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# Exhumation history and Early Cretaceous paleogeography of the Newfoundland margin revealed by detrital zircon U–Pb and fission-track studies of syn-rift Hibernia Formation strata

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ABSTRACT

Syn-rift strata in the Grand Banks of Atlantic Canada are the result of Late Triassic to Cretaceous extensional processes within the proximal domain of the Newfoundland margin. The precise timing of exhumation events in proximal domains and their significance to the stepwise, long-term development of magma-poor rift systems globally remains uncertain. We report new detrital zircon U–Pb ($n = 518$) and double-dating fission-track (FT) and U–Pb ($n = 269$) results from seven samples of syn-rift, Lower Cretaceous Hibernia Formation sandstone units from the Jeanne d'Arc basin to constrain the timing of proximal domain rift processes in the Grand Banks during the onset of hyperextension and outboard development of the necking and distal domains. Syn-depositional, Early Cretaceous U–Pb detrital zircon dates for Berriasian to Barremian strata of the Hibernia Formation indicate provenance from volcanic centers along the SW Grand Banks transform and are consistent with north-directed paleoflow into the southern Jeanne d'Arc basin. Hibernia Formation strata mostly yield Neoarchean to Paleozoic detrital zircon grains with Cryogenian to Paleozoic FT cooling populations that document the episodic exhumation of Appalachian basement and cover successions. The near-zero lag time between the ages of Early Cretaceous exhumation-related cooling and Berriasian to Barremian deposition are consistent with rapid exhumation along NNE-trending normal fault systems in the Avalon Uplift region and margins of the Jeanne d'Arc basin. Early Cretaceous FT cooling populations in Hibernia Formation strata support this rapid tectonic exhumation being coincident with the onset of hyperextension and mantle exhumation processes outboard of the Grand Banks and crustal breakup along SW Iberia that are more generally constrained by marine geophysical studies. Syn-rift strata in long-lived, proximal domain basins can therefore test the timing of exhumation processes that result from magma-poor rift development, including lithospheric thinning associated with the generation of outboard architectural elements.

## 1. Introduction

Passive continental margins result from extensional processes that affect the entire lithosphere and provide insights into the nature of continental rifting and breakup (e.g., McKenzie, 1978; Lister et al., 1986; Bradley, 2008). Although early continental rift models were based on instantaneous and uniform stretching (e.g., McKenzie, 1978), there is now consensus for non-plume-related rift development to include polyphase, depth-dependent stretching that is decoupled between lithospheric layers (e.g., Beaumont et al., 1982; Davis and Kusznir, 2004; Lavier and Manatschal, 2006; Huismans and Beaumont, 2011, 2014). Continental extension in polyphase rift scenarios takes place over 10s to >100 Myr and includes discrete modes of lithospheric stretching-thinning, hyperextension and mantle exhumation, and lithospheric breakup (e.g., Péron-Pinvidic and Manatschal, 2009). The full progression through these extensional modes results in margin-parallel architectural elements (proximal, necking, distal, outer, and oceanic domains) that collectively record continental margin development (e.g., Lavier and Manatschal, 2006; Péron-Pinvidic and Manatschal, 2009; Péron-Pinvidic et al., 2013; Huismans and Beaumont, 2014). The Newfoundland (SE Grand Banks)-Iberia conjugate margins (Fig. 1A) document the protracted breakup of supercontinent Pangea and opening

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of the North Atlantic Ocean and are used as the basis for most models of magma-poor rift evolution (e.g., Whitmarsh et al., 2001; Péron-Pinvidic et al., 2013; Sutra et al., 2013). Marine geophysical (e.g., Dean et al., 2000; Van Avendonk et al., 2006; Deemer et al., 2009; Welford et al., 2010, 2020; Pereira and Alves, 2011) and scientific drilling (e.g., Boillot et al., 1980; Müntener and Manatschal, 2006) results have been used to infer the timing of Triassic to Jurassic stretching and thinning (proximal and necking domains), Early to mid-Cretaceous hyperextension and mantle exhumation (distal domain), and mid-Cretaceous break-up-related (outer domain) events along the Newfoundland and Iberian

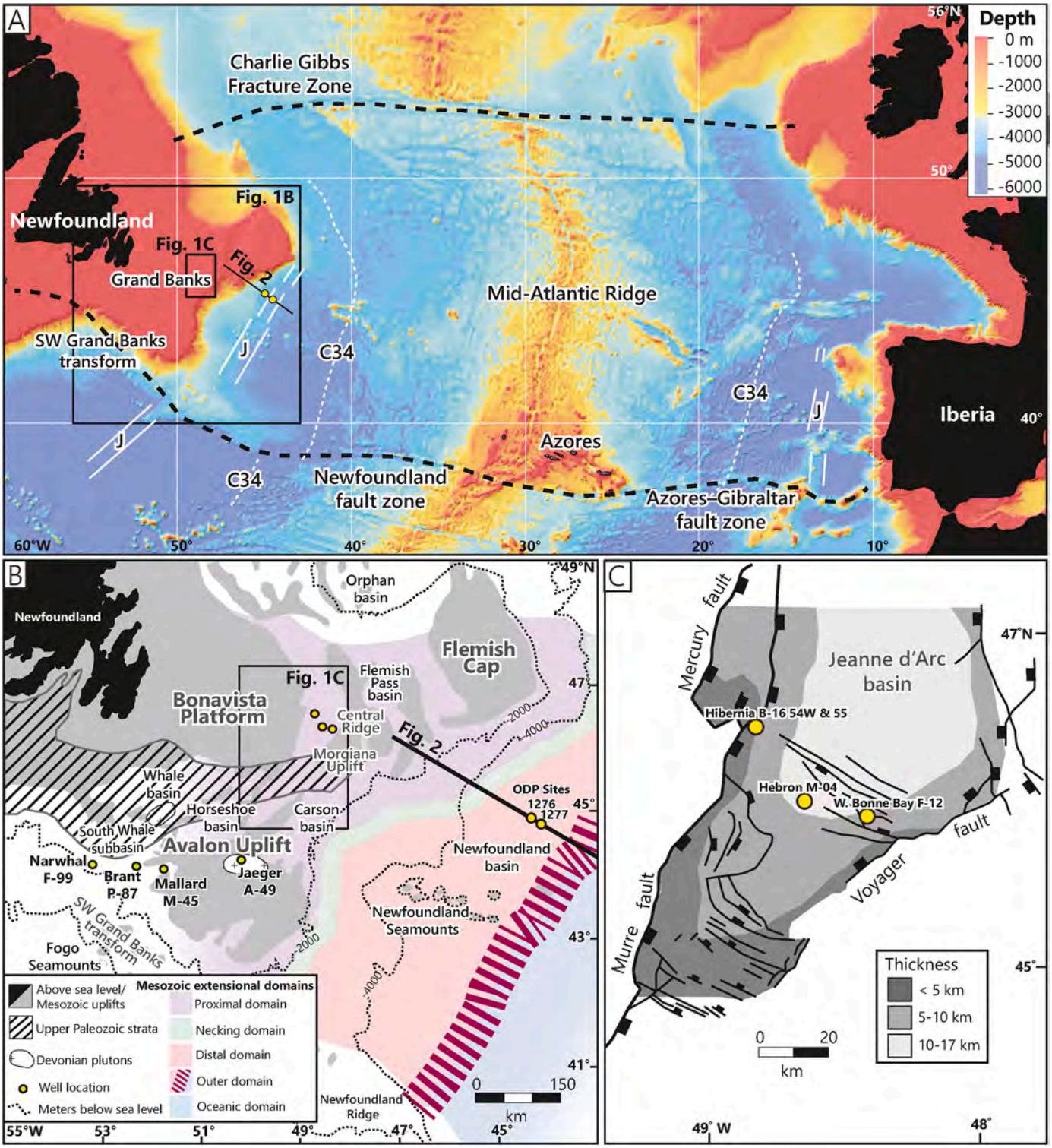


**Fig. 1.** (A) Bathymetric map of the southern North Atlantic Ocean and primary features of the Newfoundland-Iberia rift system compiled from Ryan et al. (2009) and Bronner et al. (2011). J anomaly is a linear magnetic anomaly associated with syn-to post-rift magmatism in the outer domain. C34 anomaly (~85 Ma) is the oldest undisputed seafloor spreading isochron in the modern oceanic domain. SW - Southwest. (B) Locations of Mesozoic architectural elements (Fig. 2), upper Paleozoic strata, and Devonian plutons after Grant and McAlpine (1990), Bell and Howie (1990) and Péron-Pinvidic et al. (2013). (C) Map of the southern Jeanne d'Arc basin showing sediment thickness, fault systems, and wells modified from Baur et al. (2009).

margins (Figs. 1B and 2; e.g., Pérez-Gussinyé and Reston, 2001; Bronner et al., 2011).

The Jeanne d'Arc basin (Fig. 1C) is an asymmetric graben in the proximal domain (Grand Banks) of the Newfoundland margin and contains up to 18 km of Upper Triassic to Upper Cretaceous strata that have been broadly correlated with rift and breakup episodes in the North Atlantic region (e.g., Enachescu, 1987; Sinclair, 1988; Hiscott et al., 1990a; Shannon et al., 1995; Tucholke et al., 2007; Alves and Cunha, 2018; Sandoval et al., 2019). However, the precise depositional age, provenance, and tectonic significance of proximal domain units with respect to coincident Late Jurassic to Cretaceous growth of outboard (necking, distal, outer) domains and Mesozoic paleodrainage evolution are uncertain (e.g., Hutter and Beranek, 2020; Beranek et al., 2022). This knowledge gap demonstrates the need for new studies that test the interconnected relationships between architectural elements during lithospheric extension and how they influence the source-to-sink evolution of magma-poor rift systems globally (e.g., Manatschal, 2004).

In this article, we present new detrital zircon U–Pb and fission-track double-dating results of the Hibernia Formation, an important Lower Cretaceous syn-rift unit that produces hydrocarbons in the Jeanne d'Arc basin (e.g., Sinclair et al., 1999), to test tectonic models for the Newfoundland margin, including predictions for proximal domain evolution during the onset of hyperextension and mantle exhumation in outboard architectural elements (e.g., Péron-Pinvidic et al., 2013; Sutra et al., 2013). Our results establish Berriasian to Barremian maximum depositional ages for Hibernia Formation strata near the Hibernia and Hebron oil fields and develop testable hypotheses for the Early Cretaceous paleogeography of the Grand Banks region, including north-directed drainage from the Avalon Uplift region into the Jeanne d'Arc basin that was coincident with the formation of the outboard necking and distal domains. Detrital zircon U–Pb and fission-track double-dating evidence for Early Cretaceous and older exhumation- and magmatic-cooling phases recorded by the Hibernia Formation reveal insights into the long-term thermal history of the Newfoundland margin and timing of regional exhumation in the proximal domain along the archetypal magma-poor rift system.

## 2. Geological background

### 2.1. North Atlantic rift evolution

Magma-poor rift systems are underlain by several margin-parallel architectural domains that have predictable geological elements and geophysical signatures worldwide (e.g., Péron-Pinvidic et al., 2013). In the southern North Atlantic Ocean, the Newfoundland and Iberian margins transition seaward from thick, undisturbed continental crust into proximal, necking, distal, outer, and oceanic domains that progressively developed during the Late Triassic to Late Cretaceous periods (Fig. 2; Péron-Pinvidic et al., 2013; Sutra et al., 2013). The Jeanne d'Arc basin, located in the Grand Banks of Newfoundland (proximal domain), records a polyphase subsidence history that resulted from episodic tectonism during the breakup of eastern North America, Africa, UK, Ireland, and Iberia (Sinclair, 1988; Tankard et al., 1989; Soares et al., 2012; Péron-Pinvidic et al., 2013; Sutra et al., 2013; Nirrengarten et al., 2018). The proximal domains of the Newfoundland-Iberia system initially formed by widely distributed, upper crustal extension that resulted in the formation of intracontinental rift basins, including the Jeanne d'Arc basin, over a vast region without significant thinning (Tucholke et al., 2007). Thermal subsidence and slow extensional motion between Newfoundland and Iberia (<2.0 cm/year) subsequently occurred during the Early Jurassic (Sinclair, 1988; Nirrengarten et al., 2018). The transition from decoupled to coupled deformation and early development of the necking domain at the outer edge of the Grand Banks began by the early Late Jurassic (e.g., Sutra and Manatschal, 2012). Renewed tectonic exhumation and subsidence in the Jeanne d'Arc basin and adjacent rift grabens at this time were accommodated by north-to northeast-trending normal faults (Sinclair, 1988; Tankard et al., 1989). The necking phase culminated with Early Cretaceous hyperextension and/or mantle exhumation episodes, which promoted the development of the distal domain and penetration of faults through the entire crust and mantle lithosphere (Fig. 2; e.g., Péron-Pinvidic et al., 2013). Berriasian and Hauterivian rift episodes recognized in the Jeanne d'Arc basin may correlate with the rupture of crust in the southern and northern parts of the Newfoundland-Iberia rift system, respectively (Srivastava et al., 2000; Tucholke et al., 2007; Dinis et al., 2008; Alves and Cunha, 2018; Nirrengarten et al., 2018).

