Rift Tectonics of the Eastern Canadian Continental Margin: Insights from Detrital Petrology and Provenance*

David J.W. Piper[1], Georgia Pe-Piper[2], and Yuanyuan Zhang[2]

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[1] Geological Survey of Canada, Natural Resources Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada (dpiper@nrcan.gc.ca)
[2] Department of Geology, Saint Mary's University, Halifax, Nova Scotia, B3H 3C3, Canada

Abstract

Studies of detrital petrology of sedimentary basins can provide unexpected details of hinterland tectonics in complex rift settings, such as the eastern Canadian continental margin. This study demonstrates how Triassic-Jurassic fault patterns controlling sedimentation in the Scotian Basin were overprinted by the effects of Western Europe-Newfoundland rifting in the Early Cretaceous. Major sand supply in the Scotian Basin was the result of uplift of the Labrador rift shoulder in the Late Jurassic and Early Cretaceous. Deformation of the northern Appalachians by northeast-trending strike-slip faults created Lower Cretaceous Chaswood Formation basins on land and uplifted horsts that rapidly shed sediment. These faults were reactivated Late Paleozoic structures sub-parallel to the extension direction of the evolving rift between Ireland-Iberia and the Newfoundland margin. With the onset of seafloor spreading by the Early Albian along the entire rift segment, deformation of Chaswood basins ended and the principal sand supply to the Scotian Basin was from the Labrador rift shoulder.

Introduction

Detrital petrology has long been used to track grand tectonic events: the movement of plates and the uplift of mountain belts. Detailed petrographic studies can also, commonly serendipitously, provide quite detailed information about the evolution of fault patterns and horst uplift in rift-related basins that can be used to strengthen the interpretation of detrital supply and basin evolution. This study summarizes work that contributes to understanding the rifting processes of the North Atlantic Ocean from both currently ongoing and very recently completed detrital petrology studies in the Scotian Basin and adjacent terrestrial areas of eastern Canada.

Methods

Samples were taken from conventional core from Triassic to Cretaceous sandstones and mudrocks of the Scotian Basin (Figure 1). Conventional core was used to avoid contamination problems associated with cuttings. Three major groups of analyses were completed. Technical details of these analyses have been provided in Open File reports and in some cases recent journal articles: the emphasis here is on the tectonic significance of the results.

(a) Mineralogical studies of bulk rocks. A first-order understanding of sandstones was obtained from studies of thin sections; more detail on heavy minerals (which may strongly influence bulk chemistry) was obtained from heavy mineral separates. Where possible, variably automated SEM technology was used for varietal mineral identification. Both sandstones and mudrocks were analysed by X-ray diffraction, principally to identify clay minerals.

(b) Chemical studies of bulk rocks. More than 400 bulk-rock analyses of major and trace elements and 50 analyses of Sm-Nd isotopes were made. Principal component analysis was used to explore data sets; hypotheses were tested mostly by examining covariance of small groups of elements. Trace element composition may be strongly influenced by minor mineral components and bulk composition is modified by diagenesis. Chemical composition represents total drainage basin area more completely than do studies of individual minerals.

(c) Detailed characterization of individual minerals. The geochronology of individual grains of zircon, monazite and muscovite were determined, although some grains may be polycyclic (particularly in the case of zircon) and the same grains were characterized chemically. Many other mineral grains provided useful information if characterized chemically. Interpretation of mineral chemistry is limited by the availability of comparative data from potential bedrock sources. Quartz is the principal framework grain in sandstones and several provenance types were distinguished on the basis of hot-cathode cathodoluminescence (CL) response and optical petrographic character. Feldspar was characterized chemically and by its CL response. Lithic clasts were identified optically or from backscattered electron (BSE) images and, if fine-grained, their bulk geochemistry was determined using a defocused electron microprobe beam.

