EXTENDED BASEMENT BENEATH THE INTRACRATONIC RIFTED BASINS OF THE GRAND BANKS OF NEWFOUNDLAND

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ABSTRACT
The tectonic and structural framework of the Grand Banks of Newfoundland (East Coast Canada) comprises a series of intracratonic basins and ridges developed during repeated Mesozoic rifting periods. Recent industry seismic lines and deep seismic data (Lithoprobe) allow for the recognition of coherent reflections of intrabasement provenance. The Precambrian and Paleozoic rocks of the Avalon zone, which form the core of the upper continental crust, underwent extensive block faulting and rotations at the onset of the Late Triassic-Early Jurassic phase of rifting. The extension of the continental crust initially took place in a northwest-southeast direction, on easterly dipping normal faults. One of these faults evolved into a listric megafault, which detachts in a deep crustal zone and underlies most of the Grand Banks structural elements. Its associated synthetic and antithetic faults bound the other structural provinces, basins and ridges of the shelf. The seismic lines recorded on the slope and rise, in the continent-ocean transition zone, suggest extended flood basalts of oceanic extraction lying on attenuated and subsided continental basement. This implies that in the transition zone the continental basement is not "lost" but only intruded and covered by new oceanic crust, and that this zone must be accounted for when paleocontinental reconstructions are made. Reactivation of older Precambrian and Paleozoic zones of weakness as rift-triggering faults is questioned and examples of deviations from predicted geologic grain are offered. The mantle beneath major abandoned rifts is postulated to be significantly contaminated by continental crust materials, so that a firm contact between the crust and mantle - the Mohorovicic (Moho) discontinuity - is temporarily destroyed.

INTRODUCTION
Conventional plate tectonics demonstrates that the Grand Banks of Newfoundland occupied a pivotal position during the last two cycles of plate reorganization in the northern hemisphere (Wilson, 1966; Haworth and Keen, 1979; Wilson, 1981). The Cambro-Ordovician passive margin of western Newfoundland was transformed into an active zone of convergence during Ordovician-Silurian time and then one of oblique slip during Devonian-Carboniferous time (Haworth, 1975; Strong, 1980; Williams and Hatcher, 1982). The Paleozoic orogenic phases (Taconic, Acadian, Hercynian) resulted in the accretion of the Avalon and Meguma terranes that now partly underlie the Grand Banks (Williams, 1979; Schenk, 1981).

During the Mesozoic, the Grand Banks were involved in North Atlantic rifting and ocean opening (McWhae, 1981; Wade, 1981). As a result of continental stretching, a series of intracratonic and plate-margin basins were formed (Enachescu, 1986; Grant et al., 1986a, b; Enachescu, 1987; Keen et al., 1987a; Tankard and Welsink, 1987, 1988). This paper focuses on the nature and behavior of the pre-Mesozoic rocks which formed the Grand Banks basement and are present today on the platforms and ridges and beneath the Mesozoic basins.

The studied area extends north, east and south of Newfoundland, covering over one million km² (Figure 1). This coincides partially with water depths shallower than the 200-m bathymetric contour (the actual Grand Banks), but also includes the deeper water regions around Orphan Knoll, Flemish Pass, Flemish Cap and the surrounding slope and rise zones.

REGIONAL GEOLOGY
The present-day complex regional geology off Newfoundland reflects a lengthy and complicated active and passive margin history. Briefly, the area (Figure 1) consists of:

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Fig. 1. Map showing location of the studied area, bathymetry and main geological provinces: 1) offshore extension of the Appalachian-Avalon zone, including basement platforms, ridges and isolated continental blocks such as Flemish Cap and Orphan Knoll; 2) Mesozoic abandoned rift system, including Jeanne d'Arc, Flemish Pass and South Whale Basins; 3) Newfoundland transform margin to the south; 4) true divergent margin, floored by transitional and oceanic crust to the east and 5) Avalon uplift, an Early Cretaceous northwest-southeast basement arch affecting the central and southern Grand Banks.

