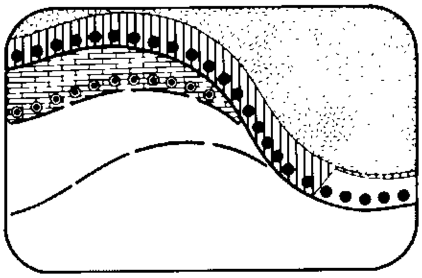

Geological Development of the Continental Margin of Atlantic Canada

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Summary

The continental margin of Atlantic Canada was formed by the rifting of continental masses in some areas and by the strike-slip motion between continental blocks in others. These motions imparted different structural characteristics to the basement. The subsequent development of the margins was controlled by thermal contraction and sediment loading which caused subsidence. These processes led to the formation of the East Coast Geosyncline. The geosyncline is divisible into a miogeocline encompassing the Mesozoic-Cenozoic succession underlying the continental shelf, and a eugeocline comprising strata of similar age underlying the continental rise and abyssal plain. The boundary between the miogeocline and eugeocline is in many areas represented by the modern and ancient continental slope.

Introduction

Beginning in the Late Precambrian and continuing throughout Paleozoic time the rocks of Atlantic Canada were deformed, metamorphosed, and intruded by granites as a result of the convergence of two major lithospheric plates. This sequence of events provided the platform upon which the continental part of our present margin is developed. In Late Triassic to Early Jurassic time rifting and sea floor spreading commenced. These events led to the development of the Atlantic Ocean Basin and the deposition of a thick sedimentary sequence of geosynclinal dimensions along its margin. The geosyncline underlies the continental shelf, rise, and abyssal plain, and is still subsiding and receiving sediment.

The formation of the marginal geosyncline depended primarily on two physical processes. The marginal area (both oceanic and continental sides) subsided from thermal contraction following the thermal expansion and uplift associated with the initial rifting process. It was further depressed by the load of sediment being deposited along the margin. It is the purpose of this paper to examine these two processes, to describe and compare the structural characteristics of the different margins of Atlantic Canada as produced by initial rifting, and finally, to follow the development of the geosyncline and its component parts, the miogeocline and eugeocline.

Tectonic History of the Southern Maritime Provinces and the Opening of the North Atlantic

The southern Maritimes are largely underlain by Paleozoic rocks, with some metamorphosed Precambrian rocks exposed on Cape Breton Island and southern New Brunswick. Much of mainland Nova Scotia is occupied by the Meguma Group of metasediments, which also extends under much of the continental shelf. The Meguma Group was deposited probably in deep water on the African side of the former Paleozoic Atlantic Ocean (Schenk, 1971; Wilson, 1966), which subsequently closed before the opening of the present Atlantic Ocean. In western Nova Scotia, the Meguma Group is overlain by shelf sediments of Ordovician to Devonian age, interbedded with andesitic volcanics.

During the Devonian there was widespread deformation; the Acadian (Caledonian) Orogeny was probably caused by the closing of the former ocean and the collision of Africa and North America. The Meguma and parts of the overlying Ordovician-Devonian rocks were metamorphosed and extensively intruded by granites. Deformation continued at intervals through the Carboniferous and Triassic with deposition in the Carboniferous and Triassic basins. Late Triassic volcanic activity (e.g., North Mountain Basalt) was associated with the initial opening of the present Atlantic Ocean basin. The present continental margin began to develop at this time with regional uplift, rifting, and subsequent subsidence and formation of the marginal geosyncline.

The central North Atlantic Ocean was formed by the separation of Eurasia and Africa from North America starting about 180 million years (m.y.) ago. The separation of Greenland from Canada probably began later, in Cretaceous time about 80 m.y. ago and these motions terminated about 47 m.y. ago. To a first approximation, each of these units moved as a rigid plate, away from a ridge crest.

The varied relative motion of these four plates made the history of the formation of the Atlantic Ocean quite complex. A reconstruction of the continents before opening was given by Bullard *et al.* (1965) using a computer to obtain the best fit of the edges of the continental shelves. The fit is very good (Fig. 1) but it gives us no indication of the configuration of the plates at different times in the evolution of the Atlantic. To obtain this detailed history we need to examine the sea-floor record, particularly the reversal pattern of magnetic anomalies. Other useful data come from the sediment sequences found by the Deep Sea Drilling Project (JOIDES), and seismic investigations of stratigraphy and fracture zones. Pitman and Talwani (1972) provided a recent synthesis of the data. The position of Europe and Africa with respect to North America at different times is shown in Figure 2. First, Africa began to separate from North America and its location is shown several times from 180 m.y. to the present. Later, Europe and North America began to separate, as well as Greenland and North America. The ages of these motions imply that England, for example, was not in the same place relative to Africa during the history of opening and demonstrates the 'jigsaw puzzle' aspect of trying to define the complex evolution of the North Atlantic Ocean.

Of particular importance to the types of continental margins found in Atlantic Canada is the way that Africa separated from North America during the first tens of millions of years of opening. Throughout that time the northern shelf of Africa slid past the southern margin of the Grand Banks, thus creating a fracture zone along the latter (Fig. 2). We call this type of margin a transform faulted margin. To the south, the continental margin is a product of rifting between Nova Scotia and Africa. These two types of margins might be expected to generate different structural characteristics and we discuss this later.

The history of the original rifting at old margins is obscured by subsequent erosion and sedimentation but a fairly clear picture of the stages of development can be obtained from rifts without significant sea-floor production such as the East African Rift and newly formed oceanic basins such as the Red Sea. The development is shown schematically in Figure 3. The rifting process starts with doming of the area and dyke intrusion through the continental plate (1). Extension commences with block faulting and the formation of a rift. The continental plate may be thinned (2). With continuing extension the oceanic plate, some 70 km thick capped by a 5 to 10 km thick oceanic crust, starts to be produced. Intrusion probably becomes restricted to a narrow zone. The new crust is intruded under and into sediments in the narrow gulf. Ocean circulation is restricted so evaporites form (3). Sea-floor spreading continues and the margin subsides (4). This pattern of uplift, evaporite formation, and subsidence is reflected in the stratigraphy and structural features found today beneath the continental shelf and margin.

