CHAPTER 5

A Regional Model for the Separation of Greenland from North America

Abstract

A new model for the crustal evolution of the southwestern Greenland margin (58.7 - 61.9°N and 48 - 53°W) was developed from gravity-derived Moho depth estimates, lithologic & geologic features interpreted from correlative geopotential anomalies, and recent seismic surveys [Chian and Louden, 1994; Chian et al., 1995a, Chian et al., 1995b; Chalmers and Laursen, 1995]. Previous kinematic models [Srivastava, 1978; Srivastava and Tapscott, 1986; Roest and Srivastava, 1989; Srivastava and Roest, 1995] suggested that the opening of the Labrador Sea caused a counterclockwise rotation of Greenland from ca. 92 to 36 Ma as a part of the opening of the North Atlantic Ocean. The kinematic model was based upon the assumption that the continent-ocean boundary was located at the Greenland shelf break with oceanic crust starting to form there at magnetic isochron 33 (c. 78 Ma). This interpretation was challenged by recent seismic surveys, which determined that rocks within a 150 km wide zone west of the continent-ocean boundary were characterized by densities and magnetic susceptibility contrasts more characteristic of rifted-continental or transitional crust. The interpretation of this zone as transitional crust was further substantiated in Chapters 3 and 4 where similar results were obtained. The model presented

here postulates that the rotational opening of the Canada Basin from 135 to 115 Ma induced a counterclockwise rotation of Greenland, which extended and thinned the Archean crust between Greenland and Labrador. This weakened crust was thus well disposed to rifting when the North Atlantic rift system propagated northward into the region at about 90 Ma. Slow extension rates and an insufficient supply of magma delayed the initiation of oceanic spreading until about 63 Ma when Greenland began to separate from North America and move with Europe.

5.1 Introduction

The Labrador Sea region (58.7 - 61.9°N and 48 - 53°W) off of Greenland's southwestern coast is shown in Figure 5.1 and contains unique evidence of the Late Cretaceous to Tertiary separation of Greenland from North America during the breakup of the supercontinent Laurasia. A better understanding of this separation may improve overall knowledge of the evolution of Greenland, the North Atlantic Ocean, and the Arctic.

Several studies have modeled the 150 km wide zone that starts at the continent-ocean boundary (COB) approximately 100 km off the Greenland coast. These studies concluded that this zone may either be oceanic crust [Srivastava and Tapscott, 1986; Roest and Srivastava, 1989; Srivastava and Roest, 1995], continental crust [Chalmers and Laursen, 1995], or transitional crust [Chian and Louden, 1994; Chian et al., 1995a; 1995b]. The origin of the crust is important because it constrains the different models that have been developed for the movement of the Greenland subplate with respect to both North America and Europe.

The kinematic models [Srivastava and Tapscott, 1986; Roest and Srivastava, 1989; Srivastava and Roest, 1995] are consistent with the relative motions of North America and Eurasia but require that the the 150 km wide zone consist entirely of oceanic

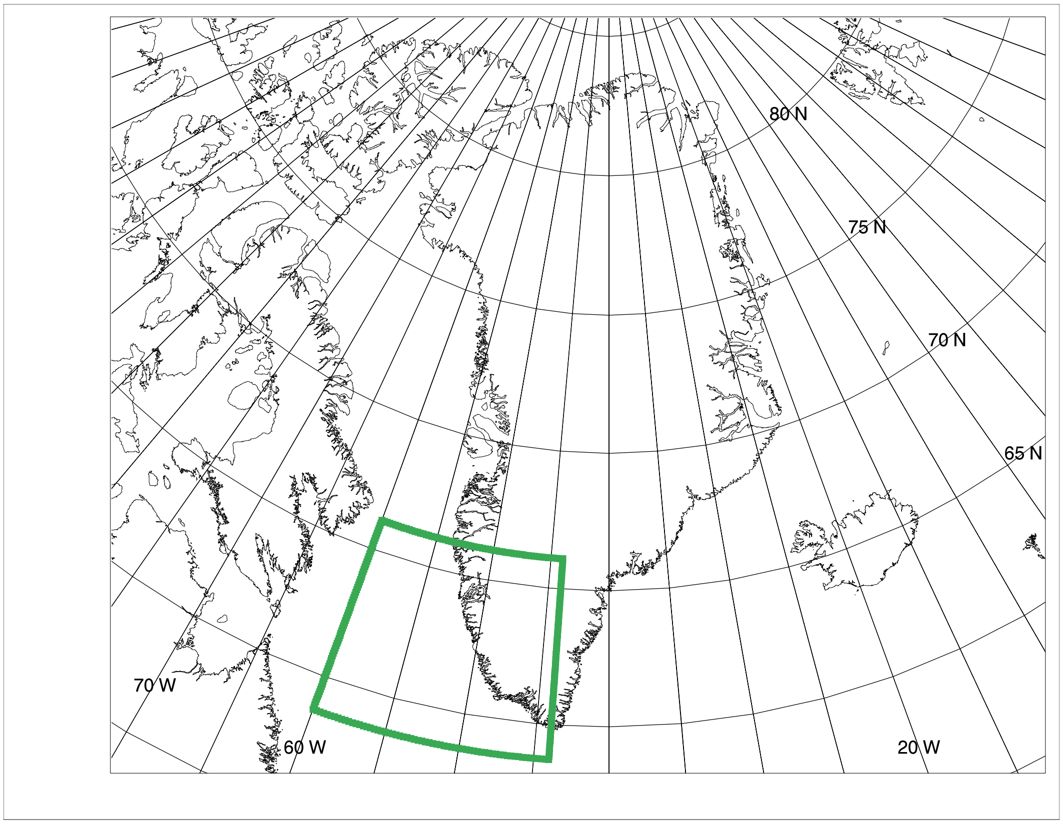

Figure 5.1: Green box delineates the study area (58.7 - 61.9°N and 48 - 53°W) for southwestern Greenland in a Lambert Equal-Area Azimuthal Projection centered on 40° W.

crust starting at about 78 Ma (isochron 33) to minimize plate overlaps when rotated close. However, the seismic surveys and borehole observations [Louden et al., 1997; Chalmers and Laursen, 1995; Chian and Louden, 1994; Chian et al., 1995a; 1995b; Balkwill, 1987; Hinz et al., 1979] have modeled local features in the crust that are inconsistent with the interpretation of the 150 km wide zone as oceanic crust and more suggestive of continental or transitional crust. The aim of this paper is to use the models presented in Chapters 3 and 4 to reconcile these apparent differences and incorporate the results from studies of regional paleostresses and structures in surrounding areas [Grantz et al., 1998; Faure et al., 1996; Lepvrier et al., 1996; Oakey, 1994; Kerr, 1980] to provide a comprehensive model for the opening of the Labrador Sea.