Early to mid-Cretaceous exhumation of continental mantle lithosphere resulted in wide transition zones of serpentinized mafic-ultramafic rocks in the distal and outer domains prior to lithospheric breakup (Fig. 2; e.g., Welford et al., 2010; Péron-Pinvidic et al., 2013). The principal stress orientation shifted to a northeast-southwest direction by the mid-Cretaceous and drove dip-slip motion along transfer faults in the Jeanne d'Arc basin that previously accommodated strike-slip displacement (Tankard et al., 1989). Final lithospheric breakup between Newfoundland and Iberia occurred by the late Aptian (e.g., Tankard et al., 1989; Sutra et al., 2013; Eddy et al., 2017) and was in part triggered by a high-volume magmatic event in the outer domain, which is now a deep-water region that includes thickened crust and underplated, exhumed mantle lithosphere (Fig. 2; Bronner et al., 2011). This magmatic event had a long-lived and complicated history of syn-to post-breakup magmatism (Nirrengarten et al., 2018) and produced a large-magnitude, linear magnetic anomaly (J anomaly; Fig. 1A).

Lithospheric breakup and the onset of seafloor spreading in the southern North Atlantic Ocean likely began in the south near the Newfoundland-Azores-Gibraltar fracture zone and propagated northwards (e.g., Alves et al., 2006; Bronner et al., 2011; Alves and Cunha, 2018). The C34 anomaly (~85 Ma) represents the oceanward extent of the outer domain and is the oldest undisputed seafloor spreading isochron in the modern oceanic domain (Fig. 1A; Bronner et al., 2011). Syn- and post-breakup magmatism persisted in the outer domain until at least 70 Ma (e.g., Jagoutz et al., 2007; Nirrengarten et al., 2018). Lithospheric breakup in the proximal domain is manifested by an unconformity referred to as the U reflection, a prominent seismic reflector at the Aptian-Albian boundary in the Jeanne d'Arc basin and elsewhere (Tankard et al., 1989; Péron-Pinvidic et al., 2013; Sutra et al., 2013; Nirrengarten et al., 2018). Thermal subsidence dominated the Jeanne d'Arc basin after regional breakup-related uplift (e.g.,Soares et al., 2014) and extension in the adjacent Orphan basin (Sinclair, 1988; Tucholke et al., 2007).

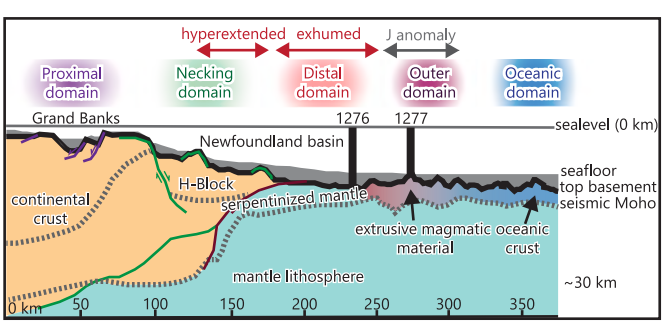


**Fig. 2.** Schematic cross-section of the Newfoundland margin with Mesozoic extensional elements after Péron-Pinvidic et al. (2013). Location of J anomaly from Bronner et al. (2011). Colored structures are associated with phases of rift development; purple = stretching (proximal domain), green = thinning (necking domain), red = exhumation (distal domain). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### 2.2. Newfoundland margin

The Newfoundland margin is mostly underlain by Proterozoic to Paleozoic rocks of the northern Appalachian orogen (e.g., Haworth and Lefort, 1979; King et al., 1986) that record the generation and accretion of arcs and microcontinents prior to the final Laurentia-Gondwana collision and assembly of supercontinent Pangea (e.g., van Staal and Barr, 2012). The Newfoundland Appalachians, including offshore sectors, from west to east include ancient Laurentian margin successions, peri-Laurentian arcs and ophiolite fragments, and the peri-Gondwanan Gander, Avalon, and Meguma terranes (Fig. 3; e.g., Williams, 1979; van Staal et al., 2021). Paleozoic tectonothermal events associated with the Taconic (500-450 Ma), Salinic (440-420 Ma), Acadian (420-400 Ma), Neoacadian (400-350 Ma), and Alleghenian (340-260 Ma) orogenies generated collision-related igneous suites and orogen-proximal basins that record Appalachian evolution (e.g., van Staal and Barr, 2012). Proterozoic to Paleozoic rocks in central and western Newfoundland yield Late Triassic zircon fission-track (Willner et al., 2019) and Jurassic and older apatite fission-track (Hendriks et al., 1993) ages, respectively, that are consistent with Mesozoic exhumation of Appalachian orogenic infrastructure (Fig. 3) and recycling of Appalachian basement and cover assemblages into the Jeanne d'Arc and related rift basins.

The Grand Banks of Newfoundland is a ~500 km-wide platform of submerged continental crust that in the Jeanne d'Arc basin region consists of Neoproterozoic (760-550 Ma) basement units assigned to the Avalon terrane or Avalonia, Cambrian to Ordovician (537-475 Ma) metasedimentary rocks and Late Devonian plutons assigned to the Meguma terrane, and upper Paleozoic terrestrial to marine strata (Maritimes basin and equivalents in Fig. 3) that originally covered the region (Bell and Howie, 1990; Tucholke et al., 2007; van Staal and Barr, 2012). The SW Grand Banks transform, which represents the southern boundary of the Newfoundland magma-poor rift margin, is part of a margin-normal, strike-slip fault system that transitions onshore into the Cobequid-Chedabucto or Minas fault zone in Nova Scotia (Fig. 3; Pe-Piper and Piper, 2004; Murphy et al., 2011). Although Late Jurassic to Cretaceous igneous rocks are only locally exposed in onshore regions of north-central Newfoundland (Peace et al., 2018) and western Portugal (Grange et al., 2008; Mata et al., 2015), offshore parts of the SW Grand Banks transform show extensive evidence for episodic syn-rift magmatism, including volcanic centers with mafic to felsic dikes, sills, and pyroclastic flows (e.g., Pe-Piper et al., 1994; Bowman et al., 2012). Upper Jurassic fluvial strata in the Jeanne d'Arc and Flemish Pass basins also yield ca. 160-145 Ma detrital zircon grains that indicate rift-related magmatism during necking domain development (Lowe et al., 2011; Hutter and Beranek, 2020; Beranek et al., 2022).

Triassic to Cretaceous syn-rift strata of the Grand Banks unconformably overlie upper Paleozoic and older rocks and filled several basins during North Atlantic rift evolution (e.g., Sinclair, 1988). Some syn-rift units are preserved on uplifted sediment ridges that now separate depocenters (e.g., Central Ridge, Morgiana Uplift; Enachescu, 1987, 1988). Periods of thermal subsidence alternated with extensional deformation and tectonic subsidence tied to the development of the proximal, necking, distal, and outer domain architectural elements (Fig. 4; e.g., Sinclair, 1988; Tankard et al., 1989; Tucholke et al., 2007). Late Jurassic to Early Cretaceous tectonic subsidence in the Jeanne d'Arc basin was episodic and evidenced by stacked depositional successions, intervening unconformities, and isopach-thickening toward extensional faults (Tankard et al., 1989; Shannon et al., 1995). Multiple erosional surfaces coalesce at the margins of the Jeanne d'Arc basin and represent the Avalon unconformity that records 50–60 Myr of rift-related deformation, uplift, and erosion (e.g., Grant and McAlpine, 1990).

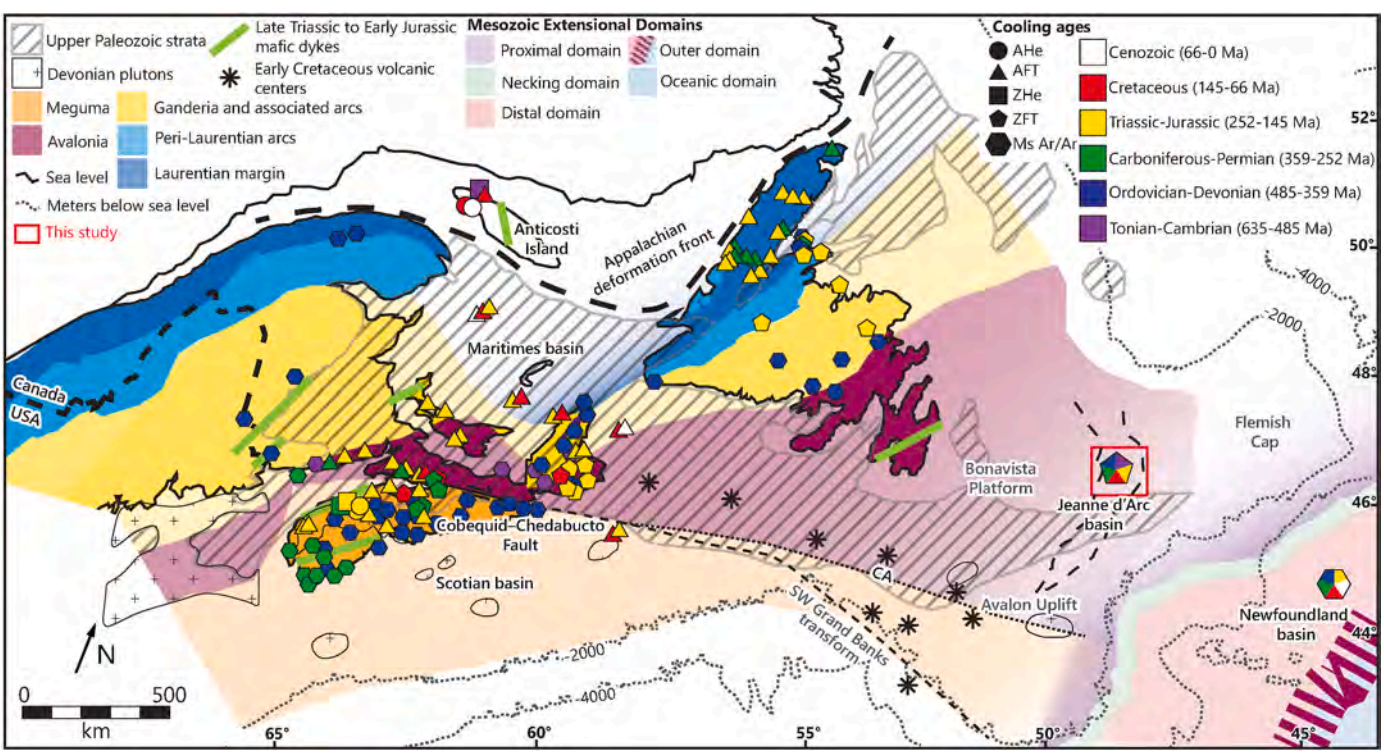


**Fig. 3.** Compiled muscovite $^{40}Ar/^{39}Ar$, zircon fission-track and (U–Th)/He, and apatite fission-track and (U–Th)/He ages from Cretaceous and older rocks in Atlantic Canada modified from Willner et al. (2019) and sources in Table 6. Tectonic map of northern Appalachians basement and early Paleozoic lithotectonic elements after van Staal and Barr (2012). Inferred extensions into offshore Nova Scotia and Newfoundland after Bell and Howie (1990). Early Triassic–Late Jurassic mafic dyke locations after Greenough (1995). Early Cretaceous volcanic centers from Bowman et al. (2012). SW - Southwest.