Integration of first-cycle mineral geochronology, which can be quite specific as to provenance, with other mineralogical and chemical data has allowed the provenance significance of particular minerals or chemical elements to be interpreted. In this way, characteristic mineral and chemical signatures have been defined for sources such as the Meguma Terrane and the Long Range of western Newfoundland.

Examples

1) Triassic-Early Jurassic Rifting of the Scotian Basin

Late Triassic rifting of the central Atlantic Ocean reactivated the Minas Fault Zone, a crustal-scale east-west strike-slip fault zone formed in the Late Carboniferous during the Alleghanian collision of Africa with North America. Thick Triassic deposits accumulated in the Fundy Graben and Orpheus Graben (Figure 2a), bounded by the Minas Fault Zone. Sedimentation continued in the Fundy Graben in the Early Jurassic, proven to be as young as Pliensbachian and inferred as young as Aalenian (Wade et al., 1996). Triassic rift-basin sediments are also known beneath the Scotian Shelf, where a widespread evaporitic halite succession accumulated. However, the Early Jurassic is represented by a hiatus in all suitable wells with good biostratigraphy in the Scotian Basin including in the Orpheus Graben (Figure 2b). Only by Middle Jurassic did sedimentation resume in those parts of the Scotian Basin that underlie the present Scotian Shelf, represented by Iroquois Formation carbonates and clastic rocks of the Mohican Formation (Figure 2c).

Detrital petrology, including the chemistry of indicator minerals such as tourmaline and garnet, from the three wells with conventional core in the Mohican Formation was recently studied by Li et al. (2012). In the Mohican I-100 well, detrital minerals are those characteristic of first cycle supply from the Meguma terrane and evidence of minerals derived from more inboard Appalachian terranes is lacking. In the Wyandot E-53 and MicMac H-86 wells, sandstones also have an exclusive Meguma terrane source, but the proportion of stable heavy minerals is higher, indicating a lower proportion of first-cycle minerals. This suggests that the source was from the Lower Carboniferous Horton Group, which was in turn sourced from the Meguma Terrane. The Canso Ridge in the Meguma Terrane, bounding the south side of the Orpheus Graben, is not a sufficiently large source area to supply these two wells with sediment. Wells in the western Orpheus Graben have a mid-Jurassic hiatus and it appears that sediment supply was across both the western Orpheus Graben and Canso Ridge. The implication is that at this time, the Minas Fault Zone was not an active tectonic element.

Previous studies may have overlooked the evidence that the southwest Grand Banks transform fault continued linearly across the North Step of MacLean and Wade (1992) at the western end of the Burin Platform, through the structurally complex zone C of Pascucci et al. (2000) in the Carboniferous Sydney Basin, and along discontinuities in aeromagnetic data (Loncarevic et al., 1989) that extend to off Cape Ray in southwest Newfoundland. A river along such a lineament in the Triassic to Jurassic would account for the great thickness of Mohican Formation beneath St. Pierre Bank (MacLean and Wade, 1992) and the lack of far-travelled detritus in the Wyandot E-53 and MicMac H-86 wells. At the same time, the continuation of subsidence of the Fundy Graben well into the Jurassic would have diverted any sediment supply from Maine or New Brunswick into the Fundy Graben and its outlet west of mainland Nova Scotia. The Minas Fault Zone was not an active lineament in the Early to Middle Jurassic of the Scotian Basin.

2) Late Jurassic to Mid-Cretaceous (Albian) Basement Faulting in the Scotian Basin

