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Aller au sommaire du numéro

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Résumé de l'article

L'idée d'un grand fleuve préglaciaire qui drainait une grande partie de l'Amérique du Nord vers les eaux arctiques du Canada moderne a été suggérée pour la première fois en 1895 par Robert A. Bell. Dans les années 1970, l'exploration pétrolière dans le détroit d'Hudson et la mer du Labrador a localisé l'immense delta submergé de ce qui est maintenant connu sous le nom de rivière Bell. Les reconstructions suggèrent que trois bras principaux de la rivière Bell se rejoignent près de la baie d'Hudson moderne. Le bras oriental drainait en grande partie le Bouclier canadien, tandis que le bras central et le bras occidental avaient des sources dans la ceinture orogénique de la Cordillère et son avant-pays dans les États-Unis et le nord-ouest du Canada actuels, respectivement.

Nous présentons de nouvelles données U–Pb sur zircons détritiques issus de sable de l'Oligocène inférieur et du Miocène inférieur provenant d'un puits d'exploration dans le delta de Saglek, dans le nord de la mer du Labrador. En conjonction avec d'autres résultats de zircons détritiques de la mer du Labrador (et d'ailleurs), ces données enregistrent la configuration et l'histoire de ce bassin versant à l'échelle continentale avec plus de détail. Les grains de zircons détritiques mésozoïques et plus jeunes (< 250 Ma) sont subordonnés aux groupes d'âge précambriens, mais les populations cénozoïques deviennent plus abondantes au cours de l'Oligocène, ce qui suggère que le bassin s'est étendu dans des zones maintenant occupées par le plateau du Colorado et la province de Basin-and Range. Les populations de grains de zircons détritiques du Protérozoïque et du Phanérozoïque dans les sédiments du delta de Saglek sont similaires à celles du fleuve Colorado du Pliocène. Les résultats corroborent une idée antérieure selon laquelle l'incision initiale du Grand Canyon et la dénudation du plateau du Colorado étaient associées à une paléo-rivière coulant vers le nord qui alimentait le bassin de la rivière Bell. Cette contribution s'est poursuivie jusqu'à la capture de cette rivière ancestrale par le bassin du golfe de Californie au Pliocène, après quoi l'excavation du Grand Canyon moderne a été achevée. Le bassin versant de la rivière Bell a ensuite été bloqué par l'expansion des calottes glaciaires du Pléistocène.

ARTICLE

The Great Preglacial "Bell River" of North America: Detrital Zircon Evidence for Oligocene–Miocene Fluvial Connections Between the Colorado Plateau and Labrador Sea

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SUMMARY

The idea of a great pre-glacial river that drained much of North America into the Arctic waters of modern Canada was first suggested in 1895 by Robert A. Bell. In the 1970s, petroleum exploration in Hudson Strait and the Labrador Sea located the massive, submerged delta of what is now known as the Bell River. Reconstructions suggest that three main branches of the Bell River joined up near modern Hudson Bay. The eastern branch largely drained the Canadian Shield, but the central and western branches had headwaters in the Cordilleran orogenic belt and its foreland in the present-day U.S. and northwestern Canada, respectively.

We present new detrital zircon U–Pb data from Lower Oligocene and Lower Miocene sand from an exploration well in the Saglek delta of the northern Labrador Sea. In conjunction with other detrital zircon results from the Labrador Sea (and elsewhere) these data record the configuration and history of this continental-scale drainage basin in more detail. Mesozoic and younger detrital zircon grains (< 250 Ma) are subordinate to Precambrian age groupings, but Cenozoic populations become more abundant during the Oligocene, suggesting that the basin had expanded into areas now occupied by the Colorado Plateau and the Basin-and-Range Province. Proterozoic and Phanerozoic detrital zircon grain populations in Saglek delta sediments are similar to those of the Pliocene Colorado River. The results support an earlier idea that initial incision of the Grand Canyon and denudation of the Colorado Plateau were associated with a north-flowing paleo-river that fed into the Bell River basin. This contribution continued until the Pliocene capture of this ancestral river by the Gulf of California basin, after which the excavation of the modern Grand Canyon was completed. The Bell River drainage basin was later blocked by the expansion of Pleistocene ice sheets.