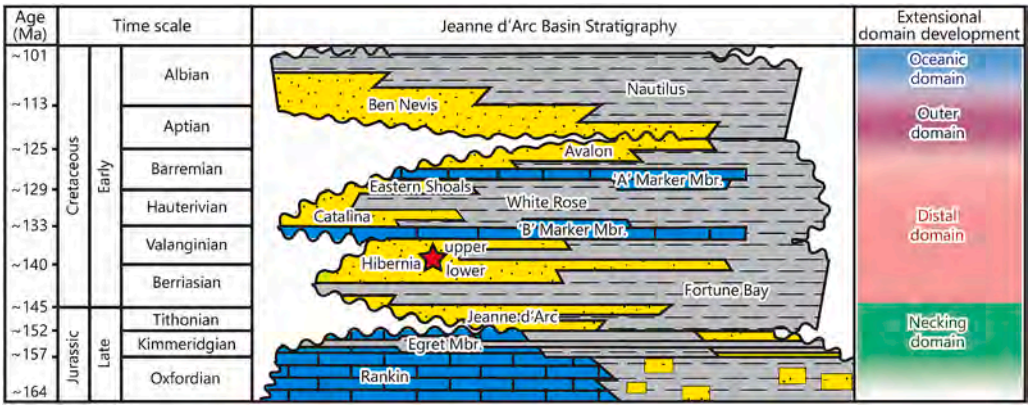


**Fig. 4.** Upper Jurassic to Lower Cretaceous stratigraphy of the Jeanne d'Arc basin compiled from Sinclair et al. (1992) and Hutter and Beranek (2020) using the geological timescale of Cohen et al. (2013, version 2022/2). Timing of extensional domain development between SW Grand Banks of Newfoundland and Iberia from Péron-Pinvidic et al. (2013). Sampled interval for this study (red star). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### 2.3. Hibernia Formation

Hibernia Formation strata have untested source-to-sink histories and geological connections with hyperextension and mantle exhumation processes that generated the necking and distal domains outboard of the Grand Banks (Fig. 4). Lower Cretaceous rock units in the Hibernia and Hebron oil fields mostly consist of nonmarine to shallow-marine strata (Tankard and Welsink, 1987; McAlpine, 1990; Sinclair et al., 1999) that contain palynomorphs, dinoflagellates, foraminifers, and ostracods with interpreted late Berriasian to Valanginian depositional ages (Ascoli, 1990; Williams et al., 1990). Regionally, Hibernia Formation strata superseded north-directed, Upper Jurassic syn-rift braided fluvial units with headwaters in the Avalon Uplift (Fig. 1B). The contact between Upper Jurassic and Lower Cretaceous strata is a disconformity that represents a brief hiatus across the Jeanne d'Arc basin (Tankard et al., 1989). Early Cretaceous rise of the Avalon Uplift to the south of the Jeanne d'Arc basin renewed the clastic source area and resulted in the northward progradation of Hibernia Formation deltaic successions (Sinclair, 1988; Tankard et al., 1989; Hiscott et al., 1990b). The lower unit of the Hibernia Formation is comprised of stacked fluvial channels in the southwest to delta-front bar facies and coastal deposits in the northeast (Sinclair, 1988; Hiscott et al., 1990b; McAlpine, 1990). The upper unit of the Hibernia Formation consists of fine-grained, shallow-marine sandstone and mudstone units that grade laterally into prodelta shale to the northwest (Hiscott et al., 1990a; McAlpine, 1990).

Lower Cretaceous sedimentary wedges in the Hibernia oil field area were deposited above rotated blocks during the growth of north-northeast-trending normal faults, including the listric Murre-Mercury fault that soles out in the mid-crust and represents the western boundary of the Jeanne d'Arc basin (Tankard and Welsink, 1987; Enachescu, 1988; Sinclair, 1988; Shannon et al., 1995; Sinclair et al., 1999). Northwest-trending transfer faults in the Jeanne d'Arc basin also accommodated Early Cretaceous tectonic subsidence and deposition of the Hibernia Formation (e.g., Tankard and Welsink, 1987).

Burial history curves for the Jeanne d'Arc basin show that Hibernia Formation strata are currently at their maximum depth (Williamson, 1992) and current borehole temperatures constrain the potential for post-depositional resetting of the zircon fission-track system. Borehole temperatures of 98–115 °C are reported in the Hebron oil field and adjacent areas (Hebron M-04 and West Bonne Bay F-12; Natural Resources Canada, 2019) and estimated ~120–125 °C in the Hibernia oil field (Hibernia B-16 55 and 54 W) using a geothermal gradient of 27 °C/km (Table 1). These borehole temperatures are below those required to thermally-reset the zircon fission-track system (~220–300°C; Tagami et al., 1998; Tagami, 2005) and zircon fission-track ages from Hibernia strata are interpreted to record original cooling of source rocks.

## 3. Methods & materials

### 3.1. Rock samples

Seven Hibernia Formation samples from the Hibernia B-16 55, Hibernia B-16 54 W, Hebron M-04, and West Bonne Bay F-12 wells were collected from the Canada-Newfoundland and Labrador Offshore Petroleum Board Core Storage and Research Centre in St. John's, Newfoundland and Labrador (Table 1, Fig. 5). These include two samples of the lower Hibernia Formation from the Hibernia oil field and five samples of the upper Hibernia Formation in the Hebron oil field and nearby areas. Each sample consisted of ~500 g of medium-to coarse-grained sandstone from full-diameter core. Zircon grains were isolated from the samples using standard mineral separation techniques of

**Table 1**
Location and lithological descriptions for Hibernia Formation detrital zircon samples.

| Sample | Well Name | Core - Box Numbers | Core Depth (mMD) | Approx. True Vertical Depth (mTVD) | Unit | Sample Description |
|---|---|---|---|---|---|---|
| 20EJ01 | West Bonne Bay F-12 | #1 - 110-113 | 4009–4013 | 3431 | Upper Hibernia | medium- to coarse-grained, subrounded to rounded, moderately-sorted, massive to normally graded, quartz arenite |
| 20EJ02 | West Bonne Bay F-12 | #1 - 92-96 | 3994–3998 | 3416 | Upper Hibernia | fine- to medium-grained, subrounded to rounded, well-sorted, massive to planar crossbedded, sublithic arenite |
| 20EJ03 | West Bonne Bay F-12 | #1 - 24-30 | 3941–3947 | 3364 | Upper Hibernia | fine- to medium-grained, subrounded to rounded, well-sorted, massive to planar crossbedded, sublithic arenite |
| 20EJ08 | Hebron M-04 | #3 - 37-42 | 3028–3037 | 3032 | Upper Hibernia | fine- to medium-grained, subrounded to rounded, well-sorted, massive to normally graded, sublithic arenite |
| 20EJ09 | Hebron M-04 | #3 - 26-33 | 3015–3025 | 3020 | Upper Hibernia | fine- to medium-grained, subrounded to rounded, poor- to moderately-sorted, wavy bedded, sublithic arenite |
| 20EJ05 | Hibernia B-16 55 | #2 - 3 | 7245–7246 | 4618 | Lower Hibernia | medium- to coarse-grained, subrounded to rounded, well-sorted, massive to planar crossbedded, quartz arenite |
| 20EJ06 | Hibernia B-16 54 W | #1 - 1-3 | 6989–6986 | 4445 | Lower Hibernia | fine- to medium-grained, subrounded to rounded, moderately- to well-sorted, massive to planar crossbedded, sublithic arenite |

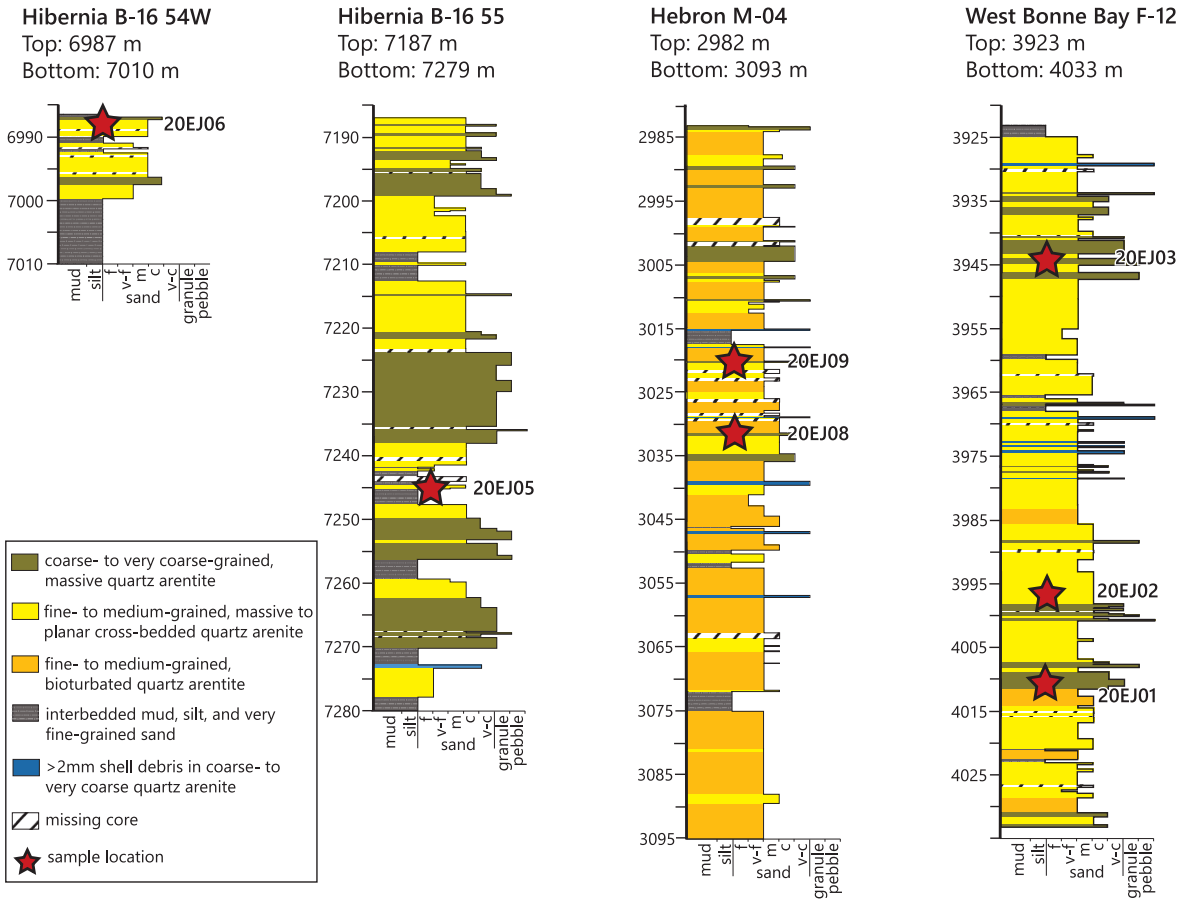


**Fig. 5.** Stratigraphy and detrital zircon sample locations for Hibernia Formation samples in Hibernia B-16 55 and 54 W (lower Hibernia), Hebron M-04 (upper Hibernia), and West Bonne Bay F-12 (upper Hibernia) wells.

crushing, milling, sieving, and magnetic and heavy liquid separation (methylene iodide) at Memorial University of Newfoundland.

### 3.2. Detrital zircon U–Pb and fission-track double-dating methods

U–Pb and fission-track (FT) measurements were made in the Geo- and Thermochronology Laboratory at the University of Calgary (Appendix A, Tables S1 and S2). For each sample, two polytetrafluoroethylene (PTFE) grain mounts were prepared and polished following the procedures of Tagami (2005) using 6, 3, and 1 μm diamond paste. Zircon grains were etched in a binary eutectic mixture of KOH:NaOH (in proportions by weight: 8.0 g KOH and 11.2 g NaOH) at 228 °C (Gleadow et al., 1976). One mount from each sample was etched for 10 h and the spontaneous fission tracks were observed. Two distinct zircon populations were present: one was over-etched with fission-tracks too dense to count (indicative of high U concentration and/or old FT age) and the other under-etched with fission-tracks too faint or infrequent to count (indicative of low U concentration and/or young FT age). To compensate for the variable etching times, the second mount from each sample were etched stepwise and spontaneous fission tracks were counted after 5, 7, and 12 h of elapsed etching time (Appendix A, Fig. S1). This approach allowed for the measurement of fast- and slow-etching zircon populations. Fission-tracks were counted using a Zeiss AxioImager M2m optical microscope equipped with a motorized stage. Fission-tracks were counted within a 900 $\mu m^2$ square grid consistent with laser spot area using a 1600x magnification. Stage coordinates were recorded for each grain and an annotated photomicrograph was used to ensure the $^{238}U/^{29}Si$ and U–Pb data were determined at the correct spot location during subsequent laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) measurements. After etching, mounts were flattened and cleaned using 2% nitric acid ($HNO_3$) in an ultrasonicator for 30 min to remove surficial common Pb.

