Provenance of Upper Jurassic to Lower Cretaceous synrift strata in the Terra Nova oil field, Jeanne d'Arc basin, offshore Newfoundland: A new detrital zircon U-Pb-Hf reference frame for the Atlantic Canadian margin

Alexander D. Hutter and Luke P. Beranek

ABSTRACT

Detrital zircon provenance studies of Terra Nova oil field strata, offshore Newfoundland, were conducted to constrain the depositional age and correlation of synrift sandstone units in the Jeanne d'Arc basin and test continuity with coeval rocks in adjacent regions. Braided fluvial sandstone intervals of the Jeanne d'Arc Formation from delineation wells K-18, C-09, and E-79 yield Mesozoic to Archean detrital zircon U-Pb populations that are consistent across the Terra Nova field. A Tithonian to Berriasian maximum depositional age for the Jeanne d'Arc Formation is proposed from circa 145 Ma detrital zircon grains in each of the nine sandstone samples analyzed. Tithonian to Berriasian detrital zircon grains have chondritic to superchrondritic Hf isotope compositions and indicate that synrift drainage systems carved valleys into the existing landscape during mantle-derived volcanism. Polycyclic Paleozoic to Archean detrital zircon grains were derived from mature, upper Paleozoic sedimentary rocks of the Avalon uplift south-southwest of the Jeanne d'Arc basin and have original provenance from the Newfoundland Appalachians, Canadian shield, and Iberia. Coeval synrift fluvial strata from the frontier Flemish Pass basin yield analogous Tithonian to Berriasian and Paleozoic to Archean detrital zircon populations and suggest

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DATASHARE 124

Tables S1 and S2 are available in an electronic version on the AAPG website (www.aapg.org/datashare) as Datashare 124.

potential Late Jurassic to Early Cretaceous continuity with Jeanne d'Arc basin units. Tithonian to Berriasian deltaic strata of the Scotian basin, southwest of the southwest Grand Banks fault zone, lack Mesozoic detrital zircon grains typical of Grand Banks basins and demonstrate that regional faulting and igneous activity controlled Late Jurassic to Early Cretaceous drainage patterns along the nascent Atlantic Canadian margin.

INTRODUCTION

Sandstone provenance studies have far-reaching impact on petroleum exploration and production (Smyth et al., 2014), including the reconstruction of sediment dispersal patterns, diagenesis and reservoir quality, reservoir continuity, and regional- to continent-scale basin models (e.g., Tobin and Schwarzer, 2014; Benyon et al., 2016; Fleming et al., 2016; Sharman et al., 2017; Klausen et al., 2018). Establishing sediment provenance reference frames can furthermore aid in the stratigraphic correlation of known reservoir units with lesser-studied rocks in frontier basins (e.g., Mange and Wright, 2007; Ratcliffe and Zaitlin, 2010). Provenance studies encompass a variety of techniques such as mineral–chemical stratigraphy (e.g., Hurst and Morton, 2014), heavy mineral assemblages (e.g., Pindell et al., 2009), bulk geochemistry (e.g., Pe-Piper et al., 2008), and geochronological and geochemical analyses of accessory minerals (e.g., Fedo et al., 2003; Link et al., 2005; Lundmark et al., 2014; Pe-Piper et al., 2014; Liu et al., 2017). Detrital zircon is often used to constrain sandstone provenance because it is highly resistant to chemical weathering and yields robust U-Pb ages (McLennan et al., 2001; Hawkesworth and Kemp, 2006; Dickinson et al., 2009; Thomas, 2011). Zircon also incorporates Hf isotopes during crystallization, which can be used to distinguish various crust-mantle sources (e.g., Augustsson et al., 2006; Gehrels, 2012; Beranek et al., 2013).

The Jeanne d'Arc basin is a 10,000-km^2- (~3800-mi^2) asymmetric rift basin located in the Grand Banks, approximately 300 km (~186 mi) east of St. John's, Newfoundland (Figure 1A). It is a prolific hydrocarbon province that includes the Terra Nova, Hibernia, Hebron, and White Rose oil fields (Figure 1B; Tankard and Welsink, 1987; DeSilva, 1999; Mann et al., 2003). As of August 26, 2019, these fields have produced over 1.8 billion bbl, with proven reserves of approximately 1 billion bbl (Canada-Newfoundland and Labrador Offshore Petroleum Board, 2019a). Although offshore oil production along the Newfoundland margin began in 1997, important questions about the origin and continuity of synrift sandstone units with respect to the timing of Mesozoic magmatism and basin development remain unanswered.

The Grand Banks underwent more than 100 m.y. of episodic extension prior to final continental breakup during the late Mesozoic (Lavier and Manatschal, 2006; Tucholke et al., 2007; Tucholke and Sibuet, 2007). Continental extension resulted in Jurassic to Cretaceous rift successions (Figure 2A) and more poorly constrained volcanic-intrusive assemblages (e.g., Helwig et al., 1974; Jansa and Pe-Piper, 1988; Sinclair, 1988). Jurassic to Cretaceous subsidence trends in the Jeanne d'Arc and related basins (e.g., Hiscott et al., 1990; Williams et al., 1999) broadly mark the timing of rift flank exhumation and resultant synrift deposition, which likely controlled the distribution of reservoir rocks in the Grand Banks (Sinclair, 1988; Sinclair et al., 1992) and outboard areas to the east. The central ridge (Figure 1B), a basement-cored horst, currently separates the Jeanne d'Arc and Flemish Pass basins (e.g., Cody et al., 2012). Upper Jurassic to Lower Cretaceous synrift sandstones of the Flemish Pass basin contain economic hydrocarbon accumulations and appear analogous to producing reservoirs in the Grand Banks (Lowe et al., 2011), suggesting shared provenance during the mid- to late Mesozoic.

New provenance studies of Jeanne d'Arc basin sandstones are required to test and develop models for Mesozoic synrift deposition along the Atlantic Canadian margin. In this paper, we use the novel laser ablation split-stream technique (e.g., Fisher et al., 2014), which features the simultaneous collection of U-Pb and Hf isotopes, to constrain the detrital zircon provenance of Upper Jurassic to Lower Cretaceous Jeanne d'Arc Formation sandstone units from three delineation wells across the Terra Nova oil field. The principal goals of this study are threefold: (1) constrain the sources of Jeanne d'Arc Formation strata, (2) use the youngest detrital zircon U-Pb population in each sample to further constrain the depositional age of the Jeanne d'Arc Formation and investigate the timing of Late Jurassic to Early Cretaceous synrift magmatism in the Grand Banks, and (3) establish

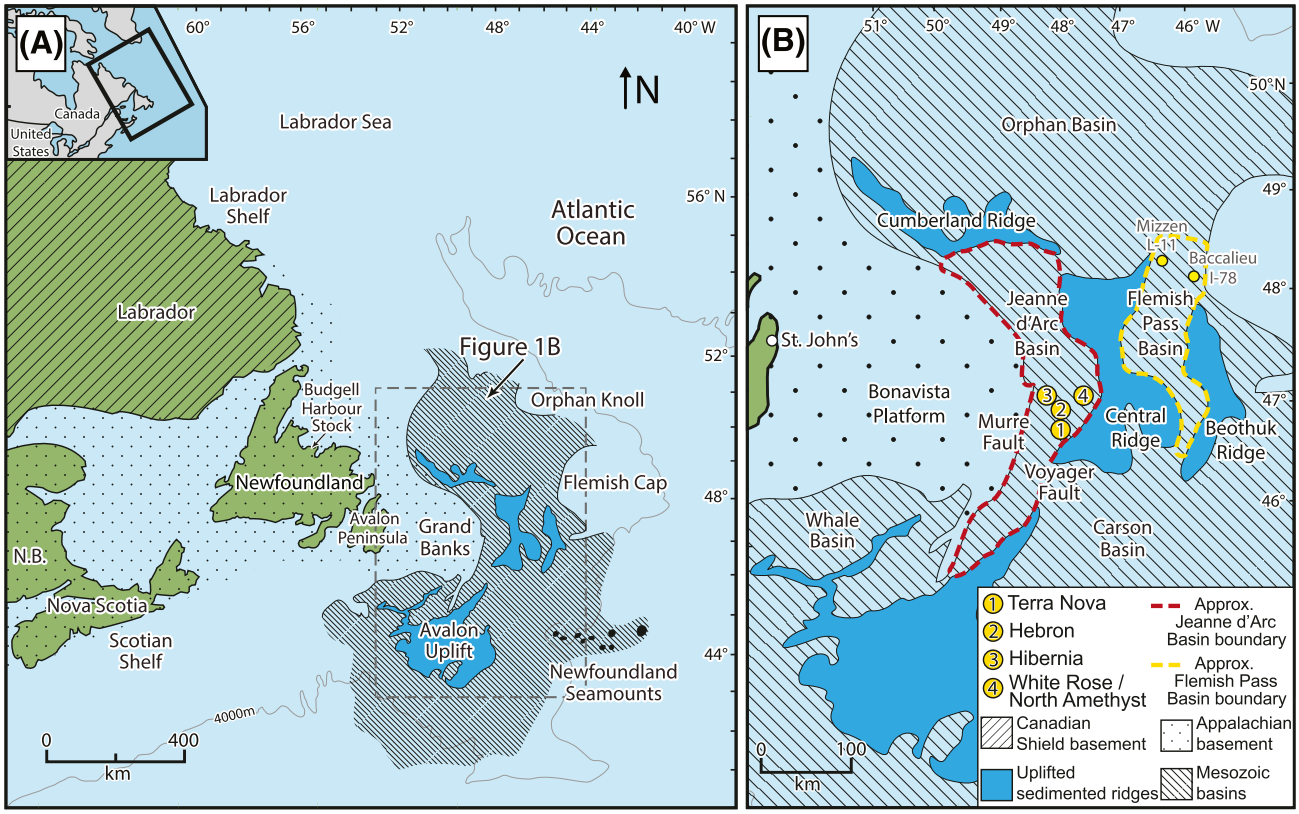

Figure 1. (A) Regional map of Atlantic Canada and Mesozoic basins in the Grand Banks modified from McAlpine (1990), courtesy of Geological Survey of Canada. (B) Location map of the Jeanne d'Arc basin, Flemish Pass basin, and uplifted basement ridges along the Newfoundland margin. Producing oil fields in the Jeanne d'Arc basin are numbered 1–4 (see explanation). Approx. = approximate; N.B. = New Brunswick.

reliable and reproducible U-Pb-Hf isotope reference frames for the Jeanne d'Arc basin that can be used to correlate similar sandstones in the frontier Flemish Pass basin and better constrain the paleogeography of Atlantic Canada.