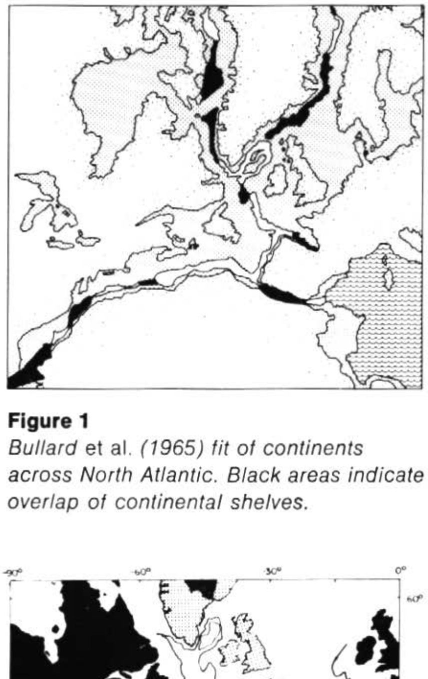

Figure 1
Bullard et al. *(1965) fit of continents across North Atlantic. Black areas indicate overlap of continental shelves.*

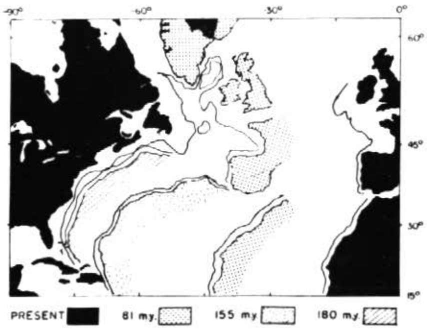

Figure 2
Cartoon showing stages of opening of the North Atlantic Ocean (after Pitman and Talwani, 1972).

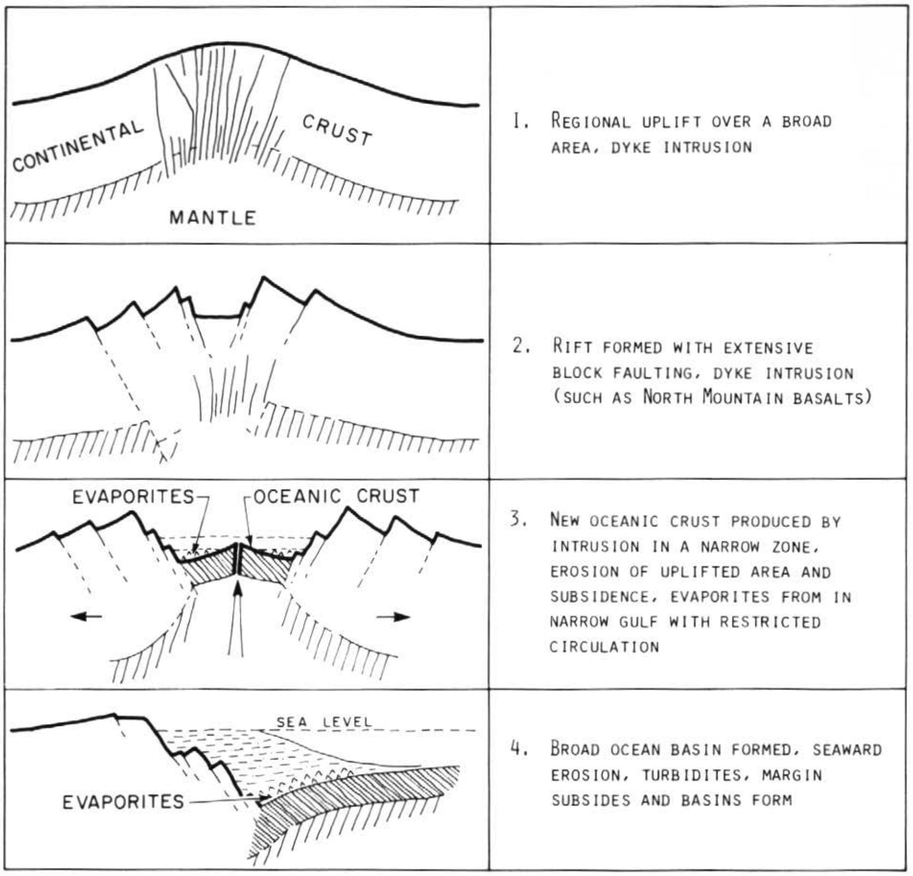

Figure 3
Schematic diagram of processes of rifting and opening of an ocean.

Physical Processes of Marginal Basin Formation

The formation of a deep sedimentary basin or geosynclinal trough along a stable rifted continental margin depends primarily on two physical processes. (1) The margin area (both oceanic and continental sides) subsides from thermal contraction following the thermal expansion associated with the initial rifting process. (2) The region is depressed by the load of sediment being deposited along the margin. We examine these two processes below. They are illustrated in Figure 4.

Because of the intrusion involved in the initial rifting process, the crust and upper mantle temperatures of the margin will be high. In fact, the thermal structure of the margin will be very similar to that of a spreading ridge. The excess elevation of a spreading ridge over old sea floor is about 2500 m arising from thermal expansion of the lithospheric plate under the ridge. A similar uplift of the margin occurs at the time of rifting. The East African Rift Zone is an example of early uplift and partial subsidence is seen in the Red Sea area, which is a newly formed ocean.

The uplifted area subsides approximately exponentially with time and the margin returns to its original height. The time constant for this process is about 50 m.y. The amount of initial uplift at the margin is probably somewhat less than for ridges, say 1500 m. However, the uplifted continental crust will be subject to surface erosion, with the drainage at first being mainly toward the continent. The ocean crust is below sea level even after uplift and is not subject to significant erosion. If the erosion was rapid (faster than the rate of subsidence), and there was neither isostatic rebound nor sediment loading, then after cooling the edge of the continental part of the margin would be some 1.5 km below sea level. The oceanic side of the margin would be at the normal sea-floor depth of about 5 km (Fig. 4). This is a very simplified model. Uplift, erosion, and subsidence do occur but the processes are complex. Sleep (1971) has worked out the details. Firstly, the erosion rate is roughly comparable to the subsidence rate so that not all of the uplifted area is eroded, but secondly there is the opposing effect that erosion results in an isostatic rebound. Consequently, some 6000 m of material must be eroded to reduce the elevation by 1500 m. The net result of these two factors is that about 3000 m of material is generally eroded. Subcrustal erosion and thinning of the continental crust by necking and normal faulting also may be important at the time of rifting, which will produce a greater lowering of the continental side of the margin.