Fission-track ages were determined using the 'zeta calibration' approach for LA-ICP-MS, using the FT age equation from Vermeesch (2017):

$$t = \frac{1}{\lambda_D} \ln\left(1 + \frac{1}{2}\lambda_D \zeta \frac{N_s}{A[U]}\right)$$

where $\lambda_D$ is the decay constant of $^{238}U$ ($1.55125 \times 10^{-10}$ year-1; Jaffey et al., 1971), ζ is the zeta calibration calculated using the calibration reference material, $N_s$ is the number of counted fission tracks over an area A, and [U] is the $^{238}U/^{29}Si$ ratio of area A. For each measurement session a ζ calibration factor was determined from a minimum of 10 measurements of Fish Canyon Tuff (28.201 ± 0.046 Ma; Kuiper et al., 2008). $^{238}U/^{29}Si$ ratios were determined using the TraceElements data reduction scheme in Iolite v. 2.5 (Paton et al., 2010). FT analyses that did not pass U–Pb data filtering protocols and three age outliers (819, 843, 899 Ma) were removed from the dataset.

U–Pb dates were determined by LA-ICP-MS using the measurement method outlined in Matthews and Guest (2017). Data were reduced in Iolite using the VizualAge data reduction scheme of Petrus and Kamber (2012). Isotopic ratios were calibrated against reference material Temora 2 (416.78 ± 0.33 Ma; Black et al., 2004) and validated using four reference materials with ages ranging from the Neoarchean to Paleogene (Appendix A, Table S1). Analyses with a probability of concordance of <1% were eliminated from the dataset (Matthews and Guest (2017)). The reported dates for grains younger and older than 1500 Ma are based on $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages, respectively. Quoted uncertainties in the text and figures include all random and

systematic components.

Maximum depositional ages (MDA) were calculated using four methods: (1) the youngest statistical population (YSP - Coutts et al., 2019; Herriott et al., 2019), which calculates the MDA as the weighted average of the youngest sub-sample of two or more grains that yield a mean square weighted deviates of ~1; (2) the youngest grain cluster at 2σ method (YGC 2σ - Dickinson and Gehrels, 2009), which calculates the MDA from the youngest three or more ages that overlap within 2σ uncertainty; (3) the youngest graphical peak method (YPP - Dickinson and Gehrels, 2009), that uses the Age Pick macro (www.laserchron.org) to calculate peaks for clusters of three or more overlapping ages at 2σ; and (4) the maximum likelihood age (MLA - Vermeesch, 2021), which uses the discrete minimum age peak from maximum likelihood modelling (Appendix A, Fig. S2).

## 4. Results

Detrital zircon analyses yielded 269 U–Pb and FT double-dated and 518 U–Pb dated grains. U–Pb age results shown in Fig. 6 include all 787 dates and are presented by well location. MDA estimates were calculated using full U–Pb dataset (Table 2). The fission-track and double-dating results are presented by Hibernia Formation member (Table 3) and with all Hibernia Formation data combined (Figs. 7 and 8; Table 4).

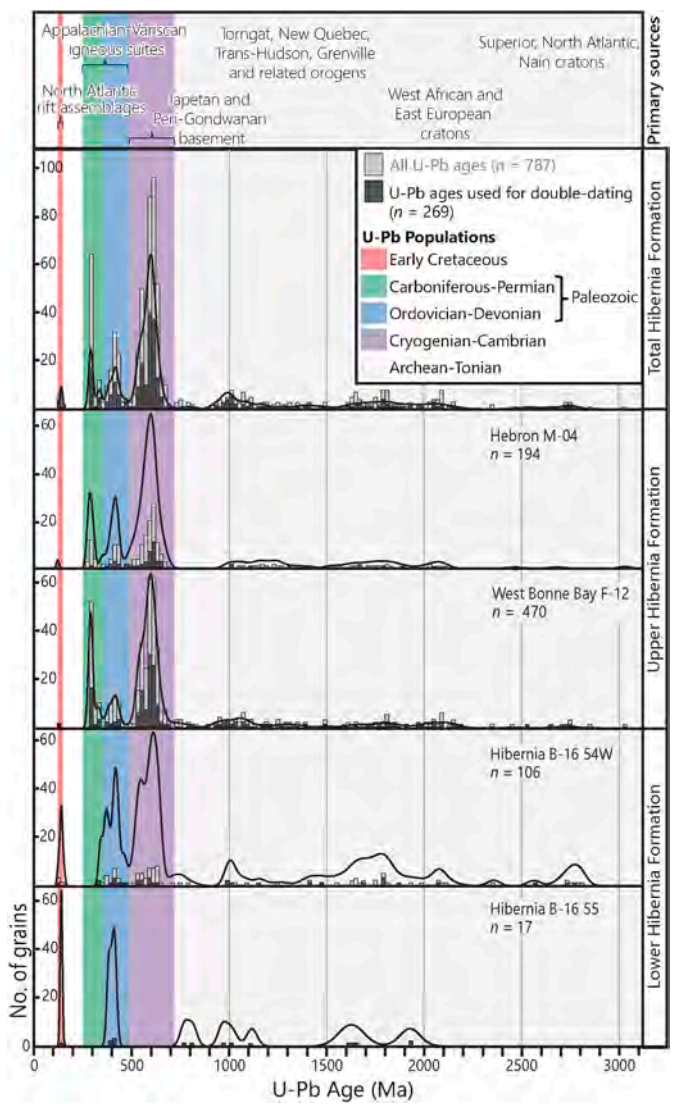


**Fig. 6.** Probability density plots (PDP) and histograms of detrital zircon U–Pb results for Hibernia Formation samples. Data pooled for Hibernia B-16 55 (20EJ05) and 54 W (20EJ06), Hebron M-04 (20EJ08 and 20EJ09), and West Bonne Bay F-12 (20EJ01, 20EJ02, and 20EJ03) samples. Primary zircon sources are listed in Table 5.

### 4.1. Detrital zircon U–Pb ages

Hibernia Formation rock samples yielded 787 U–Pb dates that show similar Archean to Tonian (3032-726 Ma), Cryogenian to Cambrian (707-493 Ma), Ordovician to Devonian (480-359 Ma), Carboniferous to Permian (358-275 Ma), and Early Cretaceous (143-123 Ma) detrital zircon U–Pb age populations regardless of lithology, grain size, geographic location, or stratigraphic position (Fig. 6). However, the proportion of grains in each U–Pb population varied from well to well. Lower Hibernia Formation samples from the Hibernia oil field (wells B-16 54 W and B-16 55) that are near the Murre-Mercury fault in the western Jeanne d'Arc basin lack 358-275 Ma populations that are recognized in upper member strata, while also yielding proportionally less Cryogenian to Cambrian and more Archean to Tonian detrital zircon grains (Fig. 6). Upper Hibernia Formation strata that are near the Voyager fault in the eastern Jeanne d'Arc basin (West Bonne Bay F-12) contain greater 358-275 Ma U–Pb populations relative to 465-360 Ma populations, whereas central Jeanne d'Arc basin strata in the Hebron oil field (Hebron M-04) yield subequal portions of both Paleozoic age groupings (Fig. 6).

MDA estimates for Hibernia Formation strata ranged from Early Devonian to Early Cretaceous (Table 2). MDA estimates for the underlying Jeanne d'Arc Formation were recalculated from Hutter and Beranek (2020) and yielded latest Jurassic to earliest Cretaceous ages (Table 2).

### 4.2. Detrital zircon fission-track ages

Hibernia Formation samples yielded 269 fission-track dates that range from 685 to 88 Ma and comprise five cooling populations (CP) and population peaks (Fig. 7A, Table 3): (1) Early Cretaceous (125 ± 3 Ma; $n = 28$); (2) Triassic to Jurassic (198 ± 3 Ma; $n = 50$); (3) Carboniferous to Permian (300 ± 3 Ma; $n = 103$); (4) Ordovician to Devonian (415 ± 9 Ma; $n = 55$); and (5) Cryogenian to Cambrian (538 ± 13 Ma; $n = 33$). Upper and lower Hibernia Formation zircon grains have consistent FT age ranges, age dispersion, and CP peaks (Table 3). Radial plots used for statistical analysis of FT dates are presented in Appendix A (Fig. S3).

## 5. Discussion

### 5.1. Depositional age of the Hibernia Formation and implications for the timing of Grand Banks tectonics and magmatism

The youngest detrital zircon grains constrain the depositional ages, correlation, and significance of syn-rift strata (e.g., Cawood et al., 2012; Herriott et al., 2019). MDA estimates for the lower and upper Hibernia Formation (Table 2) show no obvious trend with respect to location in the Jeanne d'Arc basin. Devonian to Permian (413-280 Ma) MDAs calculated with the YSP, YGC 2σ, YPP, and MLA methods are older than biostratigraphic constraints (e.g., Williams et al., 1990), likely due to the minor amounts of Early Cretaceous detrital zircon grains in Hibernia Formation rocks. The MLA is a statistical method that does not suffer from biases which affect other MDA assessments (Vermeesch, 2021) and produced Permian to Early Cretaceous (292-123 Ma) estimates for the lower and upper Hibernia Formation samples. MLA results from combined lower and upper Hibernia Formation samples yield Berriasian-early Valanginian (139 ± 5 Ma) and late Valanginian-Barremian (128 ± 6 Ma) depositional ages, respectively, which strengthen published biostratigraphic assignments and late Tithonian to earliest Berriasian depositional age estimates for the underlying Jeanne d'Arc Formation (Table 2).

**Table 2**
Maximum depositional age estimates for Hibernia and Jeanne d'Arc Formation samples using the IsoplotR algorithm of Vermeesch (2021). U = upper Hibernia Formation, L = lower Hibernia Formation.

| Sample | YSP (Ma) | MSWD | YGC 2σ (Ma) | YPP (Ma) | MLA (Ma) | Mesozoic Grains (n) | MDA Range |
|---|---|---|---|---|---|---|---|
| ***Hibernia Samples*** | | | | | | | |
| 20EJ01 (U) | 289 ± 1 | 0.96 | 287 ± 2 | 292 | 291 ± 3 | – | Permian |
| 20EJ02 (U) | 292 ± 1 | 0.79 | 290 ± 3 | 293 | 292 ± 3 | – | Permian |
| 20EJ03 (U) | 291 ± 1 | 1.02 | 287 ± 2 | 291 | 131 ± 6 | 1 | Permian/Early Cretaceous |
| 20EJ08 (U) | 282 ± 2 | 1.08 | 280 ± 2 | 287 | 123 ± 8 | 1 | Permian/Early Cretaceous |
| 20EJ09 (U) | 289 ± 3 | 0.2 | 289 ± 3 | 302 | 289 ± 8 | – | Late Pennsylvanian-Permian |
| 20EJ05 (L) | 141 ± 2 | 1.67 | 413 ± 3 | 411 | 140 ± 4 | 2 | Devonian/Early Cretaceous |
| 20EJ06 (L) | 135 ± 2 | 4.58 | 367 ± 3 | 139 | 137 ± 5 | 4 | Devonian/Early Cretaceous |
| ***Formation*** | | | | | | | |
| Upper Hibernia Fm. | 129 ± 2 | 2.92 | 282 ± 1 | 292 | 128 ± 6 | 2 | Late Valanginian-Barremian |
| Lower Hibernia Fm. | 140 ± 1 | 1.16 | 138 ± 2 | 139 | 139 ± 5 | 6 | Berriasian-Early Valanginian |
| Jeanne d'Arc Fm. | 141 ± 1 | 1.01 | 145 ± 1 | 145 | 145 ± 0.3 | 65 | Tithonian-Berriasian |

