, and new rift segments form in line with adjacent rifts to make fewer and longer segments of both rifts and transforms. We cannot expect, therefore, to find the same long segments of the present mid-Atlantic Ridge mirrored in the rift and transform pattern of the corresponding continental margins. We should expect instead to find a more complex pattern with shorter segments in the oldest ocean crust outside the ocean–continent boundary, and probably a configuration of the boundary itself resembling the initial rift as modified by attenuation of the continental crust.

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Genesis and evolution of sedimentary sequences

The Earth's surface 200 Ma ago probably consisted of one supercontinent (Pangaea) and one superocean (Panthalassa) which must have been surrounded largely by active continental margins which do not preserve an undisturbed historic record of the continental and oceanic palaeoenvironment. Sediments on passive continental margins monitor and record oceanic surface water circulation, the vertical stratification and characteristics of the oceanic water column, eustatic sea level changes, and the palaeoenvironment of the continental hinterland and of the juvenile rift.

(*a*) *Distribution of facies*

(i) *Oldest clastic and volcanic deposits.* The clastic and/or volcanic deposits which filled the earliest rift have never been drilled or sampled in a major ocean because they are too deeply buried and because their regional distribution is restricted to narrow strips along the foot of the passive continental margins. However, they are present in recent rifts which have not yet developed into a marine basin, and in fossil grabens which failed before they could expand sufficiently to contain an ocean basin. Volcanics underlying the halites of the Red Sea probably represent this stage.

(ii) *Oldest sediments on oceanic crust.* These sediments date rather precisely the time of onset of drifting and sea floor spreading. The facies reveal the environmental conditions at the time, including the depth of water and the circulation characteristics or degree of restriction of the incipient ocean basin.

(iii) *Restricted circulation facies.* Juvenile passive continental margins often preserve a sedimentary record of the early restricted marine palaeoenvironments of the small ocean basins they surround. The narrow Mesozoic South Atlantic and Cainozoic Red Sea represent typical oceanic depositional settings of evaporite formation. These salt deposits are frequently accompanied by anoxic sediments. It is presently not clear if these anoxic deposits resulted from an euxinic bottom water mass or from the massive input of detrital organic carbon from the surrounding continents. Anaerobic sediments with similar characteristics can also be preserved in an oceanic mid-water oxygen minimum (as, for example, observed in mid-Cretaceous South Atlantic and Pacific Oceans). The distribution pattern of these anoxic sediments which preserve an unusually high concentration of organic carbon along passive continental margins is virtually unknown.

(iv) *Normal continental margin facies compared with the anomalous Quaternary record.* As much as modern sea floor surface sediments have been studied, we do not have a very clear understanding of the principles and processes of the distribution of sediments on and across continental margins. Part of the problem is the anomalous sedimentary record of the Pleistocene, which we have not yet succeeded in unravelling from the Holocene facies. During the Quaternary, multiple high-amplitude fluctuations of eustatic sea level caused perturbations in this normal system of facies distribution from which the world oceans and margins have not yet recovered. Neither the environments of deposition nor the near-surface sediments have come back into equilibrium with the modern oceans. As a result, not only shore zone and shelf environments were affected by these sea level fluctuations, but also all other deeper-water environments. Continental slopes changed from realms of slow normal accumulation of sediments either to regions of high rates of deposition or in the extreme, to regions of erosion by mass movement of sediment

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deposited too rapidly for stable accumulation. The effects then obviously carried on down to the continental rise and to the abyssal plains beyond. Conversely, today, following the rapid rise of sea level and transgression across the shelves of the world during the past 15000–20000 years, most terrestrial sediment deposition is confined to the shore zone and inner shelf, while outer shelves, slopes, and rises are starved. Thus, broad areas of the outer margin are receiving only pelagic or hemi-pelagic deposits.

Understanding of the distribution and depositional patterns of sediments on continental margins is important because this is the record of the past. Environmental, provenance, oceanographic, and climatic conditions and their changes are recorded in the sedimentary record. But if we do not yet even understand the sea floor surface sediments in the modern oceans, how can we expect to interpret the past properly?

Of somewhat special interest are the important carbonate platforms which have developed along some passive margins in subtropical and tropical conditions during the Mesozoic and Cainozoic. The surfaces of these platform deposits must have remained close to sea level during their long histories as they built upward in place; hence their mean accumulation rates monitored the subsidence rates and histories of the margins in great detail.