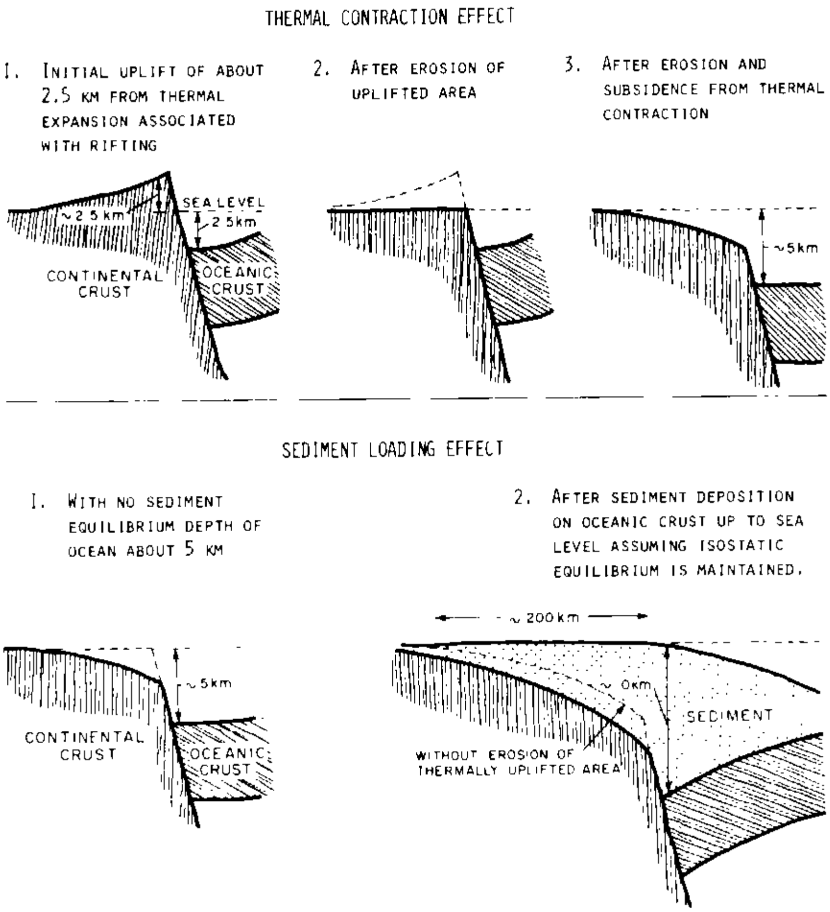

Figure 4
Schematic diagram illustrating the physical processes related to subsidence of a rifted margin.

The subsidence of the margin of Atlantic Canada has been examined recently by Keen and Keen (1973) and by Renwick (1973). An example of the subsidence of a margin with time is shown in Figure 5.

The second important process, which causes subsidence of the margin and development of a basin, is sediment loading. Gravity studies and estimates of the strength of the earth's lithosphere have shown that over broad regions isostatic equilibrium is maintained throughout erosion and sedimentation processes. The regions must have horizontal dimensions of a few hundred kilometres, i.e., several times the lithospheric plate thickness. Equilibrium requires that sediment displacing lower density sea water must be compensated by a lowering of the crust to displace the higher density mantle, thus, maintaining the same mass per unit area down to the base of the lithospheric plate where lateral flow occurs.

The subsidence due to sediment loading is illustrated in the lower half

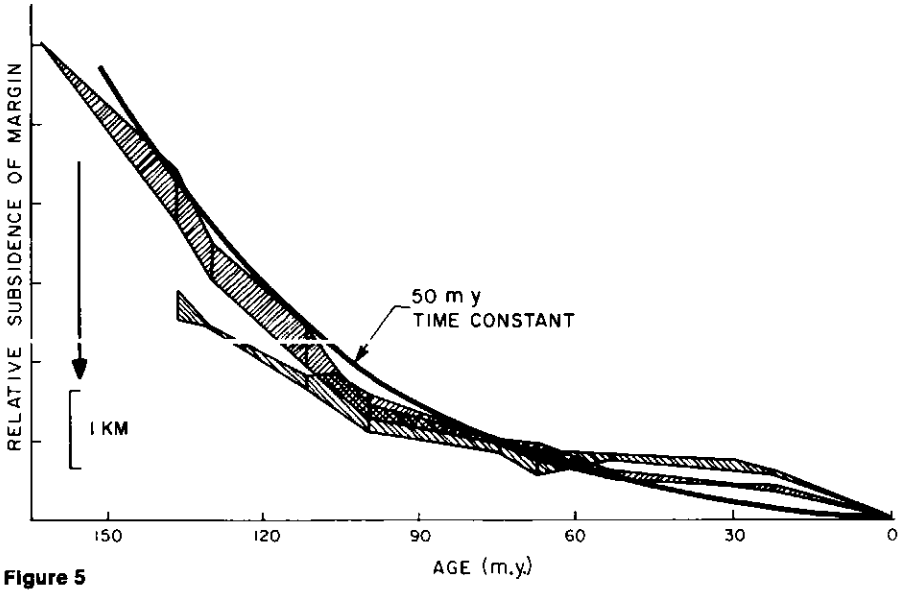

Figure 5
Subsidence of a margin as indicated by two groups of wells on the Scotian Shelf. The solid line gives the theoretical subsidence. After Renwick (1973).

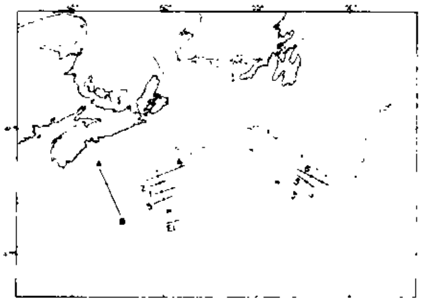

Figure 6
Location of seismic reflection lines perpendicular to the margin and refraction lines parallel to the margin. The location of the magnetic slope anomaly is shown by the dotted line.

of Figure 4. Starting with a normal 5 km deep oceanic sea floor, 10 to 12 km of sediment must be deposited to build to sea level. No further sediment can then be added because surface currents and wave action will carry any additional sediment into deeper water. This is about the maximum sediment thickness observed off Atlantic Canada. Because the oceanic and continental crust remain coupled, the adjacent continental crust also is pulled down. The diagram represents a rough approximation to the present margin, neglecting the complexities of structure arising in the original rifting process and in the original continental geology.