Huismans and Beaumont (2011, 2014) proposed that Type I non-volcanic margins (e.g., Newfoundland-Iberia) consist of major basin-forming fault systems in the proximal domain, a narrow transition or necking region with abrupt thinning of continental crust, exhumation of serpentinized continental mantle in the distal domain, and crustal breakup prior to mantle lithosphere breakup. Extensional deformation and magmatism in the proximal domain of the Newfoundland margin, including the Jeanne d'Arc basin region, began by the Late Triassic and reactivation of these fault systems continued through the Late Jurassic to Early Cretaceous onset of necking and exhumation processes (e.g., Sutra and Manatschal, 2012). Alves and Cunha (2018) predicted that Berriasian crustal rupture along SW Iberia resulted in the deposition of a Lower Cretaceous breakup sequence in the Lusitanian basin and specifically noted the time equivalence between forced regressive fluvial-deltaic intervals comprising the Torres Vedras Formation in western Portugal and Hibernia Formation in the Jeanne d'Arc basin. Our new MDA constraints from the lower Hibernia Formation confirm that sediment deposition occurred during a Berriasian rift episode and may furthermore characterize the far-field stratigraphic response to crustal breakup along SW Iberia. Berriasian to Valanginian detrital zircon grains in our lower Hibernia Formation samples indicate that some sources were located to the south of the Jeanne d'Arc basin, probably near the volcanic complexes of the SW Grand Banks transform and Collector anomaly, and suggest that crustal breakup along SW Iberia was connected to, or resulted in, mafic to felsic magmatism in the southern Newfoundland (Pe-Piper et al., 2007) and Iberia rift system (Mata et al., 2015; Pereira et al., 2017). Bowman et al. (2012) summarized the evidence for Cretaceous lava, pyroclastic, and epiclastic units in wells along the SW Grand Banks transform. Although most of these rocks in the SW Grand Banks region yielded Hauterivian to Barremian whole-rock K–Ar ages (e.g., Pe-Piper and Jansa, 1987), the Avalon Uplift must also host older, Late Jurassic to earliest Cretaceous igneous suites that were previously eroded into the southern Jeanne d'Arc basin (Hutter and Beranek, 2020). Hauterivian to Barremian detrital zircon grains in the upper Hibernia Formation correspond with the timing of Early Cretaceous extension and interpreted growth of outboard architectural elements (Péron-Pinvidic et al., 2013). For example, the establishment of Hauterivian to Barremian volcanic centers in the SW Grand Banks (Bowman et al., 2012) may indicate lithospheric melting along transfer zone systems at the southern end of the Newfoundland-Iberia rift system during regional transtension (Vaughn and Scarrow, 2003) that was related to crustal thinning, mantle exhumation, and development of the outboard distal domain.

### 5.2. Exhumation- and magmatic-related origins of fission-track cooling populations

Double-dated zircon grains in the Hibernia Formation are assigned to five cooling populations (CP) and record the long-term thermal history of the Atlantic Canadian margin (Fig. 7B, Table 4). Most zircon grains are classified as *exhumation-cooled* (91%; $n = 245$) and have U–Pb dates that are older than their corresponding FT dates (Fig. 8; Enkelmann et al., 2019). Exhumation-cooled grains occur below the 1:1 line on crystallization age versus cooling age plots and the difference between these values (ΔT) quantifies the time elapsed between zircon crystallization and the last time the zircon cooled through ~250 °C. The remaining zircon grains are classified as *magmatic-cooled* (9%; $n = 24$) and have U–Pb dates that are statistically equal (within ≤2σ error) to their corresponding FT dates and occur close to the 1:1 line on crystallization age versus cooling age plots (Fig. 8; Enkelmann et al., 2019). Despite the low number of magmatic-cooled grains, four age peaks were calculated from the U–Pb dates of the double-dated zircon grains (Table 4, Fig. 8): Early Cretaceous (137 ± 2 Ma; $n = 8$), Carboniferous-Permian (298 ± 4 Ma; $n = 7$), Silurian-Devonian (443 ± 9 Ma; $n = 4$), and Ediacaran (576 ± 8 Ma; $n = 9$). Magmatic-cooled grains may not only indicate derivation from volcanic units, but also shallow intrusive rocks in the top 5 km of the crust where magma cools quickly and results in similar FT and U–Pb dates (e.g., Malusà and Fitzgerald, 2019). Grains with ΔT < 100 Myr and not within error of the 1:1 line (6%, $n = 16$), may reflect slow magmatic cooling of deeper plutonic rocks (Fig. 8; Campbell et al., 2005). Whether these dates represent exhumation or slow-magmatic cooling is indistinguishable and for simplicity they are classified as exhumation-cooled grains.

### 5.3. Detrital zircon provenance signatures of Hibernia Formation strata

#### 5.3.1. Early Cretaceous age populations

Berriasian to Barremian (ca. 143-123 Ma) detrital zircon grains comprise 0–12% of each sample (mean = 1%) and have magmatic-cooled FT signatures that are assigned to CP1 (Fig. 8). The U–Pb ages of these zircon grains corroborate the interpreted timing of syn-rift magmatism in the southern Grand Banks region (Table 5), and primary sources include volcanic centers along the SW Grand Banks transform that are recognized in drillcore and mapped by marine seismic investigations (e.g., Pe-Piper et al., 1994; Bowman et al., 2012). Specifically, mafic to felsic sills, lavas, pyroclastic flows, and volcaniclastic rocks along the SW Grand Banks transform have yielded Valanginian to Barremian (135 ± 6 Ma to 128 ± 4 Ma) whole-rock K–Ar ages in Brant P-87 and Mallard M-45 (Fig. 1B; Pe-Piper and Jansa, 1987; Jansa and Pe-Piper, 1988; Pe-Piper et al., 1994).

#### 5.3.2. Paleozoic age populations

Paleozoic detrital zircon grains (ca. 485-251 Ma) make up 19–29% of each sample (mean = 23%) and have primary sources within Appalachian-Variscan igneous suites in the North Atlantic region (Table 5). Primary Taconic igneous sources include 467-452 Ma rocks in the peri-Laurentian realm (Fig. 3; e.g., van Staal et al., 2007) and equivalent Iberian 490-470 Ma magmatism in the Ossa-Morena and Central Iberian zones (e.g., Solá et al., 2008; Henriques et al., 2015). Salinic rocks in the Gander zone include 435-419 Ma igneous suites and

**Table 3**
Detrital zircon fission-track age population for lower Hibernia Formation (Hibernia B-16 55 and 54 W wells), upper Hibernia Formation (Hebron M-04, and West Bonne Bay F-12 wells) samples, and all Hibernia samples. Populations calculated in RadialPlotter mixture modelling (Vermeesch, 2009). Fig. 6 shows the corresponding radial plot results for all Hibernia grouping.

| Grouping | n (magmatic-cooled) | Central Value | Dispersion | Age Range | Population 1 Peak ± 1σ (Ma) | Population 2 Peak ± 1σ (Ma) | Population 3 Peak ± 1σ (Ma) | Population 4 Peak ± 1σ (Ma) | Population 5 Peak ± 1σ (Ma) |
|---|---|---|---|---|---|---|---|---|---|
| | | (Ma) | (%) | (Ma) | (% of grains) *(no. of grains)* | (% of grains) *(no. Of grains)* | (% of grains) *(no. Of grains)* | (% of grains) *(no. Of grains)* | (% of grains) *(no. Of grains)* |
| | | | | | **Early Cretaceous** | **Triassic-Jurassic** | **Carboniferous-Permian** | **Ordovician-Devonian** | **Cryogenian-Cambrian** |
| | | | | | 88-156 Ma | 157-239 Ma | 242-351 Ma | 355-473 Ma | 475-685 Ma |
| Upper Hibernia | 218 (20) | 296 ± 9 | 42 | 89–685 | 127 ± 3 (10) (*22*) | 202 ± 4 (18) (*39*) | 300 ± 3 (38) (*83*) | 411 ± 10 (20) (*44*) | 530 ± 12 (14) (*30*) |
| Lower Hibernia | 51 (4) | 272 ± 17 | 44 | 88–680 | 122 ± 6 (11) (*6*) | 183 ± 6 (21) (*11*) | 295 ± 7 (39) (*20*) | 422 ± 14 (24) (*11*) | 648 ± 42 (4) (*3*) |
| **All Hibernia** | **269 (24)** | **291 ± 8** | **42** | **88–685** | **125 ± 3 (10) (*28*)** | **198 ± 3 (19) (*50*)** | **300 ± 3 (38) (*103*)** | **415 ± 9 (21) (*55*)** | **538 ± 13 (12) (*33*)** |

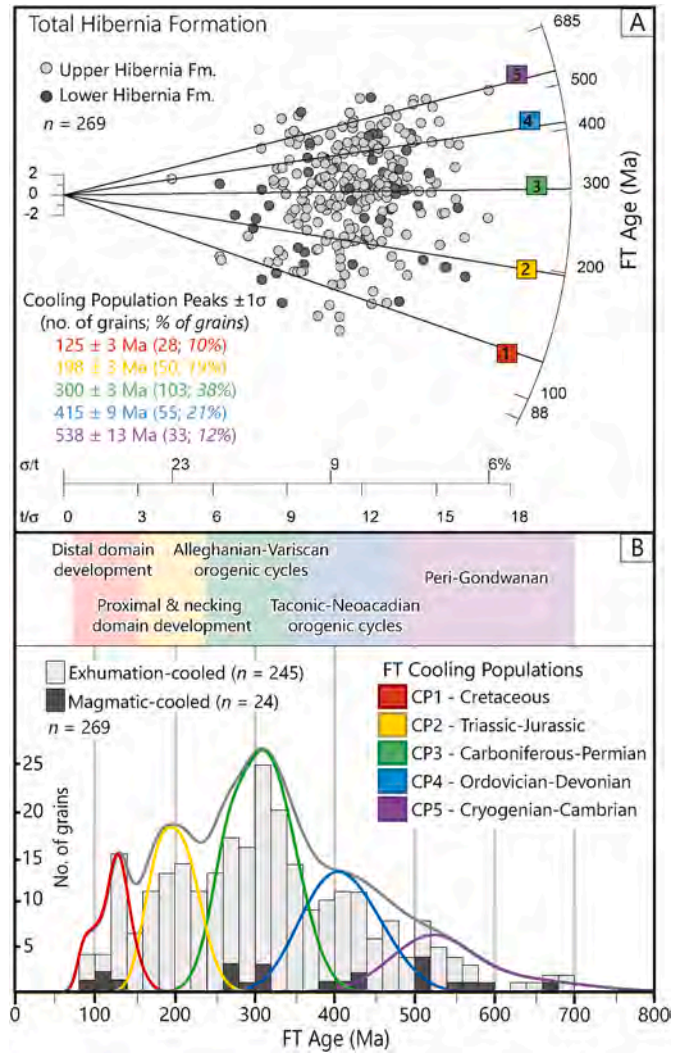


**Fig. 7.** (A) Radial plot and mixture modelling of detrital zircon fission-track (FT) results for Hibernia Formation samples. Data pooled for lower Hibernia Formation (Hibernia B-16 55 and 54 W wells) and upper Hibernia Formation (Hebron M-04, and West Bonne Bay F-12 wells) samples. Horizontal location on x-axis indicates measurement precision. t - FT age (Ma), σ - 1σ confidence interval. (B) Probability density plots (PDP) and histograms of detrital zircon FT results. Data pooled by FT cooling populations (CP) defined by finite mixture modelling; Cretaceous (CP1), Triassic to Jurassic (CP2), Carboniferous to Permian (CP3), Ordovician to Devonian (CP4), and Cryogenian to Cambrian (CP5).

425-410 Ma metamorphic complexes (e.g., O'Brien et al., 1991; Dunning et al., 1990). Acadian and Neoacadian igneous rocks are characterized by 396–357 Ma granitic plutons that span New England to Newfoundland, including the Grand Banks (e.g., Bell and Howie, 1990; Keppie and Krogh, 1999; Kellett et al., 2014, 2021).