1. An offshore extension of the Appalachian orogen, including the Bonavista platform and two isolated continental blocks, Flemish Cap and Orphan Knoll (Haworth and Keen, 1979; King et al., 1985, 1986; Parson et al., 1985);
2. A system of Mesozoic rift basins, including the Jeanne d’Arc and Flemish Pass Basins — targets of hydrocarbon exploration (Jansa and Wade, 1975; Enachescu, 1986, 1987; Grant et al., 1986b; Tankard and Welsink, 1987, 1988);
3. A southern margin of transform origin, known as the Newfoundland transform zone, along which North America separated from Africa (Grant, 1977; Sullivan and Keen, 1978; Keen and Haworth, 1985);

The timing of the main geological events and a simplified stratigraphy for this region are presented in Table 1. In this paper “the basement” is defined as the sequence of rocks which formed the peneplaned cratonic crust prior to the Mesozoic cycle of ocean opening, i.e., the Hadrynian and possibly older crystalline rocks and the Paleozoic metasedimentary and sedimentary groups (Table 1). Due to successive phases of rifting to form Tethys, the North Atlantic and the Labrador Sea, this continental basement was subjected to extension, resulting in intense faulting and major subsidence.

The core of the Avalon tectonostratigraphic unit consists of Hadrynian, and probably older, crystalline rocks, similar in character to pan-African orogenic belts (O’Brien et al., 1983; King et al., 1986). The uppermost Precambrian and lower Paleozoic metamorphic, metasedimentary, sedimentary and volcanic rocks of the Avalon terrane and the overlying middle-upper Paleozoic sedimentary succession of the Horton, Windsor, Canso-Riversdale and Pictou-Cumberland Groups are well documented and widely known in the Maritimes (Howie and Barss, 1975; Schenk, 1978; Williams and Hatcher, 1982, 1983; O’Brien et al., 1983).

Previous geological and geophysical studies showed that similar Hadrynian, lower Paleozoic and upper
Paleozoic rocks are present offshore on the Grand Banks and adjacent areas (Jacobi and Kristoffersen, 1981; Haworth and Jacobi, 1983; King et al., 1986).

**Data Base**

Different research and industry sources provide us with a data base of information on the nature and distribution of basement rocks on the continental shelf. This information is contained in well-history reports, GSC reports and papers, master's and doctorate theses, COGLA files and scientific papers included in the reference list. The information can be classified as either geological or geophysical and a summary is as follows.

**Geological Information**

Physical and lithological properties of Hadrynian, lower and middle Paleozoic rocks present on the Avalon Peninsula and elsewhere in the Maritime provinces were used to compare basement samples obtained offshore.

Submarine samples have been collected by Lilly (1965, 1966), Pelletier (1971) and King et al. (1985, 1986) in the vicinity of the Avalon Peninsula from shoals further offshore and from Flemish Cap. The locations where samples were recovered and described are displayed on the offshore Newfoundland map (Figure 2). The granodiorite samples from Flemish Cap (King et al., 1985, 1986) were compared to the Holyrood granite (McCartney, 1969; Miller, 1983), based on age and chemical composition, in an effort to establish the offshore extent of the Avalon zone. However, King et al. (1985, 1986) could not demonstrate the similarity of the two granitic bodies. Thus, the Flemish Cap granodiorite may belong to either the Avalon zone or to a more easterly African terrane. No basement rocks were recovered from the only DSDP site on Orphan Knoll (Site III), because the hole was too shallow (Laughton and Berggren, 1972).