Rapid progradation of thick sands in the Sable Sub-basin of the Scotian Basin is characteristic of the Tithonian-Albian and began in the Late Kimmeridgian in the Venture Field. Geochronology of detrital zircons (Piper et al., 2012) and monazite (unpublished) shows that these sands include rare fresh Paleoproterozoic zircons and monazite, indicating sediment supply from outside the Appalachians and Grenville Province. The most likely source is the Makkovik Province on an inferred rising Labrador rift shoulder, where the first recorded basin sediments and basalt are of Valanginian age (Dickie et al., 2011). The Tithonian is also the time when clastic detritus from Newfoundland first reached the Jeanne d’Arc basin as the Grand Banks began to rift from Iberia. The Chaswood Formation is a syn-tectonic, predominantly fluvial succession preserved in fault-bound outliers in southern New Brunswick and Nova Scotia. The oldest biostratigraphic determinations are Valanginian. However, fault-related uplift in the Appalachians likely also dates from the Tithonian, as fresh first-cycle Paleozoic and Neoproterozoic zircon and monazite in Tithonian sandstones of the Scotian Basin implies significant bedrock sources from the Appalachians. Indeed, the abundance of Neoproterozoic grains from the Avalon terrane is particularly distinctive in the Tithonian.

Detrital sediment supply to the Scotian Basin in the Valanginian remained similar to the Tithonian, although an increase in Cr in mudstones may indicate more sediment supply from western Newfoundland ophiolites. By the Hauterivian-Barremian, detrital muscovite suggests proportionally greater supply of sediment from the Meguma Terrane and scatter in those trace elements found in heavy minerals in sandstones is greater, implying a greater proportion of first-cycle supply of heavy minerals.

In the Aptian, widespread slowly accumulating shales in the Scotian Basin imply that uplift of the Meguma Terrane along a reactivated Minas Fault Zone blocked the rivers that supplied sediment to the basin through Cabot Strait. Reactivation of the Minas Fault Zone is also indicated by localization of Aptian volcanism on Scatarie Bank, on the northern side of the Minas Fault Zone and on other centres to the east identified from magnetic anomalies (Bowman et al., 2012).

The abrupt change at the base of the Albian Cree Member to sand-prone sedimentation in the Scotian Basin marks several important changes. Abundant sand supply was restored to the Scotian Basin through the Cabot Strait and detrital petrology shows that the sand supply was in part eroded from the volcanoes on the northeast margin of the basin. In the eastern Scotian Basin, mineral geochronology shows that sediment supply was overwhelmingly from Labrador, probably implying renewed uplift of the Labrador rift shoulder. Dickie et al. (2011) noted a top-Aptian unconformity in the Labrador rift basins that may be correlative with such uplift. In the central part of the Scotian Basin, detrital mineral geochronology suggests similar sources to the Hauterivian-Barremian, but with a lower proportion of Meguma Terrane muscovite and a higher proportion of fresh Meso- and Paleoproterozoic zircons from Labrador. In addition, the crystallinity of detrital illite/muscovite is higher, as is the proportion of high-grade metamorphic quartz identified by CL methods. All this suggests a greater proportion of supply from Labrador than from the Appalachians.

The main supply of sediment to the Scotian Basin was from a river (the “Sable River”) that flowed through Cabot Strait towards Sable Island. However, detrital petrology shows that the eastern part of the Scotian Basin, in the Abenaki Subbasin, was supplied by a different river (the “Banquereau River”), also flowing through Cabot Strait, but with differences in provenance that persisted throughout the Early Cretaceous. The differences between the Sable and Banquereau rivers are seen in age and textural type of zircons and the modal abundance of varietal heavy minerals (Tsikouras et al., 2011). The Banquereau River had many similarities in source with the Sable River, including the same range of first-cycle Mesoproterozoic and Paleoproterozoic igneous zircons and similar varietal types of chromite (Tsikouras et al., 2011). The zircons indicate fluvial access to the Long Range and to Labrador as far north as the Makkovik Province. The chromites indicate a common source in the ophiolites of western Newfoundland and sediments derived therefrom. The persistence of two distinct rivers for tens of millions of years is most readily accounted for if the Banquereau River occupied the northeast-trending, fault-bound Humber Valley in western Newfoundland. The Humber Fault (Figure 3) extends northeastwards offshore to intersect the Makkovik Province. If the drainage were any farther east, fresh Paleozoic zircons should be much more abundant (Lowe et al., 2011) in the eastern Scotian Basin. If the drainage were any further west, then it is difficult to understand why the Banquereau and Sable rivers did not at times join.