Paleozoic detrital zircon grains in the Hibernia Formation yield FT ages that correspond to CP4 to CP1 (Fig. 8). A Late Ordovician to early Silurian (443 ± 9 Ma; CP4) magmatic-cooled peak matches igneous ages in composite Laurentia (ca. 445-435 Ma; Whalen, 1989), Ganderia (ca. 440-419 Ma; e.g., Dunning et al., 1990), Avalonia (ca. 440 Ma; Greenough et al., 1993), and Meguma terrane (ca. 440 Ma; Keppie and Krogh, 2000). A Carboniferous to Permian (298 ± 4 Ma; CP3) magmatic-cooled peak matches the emplacement ages of plutons in the northern Appalachians (e.g., Pe-Piper et al., 2010) and Iberian Variscides (e.g., Fernández-Suárez et al., 2000; Carracedo et al., 2009). Recycled Paleozoic zircon grains in the Hibernia Formation (Table 5) were mostly sourced from upper Paleozoic assemblages (e.g., Hiscott et al., 2008;

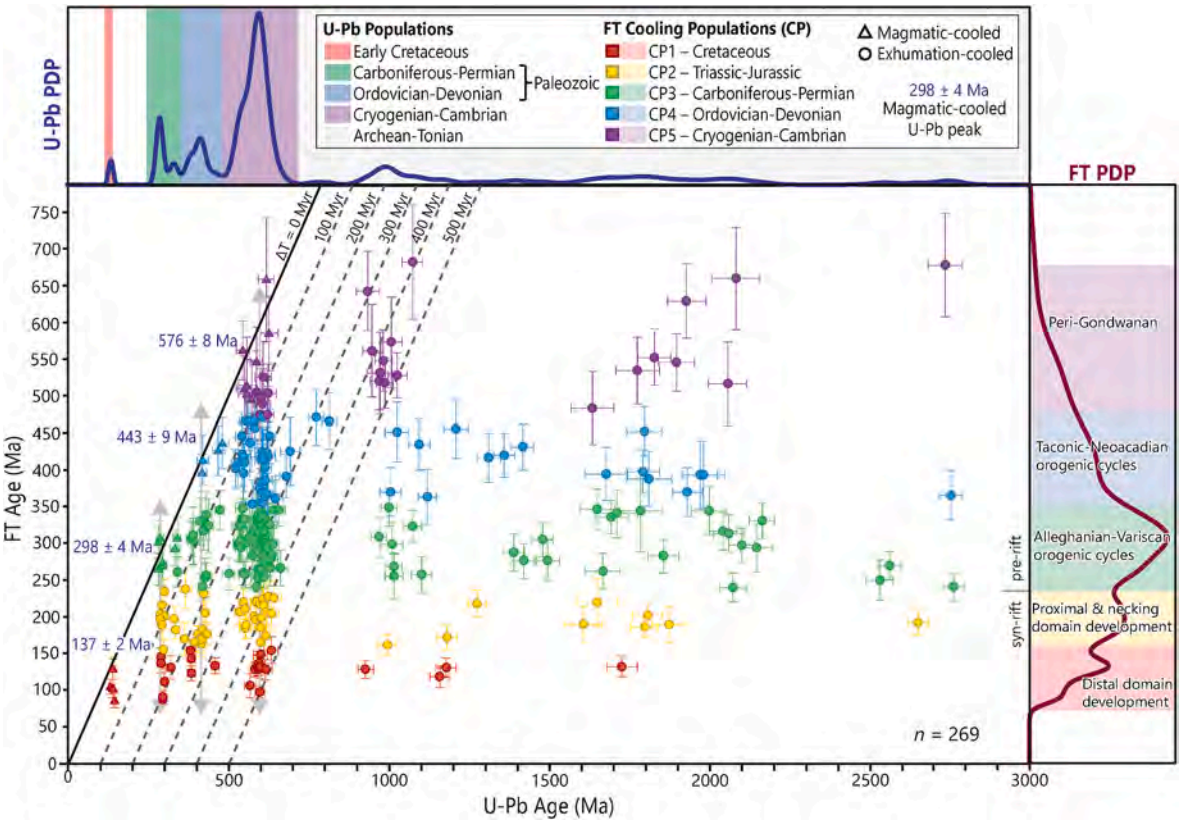


**Fig. 8.** Crystallization age versus cooling age plot and probability density plots (PDP) of detrital zircon U–Pb and fission-track (FT) double-dating results for Hibernia Formation samples. Data pooled for lower Hibernia Formation (Hibernia B-16 55 and 54 W wells) and upper Hibernia Formation (Hebron M-04, and West Bonne Bay F-12 wells) samples. FT cooling populations (CP) defined by finite mixture modelling. ΔT - difference between U–Pb crystallization age and FT cooling age.

**Table 4**
Detrital zircon double-dated mixture modelling results for exhumation-cooled FT, magmatic-cooled FT, and magmatic-cooled U–Pb ages for Hibernia Formation samples.

| Grouping | n | Central Value (Ma) | Dispersion (%) | Age Range (Ma) | Population 1 Peak ± 1σ (Ma) (% of grains) *(no. Of grains)* **Early Cretaceous** | Population 2 Peak ± 1σ (Ma) (% of grains) *(no. Of grains)* **Triassic-Jurassic** | Population 3 Peak ± 1σ (Ma) (% of grains) *(no. Of grains)* **Carboniferous-Permian** | Population 4 Peak ± 1σ (Ma) (% of grains) *(no. Of grains)* **Ordovician-Devonian** | Population 5 Peak ± 1σ (Ma) (% of grains) *(no. Of grains)* **Cryogenian-Cambrian** |
|---|---|---|---|---|---|---|---|---|---|
| Exhumation-cooled (FT) | 245 | 288 ± 8 | 40 | 89–685 | 129 ± 3 (10) *(24)* | 199 ± 3 (21) *(50)* | 301 ± 4 (39) *(96)* | 416 ± 10 (21) *(51)* | 540 ± 16 (9) *(24)* |
| Magmatic-cooled (FT) | 24 | 331 ± 38 | 56 | 88–660 | 107 ± 6 (17) *(4)* | – | 292 ± 9 (29) *(7)* | 423 ± 18 (19) *(4)* | 542 ± 19 (35) *(9)* |
| Magmatic-cooled (U–Pb) | 28 | 312 ± 34 | 58 | 131–625 | 137 ± 2 (29) *(8)* | – | 298 ± 4 (25) *(7)* | 443 ± 9 (14) *(4)* | 576 ± 8 (32) *(9)* |

Piper et al., 2012) or pre-Cretaceous syn-rift successions in the Grand Banks (e.g., Hutter and Beranek, 2020).

### 5.3.3. Cryogenian to Cambrian age populations

Cryogenian to Cambrian detrital zircon grains (ca. 720-485 Ma) make up 0–60% of each sample (mean = 49%) and have primary sources within peri-Laurentian and peri-Gondwanan terrane domains of the Canadian Appalachians, such as those that underlie the Dunnage, Gander, and Avalon zones in Newfoundland (Table 5, e.g., Krogh et al., 1988; O'Brien et al., 1996). Repeated recycling of late Neoproterozoic zircon grains through peri-Gondwanan cover assemblages, syn-to post-orogenic Paleozoic strata of the Maritimes basin, and syn-rift successions is documented in Atlantic Canada (e.g., Piper et al., 2012; Hutter and Beranek, 2020) and provide possible sources for Hibernia Formation strata (Table 5).

Cryogenian to Cambrian detrital zircon populations assigned to CP5 include both magmatic-cooled grains derived from extrusive or shallow intrusive rocks and exhumation-cooled grains with ΔT < 100 Myr that likely represent slow or lower crustal cooling of intrusive bodies (Fig. 8). Possible igneous sources in eastern Newfoundland are the 570 ± 6 Ma Berry Hills Granite (Kellett et al., 2014) and 585 ± 3 Ma Harbour Main Group (Krogh et al., 1988). Possible Variscan sources along the Iberian margin include 570-540 Ma rocks in the Ossa Morena and Central Iberian zones of Portugal (e.g., Henriques et al., 2015). The remaining FT ages for the Cryogenian to Cambrian U–Pb population are exhumation-cooled and reflect younger tectonothermal events (Fig. 8).

### 5.3.4. Archean to Tonian age populations

Archean to Tonian (ca. 3000-720 Ma) detrital zircon grains make up 14–59% of each sample (mean = 27%) and have primary sources from

**Table 5**
Summary of potential primary and recycled detrital zircon sources for Hibernia Formation strata.

| Age populations | Primary sources | Potential recycled sources in Atlantic Canada |
|---|---|---|
| *Archean to Tonian* | | |
| >2500 Ma | Superior, North Atlantic, Nain cratons | Iapetan margin sandstones, Appalachian (peri-Laurentian & peri-Gondwanan) terrane cover assemblages |
| 2200-2000 Ma | West Gondwanan cratons | Appalachian (Peri-Gondwanan) terrane cover assemblages |
| 2000-720 Ma | Torngat, New Quebec, Trans-Hudson, Grenville and related orogens | Iapetan margin sandstones, Appalachian (Peri-Gondwanan) terrane cover assemblages, Appalachian foreland & strike-slip basins |
| *Cryogenian to Cambrian* | | |
| 720-485 Ma | Iapetan and Peri-Gondwanan terrane basement (Dunnage, Gander, Avalon) | Peri-Gondwanan terrane cover assemblages, Appalachian foreland & strike-slip basins, Mesozoic rift basins |
| *Paleozoic* | | |
| 540-280 Ma | Appalachian-Variscan igneous suites | Appalachian foreland & strike-slip basins, Mesozoic rift basins |
| *Mesozoic* | | |
| 148-123 Ma | North Atlantic rift assemblages | Tithonian to Valanginian strata, Grand Banks |

the basement domains of eastern Laurentia and West Gondwana (e.g., Whitmeyer and Karlstrom, 2007). Archean zircon grains (>2500 Ma) match the ages of magmatism in the Nain, Hearne, Superior, and related cratons of North America (e.g., Hoffman, 1988) and West Africa (e.g. Henderson et al., 2016). Early Paleoproterozoic zircon ages (ca. 2200-2000 Ma) are not typical of eastern North America, but consistent with known magmatism in the West African and Eastern European cratons (e.g., Henderson et al., 2016). Late Paleoproterozoic zircon grains match the ages of 2000–1800 Ma magmatism in the Torngat, Trans-Hudson, and related orogenic belts that assembled Laurentia (e.g., Hoffman, 1988). Late Paleoproterozoic to early Neoproterozoic zircon grains (ca. 1700-720 Ma) are consistent with ages of Grenville basement in eastern Canada (e.g., Gower et al., 1991; Rivers, 1997) and Tonian to Cryogenian rift episodes along the three margins of Laurentia. Possible recycled sources of Archean to Tonian zircon grains (Table 5) include those recognized in Ediacaran to lower Paleozoic strata from the Iapetan margin in Newfoundland (e.g., Cawood and Nemchin, 2001), peri-Gondwanan cover successions of Avalonia (e.g., Barr et al., 2012; Willner et al., 2013), Meguma terrane (e.g., Waldron et al., 2009; Pothier et al., 2015), Appalachian-Variscan foreland and strike-slip basin strata (e.g., Force and Barr, 2012), and Grand Banks syn-rift successions (e.g., Hutter and Beranek, 2020). All Archean to Tonian detrital zircon grains in the Hibernia Formation are classified as exhumation-cooled and yield FT ages that are 300–2500 Myr younger than their U–Pb crystallization ages (Fig. 8).

### 5.4. Evidence for the timing of pre- and syn-rift exhumation in the proximal domain

Hibernia Formation detrital zircon grains show evidence for pre- and syn-rift phases of exhumation that correspond with the long-term tectonic development of the Newfoundland margin (Fig. 8). CP2 and CP1 are consistent with the proposed timing of Triassic to Jurassic and Early Cretaceous development of listric and planar normal fault systems, respectively, that controlled Jeanne d'Arc basin subsidence (Tankard and Welsink, 1987; Sinclair, 1988; Sinclair et al., 1999) and are generally consistent with published rift models for the Newfoundland margin based on marine geophysical data (e.g., Tucholke et al., 2007; Péron-Pinvidic et al., 2013). Rift-related cooling was likely the result of tectonic exhumation along normal faults (e.g., Murre-Mercury fault system; Enachescu, 1987) and magmatic cooling of igneous rocks adjacent to major transfer zones. Early Cretaceous cooling ages (CP1) may point to the timing of crustal breakup along SW Iberia (Dinis et al., 2008; Alves and Cunha, 2018). Furthermore, supporting the onset of hyperextension and mantle exhumation in more outboard regions by ~140 Ma (Fig. 8; e.g., Sutra and Manatschal, 2012; Nirrengarten et al., 2018) and corresponding reactivation and attenuation of normal faults over geologically short time intervals within the Grand Banks (Sinclair, 1988; Tucholke et al., 2007). The near-zero lag time between the age of the Early Cretaceous exhumation-cooled CP1 population peak (129 ± 3 Ma; Table 4) and Berriasian to Barremian deposition of Hibernia Formation strata (maximum depositional ages of 139–128 Ma) may have resulted from fault displacements and rapid tectonic exhumation along rift flanks (e.g., Saylor et al., 2012). The lack of magmatic-cooled grains within the Triassic-Jurassic CP2 (Fig. 8) points to a tectonothermal event that resulted in significant exhumation in the absence of zircon crystallization (e.g., Saylor et al., 2012), consistent with Late Triassic to Early Jurassic proximal domain development with wide corridors of upper crustal extension and mafic magmatism in Atlantic Canada (cf., Hodych and Hayatsu, 1988).