5.2 Background

Srivastava and Tapscott [1986] offered a kinematic model for the opening of the Labrador Sea that was tied into the development of the North Atlantic Ocean (see Appendix G for further details of their model). However, this model produced rotations that involved problematic directions of motion and overlap between continental masses [Kerr, 1980; Oakey, 1994]. Central to the development of this model was the identification of the continent ocean boundaries (COB) and magnetic isochrons. To achieve a better fit between the continental plates when the North Atlantic was fully closed, Roest and Srivastava [1989] updated their original kinematic model by interpreting the COB at the shelf break near the shorelines for both sides of the Labrador Sea, so that the magnetic isochrons were continuous through isochron 33 (77 Ma).

While these modifications did minimize continental overlap at closure, the implied motions for northwestern Greenland were not completely consistent with topographic lineaments [Oakey, 1994] and small scale tectonic structures [Lepvrier et al., 1996]. These studies found evidence for oblique-slip motion between Greenland and Ellesmere Island from 59 to 55 Ma (isochrons 25 to 24) as well as convergent motion between these land masses from 55 to 36 Ma (isochrons 24 to 13), which was consistent with the motions implied by the kinematic models. However, no evidence for a counterclockwise motion for Greenland at about 84 Ma was found as had been suggested by the kinematic models.

These difficulties limit the overall feasibility of the kinematic model and require that it be amended to account for local features within the Labrador Sea, as well as best fit the continental plates. A clearer picture of these features along profiles and at specific points is offered by seismic surveys and borehole measurements. These data indicate that regions that have been reinterpreted in the kinematic model as oceanic crust starting at the revised COB and containing magnetic isochrons 33 to 27 may instead be either extended continental crust [Chalmers and Laursen, 1995; Nielsen et al., 1997] or transitional crust [Chian et al., 1995a; 1995b; Chian and Louden, 1994].

Chalmers and Laursen [1995] characterized these regions, which start about 100 km off the Greenland coast and are about 150 km wide, by grabens and half-grabens that are typical of an extensional environment. They focused on the edge closest to the spreading center axis and determined that oceanic crust first began at isochron 27 (ca. 63 Ma) and that regions closer to the Greenland shoreline are magnetically and seismically best modeled by extended and intruded igneous crust. These regions are largely amagmatic but grade into synrift volcanism further northwards in the Davis Strait [Gohl and Smithson, 1993].

A geographically adjacent profile and its Labrador Shelf counterpart were also seismically examined [Chian and Louden, 1994; Chian et al., 1995a; 1995b]. The R2 profile extends perpendicular to the Greenland coast through the middle of the study area. For the R2 profile, Chian and Louden [1994] theorized that a lower crustal delamination surface accounted for an extremely thin ($\sim$ 2 km) crustal section about 100 km offshore of Greenland. They also discovered an anomalous high velocity zone approximately 150 km offshore, which they inferred to be a serpentinized mantle diapir that had originated at the time of rifting. Modeling of passive boundaries [Brun and Beslier, 1996] suggests that this zone may have been derived from the exhumation of mantle rocks from beneath the continental crust as it was thinned and separated. Chian and Louden [1994] partitioned the offshore region into a zone of continental crust that included the region of thinned crust, a zone of transitional crust above the serpentinized diapir, and a zone of oceanic crust starting with magnetic isochron 27.

Chian et al. [1995a; 1995b] used a conjugate profile on the Labrador margin in addition to a profile on the Greenland margin. They focused on the analysis of the zones of transitional crust running 350 km along both the Greenland and Labrador margins and proposed two possible origins for these zones. One possibility was a slow rate of rifting of continental crust, which would produce limited synrift melting and volcanism [Bown and White, 1995; 1994; Reid and Jackson, 1981]. Spreading rates greater than 20 km/Ma would produce mantle upwelling and heating with nearly simultaneous volcanism [White and McKenzie, 1989] as the melt moved directly upwards when spreading started. For rates less than 20 km/Ma, little or no synrift volcanism is predicted. Another possibility was the tectonic thinning of oceanic crust at a slow rate of seafloor spreading [Louden et al., 1995]. Initial seafloor spreading rates would generate crust of normal thickness that was later thinned by block faulting. This faulting resulted when the rate of crustal production at the spreading center became insufficient to keep up with the rate of plate separation.

They also proposed two theories for the rifting between Greenland and Labrador based on the two possible origins for the transitional crust. The first theory, based upon a continental origin for the crust, proposed the creation of rifting by simple shearing when the Labrador underplate delaminated from the Greenland overplate. The low-velocity upper-layer was attributed to block-faulted continental rocks, while the high-velocity lower-layer was attributed to continued necking of the lithosphere and serpentinization of mantle rocks as the Labrador Sea opened, thereby creating an extensive and serpentinized mantle layer beneath the shallow crustal layer.

Their second theory suggested that both the low-velocity upper-layer and high-velocity lower-layer of the crust were purely of oceanic origin with the crust being generated during the separation of Greenland. They suggested very low spreading rates (6 mm/a) to explain the low generation of crust during the period of 78 Ma (isochron 33) through 63 Ma (isochron 27), after which normal production of oceanic crust began (15 mm/a). The low rate of extension resulted in the generation of very thin crust [Bown and White, 1995] with an extensive shallow mantle that became serpentinized.

For both theories, slow extension (∼1 mm/a) was required from about 130 to 78 Ma when the assymetric break up began. This is also consistent with the results of Hinz et al. [1979], which noted this and two other periods of basin subsidence. The first started at about 84 Ma and slowed down at about 44 Ma. Subsidence continued at slower rates until about 36 Ma, when the second and ongoing period of subsidence began. They further noted two episodes of volcanism. Drilling on the Labrador Shelf suggested that the first occurred between ca. 140 and 130 Ma, while the occurrences of terrestrial volcanics suggested that the second volcanic episode occurred during the Paleocene (ca. 63 Ma).