Approximately 120 exploratory wells have been drilled on the Grand Banks. Only the 13 with locations shown in Figure 2 bottomed in the basement (Jansa and Wade, 1975; Barss et al., 1979; COGLA, 1985). Several conclusions can be drawn from basement coring and sampling...
in the wells. The basement rock types are numerous. Variable thicknesses of the different tectonostratigraphic successions of the basement that have been penetrated may have resulted from folding and faulting followed by erosion. The basement is situated beneath the prerift unconformity (pre-Late Triassic), where the basement is relatively deep, or beneath the Avalon unconformity (pre-Albian), where the basement is shallow and the upper Triassic to lower Aptian section has been removed or was not deposited.

On the map of tectonic and structural framework of the Grand Banks (Figure 2) the basement is shaded and locally differentiated into Paleozoic (Pz) and Precambrian (PC). This division was made on the basis of submarine samples and well-core descriptions mentioned in the literature, as well as on the integration of geophysical results. The exploratory wells, located in Figure 2, encountered basement generally in three situations: (a) when drilling
the "draped over basement horst" type of hydrocarbon prospect, the case with Cumberland B-55 (Figure 6); (b) when penetrating the upthrown block below basin-bounding faults, the case with Hibernia G-55 (Figure 3); and (c) when piercing downthrown imbricate blocks above the basin-bounding faults, the case with Linnet E-63 (Figure 6) and Murre G-77 (Figure 8). As an example, the interpretation of line a-a' (Figure 3) shows that the Hibernia G-55 well missed the Jurassic reservoir sand, crossed the fault plane and bottomed in metamorphic basement.

Geophysical information

In previous papers, structural and tectonic elements of the basement were interpreted from potential-field data (Haworth and Lefort, 1979; Jacobi and Kristoffersen, 1981; Miller et al., 1985; Miller, 1987), refraction studies

Fig. 3. Location of the Hibernia G-55 well. Uninterpreted and interpreted seismic section a-a', with location on Figure 2. The well crossed the Murre fault plane and bottomed in metamorphic basement.
(Sheridan and Drake, 1968; Haworth and Keen, 1979) and shallow high-resolution seismic (Monahan and Macnab, 1975; Fader and King, 1981; King et al., 1985, 1986).

In order to extract additional information on basement tectonics, this paper mainly utilizes industry reflection data and deep-reflection profiles. More than 200,000 km of (a) reconnaissance, (b) detailed and (c) 3D seismic data presently cover the Newfoundland shelf. Four deep-reflection profiles, part of the Canadian Lithoprobe East project (indexed 84-3; 85-1, 85-2; 85-3; 85-4), were shot by the Atlantic Geoscience Centre and discussed by Keen et al. (1986, 1987a, b) and de Voogd and Keen (1987). Their locations are displayed in Figure 2, together with industry reflection lines used to document the concepts reported in this paper. Some of the more important questions that stem from the geophysical study of the Grand Banks basement will be briefly addressed as they may apply to other rifted areas.

**BASEMENT REFLECTIONS**

The reflection seismic shot by the petroleum industry has not been previously used for investigation of the basement. Seismic processing was instead focussed on the Mesozoic sediments; no attempts to clean the noise beneath the so-called “acoustic” basement were made. Moreover, until recently it was believed that, except for a fortuitous situation, no penetration could be achieved in a deformed basement complex and that metamorphic rocks were seismically transparent. An industry line b-b’ recorded over the Bonavista Platform helps to correct this misconception (Figure 4).

Unconformities, bedding planes, thrust faults and folding in the Paleozoic and Precambrian rocks can be interpreted from the seismic data if we ignore the random noise and the severe multiple problem and make use of the Avalon-terrane regional style of deformation and faulting. However, as can be noted, the interpretation below three seconds is quite difficult and only correlations with other lines not shown here allow one to sketch fault planes and layering.

Marine deep-seismic-reflection profiles from the northern Appalachian belt including the Bonavista Platform, were first discussed by Keen et al. (1986, 1987a, b) and de Voogd and Keen (1987). Lithoprobe lines are usually recorded to 20 s and processed to 16 to 18 s. They can produce intrabasement information from deeper levels of the crust and even from the upper mantle, regions previously accessible only to refraction seismological methods or geophysical modelling.