Carboniferous to Permian (CP3) and Ordovician to Devonian (CP4; Fig. 8) cooling age populations align with the timing of the Alleghenian-Variscan and Taconic to Neoacadian orogenic cycles, respectively, and based on observed trends in other mountain belts (Reiners and Brandon, 2006; Malusà and Fitzgerald, 2019), we interpret that rock uplift and erosion (erosional exhumation) were the dominant cooling processes. CP3 contains the most grains of all the cooling populations and may signal increased erosional exhumation during the Alleghenian–Variscan orogeny (e.g., Pereira et al., 1998), predominance of Alleghanian-Variscan aged or younger source rocks, and/or the indirect supply and recycling of Iberian-derived zircon grains through upper Paleozoic strata (Hiscott et al., 2008). Upper Paleozoic to Cretaceous proximal domain strata in the Lusitanian rift basin of western Portugal yield Carboniferous to Permian (~300 Ma) detrital zircon fission-track ages (Pereira et al., 1998) and typically contain Carboniferous to Permian U–Pb populations (e.g., Rodrigues et al., 2015; Dinis et al., 2016) that are represented in upper Hibernia Formation strata (Fig. 8). However, the majority of the U–Pb ages in CP3 are Ordovician and older and do not distinguish between recycled Appalachian or Iberian sources. Cryogenian to Cambrian U–Pb ages (ca. 700-550 Ma) dominate Ordovician to Devonian CP4 (Fig. 8) and likely represent cooling of Avalonian arc successions during Acadian orogenesis. Silurian magmatic-cooled zircon grains in CP4 may show the introduction of composite Laurentian sources (e.g., Whalen, 1989); however, the persistent Cryogenian to Cambrian age population supports the hypothesis that the dominant signature reflects cooling of peri-Gondwanan terrane infrastructure.

The Cryogenian to Cambrian cooling population (CP5; Fig. 8) generally aligns with the termination of subduction along the peri-Gondwanan margin (e.g., O'Brien et al., 1996; Keppie et al., 1998) and may reflect cooling by isothermal relaxation (Malusà and Fitzgerald, 2019). The U–Pb results for CP5 yield three age populations (ca. 650–540, 1100–900, 2100-1600 Ma) that are consistent with Avalonia and related terranes (Fig. 8; Henderson et al., 2016; Stephan et al., 2019).

### 5.5. New evidence for the thermal history of the Avalon Uplift

Published zircon and apatite FT and (U–Th)/He age results for the onshore parts of the magma-poor Newfoundland and magma-rich Nova Scotian margins (Fig. 3 and Table 6) suggest that northern Appalachian rocks experienced similar Paleozoic and Mesozoic thermal events. However, offshore basement and cover assemblages of the Avalon Uplift, including upper Paleozoic strata that were the dominant sources of the Hibernia Formation, have uncertain thermal histories and detrital zircon FT systematics between the time of their deposition and

**Table 6**
Muscovite $^{40}Ar/^{39}Ar$, zircon fission-track and (U–Th)/He, and apatite fission-track and (U–Th)/He ages from Cretaceous and older rocks in Atlantic Canada. *ZFT ages from this study. (1) Hames and Bowring (1994); (2) Tagami et al. (1998); Tagami (2005); (3) Reiners et al. (2004); (4) Green et al. (1986); Ketcham et al. (1999); (5) Farley (2000); (6) Willner et al. (2019); (7) Hendriks et al. (1993); (8) Wilson and Hiscott (2007); (9) Ryan and Zentilli (1993); (10) Ravenhurst et al. (1990); (11) Arne et al. (1990); (12) Grist and Zentilli (2003); (13) Ravenhurst et al. (1989); (14) Willner et al. (2015); (15) Chang (2017); (16) Grist et al. (1992); (17) Powell et al. (2018), (18) Canadian Geochronology Knowledgebase (2013); (19) Kellett et al. (2016).

| Dating Method | Muscovite $^{40}Ar/^{39}Ar$ | Zircon fission-track (ZFT) | Zircon (U–Th)/He (ZHe) | Apatite fission-track (AFT) | Apatite (U–Th)/He (AHe) |
|---|---|---|---|---|---|
| **Nominal Closure/Annealing Temperature (°C)** | 300–400 °C(1) | 210–290 °C(2) | 160–200 °C(3) | 100–120 °C(4) | 40–80 °C(5) |
| **Western & Central Newfoundland** | 416-371 Ma(18) (19) ($\bar{x}$ = 390 Ma) | 235-212 Ma(6) ($\bar{x}$ = 227 Ma) | | 343-152 Ma(7) ($\bar{x}$ = 232 Ma) | |
| **Offshore Newfoundland** | 430-50 Ma(8) | 538-125 Ma* | | | |
| **Onshore Nova Scotia** | 579-276 Ma(14) (19) ($\bar{x}$ = 367 Ma) | 342-217 Ma(13) (14) ($\bar{x}$ = 225 Ma) | 290-192 Ma(15) ($\bar{x}$ = 220 Ma) | 244-165 Ma(9) (10) (11) (12) (13) ($\bar{x}$ = 213 Ma) | 211-165 Ma(15) ($\bar{x}$ = 180) |
| **Offshore Nova Scotia** | | | | 200 Ma(16) | |
| **Anticosti Island** | | | 761-581 Ma(17) ($\bar{x}$ = 655 Ma) | 125 Ma(17) | 48-16 Ma(17) ($\bar{x}$ = 33 Ma) |

subsequent Mesozoic exhumation. Appalachian collision-related metamorphism and magmatism, which could produce heat capable of resetting low-temperature thermochronometers, generally migrated eastwards along with the sequential accretion of volcanic arcs and microcontinents (van Staal et al., 2009) and the western limit of mountain-building is constrained by Neoproterozoic ZHe ages in Grenville basement rocks from Anticosti Island, eastern Quebec (Fig. 3; Powell et al., 2018). Thermal resetting of the zircon FT system during Alleghanian orogenesis is evident onshore Atlantic Canada (e.g., Ravenhurst et al., 1989; Willner et al., 2015, 2019) and potentially extends into offshore regions including the Avalon Uplift (Fig. 3; Wilson and Hiscott, 2007). For example, basement rocks in central Newfoundland typically yield Mesozoic zircon that are younger than overlying Carboniferous strata and confirm thermal resetting of the zircon fission-track system (>220–250 °C) between ca. 360 Ma and 235-212 Ma (Willner et al., 2019). High temperatures during

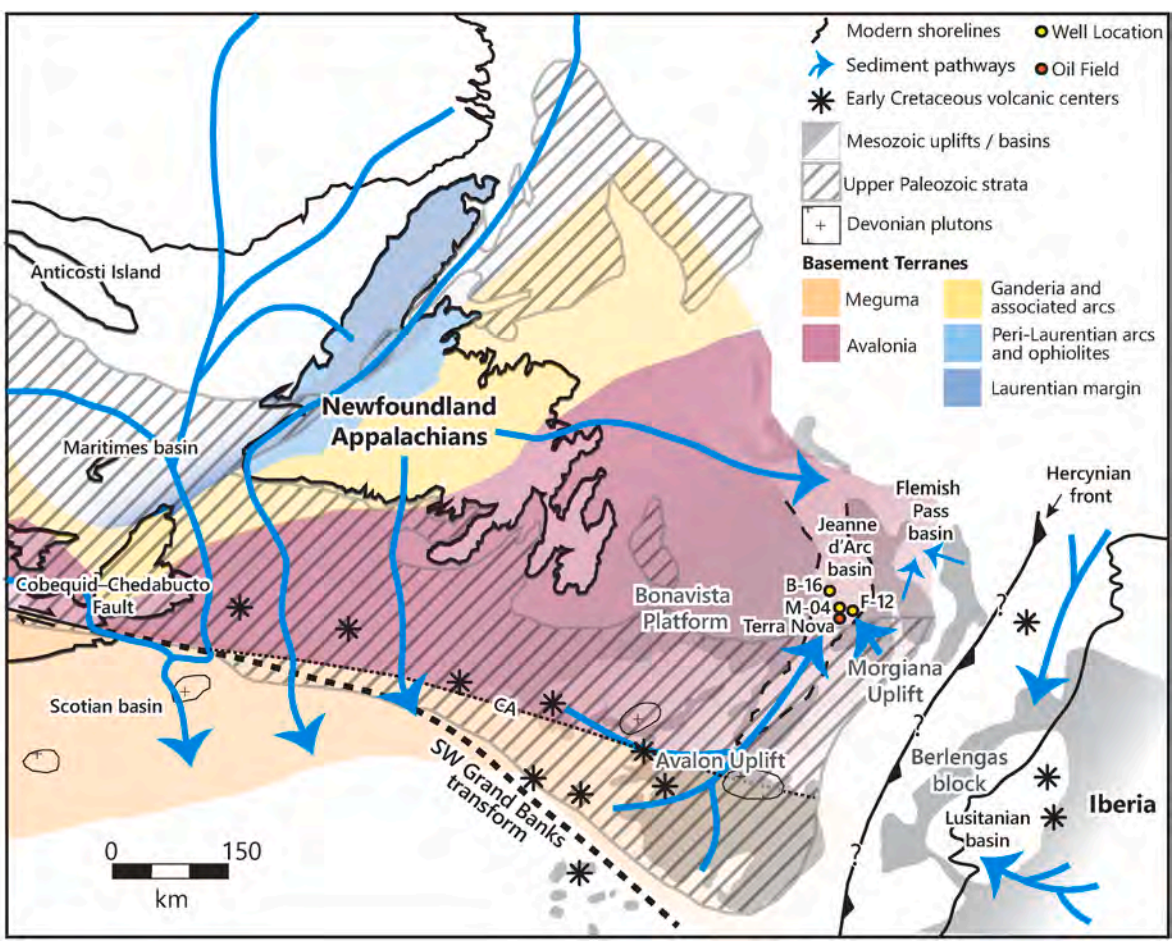


**Fig. 9.** Early Cretaceous paleogeography of North Atlantic region modified from Lowe et al. (2011), Piper et al. (2012), Dinis et al. (2016, 2021), and Nirrengarten et al. (2018). Early Cretaceous volcanic centers from Bowman et al. (2012) and Mata et al. (2015). Hibernia Formation strata are mostly sourced from Avalon Uplift and SW Grand Banks transform regions with potential southeastern input from Morgiana Uplift and Variscan foreland-hinterland elements. CA – Collector Anomaly, SW - Southwest.

Carboniferous orogenesis and magmatism are recognized in the Iberian proximal domain (e.g., Carracedo et al., 2009) and detrital zircon FT studies in central Portugal and Morocco likewise show a dominant ~300 Ma peak that represents unroofing of Variscan granitoids and adjacent basement (Pereira et al., 1998). Mesozoic deformation and magmatism along the SW Grand Banks transform and Avalon Uplift could also have reset zircon grains (e.g., Kohn et al., 1993) in Mesozoic and older strata by elevated geothermal gradients.

The Archean to Permian U–Pb signatures of exhumation-cooled Triassic-Jurassic and Early Cretaceous (Fig. 8) zircon grains in the Hibernia Formation are similar to those found in upper Paleozoic strata derived from the Appalachian-Variscian mountain system and could indicate thermal resetting of the zircon FT system on the Avalon Uplift. However, Hibernia Formation strata also contain pre-Devonian cooling ages that precede the Acadian, Neoacadian, and Alleghanian orogenic cycles, indicating that not all rocks on the Avalon Uplift were thermally reset. Alleghanian-Variscan burial and deformation or Mesozoic deformation and magmatism along the SW Grand Banks transform could have locally reset the zircon FT system in some Avalon Uplift rocks. Subsequent Early Cretaceous tectonic exhumation and erosion that supplied sediment to the Jeanne d'Arc basin may have tapped into both thermally-reset and un-reset rocks and resulted in the observed Paleozoic to Mesozoic cooling ages.