Balkwill [1987] studied the sedimentary deposits in the basins along the western edge of the Labrador Sea and concluded that a period of intra-cratonic rifting occurred from about 134 to 88 Ma, followed by drifting possibly related to oceanic spreading from 88 to 36 Ma, and massive subsidence from 36 Ma to the present. The large northwest trending half-grabens were determined from sediment ages to have been generated during the intra-cratonic phase. These faults were later re-activated at about 40 Ma, possibly as a part of slight crustal extension.

While these seismic surveys and borehole measurements provide excellent local control, they do not offer a sufficient framework to interpret the regional picture. The gap in data coverage between the profiles limits the interpretation of geologic features. Additionally, these models do not address the origin of the magnetic isochrons 31 and 33 that Srivastava and Roest [1995] used to suggest that this region contained oceanic crust. However, models of the gravity-derived Moho depths and possible lithologies and structure were developed in Chapters 3 and 4, respectively, that do address both regional and local features. These models were developed from regional potential field and elevation data, but they also were constrained by the inclusion of localized information on Moho depth estimates and geologic structure and composition.

5.3 Regional Modeling

A gravity-derived model for the Moho was determined in Chapter 3 using seismic profiles [Chian & Louden, 1994; Chian & Louden, 1992; Dahl-Jehnsen et al., 1998; Fechner & Jokat, 1996; Gregersen et al., 1988; Jackson & Reid, 1994; Reid & Jackson, 1997] as constraints. Free-air gravity anomalies (FAGA) from the National Imagery and Mapping Agency were combined with the terrain gravity effects for the integrated mass variations of the bedrock surface, and water and ice thicknesses to determine a regional Moho (Figure 5.2) using spectral correlation modeling. This Moho model was estimated by inversion using Gaussian Legendre Quadrature integration [von Frese, 1980] and assuming the Airy hypothesis of crustal isostasy. The Moho depths were estimated iteratively whereby differences with seismic depth estimates were progressively minimized to achieve a best fit between the regional model and the profiles.

The Moho depth and adjusted crustal density models determined in Chapter 3 were examined for the 150 km wide zone off southwestern Greenland and found to be inconsistent with the assumptions of oceanic origin by Srivastava and Tapscott [1986]. This region contained high densities (> 3.00 gm/cm^3) and a deep Moho root more related to a serpentinized mantle diapir or lower continental rocks [Bott, 1995a; Chian and Louden, 1994].

This region was further examined in Chapter 4, where correlative magnetic anomalies (MA) [Verhoef et al., 1996] and FAGA [Brozena, 1995; Forsberg and Kenyon, 1995] along with geologic features of Greenland's margin yielded new insight on the crust beneath the masking cover of sea water [Chapter 4]. The geologic features in Figure 5.3 for the Labrador Sea are also consistent with the data obtained by the seismic transects. Regions characterized by correlative FAGA and MA maxima are depicted with the ++ in Figure 5.3. They include the continental gneisses of the South Greenland Archean and the Ketilidian provinces. Additionally, the region of transitional crust containing possibly serpentinized mantle rocks [Chian and Louden, 1994] is also characterized by correlative FAGA and MA maxima. The shallow Moho root beneath the rifted-continental crust is characterized by correlative FAGA maxima and MA minima (+- in Figure 5.3), which is also consistent with a shallow seated mantle.

Figures 5.4 and 4.27 shows zones of shallow crustal root along the southwestern coast that are flanked by deeper roots. Deeper crust is suggested under the South Greenland Archean Gneisses and the Ketilidian province in southwestern Greenland. This crust thins rapidly to depths of 10 - 12 km just parallel to the coast and then thickens to depths of 12 - 20 km further seaward. Crustal thickness is about 12 - 20