GEOLOGICAL BACKGROUND

North Atlantic Rift Evolution

The Newfoundland margin is dominated by the Grand Banks, a broad, shallow-water shelf underlain by thick (27–35 km) continental crust that hosts Mesozoic rift basins (Figure 1A; e.g., Reid and Keen, 1990; Tucholke et al., 2007). The North Atlantic rift generally developed in Precambrian-Paleozoic terranes that accreted during the closing of the Iapetus and Rheic oceans (e.g., Nance and Linnemann, 2008; Hatcher, 2010). Along the northeastern Canadian margin, these terranes comprise the Dunnage, Gander, and Avalon zones of the Newfoundland Appalachians and successively accreted during the Early to Middle Ordovician Taconic, early Silurian Salinic, and Devonian Acadian orogenies, respectively (Figure 1A; Williams and Hatcher, 1982; van Staal et al., 1998). The Dunnage and Gander zones underlie central Newfoundland, whereas the Avalon zone underlies most of the Grand Banks platform and eastern Newfoundland, including its type area, the Avalon Peninsula (Figure 1A; Tankard and Welsink, 1989; van Staal and Barr, 2012). Paleozoic orogenic events along the Appalachian margin resulted in structural heterogeneities and discontinuities that generated planes of weakness for reactivation during later Mesozoic rifting (e.g., Manatschal et al., 2015).

The opening of the North Atlantic Ocean was driven by multiphase extension beginning in the Late Triassic and leading to lithospheric breakup in the mid-Cretaceous (Welsink et al., 1989; Tucholke et al., 2007). Continental rifting between the Grand Banks and Iberia was manifested by northwest-southeast

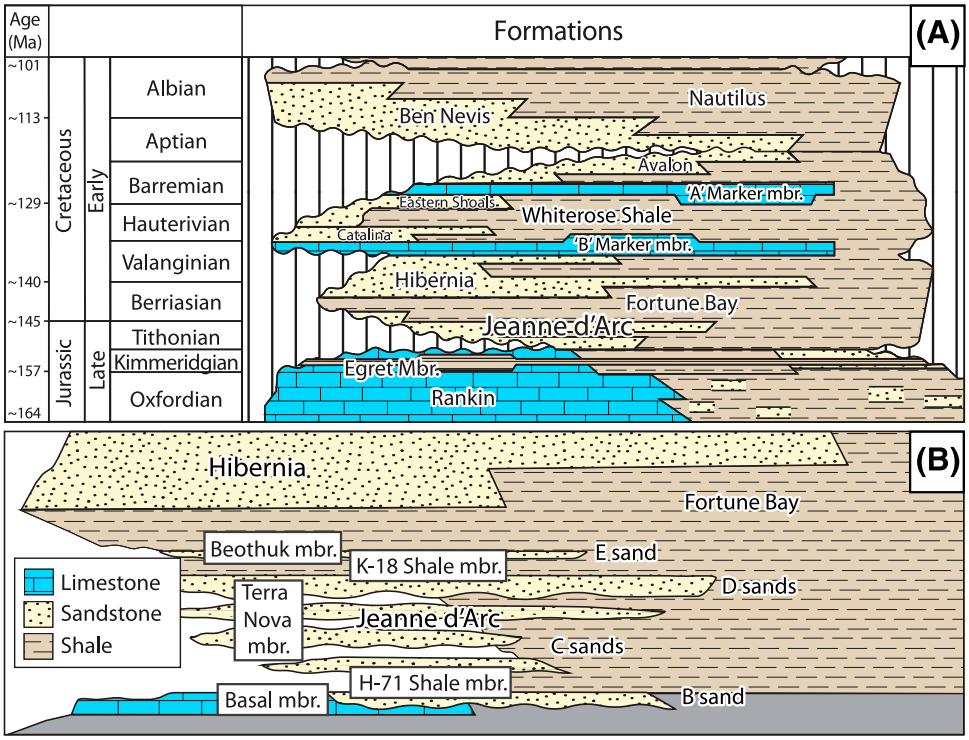

Figure 2. (A) Upper Jurassic to Lower Cretaceous stratigraphy of the Jeanne d'Arc basin compiled from Sinclair et al. (1992). The chronostratigraphic chart follows the time scale of Cohen et al. (2013). (B) Terra Nova field stratigraphy compiled from Skaug et al. (2001) and Sinclair et al. (2014). Mbr. and mbr. = Member.

extension during the Late Triassic to Early Jurassic (Tankard and Welsink, 1989; Grant and McAlpine, 1990). This early phase of crustal stretching led to the opening of continental rift graben basins along both margins (e.g., Newfoundland: Jeanne d'Arc, Flemish Pass, and Carson basins; Iberia: Lusitanian and Galicia Interior basins). The Grand Banks underwent a period of thermal subsidence before rifting propagated northward, causing east-west extension between northeast Newfoundland and western Europe during the Late Jurassic to Early Cretaceous (Tucholke et al., 2007). This thermal subsidence, and the formation of crustal thinning faults, resulted in the deepening of existing Grand Banks rift basins (Tankard and Welsink, 1989; Lavier and Manatschal, 2006). The locus of extension continued to migrate outboard from the proximal to distal margin until Aptian–Albian lithospheric breakup (Tucholke et al., 2007; Péron-Pinvidic et al., 2013). Although the Newfoundland–Iberia conjugate margins are archetypal nonvolcanic or magma-poor rift margins (e.g., Péron-Pinvidic et al., 2013), Mesozoic magmatism is recognized throughout this sector of the North Atlantic. Igneous rocks that generated during rift, breakup, and postbreakup tectonism have been recognized along the Newfoundland and Iberian conjugate margins (Pe-Piper et al., 1994, 2007; Jagoutz et al., 2007). Upper Jurassic to Lower Cretaceous strata of the Flemish Pass basin yield syndepositional detrital zircon age populations and indicate ongoing volcanic activity during rift-related tectonism and deposition (Lowe et al., 2011; McDonough et al., 2011).

Jeanne d'Arc Basin

Mesozoic extension resulted in interconnected and economically significant rift basins along the Atlantic Canadian margin (e.g., Grant and McAlpine, 1990). In particular, the Jeanne d'Arc basin has emerged as an important hydrocarbon province in the past decades (Sinclair, 1988; Tankard and Welsink, 1989; Sinclair et al., 1992). The Jeanne d'Arc basin is bounded to the north by the Cumberland ridge and West Orphan basin, the west by the Bonavista platform and Murre fault system, and the south by stratigraphic pinch-outs (Figure 1B; Tankard and Welsink, 1989; Sinclair et al., 1992). The central ridge and Voyager

fault system form its eastern boundary and partially separate it from the Flemish Pass basin, although prior to Early to mid-Cretaceous uplift, these depocenters may have formed a continuous regional basin (Jansa and Wade, 1975). Apart from the southwest-northeast listric faults that formed by initial stretching and thinning, a second trend of northwest-southeast cross-basin transfer faults accommodated extension during the Early to mid-Cretaceous (Welsink and Tankard, 2012). Both fault trends terminate below the upper Albian-Cenomanian unconformity, suggesting that the basin structure was established prior to the Late Cretaceous (Sinclair et al., 1992).

Jeanne d'Arc Formation

The Jeanne d'Arc basin contains up to 18 km (11 mi) of prerift, synrift, and postrift strata (Tankard and Welsink, 1987). Petroleum resources throughout the basin were generated from the Kimmeridgian Rankin Formation and accumulated in the Jeanne d'Arc, Hibernia, and Ben Nevis/Avalon Formations (Figure 2A; McAlpine, 1990; Sinclair et al., 1992). The Jurassic to Cretaceous stratigraphic evolution of the Jeanne d'Arc basin is reviewed by several studies (e.g., Sinclair, 1988; Hiscott et al., 1990; Shannon et al., 1995); the Jeanne d'Arc Formation is the producing reservoir unit in the Terra Nova field (Figure 2A, B) and the focus of this study.

The Jeanne d'Arc Formation records the first episode of coarse, synrift sedimentation in the Jeanne d'Arc basin (McAlpine, 1990). Using a sensu anglico interpretation for the Late Jurassic (a longer Kimmeridgian Stage and Portlandian Stage), biostratigraphic correlations based on dinoflagellate cysts, spores, and pollen indicate a mid-Kimmeridgian depositional age for the Jeanne d'Arc Formation type section in the Terra Nova K-18 well (Williams, 2003). In contrast, interfluve facies of the Jeanne d'Arc Formation yield micro- and macrofossils that correlate with ammonoid zones of early (*elegans*, *wheatleyensis*, *hudlestoni* zones; ca. 152–150 Ma), mid- (*fittoni* zone; ca. 148 Ma), and late (*anguiformis*, *oppressus?* zones; ca. 147–146 Ma) Tithonian age using a sensu gallico interpretation (a shorter Kimmeridgian Stage and Tithonian Stage) for the Late Jurassic (Sinclair, 1988; Wilcox et al., 1991; Sinclair et al., 1992, 2014; all numerical ages follow the time scale of Cohen et al., 2013). The overlying Hibernia Formation was deposited during the Berriasian to Valanginian Stages of the Early Cretaceous (Hurley et al., 1992).

Five informal members have been assigned to the Jeanne d'Arc Formation (Figure 2B; e.g., Shannon et al., 1995): (1) a basal member of laterally variable, lacustrine to restricted marine mudstone, fluvial to shallow-marine sandstone, and conglomerate units that locally overlie the Rankin Formation; (2) the H-71 shale member (named for its occurrence in North Trinity H-71), which consists of lacustrine mudstone, debris flow conglomerate, and thin sandstone beds that locally overlie the Rankin Formation; (3) the Terra Nova member, a succession of stacked and amalgamated fluvial sandstones with interbedded lacustrine mudstone and fan-delta conglomerate units; (4) the K-18 shale member (named for its occurrence in Terra Nova K-18), which contains fluvial sandstone and lacustrine mudstone units with local evidence of paleosol development; and (5) the Beothuk member, a succession of fluvial sandstone and mudstone units capped by a maximum flooding surface.

Synrift sandstone units of the Jeanne d'Arc Formation were deposited by axial, low-sinuosity fluvial systems that filled 0.5–5-km (0.3–3 mi)-wide incised valleys during fault-controlled subsidence (McAlpine, 1990; Shannon et al., 1995; Knight et al., 1998; Williams et al., 1999). Sandstone successions that lack sedimentary structures were rapidly deposited in aggrading and shifting channels proximal to the braid plain, whereas cross-stratified sands indicate a slower rate of deposition and are associated with greater distance from the braid plain (Wilcox et al., 1991). Fluvial deposits are quartz rich and mostly sourced from sedimentary rocks in upstream areas to the south-southwest, including Carboniferous–Jurassic strata of the Avalon uplift (Figure 1A; e.g., Sinclair et al., 2014); some gravelly fan-delta and debris flow deposits were sourced from transverse drainages to the southeast along the basin margin (e.g., Wilcox et al., 1991; Wishart et al., 2000).