### 5.6. Early Cretaceous paleogeography of the Grand Banks region

New detrital zircon double-dating results from the Hibernia Formation, combined with published mineral cooling ages and other geological constraints, allow us to evaluate the Early Cretaceous paleogeography of the Grand Banks region (Fig. 9). In the southern Jeanne d'Arc basin, Early Cretaceous CP1 zircon grains that cooled near the time of deposition indicate at least two sediment sources for the Hibernia Formation near the Hibernia and Hebron oil fields: (1) magmatic-cooled zircon grains that are likely first-cycle and have provenance from Berriasian and younger igneous rocks along the SW Grand Banks transform and Collector anomaly (e.g., Pe-Piper et al., 1994; Bowman et al., 2012); and (2) exhumation-cooled Paleozoic and older zircon grains that demonstrate cooling during Early Cretaceous rise of pre-Mesozoic igneous basement or thermally-reset strata in the Avalon Uplift (e.g., Enachescu, 1988; Tankard et al., 1989). These results corroborate models that support north-directed, Early Cretaceous fluvial drainage into the southern Jeanne d'Arc basin during active volcanism (e.g., Sinclair et al., 1999), which overlapped with the timing of thinning and mantle exhumation processes in the nascent necking and distal domains (e.g., Péron-Pinvidic et al., 2013). Uppermost Jurassic fluvial strata of the southern Jeanne d'Arc basin similarly had southern provenance from the Avalon Uplift (Hutter and Beranek, 2020), which suggests that Early Cretaceous exhumation processes did not result in significant changes to existing drainage patterns.

The Hibernia Formation was deposited during extensional deformation when tectonic subsidence dominated and the likely sources were local highlands adjacent to major fault systems (Tankard et al., 1989; Sinclair et al., 1999). Hibernia Formation detrital zircon grains mostly yield Cryogenian to Jurassic cooling (CP5 to CP2) and Archean to Permian U–Pb ages that are much older than the timing of Early Cretaceous deposition and characteristic of well-mixed, continental-scale drainage systems with multiple recycled sources (e.g., Cawood et al., 2012). The compositional and textural traits of Hibernia Formation rocks, in combination with inferred source regions in the southern Grand Banks, support the hypothesis that Lower Cretaceous units have provenance from mature siliciclastic strata. Syn-rift, Upper Jurassic to Lower Cretaceous sandstone units of the Jeanne d'Arc and Flemish Pass basins yield Archean to Mesoproterozoic (>2500-1000 Ma), late Neoproterozoic (ca. 760-540 Ma), and early to late Paleozoic (ca. 540-250 Ma) detrital zircon U–Pb age populations that are similar to those in the Hibernia Formation (Lowe et al., 2011; Hutter and Beranek, 2020; Beranek et al., 2022). The repeatability of these age spectra indicate that Carboniferous to Jurassic strata overlying Avalonia and Meguma basement domains were regionally extensive (e.g., Gibling et al., 2008) and represent the main sediment sources of proximal domain basins (Hiscott et al., 2008; Sinclair et al., 1999; Hutter and Beranek, 2020).

Upper Hibernia Formation strata contain unique Carboniferous to Permian (ca. 358-275 Ma) detrital zircon grains that are intepreted to represent increased contributions from the Morgiana Uplift to the southeast by late Valanginian to Barremian time (Fig. 9; e.g., Sinclair, 1988; Sinclair et al., 1999). Furthermore, upper Hibernia Formation strata from West Bonne Bay F-12 in the southeastern Jeanne d'Arc basin contain higher proportions of 358–275 Ma zircon grains than those from Hebron M-04 to the west and may indicate closer proximity to an eastern source (Fig. 9). These results point towards enhanced late Valanginan to Barremian exhumation along of the Voyager fault that represents the southeastern boundary of the Jeanne d'Arc basin or increased headward erosion during lowstand intervals that tapped rock units in the Morgiana Uplift with late Paleozoic detrital zircon grains. It is uncertain if Carboniferous to Permian igneous rocks underlie potential source areas to the east of the Jeanne d'Arc basin, however, such rocks are recognized along the Alleghanian-Variscan orogenic belt in the U.S., Atlantic Canada, and Portugal (e.g., Carracedo et al., 2009; Pe-Piper et al., 2010). Crustal thinning may have facilitated upper-crustal emplacement of late Paleozoic igneous rocks during the orogenic collapse of the Variscan orogen in western and offshore Portugal (e.g., Dinis et al., 2021). Subsquent exhumation of these late Paleozoic plutons during Triassic to Early Cretaceous extension would agree with the FT ages of Carboniferous to Permian zircon grains from the Hibernia Formation. Alternatively, late Paleozoic zircon grains may have been recycled through Alleghanian-Variscan foreland basin (e.g., Hiscott et al., 2008) or Triassic to Jurassic syn-rift strata. The scenario for reworked strata requires the mixing of two sources: (1) un-reset sedimentary rocks that preserve the ages of magmatic-cooled Carboniferous to Permian zircon; and (2) fully reset sedimentary rocks that lack evidence for Variscan cooling and instead yield Mesozoic cooling ages.

Berriasian to Barremian syn-rift strata in the northern Flemish Pass basin (Fig. 9) record fluvial drainage from Central Ridge, Flemish Cap, and other bordering highlands near the outboard edge of the proximal domain (Fig. 9; Lowe et al., 2011; Beicip-Franlab, 2015). The cooling histories of basement and overlying syn-rift rock units in this region have not been tested, however, we predict that they would show exhumation trends analogous to those reported here for the Hibernia Formation. The Central Ridge horst on the southwest side of the Flemish Pass basin was uplifted in the Early Cretaceous (Enaceschu, 1987), coincident with crustal thinning and onset of mantle exhumation farther outboard, and we anticipate that drillcore records of its basement (e.g., pre-Mesozoic rocks in Bonanza M-71) will yield late Paleozoic and older zircon grains with cooling histories that overlap with CP1. Future detrital zircon FT and U–Pb studies of Hibernia Formation-equivalent strata, especially those in the Mizzen and Bay du Nord discovery areas near the western flank of Flemish Cap, are also warranted. We expect that such Lower Cretaceous strata, which are probably sourced from upper Paleozoic cover assemblages like underlying Upper Jurassic fluvial units in the region (Lowe et al., 2011; Beranek et al., 2022), will yield Archean to Permian detrital zircon U–Pb ages with Early Cretaceous (CP1) and older (CP2-CP5) cooling histories.

The Scotian basin is located south of the SW Grand Banks transform (Fig. 9) and along the Scotian passive margin of Atlantic Canada that was established by the Middle Jurassic. Valanginian to Barremian sandy deltaic strata (Missassauga Formation) in the Scotian basin, which regionally overlie carbonate-rich Jurassic successions, represent a large clastic influx from south-southeast-directed drainage systems with headwaters in southeastern Labrador, western Newfoundland, and areas that underlie the Gulf of Saint Lawrence (Fig. 9; Piper et al., 2012; Pe-Piper et al., 2014). Piper et al. (2012) specifically predicted that some

of these rivers were fed by upper Paleozoic and older rock units in the Humber Valley region of western Newfoundland where late Paleozoic to Mesozoic cooling ages align with North Atlantic rift evolution (Fig. 3; e.g., Hendriks et al., 1993), suggesting that some tectonic exhumation events in the proximal domain of the Newfoundland margin affected the filling of the Scotian basin. Onshore equivalents of these deltaic units show evidence of syn-sedimentary deformation linked to repeated uplift along northeast-trending basement horsts (Piper et al., 2005). The regional significance of these onshore events is not fully understood, but Piper et al. (2005) and Gobeil et al. (2006) concluded that onshore Early Cretaceous deposition was linked to deformation along the Cobequid-Chedabucto fault system of northern Nova Scotia (Fig. 9) and in offshore Grand Banks basins. The apatite fission-track systems of Lower Cretaceous strata in the Scotian basin are mostly thermally reset (Grist et al., 1992) and reflect post-deposition cooling ages. In contrast, the zircon fission-track system may retain provenance information and reflect pre- and syn-rift cooling histories, like those observed in the Hibernia Formation strata, that may constrain regional exhumation processes and test potential Early Cretaceous connections between the Scotian and Newfoundland margins.

The Early Cretaceous paleogeography of the Iberian proximal domain is generally constrained by Berriasian to Barremian nonmarine to marine strata in the Lusitanian basin of western Portugal (e.g., Hiscott et al., 1990b; Dinis et al., 2008). If the model of Alves and Cunha (2018) is correct, Berriasian strata equivalent with the lower Hibernia Formation are the basal parts of a breakup succession that was generated after crustal rupture in SW Iberia (Tagus sector of Dinis et al., 2008). Lower Cretaceous strata in the central Lusitanian basin have detrital zircon and apatite FT central ages that range from $142 \pm 15$ Ma to $299 \pm 19$ Ma, which generally describe the exhumation of local rock units during late Variscan and Jurassic-Cretaceous tectonic evolution (Pereira et al., 1998), but lack older, Cryogenian to Devonian cooling populations (CP4 and CP5) typical of the Hibernia Formation and peri-Gondwanan successions along the Newfoundand margin. Recent apatite FT studies by Barbarand et al. (2021) have furthermore demonstrated that late Paleozoic intrusive rocks along the eastern side of the Lusitanian basin underwent late Tithonian to Berriasian (ca. 150-145 Ma) cooling because of breakup in the southern SE Grand Banks-Iberia rift system. Whereas Jurassic siliciclastic strata in the Lusitanian basin of west-central Portugal were derived from Variscan and Cadomian basement rocks of the Berlengas block to the west (Dinis et al., 2021), Berriasian to Barremian strata had contributions from Galicia Bank to the north and Iberian massif to the east (Fig. 9; Dinis et al., 2016), indicating that earliest Cretaceous crustal breakup and rift shoulder uplift affected regional drainage pathways. Dinis et al. (2016) concluded that these drainage systems were separated from those feeding Grand Banks basins by topographic barriers and Lower Cretaceous strata in Portugal correspondingly yield lower and higher proportions of Cryogenian to Cambrian (ca. 660-540 Ma; ~20%) and late Paleozoic (375-275 Ma; ~50%) detrital zircon grains, respectively, when compared with the Hibernia Formation.

## 6. Conclusions

Detrital zircon U–Pb and FT double-dating studies of syn-rift, Lower Cretaceous Hibernia Formation strata establish source-to-sink connections for the Jeanne d'Arc basin and constrain the timing of regional exhumation during Mesozoic tectonic development of the Grand Banks region. Early Cretaceous (143-123 Ma) magmatic-cooled zircon grains confirm Berriasian to early Valanginian and late Valanginian to Barremian depositional ages for lower and upper Hibernia Formation strata, respectively. Most Hibernia Formation detrital zircon grains (~70%) were recycled through regionally extensive, upper Paleozoic strata in the Grand Banks region and yield Neoarchean to Paleozoic (2753-281 Ma) U–Pb ages and Cryogenian to Paleozoic (685-252 Ma) FT ages. Detrital zircon double-dating results identified two discrete exhumation-cooling phases in the Grand Banks that corroborate published models for Newfoundland-Iberia rift evolution, including Triassic to Jurassic extensional deformation in the proximal and necking domains and Early Cretaceous crustal breakup, hyperextension, and mantle exhumation in the distal domain. Early Cretaceous magmatic- and exhumation-cooled detrital zircon grains in the Hibernia Formation require syn-depositional magmatism within the north-directed drainage system that fed the southern Jeanne d'Arc basin. That sediment source included thermally-reset Paleozoic cover assemblages or basement in the Avalon Uplift and syn-rift, volcanic-plutonic complexes along the SW Grand Banks transform. In conclusion, we show that syn-rift strata in the proximal domains of Type I non-volcanic margins can record exhumation-related cooling signals and archive magma-poor rift processes globally.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Datasets related to this article can be found in the supplementary materials.

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## Appendix A. Supplementary data

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