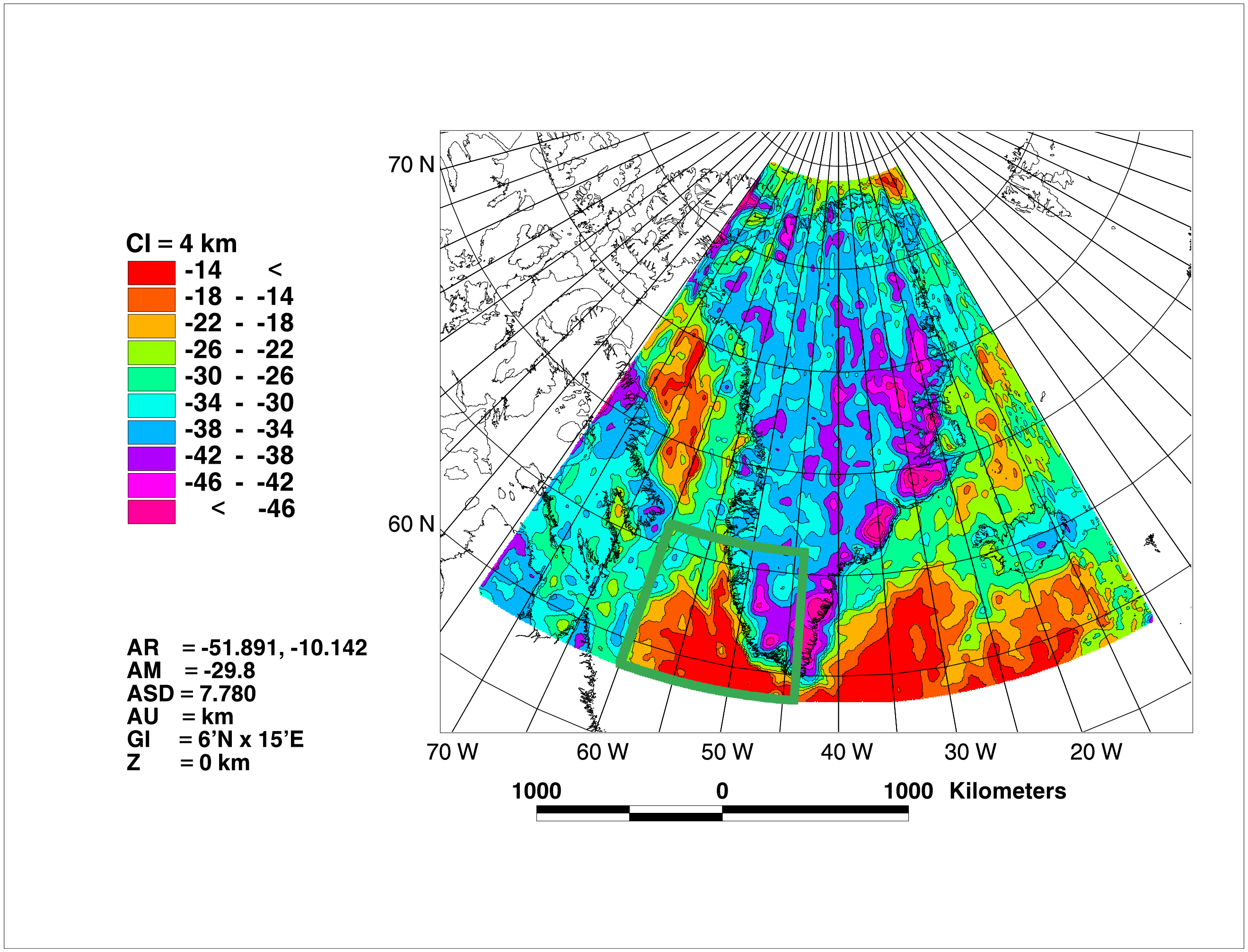

Figure 5.2: Moho model for the Greenland area estimated from the spectral correlation modeling of FAGA and the terrain gravity effects for integrated mass variations defined by the bedrock surface, and water and ice thicknesses. The area is shown in a Lambert Equal-Area Azimuthal Projection centered on 40° W. The green box delineates the study area. Note the deeper roots subparallel to the coast an extending northwards through the Davis Strait region.

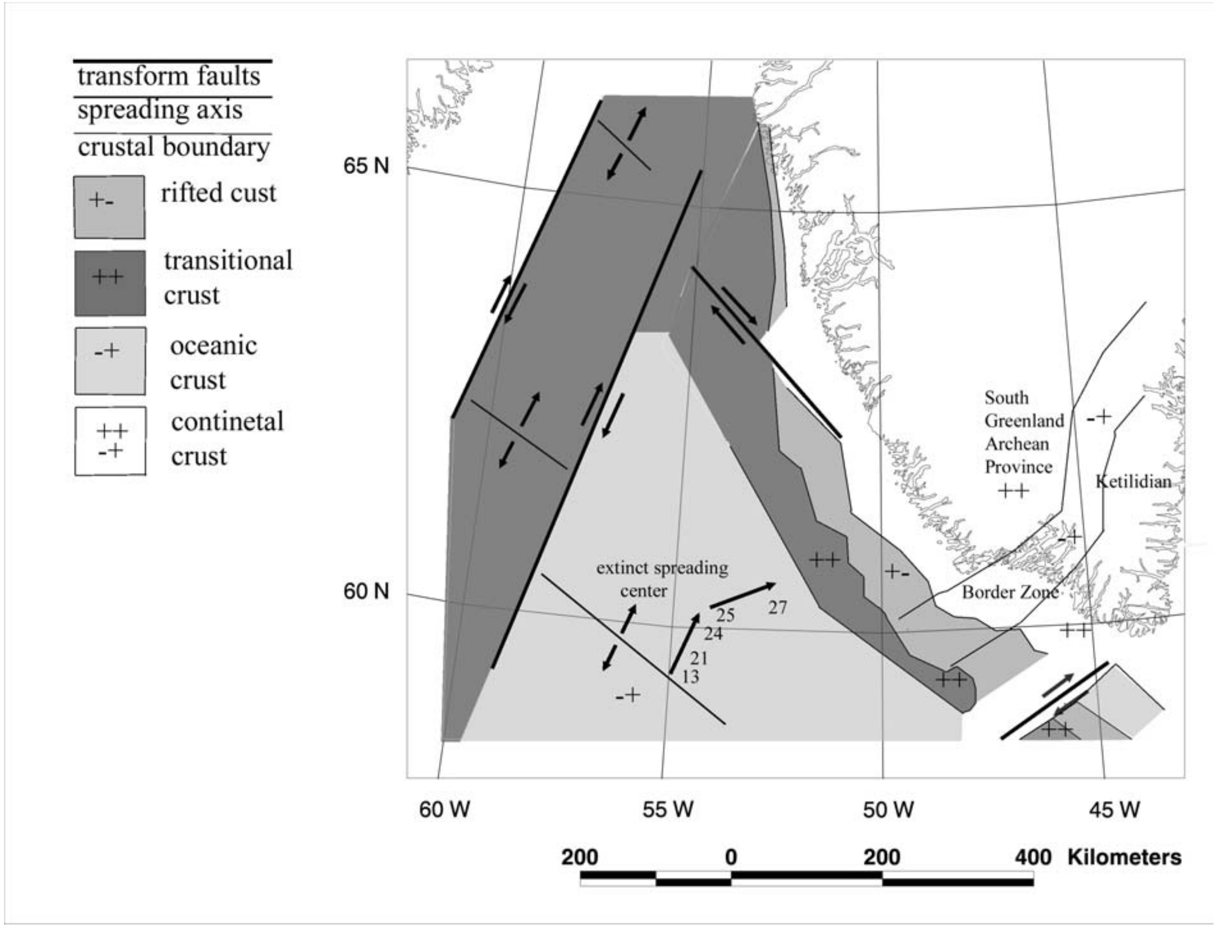

Figure 5.3: Geologic features for southwestern Greenland in a Lambert Equal-Area Azimuthal Projection centered on 50.5° W and at 62.4° N. Continental, rifted, transitional, and oceanic zones from Figure 5.4 are shown along with spreading centers and transforms faults. These features were determined partially from the Moho predictions (Figure 5.4) and by the distribution of correlative free-air gravity and magnetic anomalies [Chapter 4]. The numbers and arrows extending away from the extinct spreading ridge generally mark the positions of magnetic isochrons that are subparallel to the spreading center. Transitional and continental crust are both thickened, while oceanic and rifted-continental crust are both thin.