Terra Nova Field

The Terra Nova field is located in the southeastern Jeanne d'Arc basin, 350 km (217 mi) east-southeast of St. John's, Newfoundland (Figure 1B). It was discovered in 1984 and produced first oil in January

2002. As of August 2019, the field produced 421 million bbl (Canada-Newfoundland and Labrador Offshore Petroleum Board, 2019a). The Terra Nova field is bounded to the east and west by high-angle normal faults, the north by the transbasin Trinity fault, and the south by a stratigraphic pinch-out of the Jeanne d'Arc Formation (Wilcox et al., 1991; Wishart et al., 2000; Richards et al., 2010). A series of north-trending normal faults compartmentalize the field into four fault blocks: the west flank, graben, east flank, and far east (Figure 3A, B).

Operators in the Terra Nova field have named individual sandstone units of the Jeanne d'Arc Formation (Figure 2B; Wilcox et al., 1991; Skaug et al., 2001; Richards et al., 2010; Sinclair et al., 2014). Although the exact number and designation vary by author, the general stratigraphy consists of (1) the B sand, which corresponds with the basal member

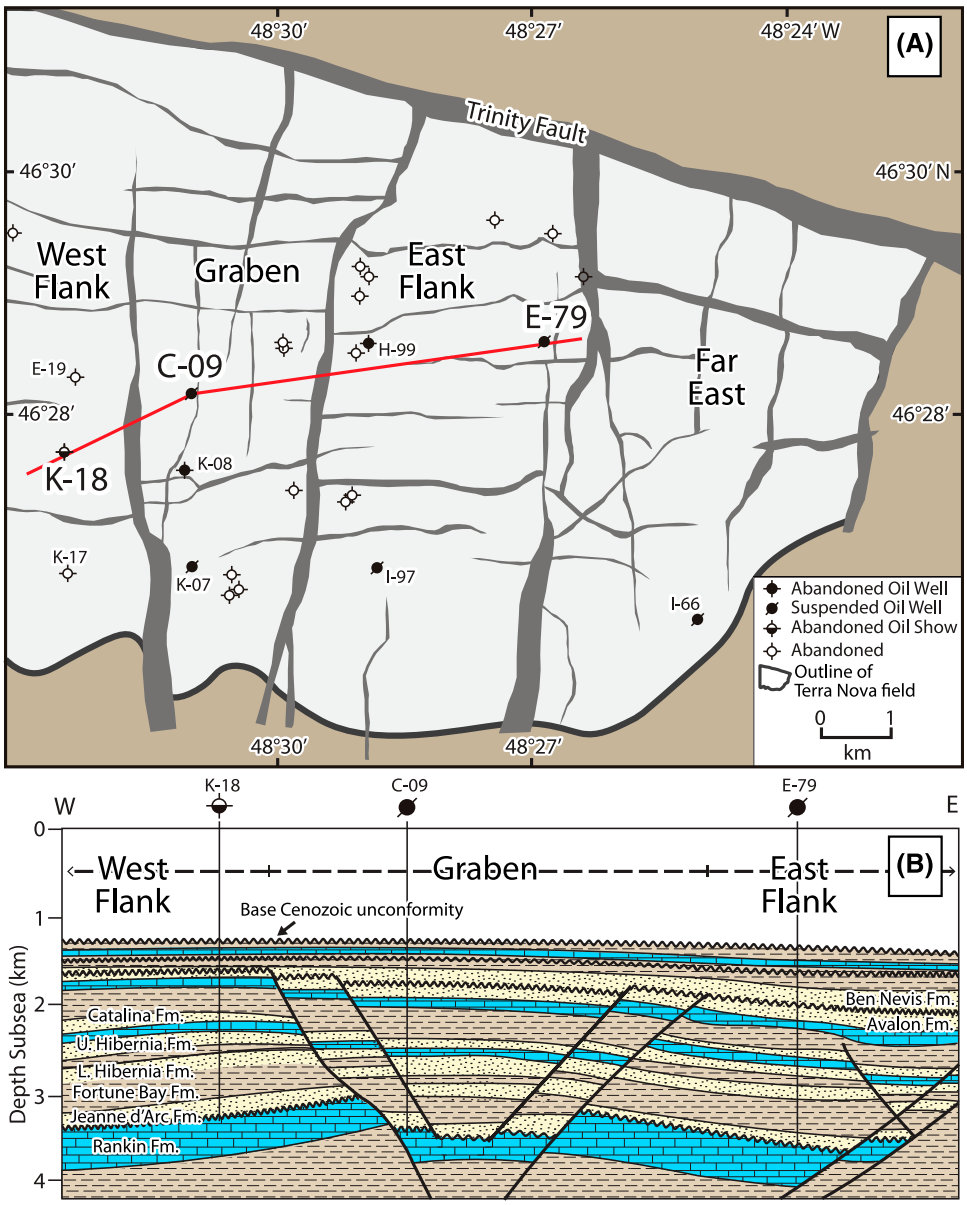

Figure 3. (A) Schematic map of the Terra Nova oil field, Jeanne d'Arc basin, modified from the Canada-Newfoundland and Labrador Offshore Petroleum Board (2019b). Delineation wells K-18, C-09, and E-79 are located along the west to east transect (red line) across the compartments of the Terra Nova field. (B) Schematic cross section of the west flank, graben, and east flank areas of the Terra Nova field modified from Wilcox et al. (1991). Fm. = Formation; L = lower; U = upper.

above the Rankin Formation; (2) the C and D sands, which host 88% of the Terra Nova resource and comprise the stacked braided fluvial units of the Terra Nova member; and (3) the E sand, which is equivalent to the Beothuk member.

MATERIALS AND METHODS

Nine sandstone samples were collected from cored sections of the Terra Nova K-18, C-09, and E-79 delineation wells at the Canada-Newfoundland and Labrador Offshore Petroleum Board Core Storage and Research Centre in St. John's (Figure 4; Table 1). Eight samples were taken from stacked fluvial facies of the Terra Nova member (six C sands, two D sands); one sample was selected from the Beothuk member (E sand). The U-Pb results were compared with the ages of Mesozoic to Archean rock units in North America (Figure 5A, B) and are shown in normalized probability density plots (Figures 6–9) prepared with an Excel macro developed at the Arizona LaserChron Center (www.geo.arizona.edu/alc). Age-corrected or initial $^{176}Hf/^{177}Hf$ ratios are reported as $\varepsilon_{Hf(i)}$ values and represent isotopic compositions at the time of crystallization relative to the chondritic uniform reservoir (CHUR). The $\varepsilon_{Hf(i)}$ versus U-Pb age plots show the depleted mantle array (Vervoort and Blichert-Toft, 1999) and crustal evolution lines that use $^{176}Lu/^{177}Hf = 0.015$ (Goodge and Vervoort, 2006).

The youngest detrital zircon grain populations were statistically evaluated to determine the maximum depositional age of Terra Nova field strata and compare with existing fossil constraints from the greater Jeanne d'Arc Formation. Individual detrital zircon grains can have variable statistical uncertainties and complex U-Pb isotope systematics, and therefore a combination of methods is used to define reliable and informative maximum depositional age results (Dickinson and Gehrels, 2009). Four methods (see Dickinson and Gehrels, 2009) were used to calculate maximum depositional ages of the Jeanne d'Arc Formation: (1) the Weighted Average routine in Isoplot (Ludwig, 2003), which is the most statistically robust method, calculates the weighted mean age of the youngest cluster of three or more grain ages that overlap at 2σ uncertainty (the weighted mean of two overlapping ages was calculated when the youngest cluster did not contain at least three ages); (2) the Age Pick macro (Arizona Laserchron Center), which reports the weighted mean age of all age clusters with three or more overlapping ages at 2σ; (3) the TuffZirc routine in Isoplot (Ludwig, 2003), which calculates the age of the youngest mode and assumes that dates on the shoulder result from analytical uncertainty (TuffZirc requires the youngest population to have at least six grains and thus is not reported for samples that do not meet this requirement); and (4) the youngest graphical mode on a normalized probability density plot.

RESULTS

Detrital Zircon U-Pb Geochronology

Laser ablation split-stream analysis yielded 921 U-Pb ages that passed data-filtering protocols (76–117 grains per sample; see Tables S1 and S2 [supplementary material available as AAPG Datashare 124 at www.aapg.org/datashare]). The nine Jeanne d'Arc Formation sandstone samples exhibit analogous Archean (>2500 Ma), Proterozoic (2200–2000, 2000–920, 760–550 Ma), Paleozoic (540–280 Ma), and Mesozoic (159–137 Ma) detrital zircon U-Pb age populations regardless of lithology, stratigraphic position, or geographic location in the Terra Nova field (Figures 6–8). The number of grains that make up each individual U-Pb age population, however, varies according to these parameters. Very fine– to fine-grained quartzarenite to sublithic arenite samples (C sands; lower Terra Nova member) contain approximately 5% more 920- to 2000-Ma detrital zircon grains than coarser-grained and more poorly sorted samples of the Jeanne d'Arc sample suite. Jurassic–Cretaceous (159–137 Ma) detrital zircon grains are generally 4% greater in the D sand (upper Terra Nova member) units. The youngest sandstone unit (E sand; Beothuk member) yields approximately 4% less 139–159 Ma and 550–760 Ma and approximately 8% more greater than 2000 Ma detrital zircon grains than underlying C and D sands.