The Lithoprobe line e-e’ in Figure 5 shows a thin veneer of postrift sediments above the Avalon unconformity. Under the unconformity, the continental crust can be divided into an upper transparent crust associated with lower Paleozoic and upper Precambrian rocks and a lower reflective crust corresponding to older Precambrian structures and layered mafic material. The Moho surface is very well imaged at about 10 s, equivalent to approximately 30 km in depth.

**MAJOR CRUSTAL FAULTS**

The most recent industry data show that the hinge zone previously defined as a Mesozoic basin border (Grant, 1987) is actually a major listric basement fault which defines the western limit of the rifted basins and the area’s master detachment zone (Enachescu, 1986, 1987). This remarkable megafault (F1 on Figure 2) is a “basin-bounding fault”. It accounts for the majority of the basement extension and allows for the creation of the half-graben-shaped rift basins (Figure 6, line d-d’).

In Figure 7, seismic line e-e’, the basin-bounding fault is almost vertical through Tertiary sediments, cuts through the entire upper crust and curves down to a deep crustal level below the 7 s of recorded data. On the downthrown side of the basin-bounding fault is the Hibernia structure, and further to the east is the depocentre of the Jeanne d’Arc Basin infilled by approximately 20 km of synrift and postrift sediments.

The segment f-f’ of Lithoprobe line 85-4 shows that the basement fault flattened very deep in the crust at about 10 s, or 30 km depth, corresponding to the Moho level (Figures 2 and 8). On the same line, the Murre G-77 well intersected the fault plane or drilled into a small synthetic imbricate block and bottomed in Paleozoic metasediments. Accordingly, the fault was named the Murre fault and is known by this name south of the Hibernia area. North of Hibernia, the same fault is sometimes referred to as the Mercury fault.

Basin-bounding faults are less visible on the seismic data collected on the Avalon uplift and southern Grand Banks. This is probably due to severe erosion of both flanks of the faults, up to a level where the fault plane is at a low angle (5 to 15°), and to the fact that the velocity contrasts across the fault plane are small (Figure 9, line g-g’).

**BASEMENT RIDGES**

A series of intrabasinal ridges were recognized east of the bounding fault. Most important for rift tectonics are basement-cored ridges such as the Central Ridge, which separates the Jeanne d’Arc Basin from the Flemish Pass Basin (Figure 2). Most of the basement ridges are, in fact, elongated horsts formed by antithetic and synthetic faults of the basin-bounding fault (Figure 10).

The Central Ridge (Figure 11, line h-h’) was an intrarift relatively high area during the initial Late Triassic rift-valley episode and had a median elevated position in the subsequent evolution of the intracratonic failed rift system (Enachescu, 1987). During the Early Cretaceous, this ridge reached its maximum elevation due to increased rotation of its basement core on the basin-bounding fault.
Fig. 4. Uninterpreted and interpreted industry line b-b' on the Bonavista Platform showing top of the basement (Avalon) unconformity, top of Hadrynian (metamorphics) unconformity, thrust faults and folding in metamorphosed rocks. The upper arrows indicate erosional surfaces and the lower arrows show fault planes. For this and the following seismic sections the key to symbols is: Σ = salt; A = top of metamorphic complex; B = prerift unconformity; C = Avalon unconformity; D = sub-Tertiary unconformity; J = Jurassic; K = Cretaceous (Lower = K1, Middle = K2, Upper = K3); Fz = Paleozoic; Pc = Precambrian; F1, BBF = basin-bounding fault.
Fig. 5. Short segment c-c', uninterpreted and interpreted, of deep seismic profile (Lithoprobe) 85-2, located on the Tail of the Bank. The interpreted section shows the Teriary platform sediments, the Avalon and sub-Tertiary unconformities merged, the crust divided into an upper transparent crust and a lower reflective crust, the Moho reflection and the mantle.

plane. The ridge was exposed as an island chain or peninsula and consequently the upper Upper Jurassic to Lower Cretaceous sediments are missing due to erosion and non-deposition. As demonstrated by the drilling of Goleonda C-64, an indurated succession approximately 5 km thick of Upper Triassic-Upper Jurassic sediments still overlies the Central Ridge basement. Intrabasinal basement rocks are at a shallower depth (1 to 2 km) in the south and can be sampled only on the narrow strip separating the South Jeanne d’Arc from the Carson-Bonnition Basin (Figure 2).