All the major outliers of the Chaswood Formation are developed along northeast-trending faults, many of which have deformed the Lower Chaswood Formation in a manner suggestive of dextral strike-slip motion (e.g. Gobeil et al., 2006), creating a series of horsts and graben. Using detrital muscovite geochronology to match deposits to potential sources suggests that Chaswood rivers in central Nova Scotia flowed southwestward along northeast-trending faults (Reynolds et al., 2010). Basement faults on the Scotian Shelf that were demonstrably active in the Early Cretaceous trend northeast (Pe-Piper and Piper, 2012). Together with the evidence for the Banquereau River in the Humber fault zone, northeast-trending strike-slip faults, many reactivating older Late Devonian-Early Carboniferous structures, appear to be the dominant cause of graben subsidence and associated basement uplift in the Early Cretaceous. In the Chaswood Formation, many Valanginian-Barremian sequences are folded or tilted, in some cases with progressive deformation, and unconformably overlain by Aptian-Albian sediments that are little or un-deformed. Thus the stratigraphic evidence is for principal deformation on the northeast-trending faults to be Valanginian-Barremian, with detrital petrology evidence that the deformation may have begun in the Tithonian. This period of deformation corresponds to the timing of extreme lithospheric extension between western Europe and the Newfoundland continental margin that culminated in sea-floor spreading and the creation of oceanic crust, with ocean crust dating from Barremian in the J-Anomaly Ridge in the south and Early Albian at Goban Spur and northwards to the Charlie Gibbs Fracture Zone. Thus the Chaswood deformation appears to have begun with the onset of rifting and ended with the onset of sea-floor spreading in the sector of the North Atlantic Ocean between the Grand Banks and Orphan Knoll. The dextral strike-slip fault direction was sub-parallel to the regional extensional direction.

Although the dominant deformation was taken up on northeast-trending faults, there was also renewed motion on the Minas Fault Zone. This is indicated by differential subsidence in Orpheus Graben, with tilting and erosion of the Canso Ridge throughout the Valanginian-Barremian that resulted in enhanced supply of Meguma Terrane sediments to the basin in the Hauterivian-Barremian, culminating in the blocking of southeastward-flowing rivers in the Aptian and their diversion to the Bay of Fundy. The Minas Fault Zone (Figure 3) was inactive throughout the Middle Jurassic, but the major crustal lineament was oriented so that it could take up some of the dextral strike-slip motion on the northeast-trending faults once extension started between Europe and Newfoundland in the Tithonian. Its orientation is such that it would tend to take up some local extension, indicated by the differential subsidence of the Orpheus Graben.

In the Albian, detrital petrology indicates principal sediment supply to the Scotian Basin from the Labrador rift shoulder, where sea-floor spreading had not yet begun. The lack of new deformation and uplift throughout the Appalachians led to a gradual reduction of sediment derived therefrom.

Conclusions

Studies of detrital petrology, mineralogy and geochemistry have provided new insights into the nature of hinterland faulting and uplift during continental rifting adjacent to the Scotian Basin preceding sea-floor spreading during the evolution of the North Atlantic Ocean. Although the Minas Fault Zone was important in localizing the Fundy and Orpheus grabens in the Triassic, it was probably inactive during the main Early Jurassic phase of rifting and clearly inactive during middle Jurassic sea-floor spreading.

Voluminous supply of sand to the Scotian Basin in the Tithonian and Early Cretaceous was a consequence of two tectonic processes: (a) uplift of the rift shoulder in Labrador, and (b) development of horsts and grabens throughout the Appalachians as a result of dextral strike-slip faulting parallel to the extension direction between the Newfoundland margin and western Europe. With the onset of seafloor spreading in the Early Albian, Appalachian faulting and uplift ceased and Albian sand supply was principally from Labrador.