Detrital Zircon Hf Isotope Geochemistry

The Hf isotope results of dated zircon grains show a continuous range from superchrondritic to subchondritic (depleted mantle- to evolved crust-like values; e.g.,

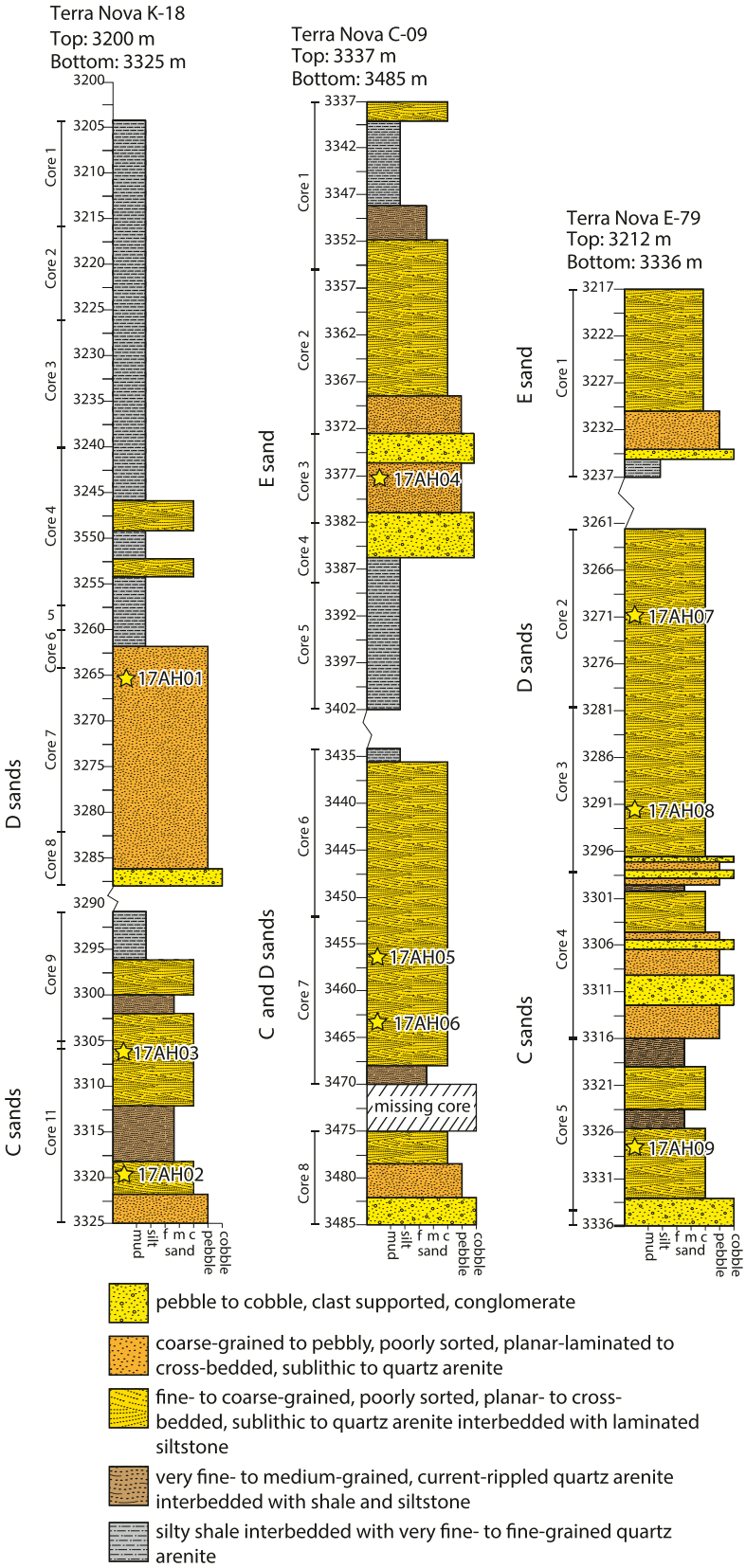

Figure 4. Jeanne d'Arc Formation stratigraphy and detrital zircon sample locations in Terra Nova wells K-18, C-09, and E-79. Note vertical scale changes between each well. f = fine; m = medium; c = coarse.

Table 1. Summary of Detrital Zircon Samples Collected from Terra Nova Field

Sample	Well	Core Depth, m	Member	Sand	Lithology
17AH01	K-18	3265–3271, box 7	Terra Nova	D	Medium- to coarse-grained, subrounded to rounded, moderately to well-sorted, planar cross-bedded to massive, lithic to sublithic arenite
17AH03	K-18	3306–3311, box 11	Terra Nova	C	Very fine– to fine-grained, subrounded to rounded, moderately to well-sorted, planar cross-bedded, quartzarenite
17AH02	K-18	3317–3323, box 11	Terra Nova	C	Fine-grained, subrounded to rounded, well-sorted, parallel laminated to planar cross-bedded to massive, quartzarenite
17AH04	C-09	3380–3381, box 3	Beothuk	E	Fine- to coarse-grained, subangular to subrounded, poorly to moderately sorted, massive to normally graded, sublithic arenite
17AH05	C-09	3457–3459, box 7	Terra Nova	C	Fine- to medium-grained, subangular to subrounded, moderately to well-sorted, planar cross-bedded, sublithic arenite
17AH06	C-09	3465–3468, box 7	Terra Nova	C	Fine- to medium-grained to pebbly, subangular to subrounded, poorly to moderately sorted, massive to normally graded, sublithic arenite
17AH07	E-79	3268–3270, box 2	Terra Nova	D	Fine- to medium-grained, subangular to subrounded, moderately to well-sorted, planar cross-bedded to massive, sublithic arenite
17AH08	E-79	3291–3293, box 3	Terra Nova	C	Fine- to medium-grained, subangular to subrounded, moderately to well-sorted, planar cross-bedded to massive, sublithic arenite
17AH09	E-79	3328–3330, box 5	Terra Nova	C	Fine- to medium-grained, subangular to subrounded, moderately to well-sorted, massive, sublithic arenite

$\varepsilon_{Hf[i]}$ = +10 to −10) or superchondritic to chondritic to slightly subchondritic (depleted mantle- to CHUR-like values; e.g., $\varepsilon_{Hf[i]}$ = +8 to −3) compositions that are indicated by vertical age arrays in Figures 6–8. superchrondritic to subchondritic Hf isotope arrays are illustrated by Archean to Paleozoic U-Pb age populations circa 2700, 1800, 1400–1300, 620, and 430 Ma, whereas superchondritic to chondritic to slightly subchondritic Hf isotope arrays are shown by Proterozoic to Mesozoic U-Pb age populations circa 1650, 1300–960, 380–340, and 159–137 Ma.

Maximum Depositional Ages

Table 2 shows the maximum depositional age calculations for the Jeanne d'Arc Formation. Seven of the nine ages calculated with the statistically robust weighted mean age routine yielded overlapping Late Jurassic to Early Cretaceous results for the Terra Nova and Beothuk members (C, D, and E sands) of 145 ± 1 Ma to 145 ± 5 Ma (145.0 Ma is the Tithonian–Berriasian boundary; Cohen et al., 2013); the two remaining samples yielded weighted mean ages of 142 ± 1 Ma and 144 ± 17 Ma. The Age Pick macro calculated 145–147 Ma ages for six of the nine samples, whereas the other three returned Devonian (358–394 Ma) ages. The TuffZirc routine was suitable for five samples and returned overlapping 145–146 Ma ages for the Terra Nova and Beothuk members. The youngest graphical peak in a normalized probability plot returned ages of 144–146 Ma for eight samples and 141 Ma for one C sand sample. Upper Jurassic to Lower Cretaceous zircon grains in the Jeanne d'Arc Formation have a range of angular to subrounded morphologies that apparently show no correlation with U-Pb age.

DETRITAL ZIRCON PROVENANCE INTERPRETATIONS

Archean to Early Neoproterozoic Age Populations

Archean to early Neoproterozoic detrital zircon grains (22%–49% of each sample, $\bar{X}$ [mean] = 39%) are interpreted to have original provenance from Precambrian basement rocks (Table 3). Archean populations (>2500 Ma) match the ages of magmatism in the Superior, Nain, and related cratons of North America (e.g., Hoffman et al., 1989; Scott, 1995), whereas early Paleoproterozoic (2200–2000 Ma) age populations are rare in Laurentia (Hoffman, 1988) and suggest West Gondwana craton sources (e.g., Willner et al., 2013) that were recycled

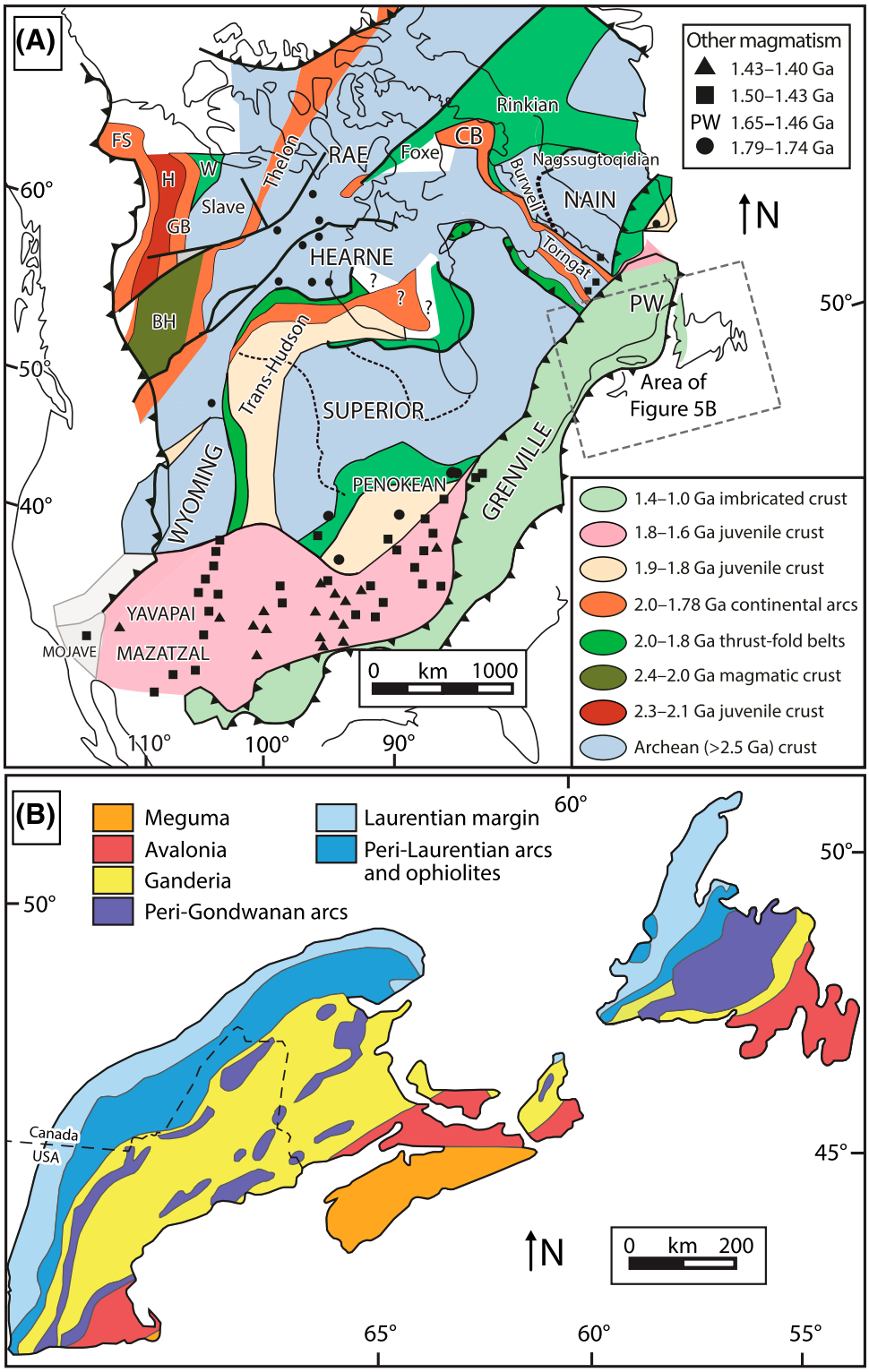

Figure 5. (A) Precambrian basement domains of the Laurentian craton modified from Ross and Villeneuve (2003) and Whitmeyer and Karlstrom (2007). (B) Proterozoic to Paleozoic basement domains of the northern Canadian Appalachians modified from Hibbard et al. (2006), courtesy of Geological Survey of Canada. BH = Buffalo Head terrane; CB = Cumberland batholith; FS = Fort Simpson magmatic arc; H = Hottah terrane; PW = Pinware terrane; W = Wopmay orogen.