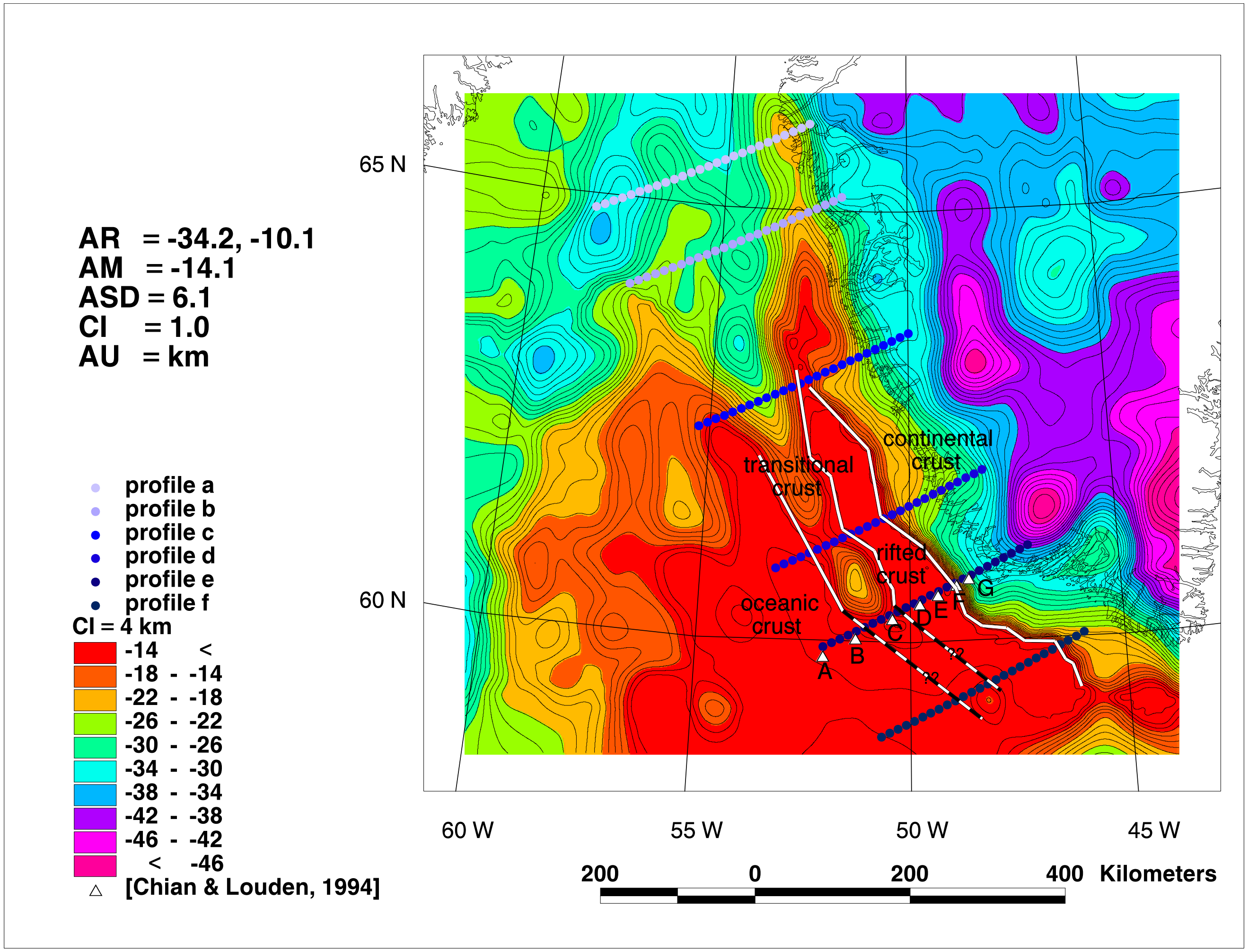

Figure 5.4: Moho model for southwestern Greenland in a Lambert Equal-Area Azimuthal Projection centered on 50.5° W and at 62.4° N. White triangles indicate the seismic survey points of the R2 profile from Chian and Louden [1994]. White lines delineate the boundaries between the oceanic, transitional, rifted continental, and continental crust.

km in the Labrador Sea area, but thickens considerably and shows greater variability in the Davis Strait area.

The results from both Chapters 3 and 4 were consistent with those presented by Chian and Louden [1994] along there R2 seismic depth profile. This profile is shown in Figure 5.4 by the white triangles overlain on the subset Moho depth model, which covers the region delineated by the box in Figure 5.2. The R2 profile and values interpolated from Figure 5.4 are presented in Figure 5.5. The two profiles are highly correlated (CC=0.95) with the R2 profile having greater amplitudes. Moho undulations are not as well resolved in the interpolated geopotential data, because they are derived from analyses of more regional geopotential fields.

The high velocity zone that Chian and Louden [1994] suggested may reflect serpentinized mantle material is located near point D in Figure 5.5. The steep rise just to the right of it is the location determined for the anomalously shallow Moho root. These same features are generally evident in the geopotential data.

Chian and Louden [1994] interpreted their R2 profile for three crustal regions. The continental crust of Greenland graded into a region of transitional crust and then into oceanic crust. In Chapter 3, their zone of transitional crust were further subdivided into two distinct regions containing purely transitional crust and rifted-continental crust. The consequent four crustal zones are 1) continental, 2) rifted-continental, 3) transitional, and 4) oceanic. The origin and significance of these zones will now be examined for the broader Labrador Sea region and adjacent areas.

In the following sections, the models determined from the FAGA and MA data sets will be combined with the seismic and borehole data to determine a possible alternative to the kinematic model for the evolution of crust in the Labrador Sea area [Srivastava and Tapscott, 1986; Roest and Srivastava, 1989]. This effort will attempt to incorporate the results of the seismic surveys while conforming as much as possible