The two major aspects of the problem of facies distribution are:

(1) What is the distribution of the anomalous Quaternary facies, and what changes did Quaternary conditions cause in the envionments of deposition in the oceans which have misled us in our attempts to understand Holocene or post-glacial processes? How can these changes help us to understand other eustatic or tectonic changes of sea level, transgressions and regressions?

(2) What are the 'normal', non-glacial processes of distribution and deposition of sediments, and at what age horizons can we find such a 'normal' sequence?

(v) *Displaced sediments; gravity slides.* Gravity sliding, already discussed briefly as one mechanism of deformation of the internal structure of passive margins, takes on an even greater significance in our attempts to understand and read the record of sedimentary sequences. Mass movements of sediments take all forms, from transport of sediments down canyons and fan valleys by turbidity currents, to catastrophic slides which displace large volumes of sediments from shallow water environments to deeper water environments. How can we recognize them in cores from the oceans or outcrops of ancient sediments?

(*b*) *Diagenesis of sediments*

The first early diagenesis of sediments occurs in the top few metres of the ocean floor, and the processes within this benthic boundary layer are the subject of intensive studies of biologists, sedimentologists, chemists, and physicists.

Following this early diagenesis, lithification proceeds with expulsion of interstitial waters, expulsion of water associated with the collapse of clay minerals, and reduction of porosity and permeability. This results in a redistribution of fluids into porous layers alternating with nonporous layers, leading to chemical reactions between the pore fluids and the host rocks. In this context the thermal history which these sediments undergo is of great importance.

The diagenetic history of shelf sequences should be compared and contrasted with diagenesis in the adjacent slope and rise régimes. The results could offer most valuable background data to scientists involved in hydrocarbon exploration, and these studies are of great relevance for the evaluation of the waste disposal potential of continental margins. Diagenetic studies can be

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undertaken only if the holes are cored more or less continuously, and all logs relevant for a petrophysical evaluation are run. Extensive sampling of subsurface fluids is also of prime importance.

The diagenesis of organic matter with depth is important in understanding the cycle of carbon between lithosphere, biosphere, and atmosphere and in following processes such as the origin and maturation of petroleum. Most of the world's organic carbon is in sedimentary rocks. Possibly half of these sediments are on the continental rise, and yet almost nothing is known about their organic character. What is the source of organic matter in the outer continental margins? How much is there, and how well is it preserved? How is it altered biologically and thermally with depth? Is there enough of the right kind of organic matter to form petroleum? Considering the enormous volume of slope and rise sediments, this represents a huge gap in our understanding of the carbon cycle.

The high-pressure, low-temperature conditions of outer continental margin sediments are ideal for the formation of methane and related gas hydrates, assuming there is sufficient organic matter and microbial activity. At ocean bottom temperatures, about 300 m of water plus sediments is adequate to form gas hydrates or clathrates. Such hydrates are known to be widespread under permafrost areas on continents, and seismic data and drilling logs of a few deep-sea holes provide indirect evidence of their possible presence under outer continental margins. Methane is not normally at the sediment surfaces, since reduction of pore water sulphate must be completed prior to methane generation, but its presence begins in the first metre and continues for tens or hundreds of metres. The thickness of the hydrate formed will depend on the geothermal gradient, pressure, and quantity and composition of accumulated gas. A thick gas hydrate will block fluid interchange between sediments and water and can accumulate large quantities of free gas underneath the solid phase. The formation and decomposition of hydrates during glacial stages can cause substantial tectonic movement of sediments due to the pressures developed. Virtually nothing is known of the distribution of hydrates on the outer continental margins. However, the presence of hydrates in these areas can be verified by a recently developed pressure core barrel.

(*c*) *Palaeoenvironmental conditions*

(i) *Palaeoclimatology*. Continental margins act as pathways for the terrigenous material delivered in particulate or dissolved form from the continental hinterland. The quantitative and qualitative composition of this terrigenous input is controlled by the geology of the continental hinterland, by the climatic processes above it, and by the size of the drainage basins which supply the terrigenous material to the continental edge. The end-members climatic systems which should be studied are polar–subpolar, transitional–temperate, dry–subtropical, and humid–tropical.