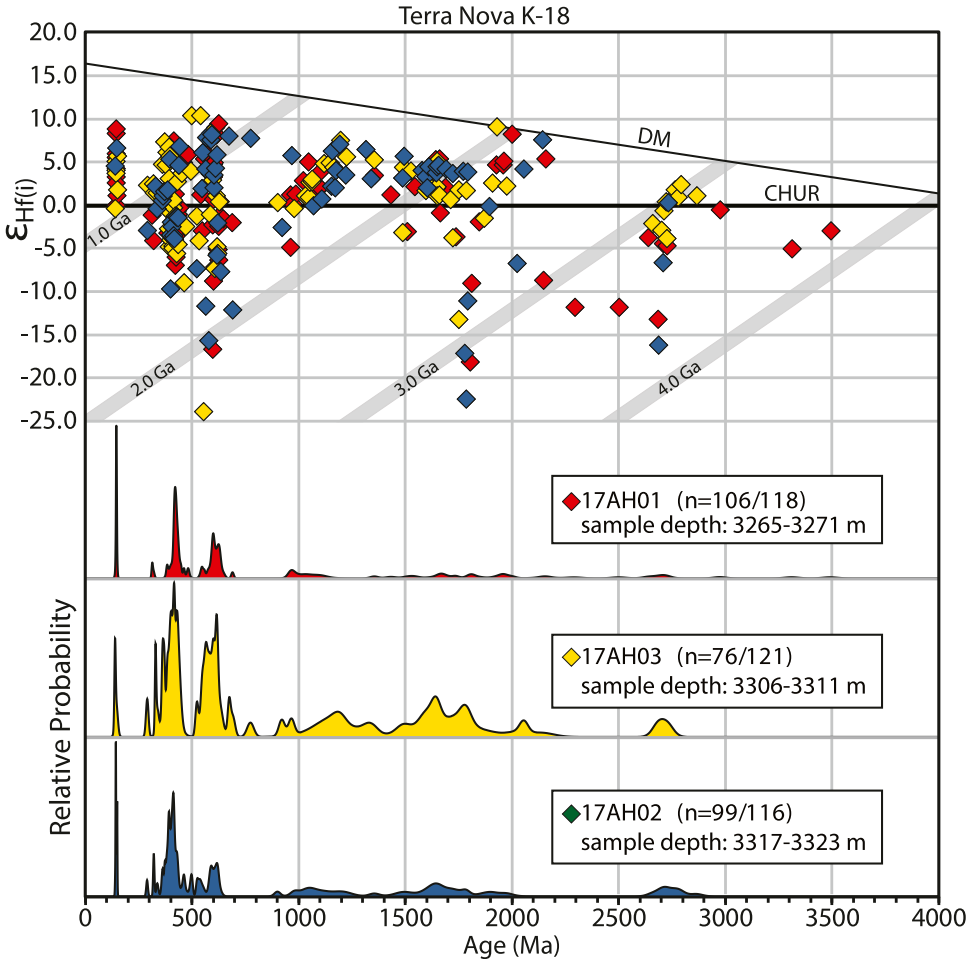

Figure 6. Terra Nova K-18 detrital zircon U-Pb-Hf results for sample 17AH01 lithic to sublithic arenite, sample 17AH03 quartz arenite, and sample 17AH02 quartz arenite. The number of detrital zircon grains that passed data filtering protocols relative to the total number of analyses for each sample is shown with sample information. For example, 106 of 118 detrital zircon grains from sample 17AH01 were less than 10% discordant and were used for interpretation purposes. See Appendix for supporting information. εHf(i) = the initial Hf isotope composition relative to the chondritic uniform reservoir (CHUR); DM = depleted mantle.

through peri-Gondwanan terranes in the Canadian Appalachians. Late Paleoproterozoic detrital zircon ages are consistent with derivation from circa 2000–1800 Ma rocks in the Torngat, New Quebec, Trans-Hudson, and Penokean orogens (Hoffman et al., 1989; Whitmeyer and Karlstrom, 2007). The Grenville orogen was the culmination of Paleoproterozoic to early Neoproterozoic subduction-accretion processes along eastern Laurentia and is characterized by circa 1700–920 Ma rocks (e.g., Rivers, 1997) and detrital zircon ages (e.g., Rainbird et al., 2017). The Long Range inlier is the largest exposure of Grenville basement in the Newfoundland Appalachians and contains circa 1630–1250 Ma gneiss units that are intruded by 1030–985 Ma granitoid plutons (e.g., Gower et al., 1991; Heaman et al., 2002). Ediacaran to lower Paleozoic strata in the Humber zone of western Newfoundland yield recycled detrital zircon grains that were originally sourced from the Long Range inlier and other Precambrian basement domains, including Iapetan rift margin strata with 2850–2600, 1950–1750, and 1450–950 Ma age populations (e.g., Cawood and Nemchin, 2001).

Neoproterozoic to Earliest Paleozoic Age Populations

Neoproterozoic to earliest Paleozoic detrital zircon grains (13%–32% of each sample, $\bar{X}$ = 21%) are interpreted to have provenance from peri-Gondwanan

Table 2. Calculated Maximum Depositional Ages for Jeanne d'Arc Formation Strata

Sample	Weighted Mean Age, Ma	Age Pick, Ma	TuffZirc, Ma	Youngest Graphical Peak, Ma
17AH01	145 ± 1 (n = 7)	145 (n = 10)	145 +2/−1 (n = 10)	145
17AH03	142 ± 3 (n = 2)	370 (n = 3)	–	141
17AH02	145 ± 2 (n = 4)	145 (n = 4)	145 ± 1 (n = 4)	145
17AH04	145 ± 1 (n = 2)	358 (n = 3)	–	144
17AH05	144 ± 17 (n = 2)	394 (n = 10)	–	144
17AH06	145 ± 1 (n = 8)	147 (n = 13)	146 +1/−2 (n = 12)	146
17AH07	145 ± 1 (n = 9)	145 (n = 13)	146 ± 1 (n = 11)	145
17AH08	145 ± 1 (n = 8)	145 (n = 8)	145 ± 1 (n = 8)	145
17AH09	145 ± 5 (n = 3)	145 (n = 4)	–	145

Abbreviation: – = not applicable.

arc successions and their adjacent basins in the Canadian Appalachians (Table 3). Primary sources in eastern Newfoundland (e.g., Krogh et al., 1988; Tucker and McKerrow, 1995; O'Brien et al., 1996; Murphy et al., 2008) and Nova Scotia (e.g., Barr et al., 1990, 2012; Keppie et al., 1998; Murphy et al., 2004) include circa 763–730, 680–620, and 580–550 Ma igneous complexes of Avalonia. Most Avalonian magmatic rocks have superchondritic Nd-Hf isotopic signatures (e.g., Pollock et al., 2015), but some intrusive suites yield subchondritic compositions that indicate contributions from evolved crust (Kerr et al., 1995). Neoproterozoic–lower Paleozoic strata in Avalonia similarly have superchondritic to chondritic 760–550 Ma detrital zircon grains with only minor excursions to highly negative $\varepsilon_{Hf(i)}$ values (Willner et al., 2013; Pollock et al., 2015).

Early to Late Paleozoic Age Populations

Early to late Paleozoic detrital zircon grains (22%–40% of each sample, $\bar{X}$ = 33%) are interpreted to have provenance from Appalachian–Variscan magmatic rocks and related sedimentary basins in the North Atlantic region (Table 3). Primary Appalachian sources in central Newfoundland (e.g., Chorlton and Dallmeyer, 1986; Dunning et al., 1990; O'Brien et al., 1991; Valverde-Vaquero et al., 2006; Kellett et al., 2014) and Nova Scotia (e.g., Clarke et al., 1997; Keppie and Krogh, 1999; Kontak et al., 2004) include Cambrian–Devonian rocks of the Dunnage and Gander zones that formed during Taconic, Salinic, and Acadian orogen evolution. Mississippian–Permian igneous rocks are potential sources for circa 360–300 Ma detrital zircon grains in onshore and offshore

Table 3. Summary of Primary and Recycled Detrital Zircon Sources for Jeanne d'Arc Formation Strata

Age Populations	Primary Sources	Potential Recycled Sources in Atlantic Canada
Archean		
>2500 Ma	Superior, North Atlantic, Nain cratons	Iapetan margin sandstones, Appalachian (peri-Laurentian and peri-Gondwanan) terrane cover assemblages
Proterozoic		
2200–2000 Ma	West Gondwanan cratons	Appalachian (peri-Gondwanan) terrane cover assemblages
2000–920 Ma	Torngat, New Quebec, Trans-Hudson,	Iapetan margin sandstones, Appalachian foreland and strike-slip basins, Grenville and related orogens
760–550 Ma	Peri-Gondwanan terranes	Peri-Gondwanan terrane cover assemblages, Appalachian foreland and strike-slip basins
Paleozoic		
540–280 Ma	Appalachian–Variscan igneous suites	Appalachian foreland and strike-slip basins
Mesozoic		
159–137 Ma	North Atlantic rift assemblages	Kimmeridgian to Tithonian strata, Grand Banks