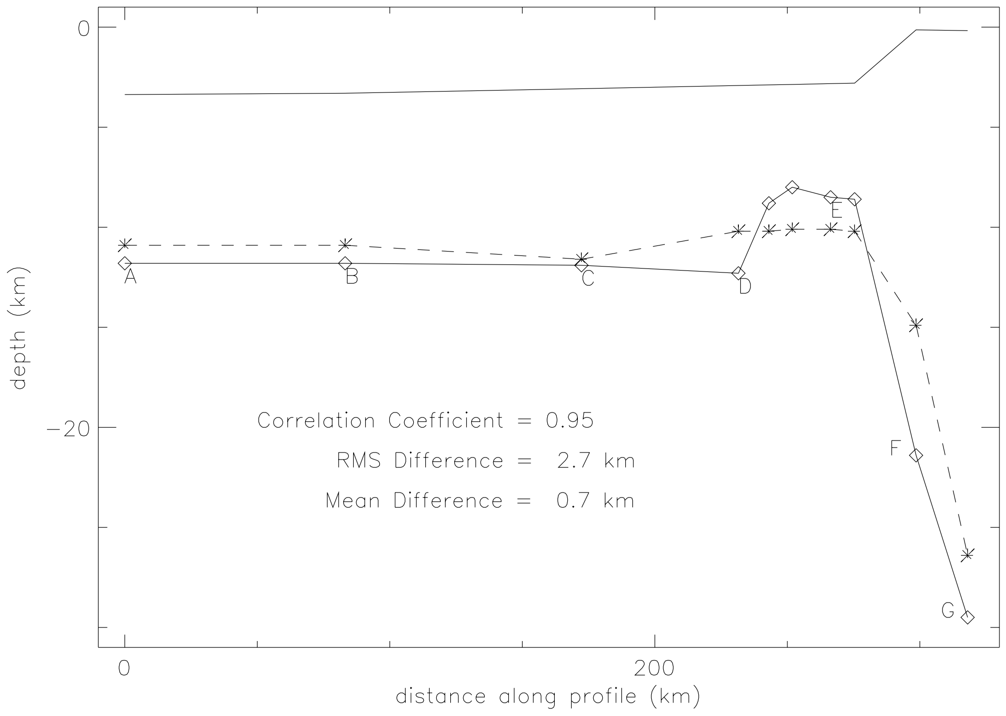

Figure 5.5: Comparison between the R2 profile of Chian and Louden [1994] (diamonds) and a coincident Moho profile interpolated from Figure 5.4 (asterisks) across southwestern coast of Greenland. Upper solid line shows the ocean bottom. Letters refer to seismic stations from Chian and Louden [1994]. The high velocity zone that Chian and Louden [1994] suggested may reflect serpentinized mantle material is located near point D. The steep rise just to the right of D reflects the anomalously shallow Moho root. This feature is also reflected in the interpolated profile but not as sharply defined.

the kinematically determined motions of Greenland and other tectonic models for the Arctic region [Kerr, 1980; NRC, 1993; Grantz et al., 1998].

5.4 Crustal Modeling and Analysis

Typical passive boundaries consist of continental crust grading into transitional crust and then into oceanic crust [Chalmers and Laursen, 1995; Dehlinger, 1978]. In the study region, however, an added zone of rifted-continental crust seems to be present. Based upon the orientation of the contacts between the continental & rifted-continental crust and the rifted-continental & transitional crust, a rotational extension is assumed for the formation of the rifted-continental crust. This region narrows northward in Figure 5.2 suggesting that this extensional feature originated from a rotation point near Ellesmere Island. Kerr [1980] also suggested a rotational opening for the region based on an analysis of regional extensional and compressional features. He determined a first order pivot point also located at the southern tip of Ellesmere Island.

This rotation is in contrast to the marked ENE-WSW linear extension indicated by isochrons 27 - 25 and the NE-SW linear extension indicated by isochrons 24 - 21 and associated transform faults. The change in oceanic spreading direction between isochrons 25 and 24 appears to be consistent with a major change in plate motions at about 56 Ma [Srivastava and Tapscott, 1986; Roest and Srivastava, 1989]. Although relatively weak due to deceased crustal production, the presence of isochrons 20 through 13 indicate a northwesterly motion, which is consistent with the motions implied by the kinematic model [Srivastava and Tapscott, 1986; Roest and Srivastava, 1989]. Hence, it is unlikely that the rotational extension that caused the rifted-continental crust is unlikely to have originated between isochrons 27 to 13. Since

Greenland probably moved with North America since isochron 13 (ca. 36 Ma), this rotation must have occurred before isochron 27 (63 Ma).

Evidence from isochrons situated near the Julianhaab Fracture Zone in the southern Greenland margin (Figures refgeomap) also indicate that the rifted-continental crust pre-dates the first oceanic crust that is at least 63 Ma (isochron 27) in age [Chapter 3; Escher and Pulvertaft, 1995].

Further north in Figure 5.4, a northwest trending fault offsets the rifted-continental crust at about 63°N and 53°W. This fault appears to be either a right-lateral transform fault or a northeast dipping normal fault or half-graben [Escher and Pulvertaft, 1995]. Balkwill [1987] suggested that a regional NE-SW tension between 134 and 88 Ma may have produced large northwest-trending half-grabens throughout the Labrador Basin. Assuming this feature is a half-graben formed during that extensional environment, then the rifted-continental crust that it cuts across can be dated as older than 88 Ma and may even be as old as 135 Ma. The formation of this crust would clearly predate the formation of oceanic crust in the region.

This timing may possibly link the opening of the Labrador Sea and Canada Basin. Grantz et al. [1998] also proposed a rotational opening for the Canada Basin between 135 and 115 Ma. The supercontinent of Pangea had begun to break up at about 190 Ma into Laurasia and Gondwana [Smith et al., 1994]. By about 130 Ma, Laurasia began to break up with rifting and eventual seafloor spreading occurring in the northern North Atlantic and the Arctic Oceans [Srivastava and Tapscott, 1986]. The earliest onset of rifting (and therefore tension) and crustal extension occurred in the Labrador region at about 130 Ma. This timeframe is consistent with the formation of the Canada Basin in the Arctic Ocean as revealed by stratigraphic and geophysical evidence [Grantz et al., 1998]. The opening of the Canada Basin occurred between about 135 and 115 Ma as a 50° rotation about the McKenzie Delta. As shown