Acknowledgements

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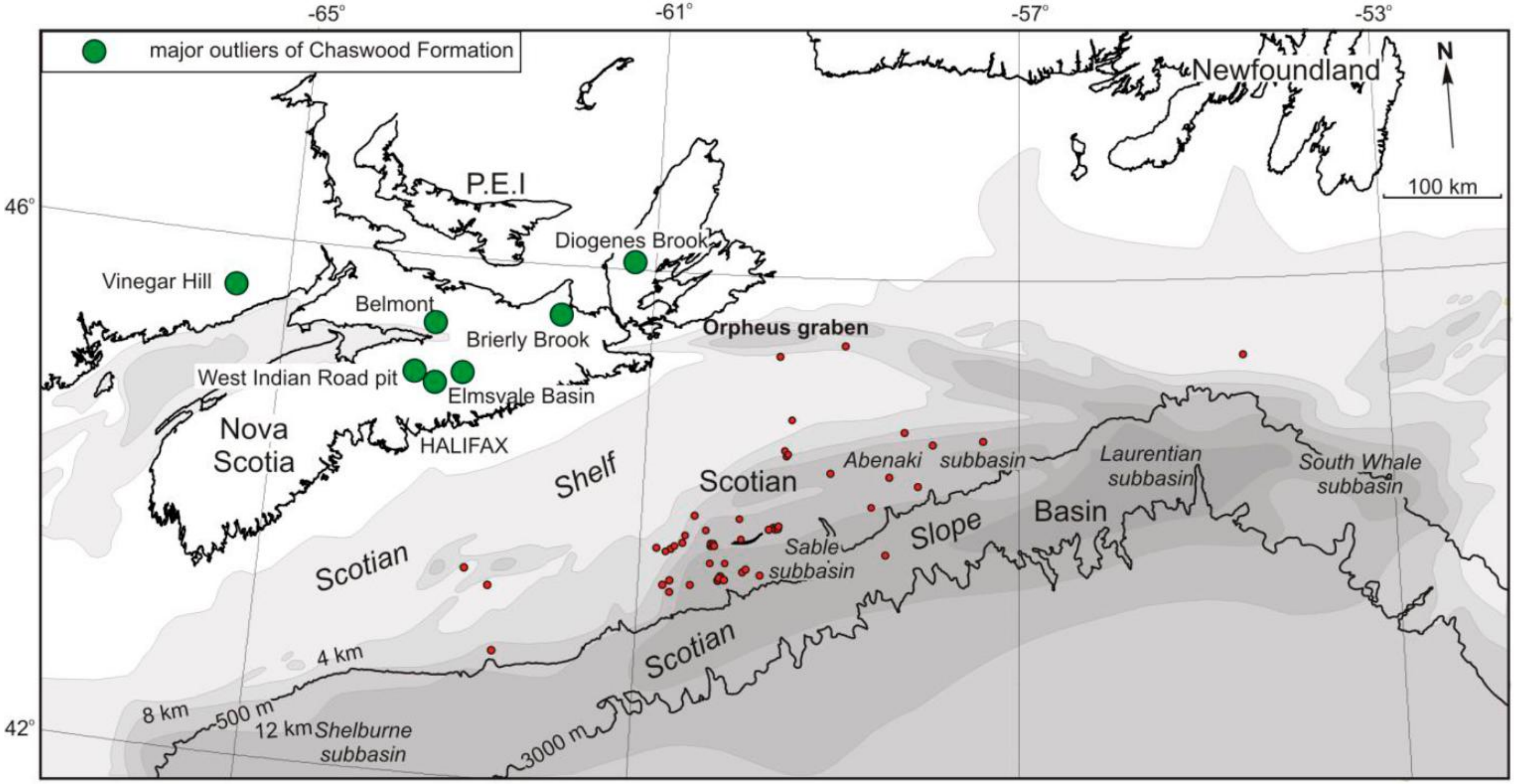

Figure 1. Map of Scotian Basin showing wells for which detrital petrology has been studied.