TRANSFER FAULTS

Cross-basin faults were interpreted from the seismic lines (Figure 12, i-1) and potential-field data. These have been recently referred to as transfer faults, which are the continental equivalent of the oceanic transform faults that offset midoceanic ridges (Gibbs, 1984; Enachescu, 1986, 1987; Tankard and Welsink, 1987, 1988). These faults allow for changes in the direction or amount of slip of the basin-bounding fault.

Transfer faults are recognized on seismic lines only when structural style and lithologies vary dramatically across the fault plane. Scissor-type motion involving both sedimentary infill and basement typically occurs along transfer faults. They are most probably rooted in the same deep crustal detachment zone as the basin-bounding faults.

The Dominion transfer fault (Figure 2) offsets the major structural and tectonic elements of the northeastern Grand Banks (Enachescu, 1987). Other transfer faults that may compartmentalize the basement on the Grand Banks are not as visible in the geophysical data and, therefore, were not included in the tectonic framework (Figure 2). Etheridge et al. (1985, 1987) and Tankard and Welsink (1987, 1988) suggest a higher density of such faults fragmenting, respectively, offshore southeastern Australia and the Grand Banks Basin. Seismic data, at least for the area in Figure 2, offer no evidence that the rigid continental basement underlying the Grand Banks was densely faulted oblique to the basin margins (5 to 10 km between transfer faults). Such density of transfer faults would create numerous compressional features in the overlying sediments, which is not the case for the Mesozoic sediments of the Jeanne d’Arc Basin.

CONTINENT-OCEAN TRANSITION ZONE

The transition zone between the continental and oceanic crust was crossed by Lithoprobe line 85-3 (Figure 13, segment j-j'). Two conspicuous slanted reflection zones, suggesting normal faulting and extension, are observed beneath the Aptian breakup unconformity. A lowermost peculiar strip of reflections appears at the theoretical depth of the oceanic Moho (de Voogd and Keen, 1987). The interpretation of Figure 13 places a thin wedge of continental crust beneath a thick blanket of oceanic basalts, with extensional faults in both layers. Basic intrusions and basaltic lavas are believed to have been emplaced and subsequently extended above an already faulted and subsided basement. The strong magnetic sig-
Fig. 5. Industry reflection line d-d', across northern Jeanne d'Arc Basin, showing the basin-bounding fault (F1), the half-graben sedimentary basin and the Cumberland Ridge with Cumberland B-55 well location. Linnet E-63 encountered Paleozoic metasediments in a small rotated basement block.
nature of this unusual terrane, shown in Figure 14 and in the magnetic anomaly maps and profile of the Atlantic slope (Jacobi and Kristoffersen, 1981), is caused by the presence of thick (5 to 8 km) basic igneous rocks under a thin (1.5 km) sedimentary cover and not by a true oceanic crust.

The boundary between continental and oceanic crust was placed west of the Figure 13 segment, at the base of the slope, by Sullivan (1983) and Keen and de Voogd (1988). The manner of extension and the seismic interval velocities of the deeper layer, however, are characteristic of continental crust, and the true extent of continental crust must be moved farther east, approximately 700 km from the Newfoundland coastline. When attempting paleocontinental reconstructions based on bathymetric contours or magnetic lineations, unexpected gaps between continents often occur (Vink, 1982; Masson and Miles, 1984). The interpretation of Figure 13 suggests that these gaps may be due to ignoring similar strips of “lost” continental crust, which are obscured by deep subsidence and a blanket of oceanic basalts.