Structural Characteristics of Rifted and Transform Faulted Sections of the Margin

The most important source of information about the structure of the margin is geophysical data, particularly seismic measurements but also gravity and magnetic measurements. Many investigators have made important contributions to studies of the Atlantic margin, beginning with studies by workers at the Lamont Geological Observatory in the early 1950s. The results have been reviewed by Emery and Uchupi (1972) and Keen (1974).

A thick accumulation of sediments within which there are numerous diapiric structures is characteristic of the rifted margin along the continental rise off Nova Scotia. These diapirs, which are sometimes referred to as the 'ridge complex', often occur within several hundred metres of the sea floor and may in places be exposed. They could be composed of either salt or shale. The diapirs are associated with velocities of about 3.5 km/sec, which is somewhat low for salt. Nevertheless, it is tempting to speculate that they originate from evaporites deposited during the first stages of continental separation.

There are distinct gravity and magnetic anomalies across the margin. The gravity anomaly appears to be associated with the thinning of the crust from continental to oceanic, and with a change in water depth from approximately 200 m on the shelf to about 4000 m on the continental rise. There is also a prominent magnetic anomaly, the slope anomaly, which parallels the entire eastern margin of North America (Figs. 6 and 7). Its origin has been in dispute but it is generally believed to be related to the initial breakup of the continents and hence may mark the location of the ocean-continent transition. Based on seismic measurements, Keen *et al.* (1975) showed that the transition zone was 60 km or less in width. Using these measurements, the magnetic slope anomaly could be accounted for by a model consisting of a thick continental crystalline basement layer abutting a thin oceanic basement layer. The thicknesses of these layers were known from seismic measurements and the magnetization was either measured or deduced from studies of magnetic anomalies over individual topographic features. Similar results were obtained for the magnetic anomaly over the transform faulted margin south of the Grand Banks (Fig. 7).

Figure 8 shows the measured seismic structure across the rifted margin along the refraction lines shown in Figure 6. Outside the area occupied by the slope anomaly, beneath lines 1, 3, and E1, normal oceanic crust is found consisting of layers 2 and 3. These have velocities of about 5 and 6.5 km/sec respectively. The crust is relatively thin, about 15 km, and this is typical of oceanic crust found elsewhere. Within the area of the slope anomaly and diapiric structures, beneath line 2, the measured velocities are anomalous. In this area, layer 2 appears to be absent and the sedimentary strata are underlain by rocks exhibiting a high velocity, 7.4 km/sec. Perhaps the area of high velocity represents the zone in which new crustal material of gabbroic composition was intruded under thick sediments. After a separation of some tens of kilometres occurred more

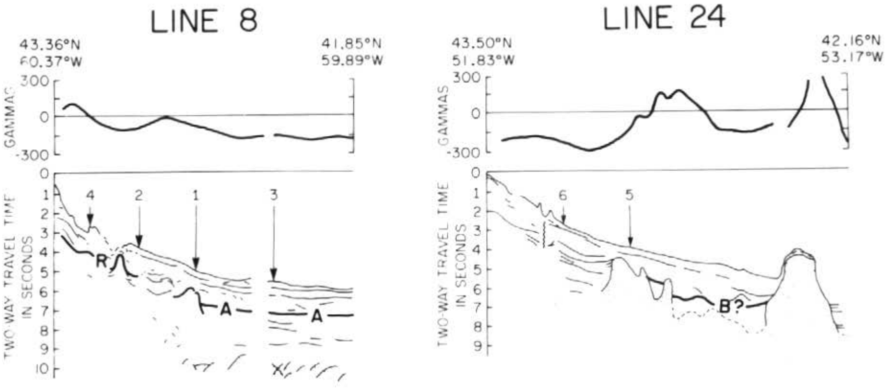

Figure 7
Line drawings of seismic reflection records over rifted (left diagram) and transform (right diagram) margins along with the magnetic profiles. The positions of the lines are shown in Figure 6. The stippled areas denote oceanic basement. The top of the ridge complex is marked 'R' and sedimentary horizons A and B are also indicated. The magnetic slope anomaly is best seen on line 8, as a double peaked feature.