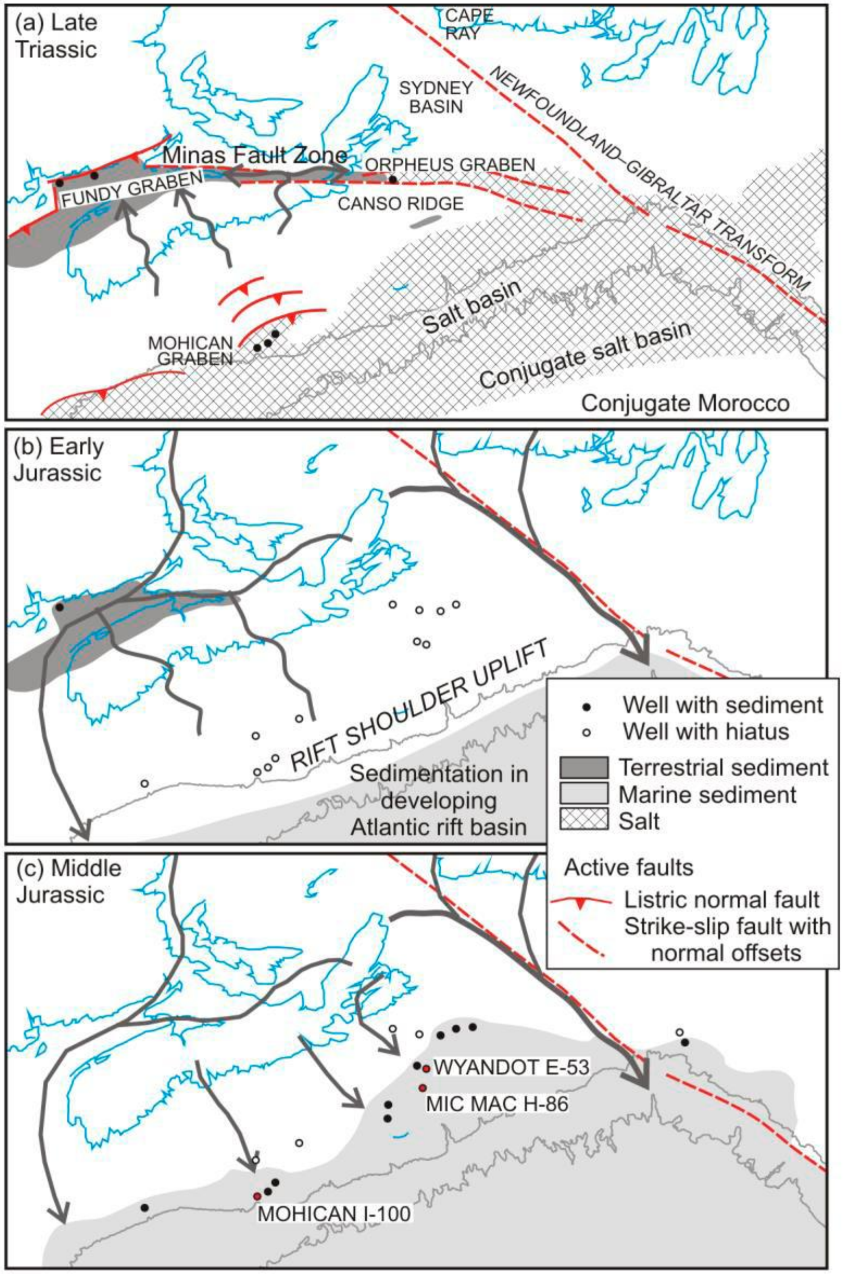

Figure 2. Inferred Late Triassic to Middle Jurassic tectonic evolution of the Scotian Basin (modified from Li et al., 2012).