(ii) *Palaeoceanography*. After the ocean basins matured into their present configuration, continental margins distorted the largely latitudinal surface water circulation. They also provide stable, continuous shallow-water benthic palaeoenvironments of the global ocean. The distortion of the wind-driven latitudinal surface-water circulation results in the western and eastern boundary currents along the continental edge and in major divergences which can be assumed to represent the most unstable and sensitive components of the oceanic surface water circulation. The boundary currents separate stable stratified central water masses from the more complex and mixed shelf waters over the inner part of the continental margin. The establishment and history of this hydrographic regime can be studied only by transects across passive continental

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margins. Owing to their higher sedimentation rates, continental margins provide possibilities for understanding the development of the pelagic palaeoenvironment which cannot be obtained in the central parts of the oceans themselves. The most typically developed western boundary current can be studied off the eastern U.S.A.; the best eastern boundary current can be studied off southwest Africa.

Transects of drill sites across passive continental margins also provide insight into the vertical structure of the oceanic water column through time, because it is here where the intermediate and deep oceanic water masses impinge upon the rise and slope of the continents. We have little evidence for the mode of deep water movement in the pre-Glacial, Mesozoic, and Cainozoic oceans, but since the middle of the Tertiary these water masses have been downwelled in the 'glacial' polar regions near continents of the northern and southern hemisphere. The only accessible example to drilling is in the Norwegian and Greenland Seas.

(*c*) *Hiatuses and eustatic sea level fluctuations*

The good correlation of the Late Mesozoic and Cainozoic calcite compensation depth with the sequence of eustatic sea level fluctuations over the inner part of the continental margins proves the close linkage of the oceanic deep to the shallow continental margin palaeoenvironment. Hiatuses in the stratigraphic record from passive continental margins mark oceanographic events which have prevented sediment accumulation for a certain time or which have removed portions of the sediment column. Indicators for transgressions and regressions have been traced on seismic records across many continental margins. Their isochronal and global occurrence has led to the hypothesis that they have been caused by eustatic sea level fluctuations reflecting major changes of sea floor spreading rates and/or other global tectonic events in addition to the pulsations of the Late Cainozoic glacial ice sheets.

Geophysics

Our explanations remain somewhat ambiguous for several geophysical phenomena which have been observed over different passive continental margins. For example:

(*a*) *Gravity edge anomalies of continental slopes*

Are these edge effects, or do they correspond to buried ridges of high-density material?

(*b*) *Magnetic slope anomalies*

Do these correspond also to buried ridges or dikes which are more highly or differently magnetized than the neighbouring rocks, or do they possibly correspond to the junction between continental and oceanic basement?

(*c*) *Magnetic quiet zones*

A magnetic quiet zone occurs seaward of the continental slope in many marginal areas. Do these quiet zones correspond to ocean crust that was created during a long period of constant magnetic field polarity; do they indicate that some process has erased the magnetic signature normally acquired by ocean crustal rocks; are these zones underlain by continental or transitional basement rocks; or are these regions which, during the early history of opening of a juvenile ocean, received sediment so rapidly that normal sea floor magnetic anomalies did not form?

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Geophysical surveying is the only method we have for acquiring deep subsurface information on a regional scale. Interpretation of these data can be made with confidence only after some calibration by actual sampling through drilling. With such calibration we can then go on to use geophysics to build regional structural and stratigraphic models of real value.

PRESENT STATUS OF THE IPOD PASSIVE CONTINENTAL MARGIN PROGRAMME

In terms of the flow chart of figure 2, this programme is in the middle of a brief hiatus. Passive margin drilling has been completed along the African–Atlantic margin, off the Iberian Peninsula, in the Bay of Biscay, off the Rockall Plateau, and in the Norwegian Sea. In addition, a limited amount of drilling has been done off the outer margin of eastern United States. We are now in the synthesis and feedback stage indicated in the flow chart. Preliminary analyses have been completed, and preliminary syntheses are presented in this symposium volume. On the basis of these syntheses and continuing analyses and other syntheses to be presented in the next few years, both the working model of evolution of passive margins and our enumeration and descriptions of the general geological and geophysical problems of passive margins are and will continue to be revised before the end of the present hiatus and resumption of passive margin drilling.

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While not listed and referenced in detail, the papers presented and published in this Symposium are the source for much of the technical discussion in this summary paper.

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