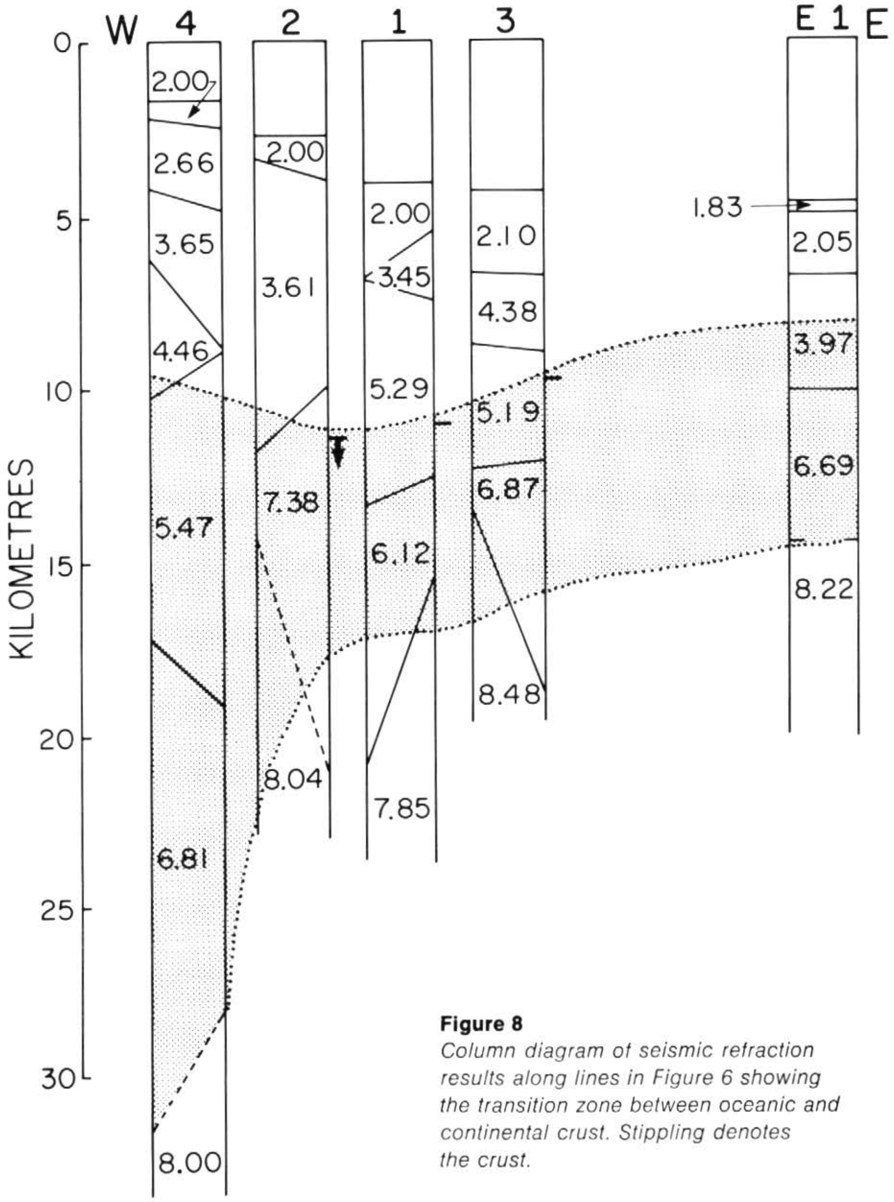

Figure 8
Column diagram of seismic refraction results along lines in Figure 6 showing the transition zone between oceanic and continental crust. Stippling denotes the crust.

normal sea floor (4 to 5 km/sec) began to be produced (Keen *et al.*, 1975). Line 4, towards the continental shelf, exhibits velocities and layer thicknesses which can be correlated with those measured on the Scotian Shelf and we believe that continental crust occupies this area. Therefore, beneath line 2 we may be observing the crustal structure associated with the earliest stages of rifting (Fig. 3) and this area may mark the true transition region.

As indicated above, the continental margin off Atlantic Canada has sections that developed in two distinct ways. Rifted sections such as that off Nova Scotia are the start of lines of sea floor accretion and are approximately perpendicular to the direction of continental separation. Other sections produced by transform faults early during the opening, such as the southern margin of the Grand Banks, are offsets of the rifted segments and are parallel to the direction of opening (Fig. 9). The transform produced sections generally occur along old lines of weakness in the continent that is being split. The transform faulted margin south of the Grand Banks followed an old fault system, which extends across the Scotian Shelf and Nova Scotia, and through the Bay of Fundy (Fig. 10). We

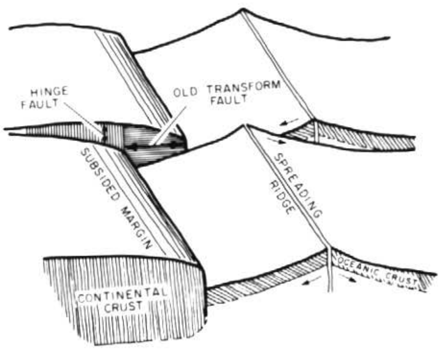

Figure 9
Sketch of marginal basin truncated by an old transform fault. Note hinge fault extension into continent which may follow old line of weakness. Sediment is omitted for clarity.