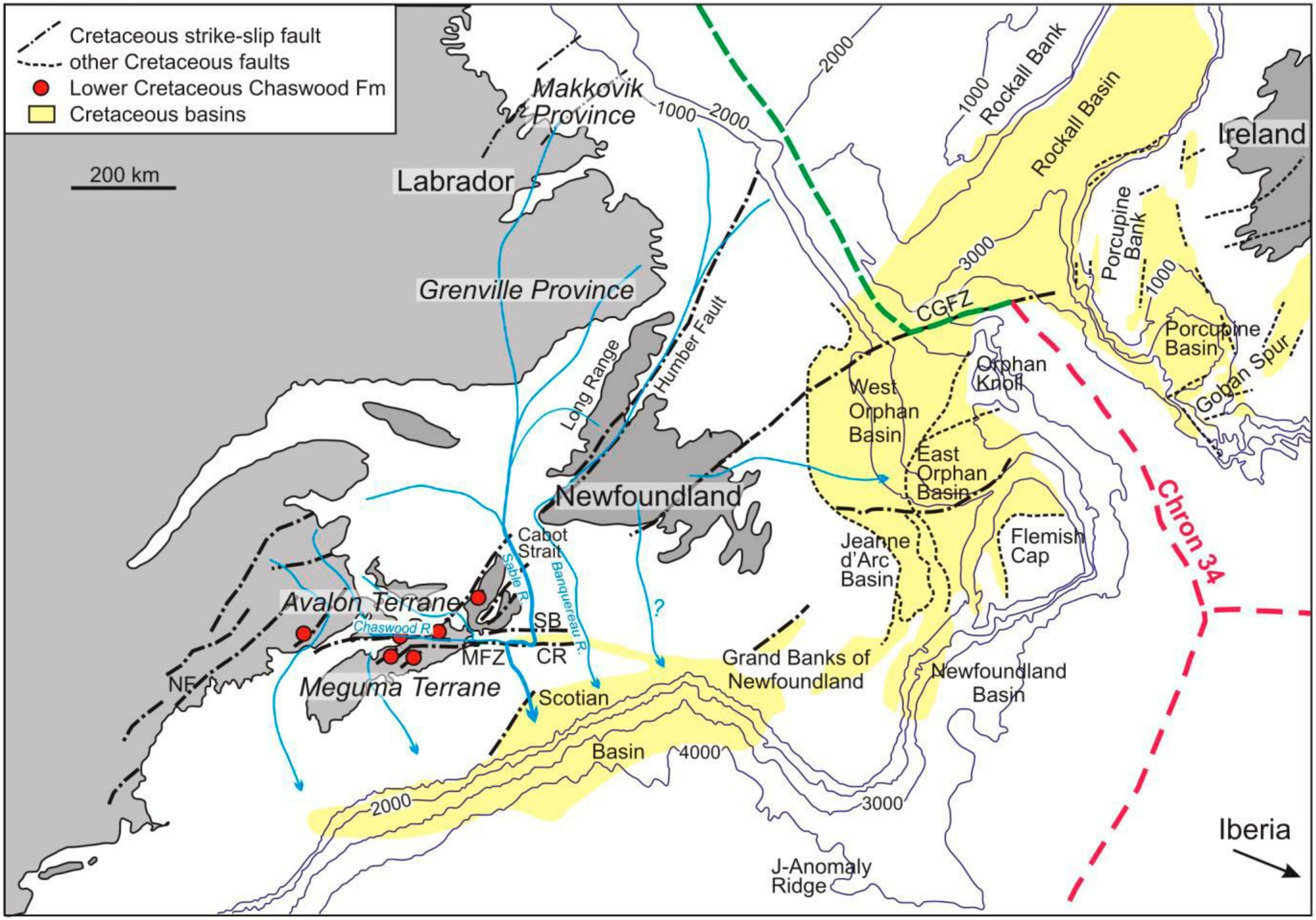

Figure 3. Paleogeographic reconstruction at Chron 34 (84 Ma, Santonian) modified from Welford et al. (2012) showing the inferred hinterland tectonics to the Scotian Basin. CR = Canso Ridge; NF = Norumbega Fault; MFZ = Minas Fault Zone; SB = Scatarie Bank.