RÉSUMÉ

L'idée d'un grand fleuve préglaciaire qui drainait une grande partie de l'Amérique du Nord vers les eaux arctiques du Canada moderne a été suggérée pour la première fois en 1895 par Robert A. Bell. Dans les années 1970, l'exploration pétrolière dans le détroit d'Hudson et la mer du Labrador a localisé l'immense delta submergé de ce qui est maintenant connu sous le nom de rivière Bell. Les reconstructions suggèrent que trois bras principaux de la rivière Bell se rejoignent près de la baie d'Hudson moderne. Le bras oriental drainait en grande partie le Bouclier canadien, tandis que le bras central et le bras occidental avaient des sources dans la ceinture orogénique de la Cordillère et son avant-pays dans les États-Unis et le nord-ouest du Canada actuels, respectivement.

Nous présentons de nouvelles données U–Pb sur zircons détritiques issus de sable de l'Oligocène inférieur et du Miocène inférieur provenant d'un puits d'exploration dans le delta de Saglek, dans le nord de la mer du Labrador. En conjonction avec d'autres résultats de zircons détritiques de la mer du Labrador (et d'ailleurs), ces données enregistrent la config-

Geoscience Canada, v. 49, https://doi.org/10.12789/geocanj.2022.49.184 pages 29–42

GC Data Repository: https://GAC.ca/GC-data-repository

uration et l'histoire de ce bassin versant à l'échelle continentale avec plus de détail. Les grains de zircons détritiques mésozoïques et plus jeunes (< 250 Ma) sont subordonnés aux groupes d'âge précambriens, mais les populations cénozoïques deviennent plus abondantes au cours de l'Oligocène, ce qui suggère que le bassin s'est étendu dans des zones maintenant occupées par le plateau du Colorado et la province de Basin-and Range. Les populations de grains de zircons détritiques du Protérozoïque et du Phanérozoïque dans les sédiments du delta de Saglek sont similaires à celles du fleuve Colorado du Pliocène. Les résultats corroborent une idée antérieure selon laquelle l'incision initiale du Grand Canyon et la dénudation du plateau du Colorado étaient associées à une paléo-rivière coulant vers le nord qui alimentait le bassin de la rivière Bell. Cette contribution s'est poursuivie jusqu'à la capture de cette rivière ancestrale par le bassin du golfe de Californie au Pliocène, après quoi l'excavation du Grand Canyon moderne a été achevée. Le bassin versant de la rivière Bell a ensuite été bloqué par l'expansion des calottes glaciaires du Pléistocène.

Traduit par la Traductrice

INTRODUCTION

Robert Bell (1841–1917) was a pivotal figure in the establishment of the Geological Survey of Canada and mapped many poorly known Arctic and Subarctic regions. He is remembered as a controversial figure (e.g. Zaslow 1975; Brookes 2016) but also for his many scientific insights. At an early meeting of the Royal Society of Canada he proposed that pre-glacial North America had a continental-scale drainage system feeding a huge river that discharged into the Atlantic Ocean through the area of modern Hudson Bay (Bell 1895). The scale of this drainage system was similar to that of the modern Amazon Basin of South America. Jackson (2018) provides a short readable summary of the evolution of ideas about this great vanished river, which is now known as the "Bell River", in honour of the geologist who first conceived of it. Suggested configurations of the Bell River basin for Paleocene and Oligocene times are shown in Figure 1A and B, respectively.