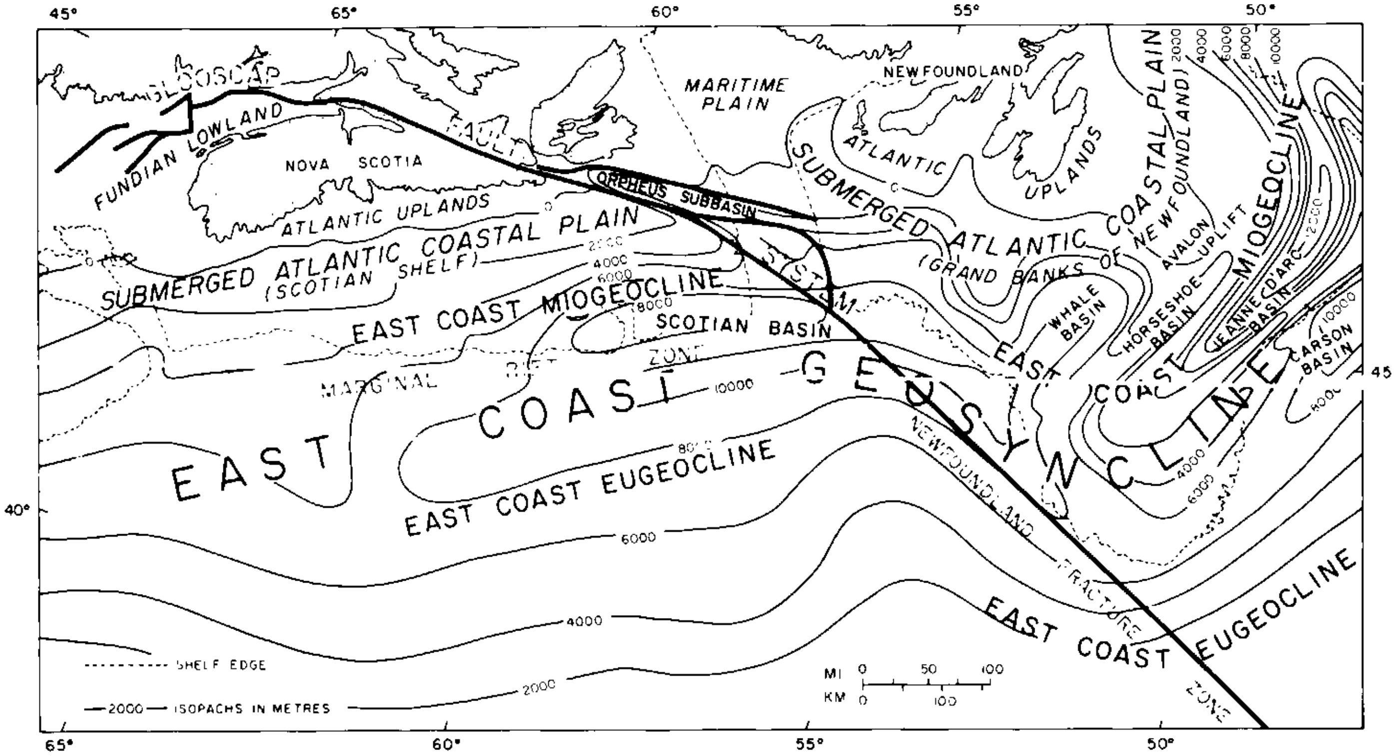

Figure 10
Geomorphic and geologic elements of the Atlantic Margin south of Nova Scotia and Newfoundland. Sedimentary thicknesses are shown in metres and were derived from Sherwin (1973). Diagram taken from King (in press).

have also discussed how the new ocean floor and adjacent continent at a rifted margin are initially uplifted through thermal expansion of the lithosphere and then subside. The amount of subsidence of both the new ocean floor and continent across the rifted margin should be the same because the continental and oceanic lithosphere are coupled. In contrast, the oceanic and continental lithosphere across a transform margin will have been decoupled and the amount of subsidence across this type of margin will be different for the continental and oceanic parts. The continental portion will have subsided less than the oceanic side. This is shown schematically in Figure 9. The subsidence of the rifted portion of the margin will result in hinge faulting (but no strike-slip motion) along the prolongation of the transform fault into the continent as suggested by Wilson (1966) and Francheteau and LePichon (1972). This faulting may follow the old lines of weakness and lead to the development of sedimentary basins, but the old lines of weakness may have significantly different directions than the transform margin. The Orpheus sub-basin (Fig. 10) appears to be an example and may have resulted from hinge faulting due to different degrees of subsidence along the prolongation of this transform fault inland.

The structural characteristics of the rifted and transform margins are strikingly different. Firstly, the diapiric structures typical of the rifted margin off Nova Scotia are not observed in the southern margin of the Grand Banks. During the early stages of opening there was a narrow sea along the rifted margin, ocean circulation was restricted, and evaporites were deposited (Fig. 3). Along the transform margin the continents were sliding by each other and were not separated during the time of evaporite deposition. Possibly, this accounts for the lack of diapiric structures. Secondly, from Figure 7 it becomes apparent that the topography of the basement along the rifted margin is relatively gentle and similar to that observed in the ocean basin elsewhere. Along the transform margin south of the Grand Banks the basement exhibits dramatic topographic relief, as much as 4 km. These structures do not appear to have deformed the sediments surrounding them, which means that they were probably formed during the original creation of ocean crust. It is not clear from the data whether the relief is due to the formation of seamounts or to block faulting of the basement.

Development of the East Coast Geosyncline

In order to emphasize the role of geosynclinal concepts along our margin, King (1975) suggested naming the subsiding Mesozoic-Cenozoic section the East Coast Geosyncline. The sedimentary wedge underlying the continental shelf and for the most part overlying Paleozoic basement becomes the East Coast Miogeocline, and the prism underlying the continental rise and overlying oceanic basement of post-Triassic age becomes the East Coast Eugeocline.

The adjacent wedges together constitute a complete synclinal trough. Figure 10 shows some of the major geologic and geomorphic elements along the Scotian Shelf and Grand Banks segments of the East Coast Geosyncline, but the presentation is by no means complete. For example, major block faults associated with the initial breakup of the continents probably parallel the axial trend of the geosynclinal deposits but such faults have not as yet been systematically mapped. The basins also require further delineation and subdivision. Jansa and Wade (1975) proposed the name Scotian Basin and divided it into sub-basins and grabens. The main purpose of Figure 10 is to separate the geologic and geomorphic elements, and to arrange the various orders of geologic entities into a logical sequence, for example geosyncline, miogeocline and eugeocline, basins and sub-basins. It is thought that this usage circumvents the difficulties implicit in the use of geomorphic qualifiers such as coastal plain sediments, continental shelf and rise deposits, etc. Geomorphic terminology could then be applied properly and specifically to describe the geomorphic and paleogeomorphic elements on and within the broad, three dimensional, geosynclinal element.

Figure 11 is an interpretation of a processed seismic record run for a participation survey by SEISCAN-DELTA Ltd. The profile was located south of Halifax (line AB in Fig. 6) and run across the continental shelf and rise for 263 km. The vertical exaggeration is approximately six times. The section is fairly typical of the western Scotian Shelf for the features we wish to emphasize. It was chosen from the western half of the shelf where the section is thinnest in order to show as wide a spectrum of the stratigraphic succession as possible. Well-history reports for nearby exploratory wells were used to aid in the interpretation.

The salient features of the profile are the thick wedge of seaward dipping strata underlying the continental shelf and slope, the much larger prism of strata associated with the continental rise, and the boundary zone in the area of the continental slope and upper rise where these sedimentary accumulations overlap. This zone dips steeply seaward beneath the continental rise sediments and appears to be a continuation at depth of the present slope. The shelf associated strata belong to the miogeocline, the rise strata to the eugeocline, and the zone between the couplet probably constitutes a "fossil continental slope".

The Miogeocline. The miogeoclinal sediments on the profile (Fig. 11) wedge out approximately 50 km northwest of the profile at a point 50-60 km seaward of the present coastline. They dip gently seaward at an angle of 0.5-1° and continue at depth beyond the present continental slope. The miogeoclinal sequence is thickest near the shelf edge where a thickness of 4.5-5 km is indicated. East of the profile the miogeocline thickens into the Scotian Basin where thicknesses at the shelf edge are as great as 9-10 km.

At the updip end of the miogeocline the beds conform closely to the attitude of the underlying Paleozoic basement, but at a point 50 km along the profile the basement drops away suddenly and the sequence thickens. The basement is probably faulted at this point.