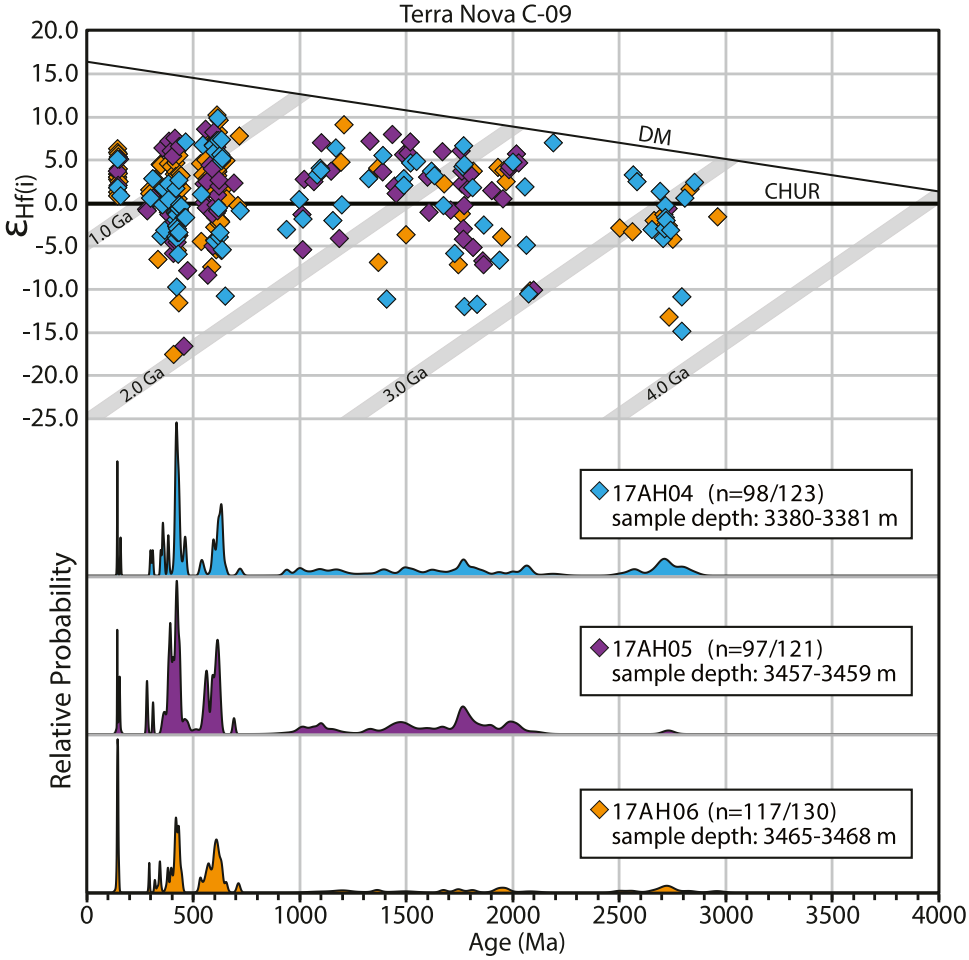

Figure 7. Terra Nova C-09 detrital zircon U-Pb-Hf results for sample 17AH04 sublithic arenite, sample 17AH05 sublithic arenite, and sample 17AH06 sublithic arenite. Sample information and abbreviations follow those explained in Figure 6. εHf(i) = the initial Hf isotope composition relative to the chondritic uniform reservoir (CHUR); DM = depleted mantle.

Nova Scotia (e.g., MacLean et al., 2003; Pe-Piper et al., 2010). Appalachian foreland and strike-slip basin strata yield Paleozoic and older detrital zircons (e.g., Murphy and Hamilton, 2000; Force and Barr, 2013) and represent recycled source areas in Atlantic Canada. Primary sources in the Variscan belt of Portugal and Spain, which would have been proximal to the Jeanne d'Arc basin prior to the onset of Late Cretaceous seafloor spreading, include circa 530 Ma and 490–470 Ma igneous rocks in the central Iberian and Ossa–Morena zones (e.g., Valverde-Vaquero and Dunning, 2000; Solá et al., 2008; Carracedo et al., 2009; Henriques et al., 2015, 2016). Late Pennsylvanian–early Permian zircon grains are minor in the Jeanne d'Arc Formation (n = 23), but 71% are analogous in age to late Variscan (311–286 Ma) granitoids in Iberia (e.g., Fernández-Suárez et al., 2000; Gutiérrez-Alonso et al., 2011) and, by extension, the potential ages of recycled detrital zircon grains in upper Paleozoic foreland basin deposits offshore Newfoundland (e.g., Hiscott et al., 2008).

Mesozoic Age Populations

Late Jurassic to Early Cretaceous detrital zircon grains (3%–13% of each sample, $\bar{X}$ = 7%) are interpreted to have provenance from North Atlantic rift successions (Table 3). Primary or recycled sources that directly correspond to the new Oxfordian to Berriasian detrital zircon ages in the Jeanne d'Arc Formation, however, are uncertain. Published whole-rock K-Ar and fossil constraints in the Avalon uplift region of the Grand Banks include the following: (1) Tithonian to Berriasian mafic rocks, Narwhal F-99 well (e.g., Pe-Piper

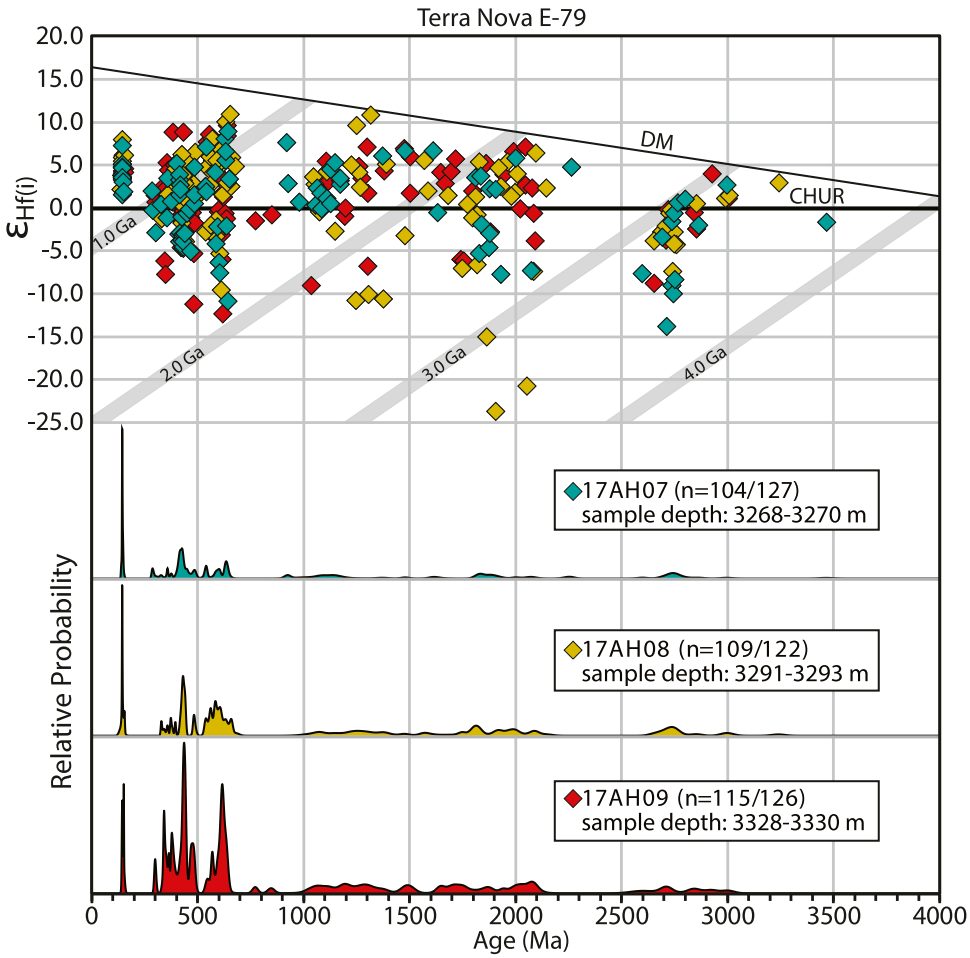

Figure 8. Terra Nova E-79 detrital zircon U-Pb-Hf results for sample 17AH07 sublithic arenite, sample 17AH08 sublithic arenite, and sample 17AH09 sublithic arenite. Sample information and abbreviations follow those explained in Figure 6. εHf(i) = the initial Hf isotope composition relative to the chondritic uniform reservoir (CHUR); DM = depleted mantle.

et al., 2007); (2) Valanginian to Barremian mafic, volcaniclastic, and felsic volcanic rocks with chondritic Nd isotope compositions ($\varepsilon_{Nd[i]}$ = +0.7 to +1.9), Mallard M-45 well (Pe-Piper et al., 1994; Bowman et al., 2012); and (3) Valanginian basalt flows, granophyric granite, and volcaniclastic rocks with chondritic Nd isotope compositions ($\varepsilon_{Nd[i]}$ = +1.0 to +4.9), Brant P-87 well (Pe-Piper et al., 1994; Bowman et al., 2012). Mafic-ultramafic intrusive rocks of the Budgell Harbor stock (Figure 1A) and related lamprophyre dikes that yield Kimmeridgian to Valanginian K-Ar ages (e.g., Helwig et al., 1974; Strong and Harris, 1974) are also known in northeastern Newfoundland. Along the Iberian margin, alkaline mafic rocks in western Portugal yield ages of 147–142 Ma (titanite U-Pb; Grange et al., 2008), and amphibolite units drilled at Ocean Drilling Program sites 1067 and 1068 were dated at 167–140 Ma (hornblende $^{40}Ar/^{39}Ar$) and 142–133 Ma (plagioclase $^{40}Ar/^{39}Ar$; Jagoutz et al., 2007).

DISCUSSION

Depositional Age of the Jeanne d'Arc Formation and Timing of Grand Banks Magmatism

The youngest detrital zircon grains can estimate the maximum depositional age of synrift strata and constrain the timing of syndepositional magmatism (e.g., Cawood and Nemchin, 2001; Cawood et al., 2012). Jeanne d'Arc Formation strata yield overlapping results that confirm Late Jurassic to Early Cretaceous maximum depositional ages for the Terra Nova and Beothuk members (C, D, and E sands) in the Terra Nova

field. Specifically, the youngest detrital zircon grains indicate late Tithonian to early Berriasian boundary ages using the four calculation methods (Table 2), including five samples that returned weighted mean ages of 145 ± 1 Ma and represent the most robust estimate of depositional age. These new radiometric data complement and further refine previous mid- to late Tithonian (ca. 148–146 Ma) age estimates for C, D, and E sand units based on stratigraphic correlations with Boreal ammonoid zones (Sinclair et al., 2014). Compaction-corrected sediment accumulation rates for the sampled C, D, and E sand intervals (Figure 4) are approximately 0–210 m/m.y. (~0.09 to ~0.21 mm/yr) using the new depositional age constraints, which overlap with the estimated values for Mesozoic rift fluvial strata (0.03–0.60 mm/yr) in the eastern United States and maritime Canada (e.g., Schlische and Olsen, 1990).

Whole-rock K-Ar dating studies have mostly identified Valanginian and younger igneous and volcaniclastic rocks in the Grand Banks region (e.g., Pe-Piper et al., 1994). The new Jurassic and Cretaceous detrital zircon ages presented in this paper greatly expand the known duration of igneous activity in the Grand Banks and not only confirm Tithonian to Berriasian (ca. 145 Ma) synrift magmatism during Jeanne d'Arc Formation deposition but also provide evidence for early Tithonian to Kimmeridgian to latest Oxfordian (151–159 Ma) magmatism in the southern Grand Banks. Late Jurassic to Early Cretaceous detrital zircon grains have a restricted range of superchondritic to chondritic Hf isotope compositions, which suggests that their parent igneous rocks had common mantle-crust sources during North Atlantic rift evolution.