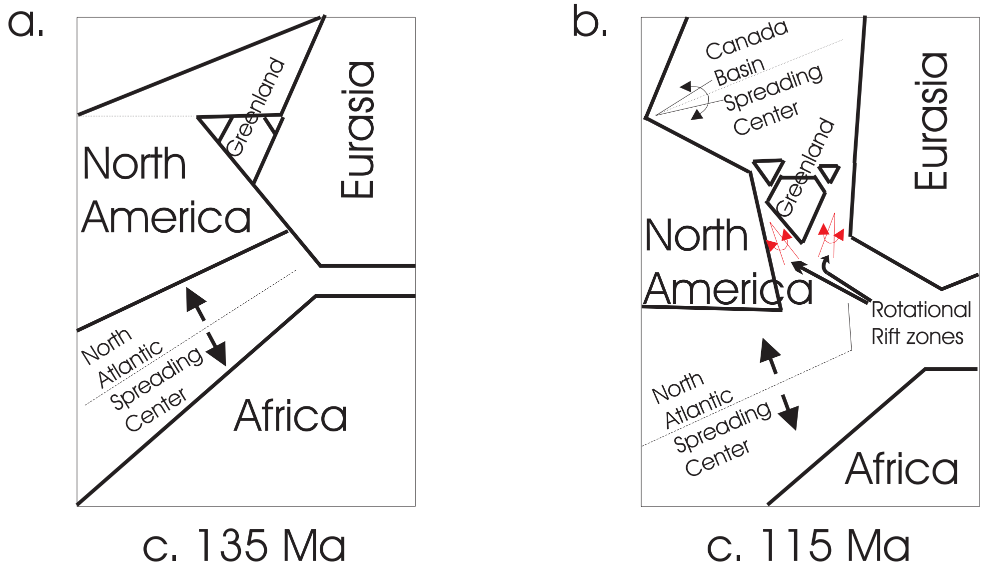

Figure 5.6: Rotational Rift Model for Laurasia. Panel **a.** shows the possible orientation of the Laurasian subplates and the African plate at about 135 Ma just prior to the rotational opening of the Canada Basin proposed by Grantz et al. [1998]. Panel **b.** shows the post-opening positions of the subplates. The clockwise rotation of northeastern North America would induce counterclockwise extension in the Labrador Sea and Rockall Trough regions. The continental crust between the older and thicker cratons may have thinned and rifted in rotational tensioning of the crust. The first order pivot point suggested in by the rifted-continental crust is located just south of Ellesmere Island.

in Figure 5.6, this crustal extension This could have induces a clockwise rotation into northeastern North America, Greenland, and the Eurasian landmass attached to Greenland.

In Figure 5.6, the clockwise rotation implied by the Canada Basin opening would introduce crustal tension in the northeast portion of North America (Greenland) where it was joined with Eurasia. Thus slow extension for the Labrador Sea region would result from the opening of the Canada Basin by rotational extension. These results are also consistent with paleostress models determined for this timeframe in the region [Faure et al., 1996; Lepvrier et al., 1996; Balkwill, 1987].

The Canada Basin was perhaps completely opened by 115 Ma before the beginning of the Cretaceous quiet period [Grantz et al., 1998], which would have ended the crustal extension. However, at approximately this same time, the North Atlantic rift zone began to dominate lithospheric dynamics for the Labrador Sea region [Myrhe et al., 1992]. This rift system propagated very slowly into the North American craton and may have acted upon continental crust previously weakened by the passage of the Madiera and Canary Island hotspots at about 200 Ma [Morgan, 1983].

Additionally, the rifting rate can be calculated based on the 20 Ma interval and the amount of delamination and crustal thickness determined from the Moho depth model (Figure 5.4) and the model presented in Chian et al. [1995a; 1995b]. From these models, approximately 200 km of extension possibly occurred within the rifted-continental on both margins assuming an original thickness of 34 km. This would indicate a 1.1 cm/a (220 km/ 20 Ma) rate of rifting in the locality of the R2 profile in the middle of the study area, which has been suggested by Bown and White [1995] as being insufficient to generate synrift volcanism.

Ernst [1998] suggested the presence of another plumehead under Ellesmere Island at about 95 Ma. Transition of this hotspot under Greenland to central and eastern Greenland is predicted by several models [Lawver and Müller, 1994; Morgan, 1981; Brozena, 1995]. Magma flows generated from this hotspot as it advanced under Greenland would have been controlled by Moho relief. By about 60 Ma, the hotspot was closer to the east coast than the west. Hence, the magma flowing into the triple junction created by the North Atlantic rift system south of Greenland may have been slowly have been choked off along the Labrador Sea fork and completely stopped by 36 Ma (isochron 13).

The plate motions indicated for Greenland then include a counterclockwise extension concurrent with the opening of the Canada Basin (ca. 130-115 Ma). This extension possibly exhumed mantle material from beneath the Greenland coastline and serpentinized the leading edge [Brun and Beslier, 1996; O'Hanley, 1996; Chian and Louden, 1994]. This would be followed by an initial ENE-WSW extension where transitional crust was created during rifting with the first oceanic crust having been created at about 63 Ma (isochron 27). Initiation of the Reykjanes Ridge spreading center would have resulted in a more northeasterly motion for Greenland and development of oblique spreading at the Labrador Sea spreading center and along the Nares Strait. After about 50 Ma (isochron 20), the Labrador Sea spreading center was slowly choked off from the magma supply of the Iceland hotspot by the deepened continental crust of Greenland. A more northwestern motion for Greenland resulted then, generating the compressional phase of the Eurekan Orogeny.

The generation of a possible serpentinized mantle diapir during the initial rotational rifting would account for a magnetic lineation that was weak and sub-parallel to the coast line at about the location assigned to isochron 33 by Srivastava and Roest [1989]. The serpentinization that may have occurred to the mantle material at the rupture where oceanic crust began to be generated would account also parallel the coastline and would account for isochron 31 determined by Srivastava and Roest [1995].

5.5 New Regional Tectonic Model

In view of the above results and discussion, the following revised tectonic model for the study region may be posed. The Greenland area formed one of the oldest and thickest parts of the Laurasian craton that had joined North America to the Eurasian landmass during the Caledonian Orogen at about 500 Ma [Friend et al., 1996; Nutman et al., 1996; Chian and Louden, 1992 Pedersen et al., 1989]. Then the

Canada Basin opened from about 135 to 115 Ma by pivoting around the McKenzie Delta [Grantz et al., 1998; Jackson et al., 1995].

This opening induced a counter-clockwise rotation of Greenland (Figure 5.6) and a slow rotational extension ($\sim$1 mm/a) to the northeast-southwest in the Labrador Sea region [Balkwill, 1987; Faure et al., 1996]. This slow rotation did not appear to produce significant geologic features in Ellesmere or Axel Heiberg Islands [Oakey, 1994; Lepvrier et al. 1996], but did produce a wide thin zone of thin rifted-continental crust between Greenland and Labrador [Chian and Louden, 1994; Chian et al., 1995a; 1995b]. This zone is characterized by listric faulting at the surface [Chalmers and Laursen, 1995] and a delamination within the lower crust. Synrift volcanism accompanied the initial stages (ca. 130 Ma) of this extension [Hinz et al., 1979; Srivastava and Tapscott, 1986].

When opening of the Canada Basin was completed, the North Atlantic rift system and the Iceland hotspot became dominant tectonic forces in the region. At about 95 Ma, rifting associated with the opening of the North Atlantic began in the southern regions of the Labrador Sea in accordance with the kinematic model of Srivastava & Tapscott [1986] and Roest & Srivastava [1989]. At about 88 Ma, basin subsidence increased significantly, marking an increase in the extension to the ENE-WSW.