Towards the upper part of the profile the Tertiary beds take on a progradational aspect that is not so apparent in the underlying Cretaceous beds although it could be present in the Jurassic beds. Tertiary beds have an initial dip analogous to foresets but as we will see later they were not always deposited in shallow water. For the remainder of the section the reflectors are strong and regular and sometimes run the entire width of the miogeocline. They slowly diverge in a seaward direction and the sedimentary units 'thicken out' at the former shelf edge with very little evidence of progradation. Thickening-out of strata was emphasized by Dietz and Holden (1966) as one of the most characteristic features of half a geosyncline, a syncline with the outer limb missing.

Salt diapirs are common in the miogeocline but do not appear on this particular profile.

The exploratory drilling program in the offshore has provided a wealth of information on the vertical succession in the miogeocline. From these data McIver (1972) proposed the framework and terminology for the Mesozoic-Cenozoic succession,

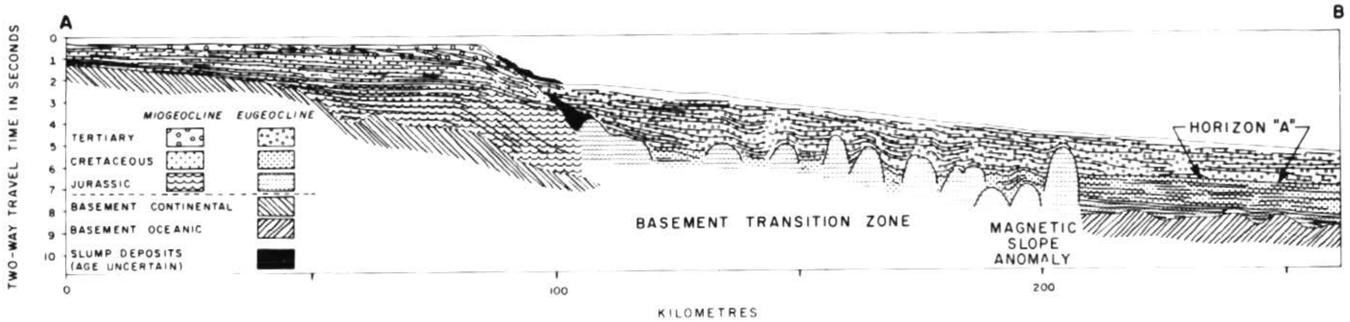

Figure 11

Interpreted processed seismic section across the Nova Scotia margin showing miogeocline and eugeocline. The location is shown in Figure 6.

together with a description and geologic history of the stratigraphic units. The Scotian Shelf section of the East Coast miogeocline overlies a basement of Paleozoic crystalline and metasedimentary rocks; essentially an offshore extension of the rocks of the Meguma platform. Some Carboniferous and Triassic rocks might occur locally. North and east of the Glooscap fault system (Fig. 10), Carboniferous rocks in association with metamorphic rocks of the Avalon platform predominate as basement for the miogeocline. On the Grand Banks (AMOCO Canada and Imperial Oil, 1973) and to some extent on the Scotian Shelf the lower part of the miogeoclinal section was deposited within structural sub-basins defined by faulted basement blocks. Some of these sub-basin structures were formed in response to initial rifting movements in Triassic and Early Jurassic time. In some instances, as pointed out earlier, these movements occured along pre-existing structural lines of weakness, for example in the Orpheus sub-basin along the Glooscap fault system. The extreme seaward edge of the miogeocline might be underlain by oceanic basement but this will only be known when the transition zone between oceanic and continental crust has been adequately defined.

From McIver's (1972) description of the section, it is clear that the miogeoclinal sediments accumulated under a wide range of conditions and by a variety of processes including restricted environments and the accumulation of salt and redbeds, carbonate bank and deltaic deposits both with a variety of associated facies, and deep-water sediments with the accumulation of chalk, marl, and marine shale. These are blanketed by the Pleistocene and Recent deposits of glacial till, glacial marine sediment, basal transgressive deposits of sand and gravel, and accumulations of clay and silt in the deeper areas of the shelf. The broad framework of sedimentation appears to have been one of up-building on a slowly subsiding shelf with variations introduced by sea-level changes and rates of sediment supply. Sedimentation was sometimes interrupted by erosion and at times the depositional surface constituted a submerged coastal plain topography as it is today. Some of the sea-level changes were probably eustatic resulting from volume changes in the mid-ocean ridge systems. At least one sea-level change was caused by a late Early Cretaceous uplift on the Grand Banks and several sea-level changes accompanied glaciation.

The Eugeocline. According to Mitchell and Reading (1969) the Atlantic-type geosyncline includes the abyssal plain, continental rise, and continental shelf. In Figure 11 only the continental rise portion of the eugeocline is shown. Beyond the section the sediment thickness decreases progressively, underlying the Sohm Abyssal Plain and towards the mid-Atlantic Ridge. As it appears in the section, the eugeocline is thickest (approx. 4.5-5 km in this section, but generally thicker) beneath the upper continental rise where it begins to lap on the adjacent miogeocline. Sediment thickness over oceanic basement at the outer end of the profile is approximately 3.5-4 km. The eugeocline is at least 2.5-3 times larger than the miogeocline.

Beds in the eugeocline dip gently seaward off the upper continental rise at an angle of approximately 0.25-0.50° and assume an almost horizontal attitude as the abyssal plain is approached. Local variations in dip occur where diapirs have intruded the strata. Reflectors in the upper part of the section compare quite closely with the attitude of the sea bed, but deeper in the section the dips tend to decline. At greater depths beyond the limit of penetration the dips could conceivably become horizontal or even reverse slightly to a landward direction because of subsidence.

Diapiric structures appear to dominate the continental rise part of the eugeoclinal section. These structures were first noted by Emery *et al.* (1970) who referred to them as the "ridge complex" and suggested that they represent basement. Like Sherwin (1973), we interpret the structures as salt diapirs so that the basement configuration on the section would dip deeply beneath the upper continental rise deposits. This interpretation suggests that the diapiric structures are not important features to the overall framework of the eugeocline. They do, however, point to the presence of salt deep in the section and it seems reasonable to assume that it is of Jurassic age, similar to that of the salt (Argo Formation) in the miogeocline.