From a hydrocarbon exploration prospective, the new results indicate that Tithonian to Berriasian detrital zircon grains are predictable time-stratigraphic markers for at least some oil-bearing Upper Jurassic to Lower Cretaceous strata in the Jeanne d'Arc basin. Tithonian to Berriasian detrital zircon grains are also recognized in Upper Jurassic to Lower Cretaceous strata of the Flemish Pass basin (Lowe et al., 2011; McDonough et al., 2011) and similarly demonstrate that some frontier reservoir units show evidence of syndepositional magmatism. However, Terra Nova field samples yield overlapping maximum depositional ages that show no apparent younging trend upsection (Table 2), and therefore these youngest grains may not be suitable for discriminating intra–Jeanne d'Arc Formation stratigraphy (e.g., Terra Nova versus Beothuk members; C versus D sands). Kimmeridgian strata of the underlying Rankin Formation, which are incised by Jeanne d'Arc Formation fluvial systems in the Terra Nova field, are probable repositories (primary or recycled) of Kimmeridgian and older (ca. 151–159 Ma) detrital zircon grains and predictable time-stratigraphic markers for at least some hydrocarbon source rock successions in the Grand Banks. Future research on Kimmeridgian and older strata in the Jeanne d'Arc basin are warranted to test this hypothesis.

Comparisons with Flemish Pass Basin Sandstone Units, Offshore Newfoundland

The new Jeanne d'Arc Formation data provide the first detrital zircon reference frame for Jeanne d'Arc basin synrift strata and can be used to test connections with coeval and economically prospective rocks in adjacent basins. The Flemish Pass basin is located approximately 400 km (~250 mi) east of St. John's and separated from the Jeanne d'Arc basin by the central ridge basement uplift (Figure 1A; Cody et al., 2012). The Flemish Pass and Jeanne d'Arc basins share a common rift evolution and stratigraphy (Foster and Robinson, 1993) and have similar hydrocarbon systems (e.g., Magoon et al., 2005; Enachescu et al., 2010). Flemish Pass hydrocarbons were generated by Kimmeridgian source rocks equivalent to the Egret Member of the Rankin Formation and accumulated in overlying Upper Jurassic and Lower Cretaceous sandstones. Tithonian braided fluvial sandstone units informally assigned to the Bodhrán Formation are time equivalent to the Jeanne d'Arc Formation based on fossil (Ainsworth et al., 2015) and lithological observations (Haynes et al., 2013) but may have different provenance (e.g., Lowe et al., 2011; McDonough et al., 2011). Lowe et al. (2011) concluded that an east-directed, 400- to 500-km (250–310 mi)-long drainage system delivered Tithonian to Berriasian sediment to the Flemish Pass basin from sources to the west and northwest, including the Dunnage, Gander, and Avalon zones of the Newfoundland Appalachians and upper Paleozoic strata of the northeast Newfoundland shelf.

Figure 9 compares the detrital zircon U-Pb signatures of Jeanne d'Arc Formation (this study) and

Upper Jurassic to Cretaceous rocks from the Flemish Pass basin (Lowe et al., 2011). Although the total number of U-Pb analyses varies between samples, Jeanne d'Arc and Bodhrán Formation strata share Late Jurassic to Early Cretaceous (150–140 Ma), Mississippian (344 Ma), Silurian to Devonian (420–410 Ma), Ediacaran (630–585 Ma), and Archean (2800–2700 Ma) ages. The Jeanne d'Arc and Bodhrán Formation sample suites also have consistent detrital zircon grain abundances as evidenced by similar Archean to early Neoproterozoic (39% vs. 43%), late Neoproterozoic to earliest Paleozoic (21% vs. 23%), early to late Paleozoic (33% vs. 31%), and Mesozoic (7% vs. 4%) age populations. The available detrital zircon and other geological data therefore permit braided fluvial sandstone units of the Jeanne d'Arc and Flemish Pass basins to be depositionally correlative during Tithonian to Berriasian time (e.g., Haynes et al., 2013). We propose that both units were part of a north-northeast–directed braided fluvial system that incised the Rankin Formation and sampled igneous and sedimentary rock successions in the Avalon uplift region. Future detrital zircon U-Pb-Hf studies of Flemish Pass strata should be able to test this hypothesis and better constrain Tithonian to Berriasian fluvial connectivity between the Jeanne d'Arc and Bodhrán Formations.

Lower and mid-Cretaceous strata in the Flemish Pass basin, named Hibernia and Avalon Formation equivalents by Lowe et al. (2011), respectively, lack Mesozoic detrital zircon grains that are typical of Tithonian to Berriasian sandstone intervals (Figure 9). Although there are no corresponding detrital zircon provenance data from Hibernia and Avalon Formation (Berriasian–Valanginian to Aptian) strata in the Jeanne d'Arc basin, we speculate that the absence of such detrital zircon grains may indicate the burial or erosion of primary or reworked Mesozoic parent rocks, predominance of zircon-poor mafic source rocks during the Early to mid-Cretaceous, or drainage reorganizations associated with the Early to mid-Cretaceous uplift of the central ridge.

Implications for Late Jurassic to Early Cretaceous Paleogeography

Lithospheric stretching and thinning processes that occurred during the early phase of North Atlantic rift evolution (e.g., Péron-Pinvidic et al., 2013) resulted in the Mesozoic exhumation of basement and cover assemblages in onshore areas of Newfoundland (e.g., Hendriks et al., 1993; Willner et al., 2019) and the resultant filling of rift basins in the Grand Banks (e.g., Hiscott et al., 1990). Jeanne d'Arc Formation alluvial lithofacies were generated in response to Late Jurassic to Early Cretaceous rift tectonism and in the Terra Nova field sourced from two areas: (1) conglomeratic lithofacies that represent alluvial fan or flood plain deposits were derived from the uplifted basin margin to the southeast and (2) sandy lithofacies that represent axial, braid-plain deposits were derived from the Avalon uplift to the south-southwest (e.g., Wilcox et al., 1991). The fluvial sandstone units of the Terra Nova field are quartz rich and dominated by polycyclic Paleozoic to Archean detrital zircon grains, which likely have provenance from preexisting, mature Carboniferous to Jurassic siliciclastic strata that were stripped off the Avalon uplift during Late Jurassic to Early Cretaceous tectonism. The presence of well-mixed, compositionally and texturally mature source rocks may also explain the repeatability of Paleozoic to Archean detrital zircon U-Pb age spectra in the Jeanne d'Arc Formation despite the expected poor mixing of braided fluvial sediment (e.g., DeGraaff-Surpless et al., 2003). Late Jurassic to Early Cretaceous detrital zircon populations in each sandstone sample, which we infer to be ultimately derived from the Mesozoic extrusive-intrusive belt along the southwest Grand Banks fault zone; (e.g., Pe-Piper et al., 1994), reinforce the evidence for south-southwest provenance (Figure 10A, B). Tithonian to Berriasian erosion of the Avalon uplift also explains exotic 310–285 Ma detrital zircon grains in the Jeanne d'Arc Formation (this study) and coeval units of the Flemish Pass basin (McDonough et al., 2011) as being recycled through upper Paleozoic foreland basin deposits of the southeastern Grand Banks (see locations in Figure 10B) but originally derived from late Variscan granitoid units of Iberia (cf., Hiscott et al., 2008).

Late Jurassic to Early Cretaceous paleogeographic models for Atlantic Canada have been mostly constrained by multiproxy sediment provenance studies of Scotian and Georges Bank basin strata, offshore Nova Scotia (e.g., Pe-Piper and MacKay, 2006; Tsikouras et al., 2011; Piper et al., 2012; Chavez et al., 2019). For example, Late Jurassic to Early Cretaceous river systems that fed the central Scotian basin are interpreted to have headwaters in Precambrian basement

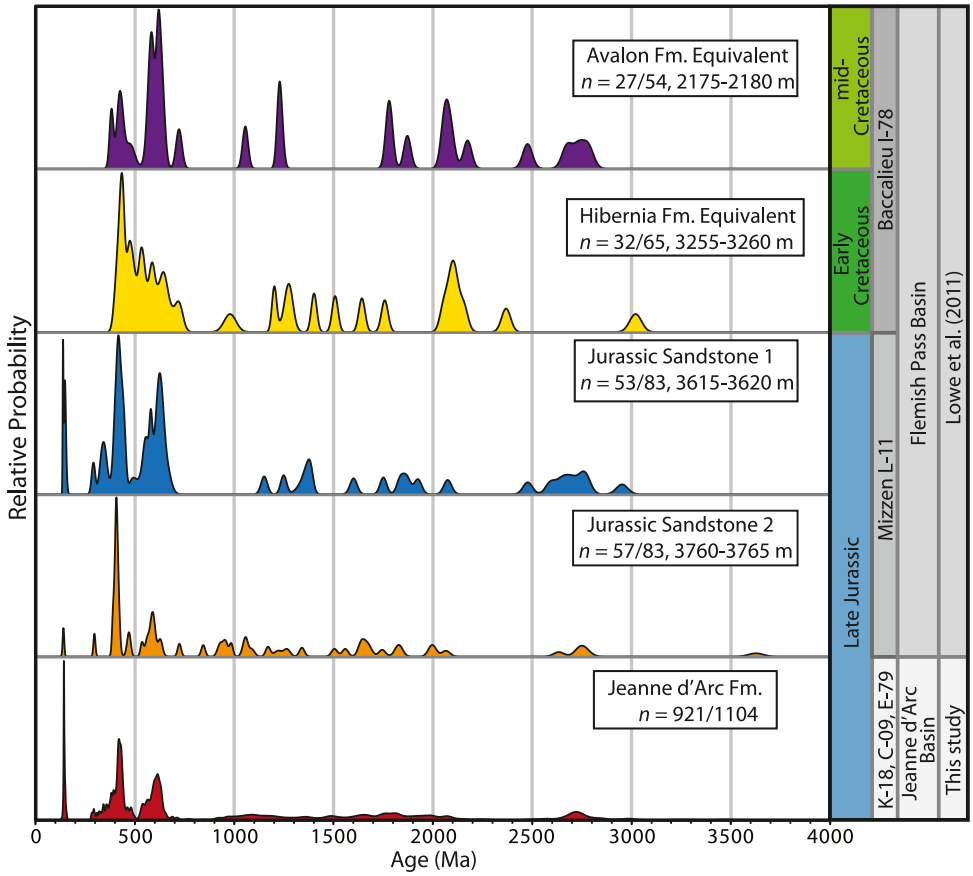

Figure 9. Detrital zircon U-Pb ages for Upper Jurassic to Lower Cretaceous strata of the Jeanne d'Arc basin (Terra Nova K-18, C-09, E-79; this study) and Upper Jurassic to mid-Cretaceous strata of the Flemish Pass basin (Mizzen L-11 and Baccalieu I-78; Lowe et al., 2011). Sample information and abbreviations follow those explained in Figure 6. Fm. = Formation.