The F2 lineament in Figure 2 must be regarded as a major down-to-the-ocean fault zone and not as the continental-ocean boundary (COB). Beyond F2, on the continental slope and rise, lies the transition zone, made of the easternmost sectors of Mesozoic basinal areas (e.g., Carson-Bonnition Basin), basement ridges, volcanic mounds, batholiths and atypical terranes such as those interpreted in Figure 13. The continent-ocean transition zone is therefore geologically complex and is probably limited oceanward by the magnetic lineations J(Ms) in the south and 34 in the north.

**NEWFOUNDLAND GEODYNAMIC MODELS**

The geologic section A-A’ (Figure 14) summarizes the main tectonic and structural elements of the Grand Banks. The basement platforms, the basin-bounding fault, the basement-cored Central Ridge, the two intracontinental abandoned rift basins (Jeanne d’Arc and Flemish Pass), the Flemish Cap basement block, and the continental-ocean transition zone underlying a thinned plate-margin basin, are interpreted from potential-field maps, regional seismic lines and existing well control (Enachescu, 1987). This particular cross section was chosen to describe the area because it almost balances with a β factor of 1.54. Similar transects to the north and south, perpendicular to the Jeanne d’Arc Basin axes, do not balance and consequently are not shown here. Intersection of these sections with transfer zones or local transient faults may explain the lack of balancing. In my opinion, perfect balancing of a section in a complex rifted zone such as offshore Newfoundland is difficult to achieve and exceptionally rare. There will always be oblique slip of certain blocks, resulting in an imbalance of the basement material in any given vertical plane. Only a tentative three-dimensional balancing can be successful if the actual basement configuration is adequately known.

Various geodynamic models of continental stretching and basin formation have been proposed for this area during the last 10 years. The extensional models of McKenzie (1978), Wernicke (1981, 1985) and Wernicke and Burchfiel (1982) can be considered as end-member models (Coward, 1986), the first symmetrical and the second asymmetrical. Some authors suggest hybrid models applicable to an area of increased complexity such as the Grand Banks (Keen et al., 1981; Keen et al., 1987a, b). However, there is a pronounced structural asymmetry in both strike and dip directions, confirmed by various geophysical data, that most likely supports variants of a simple-shear extensional model, such as those published by Wernicke (1985, Figure 3), Beach (1985, 1986).
Coward (1986), Lister et al. (1986), Allmendinger et al. (1987), and Pinet et al. (1987).

The reflector “S” of de Charpal et al. (1978), which is probably an upper crustal detachment on the Galicia Bank, is missing in the studied area. Therefore, Grand Banks geologic cross-sections and extensional models can be constrained only by a lower crustal detachment, which may die out at the base of the crust or may be rooted in the upper mantle.

By studying the conjugate European margin, a group of French researchers proposed variants of Wernicke’s continental stretching model for the Grand Banks-Iberian Shelf (Boillot et al., 1987a, 1988) or the Grand Banks-Goban Spur (Malod, 1987) separations. These models envision a lithosphere-penetrative simple shear and both result in crustal asymmetry of the opposing margins. Mantle-derived serpentinized peridotite was recovered at the base of the continental slope, both by ODP leg 103...
Fig. 9. Lithoprobe Line 85-1, p. 2 in Figure 2, crossing the Bonavista Platform, Whale Basin, Horseshoe Basin and Tail of the Bank. On the uninterpreted line it is difficult to discern major fault planes and dipping basement extensional surfaces. Erosion has removed the steep portion of the fault blocks. The basins are less deep than their northern counterparts (Erichton and others, 1987). The basen bounding fault penetrates the basement to the Moho level. The Moho reflection is very well-imaged beneath the Tail of the Bank and poorly imaged beneath the central portion of the abandoned rift. A multitude of rotated basement blocks slide along the bounding fault plane toward the central zone of the rift. The gravity and magnetic low-frequency curves used in interpreting line 85-1 are displayed between the uninterpreted and interpreted seismic lines.
Fig. 10. Simplified diagram showing partition of the downthrown basement block by antithetic and synthetic faults to the basin-bounding fault. This category of basement-involved faults (Enachescu, 1987) creates the alternating graben/horst structure of the Grand Banks.