The vertical succession in the eugeocline is not so well known as that of the miogeocline underlying the Scotian Shelf and Grand Banks. Dietz (1972) likened the eugeoclinal deposits to a huge apron composed of coalescing sedimentary fans developed by turbidity currents, and Heezen *et al.* (1966) suggested that a significant amount of sediment is probably transported by geostrophic boundary currents. From seismic reflection profiles, Emery *et al.* (1970) recognized major sedimentary units and concluded that a large proportion of them were turbidites, pelagic sediment, and zones characterized by slumps and slides.

Further information on the nature of the vertical succession in the eugeocline is provided through the JOIDES drilling program, in particular from sites 105-108, which were drilled closest to the local area (Ewing and Hollister, 1972). Holes 105 and 106 were drilled on the lower continental rise and provided most of the data. Hole 105 sampled much of the lower section between Horizon A and oceanic basement, as well as some Tertiary and Quaternary sediment overlying Horizon A. Hole 106 provided a thicker section of Tertiary and Quaternary strata down to Horizon A. Holes 107 and 108 on the continental slope were much shorter and encountered Quaternary and Tertiary sediments, respectively. The principal lithologies encountered were basalt, Late Jurassic and very Early Cretaceous limestones and chalks, Early Cretaceous dark clay, multicoloured volcanogenic clays of uncertain age, Eocene-Pliocene hemipelagic mud, and Quaternary turbidites (Fig. 12). Ewing and Hollister (1972) and Lancelot *et al.* (1972) found that these lithologic facies probably have a basin-wide expression because they correlate well with the seismic stratigraphy and were found in other JOIDES drilling sites farther to the south. It is probable that many of the horizons extended north to the eugeocline off Nova Scotia. These authors also suggested that the depositional regime prior to Horizon A produced an enormous more or less horizontal plain, while the regime above Horizon A produced the continental rise. They belived that this transition from basin leveling to continental rise construction was mainly due to the onset of vigorous bottom-water movement judged to correspond to the time when the opening of the Atlantic Ocean had proceeded far enough to permit large-scale inter-basin circulation of deep water.

From an examination of Figure 11 it is clear that Horizon A approaches a horizontal attitude on the lower continental rise, but at the base of the ancient continental slope it is approximately two km higher in the section. This suggests that there was a continental rise prior to Horizon A time, but that it did not extend as far seaward.

The Interface between the Miogeocline and Eugeocline. The interface between the miogeocline and eugeocline off Nova Scotia occurs in the area of the continental slope. In Figure 11 the slope dips seaward quite regularly at an angle of approximately 3-4° extending into the subsurface for at least 6 km as measured along this slope. At depth, the fossil slope appears on the profile as a zone characterized by irregularities with associated side echoes. The zone varies in thickness and is approximately 800 m thick in one area. These broader zones probably represent extensive slump deposits and on some profiles, where the zones are very wide, might represent a lateral migration of the ancient slope. Some profiles along other parts of the margin show that the boundary is not always so conspicuous. This is especially true for areas where the slope is poorly defined and the continental rise appears to start at the shelf edge.

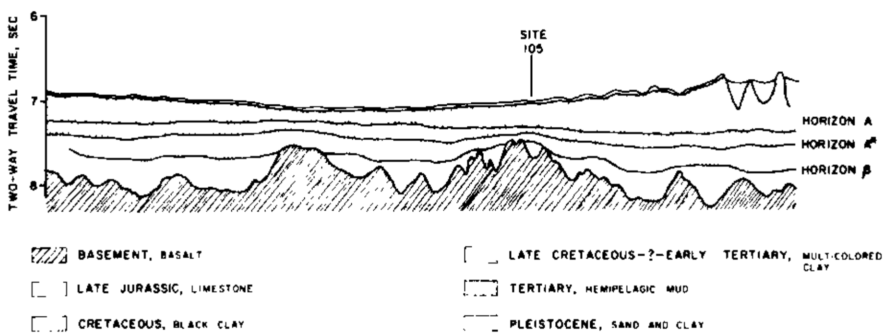

Figure 12
Sedimentary section in the vicinity of JOIDES drill site 105. (After Lancelot et al., 1972).

The boundary separating the geosynclinal couplet is clearly defined by the truncated beds of the miogeocline against the fossil slope and an onlap of eugeoclinal beds against the seaward side of the slope. Contrast is further enhanced by the age relationships between beds on either side of the interface interpreted on the basis of exploratory well data from the miogeocline and data from JOIDES drilling in the eugeocline. For example, Cretaceous formations of the miogeocline are in juxtaposition with Tertiary formations in the eugeocline. A trace of beds of equivalent age between the miogeocline and eugeocline mimics the slope of the present surface.

One might suggest that the boundary represents a fault caused by a gigantic slump but this is unlikely because of the change in the sedimentary regime on either side of the feature. For example, the Tertiary beds in the miogeocline have an initial dip as a result of progradation, but these structures do not occur in the eugeocline. One would expect them to occur on either side of the boundary if it had been formed as a result of faulting. It is more likely that the boundary is a geomorphic surface that has developed progressively upward through the geologic column as a result of periodic mass wasting similar to what is occurring on the slope at the present time. The overall shape and attitude of the surface were controlled to a large degree by the balance between sediment supply and rate of subsidence throughout the history of the miogeocline. During times of rapid sediment supply the miogeoclinal sediments probably prograded the ancient slope, extending the realm of the miogeocline seaward, while at times of greater slumping activity, especially during low sea level stands when submarine canyons were actively eroded, and during periods of strong boundary current activity, the prograded beds would be cut back. If subsidence progressed more rapidly than sedimentation, the slope would not be so prominent and depositional beds would probably run continuously from the miogeocline to the eugeocline. Both conditions would allow the miogeoclinal beds to thicken seaward and with subsequent slumping the miogeoclinal beds would thicken out against the interface.

Dietz and Holden (1966) emphasized the phenomenon of thickening-out because it is observed in both modern and ancient geosynclines. They provided an explanation for thickening-out in miogeoclines with a marginal carbonate reef, but did not satisfactorily explain the phenomenon for a clastic miogeocline. The ideas presented above regarding slope evolution and the development of fossil slopes appear to provide a satisfactory explanation for thickening-out of beds in the clastic miogeoclines. The ideas can be tested by the examination of deep seismic profiles on a number of Atlantic-type margins in various stages of development.

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