units of Labrador, Paleozoic cover assemblages and ophiolites of western Newfoundland, and thick accumulations of Carboniferous strata in onshore and offshore regions of Nova Scotia and Newfoundland (Figure 10B). Although located immediately southwest of the southwest Grand Banks fault zone and its Mesozoic extrusive-intrusive centers, Tithonian to Berriasian strata offshore Nova Scotia apparently lack Late Jurassic to Early Cretaceous detrital zircon grains (Piper et al., 2012) that are typical of coeval units in the Jeanne d'Arc (this study) and Flemish Pass (Lowe et al., 2011) basins to the north. Faulting and igneous activity in the southwestern Grand Banks likely affected regional drainage patterns such that Late Jurassic to Early Cretaceous detrital zircon grains were not transported south-southwest into the Scotian basin. Aptian to Albian strata of the Scotian basin, however, yield 127–105 Ma detrital zircon grains derived from volcanic centers along the greater southwest Grand Banks fault zone system (Piper et al., 2012) and therefore indicate drainage capture or rearrangement following Early to mid-Cretaceous mantle exhumation events or mid-Cretaceous lithospheric breakup (e.g., Tucholke et al., 2007; Péron-Pinvidic et al., 2013) between Newfoundland and Iberia.

CONCLUSIONS

Detrital zircon U-Pb-Hf results from the Jeanne d'Arc Formation provide new constraints on synrift sandstone deposition in the Jeanne d'Arc basin and its significance to Grand Banks stratigraphy. Sandstone units from delineation wells K-18, C-09, and E-79 contain circa 145 Ma detrital zircon U-Pb populations and indicate Tithonian to Berriasian maximum depositional ages for Jeanne d'Arc Formation strata in the Terra Nova oil field. The precise locations of igneous

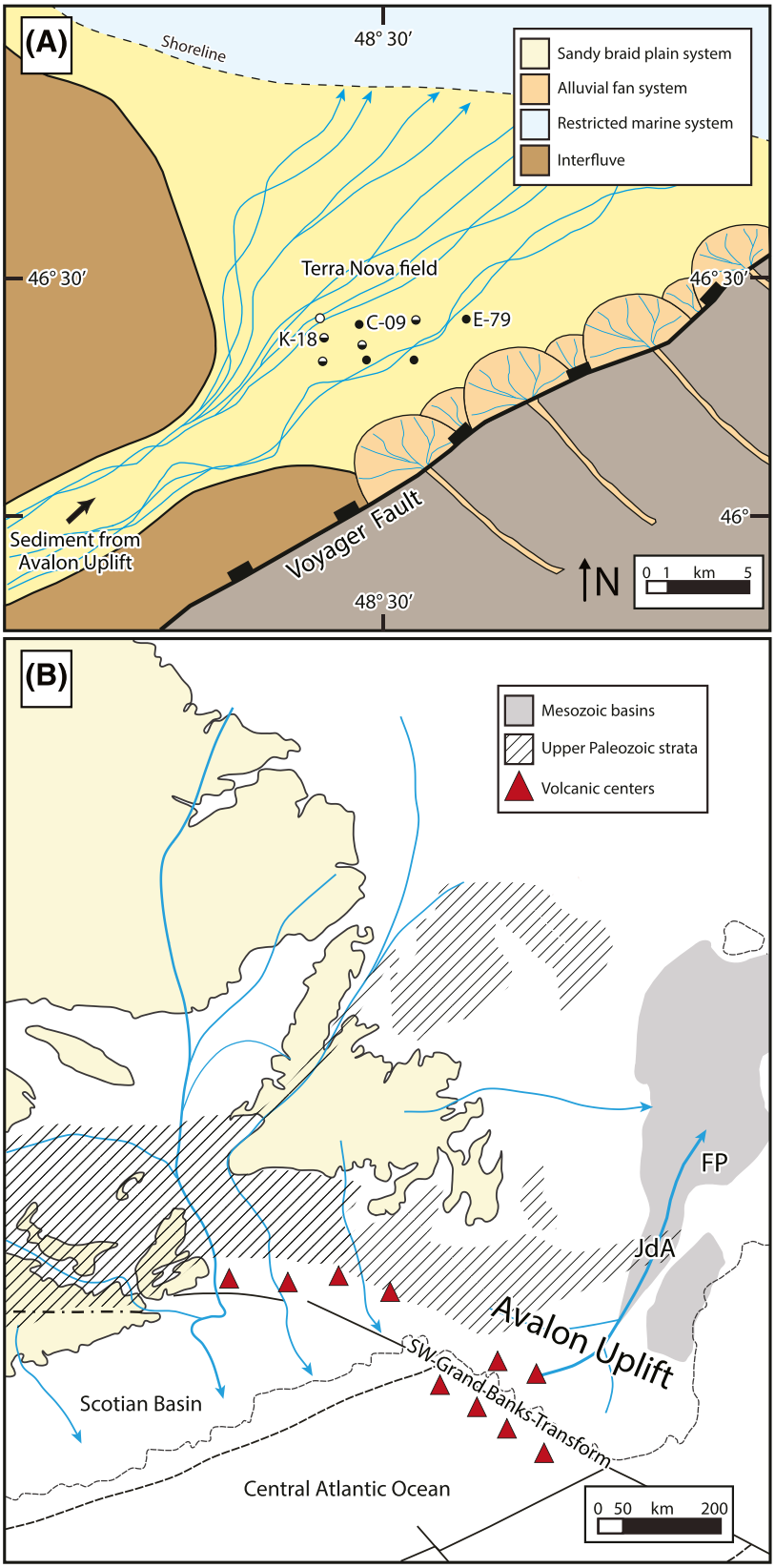

Figure 10. Late Jurassic to Early Cretaceous paleogeography and paleodrainage maps of (A) Terra Nova field and greater southern Grand Banks modified from Wilcox et al. (1991) and (B) Nova Scotia and Newfoundland margins of Atlantic Canada modified from Lowe et al. (2011) and Piper et al. (2012). FP = Flemish Pass basin; JdA = Jeanne d'Arc basin; SW = southwest.

source rocks are uncertain, but the new U-Pb data are broadly consistent with the existence of Jurassic and Cretaceous rift-related units in the southwestern Grand Banks. The Hf isotope compositions of Tithonian to Berriasian detrital zircon grains reveal that synrift magmatic rocks were mantle derived but variably contaminated with continental crust. Jeanne d'Arc Formation strata mostly contain polycyclic Archean to early Mesoproterozoic and Neoproterozoic to early Paleozoic detrital zircon populations with Canadian shield and Newfoundland Appalachians provenance, respectively. These detrital zircon grains were derived from preexisting, Carboniferous to Jurassic sedimentary rocks in the Avalon uplift region to the south-southwest and transported by axial routing systems that incised the existing landscape. Minor populations of late Paleozoic detrital zircon grains likely have provenance from upper Paleozoic strata in onshore and offshore regions of Atlantic Canada and do not necessarily indicate Late Jurassic to Early Cretaceous drainage connections with Variscan basement sources in Iberia. Jeanne d'Arc Formation U-Pb age spectra are analogous to those in the Mizzen field to the northeast and suggest that a single fluvial system connected the Jeanne d'Arc and Flemish Pass basins during the Late Jurassic to Early Cretaceous. Lower to mid-Cretaceous strata of the Flemish Pass basin lack these young grains and suggest that Tithonian to Berriasian zircon sources may have been eroded or buried or were not sampled by river systems after regional faulting and uplift of the central ridge complex.

APPENDIX

Detrital Zircon U-Pb and Hf Isotope Methods

Detrital zircon grains were separated from rock samples by rock grinding, sieving, and heavy liquid (bromoform, ~2.85 g/cm^3; methylene iodide, 3.3 g/cm^3) methods and subsequently handpicked, placed on double-sided tape, and mounted in epoxy. After polishing to expose the cores of the zircon crystals, cathodoluminescence imaging was completed using a JEOL JSM 7100F field emission scanning electron microscope at Memorial University of Newfoundland. Cathodoluminescence images were used to target homogenous regions in the zircon grains, avoiding complex internal structures, fractures, and areas of potential Pb loss.

The U-Pb and Hf isotope ratios were measured using the laser ablation split-stream method (e.g., Fisher et al., 2014) at the Micro Analysis Facility, Bruneau Centre for Research and Innovation, Memorial University of Newfoundland. Zircon crystals were ablated with a GeoLas 193 nm excimer laser ablation system using a 40 µm spot-size, laser fluence of 5 joules/cm^2, pulse rate of 10 Hz, and 600 shots with a total analysis time of approximately 120 s (~30 s background measurement, ~60 s ablation, and ~30 s washout). Ablated material was evacuated from the ablation chamber via He carrier gas and split using a baffled y-connector. The Hf isotopes were analyzed using a ThermoFinnigan NEPTUNE multicollector inductively coupled plasma mass spectrometer (ICP-MS), and U-Pb isotopes were measured using a ThermoFinnigan ELEMENT XR magnetic sector ICP-MS.

Time-integrated U-Pb signals were analyzed offline using Iolite software (Paton et al., 2011). Age calculations were made using the VizualAge routine, which includes a correction routine for down-hole fractionation (Petrus and Kamber, 2012). Corrections for instrumental mass bias were made by referencing the 1065 Ma zircon standard 91500 (Wiedenbeck et al., 1995) for U-Pb analyses, whereas the 337 Ma zircon standard Plešovice (Sláma et al., 2008) was used to calibrate ^{176}Hf/^{177}Hf ratios. The typical analytical workflow consisted of 6 standard analyses, 12 unknown analyses, 6 zircon standard analyses, and so forth. Analyses with high error (>10% uncertainty) or excessive discordance (>10% discordant, >5% reverse discordant) were excluded from plots and interpretation. The reported ages for grains younger and older than 1000 Ma are based on ^{206}Pb/^{236}U and ^{207}Pb/^{206}Pb ages, respectively. Initial epsilon Hf ($\varepsilon_{Hf[i]}$) calculations used a decay constant of 1.867 x 10^{-11} (Scherer et al., 2001) and present-day CHUR values of ^{176}Hf/^{177}Hf = 0.282785 and ^{176}Lu/^{177}Hf = 0.0336 (Bouvier et al., 2008).

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