Also at about 95 Ma, a hotspot was situated under Ellesmere Island [Ernst and Buchan, 1998; Brozena, 1995; Morgan; Jackson et al., 1986]. Chemical similarities between the rocks of the Alpha Ridge and the Iceland Ridge suggested that the ridges may have been derived from the same hotspot [Jackson et al., 1986; Sweeney and Weber, 1986; Vogt et al., 1982; Weber, 1987]. Several theories [Morgan, 1981; Lawver and Müller, 1994; Brozena, 1995; Nadin et al., 1997] have been put forth for the wanderings of the hotspot beneath central Greenland at about 63 Ma and to the east coast of Greenland at about 50 Ma. As the hotspot moved closer to the east coast, this affected the likely path of the magma to the surface.

For example, the hot spot may have formed a secondary plumehead with magma being funneled [Anderson, 1998; King and Anderson, 1995; Sleep, 1997] along the base of the interior Greenland crust to the thinner continental edges at Diskó Island at about 63 Ma [White and McKenzie, 1989; Nielsen et al, 1998; Hinz et al., 1979; Gohl and Smithson, 1993]. Volcanic underplating apparently did not occur in the Labrador Sea region [Chian and Louden, 1992; 1994], due possibly to the influence of the Moho that altered the flow of magma from the center of the plumehead away from the Labrador Sea region [Nielsen et al., 1997]. Examination of Figure 5.4 shows that the crustal roots under southern Greenland are deep (30+ km) and may have screened the region from a hotspot source located under central Greenland. Thus, the hotspot could not have provided a direct supply of magma to create the Labrador spreading center but could have provided a minimal supply to continue to produce oceanic crust.

The region had already been extended and thinned during the opening of the Canada Basin possibly resulting in exhumed and serpentinized mantle material at the inner edge of the transitional crust. A rupture occurred at 63 Ma (isochron 27) possibly along a line of weakness near the eastern edge of the basin caused by the passage of an earlier hotspot [Morgan, 1983]. The initial rupture possibly produced the outer magnetic lineation as upwelling mantle material became partially serpentinized and formed the base of the transitional crust [Brun and Beslier, 1996; O'Hanley, 1996]. This zone of serpentinized mantle is sub-parallel to the coast about 200 km offshore of southwestern Greenland [Chian and Louden, 1994; Chian et al., 1995a; 1995b] to just under the shoreline in western Greenland [Gohl and Smithson, 1993]. Some synrift volcanism [Hinz et al., 1979] developed during the initial rifting but subsided when

ENE-WSW seafloor spreading initiated forming oceanic crust containing isochron 27 [Chian and Louden, 1994; Chalmers and Laursen, 1995]. This separation may have caused the initial oblique movement of the Eurekan Orogeny when Greenland moved past Ellesmere Island along the Nares Strait [Oakey, 1994; Lepvrier et al., 1996].

At about 56 Ma (isochron 24), the relative location of the hotspot beneath Greenland had shifted sufficiently to the east that the secondary plume at Diskó began to become inactive and another in the Scoresby Sund region was initiated [White and McKenzie, 1989]. At this time, the motion between Greenland and North America changed as the Lomonosov Ridge separated from the Eurasian Basin and seafloor spreading developed in the Greenland and Norwegian Seas [Srivastava and Tapscott, 1986; Vogt, 1986]. Extension in the Greenland and Norwegian Seas eventually rifted the Rockall-Hutton Bank from southeastern Greenland [Dahl-Jensen et al., 1998; Toft and Arkani-Hamed, 1993; Hauser et al., 1995; Holbrook et al., 1998] and began forming the Reykjanes Ridge.

This ridge along with the Labrador spreading axis formed a triple junction just south of Greenland. The eastern branch of this triple junction then formed a continuous spreading axis for the North Atlantic from south of the Charlie Gibbs Fracture Zone to the Arctic Ocean. Greenland's direction of motion changed to the north and resulted in increasingly oblique movement along the Nares Strait. This oblique motion was reflected in a parallel direction of isochron emplacement in the Labrador Sea and transform fault development.

After about 50 Ma (isochron 21), the Icelandic hotspot was probably under the Scoresby Sund region of Greenland [Nadin et al., 1997] and actively developing the Greenland-Scotland Ridge [Srivastava and Tapscott, 1986]. Greenland began to move to the northwest and initiated the compressional phase of the Eurekan Orogeny in Ellesmere Island [Oakey, 1994; Lepvrier et al., 1996].

The magma flow to the Labrador spreading center began to shut down when the Icelandic hotspot moved offshore of the eastern coast of Greenland. The deep crustal roots of the South Greenland Archean province acted to slow the production of oceanic crust to slower than the separation of the plates such that extension began to thin the oceanic crust by block rotation [Louden et al., 1997]. Eventually by 36 Ma (isochron 13), production completely halted and Greenland began to move with North America [Srivastava and Tapscott, 1986].

5.6 Conclusions

Tectonic models of the Labrador Sea were examined to reconcile local geological and geophysical data with the origin and evolution of the Labrador Sea region. These models and the seismic data indicate the presence of 4 zones along the coast related to rifting and oceanic spreading. These zones include continental, rifted-continental, transitional, and oceanic crust that were generated between 135 and 36 Ma.

In particular, the seismic data across the continental margin of southwestern Greenland into the Labrador Sea indicate changes from deep Moho under the continental terrain, to extremely thinned and shallow rifted continental crust, then to deeper transitional crust which thins again as oceanic crust. The model presented here indicates that the zone of rifted-continental crust was generated by rotational extension related to the opening of the Canada Basin from 135 to 115 Ma and not by the North Atlantic rift system at 84 Ma. These extensional forces were derived from slow but steady extension and rotation of the interior of Laurasia.

This rotation of the Greenland sub-plate accounts for some of the separation that occurred between Labrador and Greenland. The remaining motion may reflect the generation of transitional crust and later oceanic crust after 63 Ma (isochron 27) when the Iceland hotspot possibly contributed magma.

The realignment of continents that occurred at 63 Ma (isochron 24) created a triple junction between the North Atlantic, Labrador, and Reykjanes spreading centers. It also resulted in a 50° change in the direction of Greenland's movement from the ENE to the NE with respect to the Labrador spreading center. The movement of Greenland over the hot spot after about 50 Ma (isochron 21) resulted in a greater supply of magma to the Reykjanes spreading center and the eventual termination by 36 Ma (isochron 13) of spreading in the Labrador Sea.