Fig. 11. Seismic line h-h' over the Central Ridge. This ridge separates the main Mesozoic basins of the Grand Banks: west of the ridge is the Jeanne d'Arc Basin, while to the east is the Flemish Pass Basin. The core of the ridge comprises inferred Hadrynian (Upper Precambrian) and Paleozoic rocks. A salt layer folded and probably faulted lies on top of the basement. Depth to basement in the middle of the panel is approximately 7 km.

Fig. 12. Industry seismic line i-i' intersecting the Dominion transfer fault. The character of the Cretaceous and Jurassic reflections and the style of the deformation change dramatically across this fault zone. The left block moved down and out of the plane, while the right block moved up and into the plane of the illustration. The basement is here deeper than 7 s and, hence, not shown by the seismic section.
Fig. 13. Uninterpreted and interpreted segment jj' of the Litho-probe line 85-3. Two peculiar oblique-reflection zones are visible beneath the Aptian breakup unconformity. The proposed interpretation shows extended and subsided continental basement (2) beneath an extended basaltic layer (1). The oceanic rocks intruded and flooded an already foun-dered basement and are responsible for the strong magnetic signature of these terranes.
Fig. 14. Regional geotransverse A-A' across the Grand Banks, including the Bonavista Platform, Jeanne d'Arc Basin, Hibernia oilfield, Central Ridge, Flemish Pass Basin, Flemish Cap and the transition zone between continental and oceanic crusts. The residual gravity in mgal and total magnetic intensity in nT are displayed on top of the geotransverse. A double fault rift with central high geometry was proposed for the Jeanne d'Arc Flemish Pass pair of basins (Enocheh, 1987). (Interpretations are: A — top of metamorphic complex (Hyaloclastite), B — top of gneiss basement; C — Avalon pre-Archean; D — sub-Tertiary. A transition zone is juxtaposed between continental crust (Flemish Cap) and oceanic crust (Atlantic Ocean Ridge), consistent with basement intruded and flooded by basaltic. CCG denotes contaminated continental crust. A major break was introduced over the Flemish Cap area in order to keep the cross section to an acceptable size.)
and by a submersible cruise, west of Galicia Bank. This suggests that mantle rocks were emplaced at the North Atlantic paleorift axes before the beginning of seafloor spreading (Aptian Age). Boillot et al. (1987a, b, 1988) concluded that tectonic denudation of the mantle took place by nonuniform stretching of the continental crust. A major crustal detachment fault underlies the entire rifted area beneath the eastern Newfoundland shelf and slope. Symbols as described by Boillot et al. (1988) are: 1 = lithosphere subcrustal peridotite; 2 = upwelling peridotite experiencing partial melting and behaving as an asthenospheric bulge; 3 = poorly depleted asthenospheric peridotite further accreted to the lithosphere; G = gabbro.

**DISCUSSION**

Two intriguing problems concerning the nature of basement in rifted areas deserve comment. The first refers to the "inheritance" hypothesis, in which rift-bounding megafaults are presumed to be reactivations of older weak zones such as deformation fronts, major thrust faults, suture zones, subduction zones, etc. (Haworth and Keen, 1979; Haworth, 1981; Brewer and Smythe, 1984; Grant et al., 1986b; Tankard and Wink, 1987, 1988). This hypothesis is largely embraced and used by researchers in different regions of the world to explain rift-related, normal or strike-slip faults, and it seems at first very logical (Fitteridge et al., 1984, 1985, 1987; Masson and Miles, 1984; Grant et al., 1986a, b). However, data do not always support this assumption (e.g., Beach, 1985, 1986). For example, the Jeanne d'Arc and Whale Basins have bounding faults with crustal-scale displacements that, as a general rule, cut across older Appalachian trends (Figure 2). The same disregard for older features is shown by a large number of other major basement faults that fragment the Grand Banks. It is clear that in this area, and perhaps elsewhere, "inheritance" is not a general rule and extension can create new fault trends which ignore the previous fabric.

Another intriguing observation of this and other studies (e.g., Meissner, 1986, chapter 6; Pinet et al., 1987) is the lack of a clear Moho reflector beneath the central zone of the relatively young rifted basins. Lithoprobe lines show that the Moho reflection is well imaged beneath platforms and ridges (Figures 5 and 9) but poorly imaged beneath the basins (de Voogd and Keen, 1987). On line drawings of deep reflection profiles, the Moho is sometimes liberally traced above (most frequently) or below the interpolated horizontal position, in a zone where, in fact, there is a lack of coherent reflections. Although some authors suggest that this lack of coherency is due to attenuation and absorption of seismic waves by the basin infill, or to scattering of the waves (Keen et al., 1987a) caused by increased complexity of the rift, there is no conclusive proof for the suggestion that seismic energy is less capable of penetrating the basal areas than equally complex basement rocks of the Appalachian orogen. Instead, I believe that the seismic data truly reflect a poorly developed Moho beneath the basins. Although speculative, I suggest that, beneath basins established on the downthrown side of deep crustal detachment zones, there is a zone where the lower crust was fragmented, intruded and partly assimilated by mantle material (Figure 9). The mantle itself is contaminated by crustal constituents, and thus, the sharp contrast between lower crust and upper mantle, which is the Mohorovičić discontinuity, is locally destroyed and replaced by a transient transitional zone. Only with time will the material in the crust-mantle transition zone be rearranged and the velocity contrast which marks the Moho discontinuity be restored. When balancing geologic cross-sections in extensional terranes (Gibbs, 1983), by rotating back the basement blocks to their prerift position, there is always some crustal material unaccounted for if the Moho is constrained to be flat. A portion of the lower crust can only "vanish" in this way through assimilation of the roots of the rotated blocks into the upper mantle. A lower-continental-crust/upper-mantle mix is formed, and hence, a gradual increase of the seismic velocities instead of an abrupt velocity contrast is expected.

**CONCLUSIONS**

The Grand Banks basement consists of various Precambrian and Paleozoic successions and has a variable thickness above the Moho. Significant intrabasement reflections from deeper zones can be seen on both indus-
try seismic and Lithoprobe lines. Extension of the base-
ment occurred along a major, listric, easterly dipping normal 
fault, which is designated here as a basin-bounding fault. This fault is actually the western portion of the 
master detachment between the opposing lower-plate margin (Grand Banks) and upper-plate margin (Iberia Shelf). Its associated synthetic and antithetic faults created the alternating half-graben/ridge structure of the Newfoundland rifted margin. The complexity of base-
ment faulting is increased by transfer faulting. Extended and subsided basement is present beneath an oceanic-type layer further offshore on the continental slope and rise. There is a large zone floored by transitional (intermedi-
ate) crust and, therefore, the continent-ocean boundary is
not a sharp contact as often interpreted. The continental crust is present offshore beyond the lower continental 
slope, up to a distance of 700 km from the Newfoundland coast line (east of Flemish Cap). The chain of magnetic anomalies interpreted as J(Ms) in the south, and 34 in the
north, are the first indications of true oceanic crust.

General claims for the reactivation of older zones of weakness as rift-forming faults and the presence and position of Moho beneath rift basins need better docu-
mentation and theoretical treatment before being accepted as hard-and-fast rules.

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EXTENDED BASEMENT BENEATH THE INTRACRATONIC RIFTED BASINS

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