A river system of such size must have had a large delta, and strong confirmation of Bell's idea came with the discovery of that delta, now submerged beneath the Labrador Sea, Baffin Bay, and Davis Strait (Fig. 1A, B). Hydrocarbon exploration on the Labrador-Baffin shelf in the 1970s and 1980s chronicled the age and configuration of the abandoned Saglek delta, which straddles Hudson Strait, at the proposed outlet of the Cenozoic Bell River (McMillan 1973; Balkwill et al. 1990; Dickie et al. 2011; Jauer and Budkewitsch 2010; Jauer et al. 2014; Fensome et al. 2016). The Saglek delta is truly enormous, containing at least 2.6 million cubic kilometres of clastic sediments (Balkwill et al. 1990).

Clastic sedimentary rocks preserve 'fingerprints' of their source regions through their clast compositions, geochemistry and other attributes. The most powerful tracers of provenance are detrital zircon U–Pb populations, which can be compared directly with crustal age distributions in areas thousands of kilometres from their sites of deposition (e.g. Gehrels 2014).

A recent study by Corradino et al. (2022) presents important detrital zircon data from an exploration well in the Labrador Sea. Their study involved Lower Miocene and Upper Oligocene sands that represent the Saglek delta, together with fluvial strata of equivalent age from the Great Plains. The presence of Mesozoic and younger (< 250 Ma) detrital zircon grains in both regions was interpreted as an indication of primary and recycled 'Cordilleran' sources, inferred to be in southwestern Canada. This conclusion adds to other accumulated evidence supporting the existence of the Bell River. Corradino et al. (2022) also present Nd–Sr isotopic compositions of fossil material and discuss the possible influence of the Bell River on North Atlantic oceanic circulation patterns and climate cycles in the Cenozoic transition from hothouse to icehouse states.

Here we report new detrital zircon U–Pb age data from Lower Oligocene and Lower Miocene sand in exploration well Rut H-11 in the Saglek delta, which was also sampled by Corradino et al. (2022). We sampled specific intervals in this well to test Sears' (2013) hypothesis that the Saglek delta was the ultimate sink for some sediment that was sourced from the Colorado Plateau – Great Basin area in Early Oligocene–Early Miocene times. We also discuss the possible framework in which changes in drainage basin architecture link the histories of two areas in opposite corners of North America.

Sears' (2013) hypothesis was indirectly supported by paleogeographic maps of Blum and Pecha (2014) and Blum et al. (2017). They interpreted detrital zircon U–Pb age data from sediments on the Gulf of Mexico shelf and concluded that Oligocene uplift of the north-trending New Mexico, Colorado, and Wyoming Rockies truncated the western headwaters of the Gulf of Mexico drainage basin. Such a truncation would have permitted Oligocene capture of drainage from the Colorado Plateau and Wyoming Rockies by the Bell River basin, coinciding with the initial erosion of the Grand Canyon (Sears 2013). Figure 1A shows the overall configuration of the Bell River drainage basin in Paleocene times, and Figure 1B shows its possible configuration in Oligocene times. We suggest that a substantial area was transferred from the Gulf of Mexico basin into the Bell River basin during the Oligocene. The hypothesis implies that detrital zircon populations diagnostic of this source area should appear in the Saglek delta at this time, and our research tests this prediction.

THE BELL RIVER: EVIDENCE AND UNDERSTANDING

The Saglek delta curves across 1500 km of the Labrador Sea's west margin (Jauer and Budkewitsch 2010; Jauer et al. 2014). Seismic reflection profiles and exploration wells indicate that its sedimentary fill exceeds 8 km in thickness (Enachescu 2011) making the Saglek basin the largest Cenozoic depocenter along the eastern margin of North America (Balkwill et al. 1990). McMillan (1973), Balkwill et al. (1990), Duk-Rodkin and Hughes (1994), Dickie et al. (2011), and Jauer et al. (2014) interpreted the Saglek delta as the outflow deposit of a 'super-river' that embraced most of Canada and parts of the north-central U.S., as shown in Figure 1A. McMillan (1973) named this the "Bell

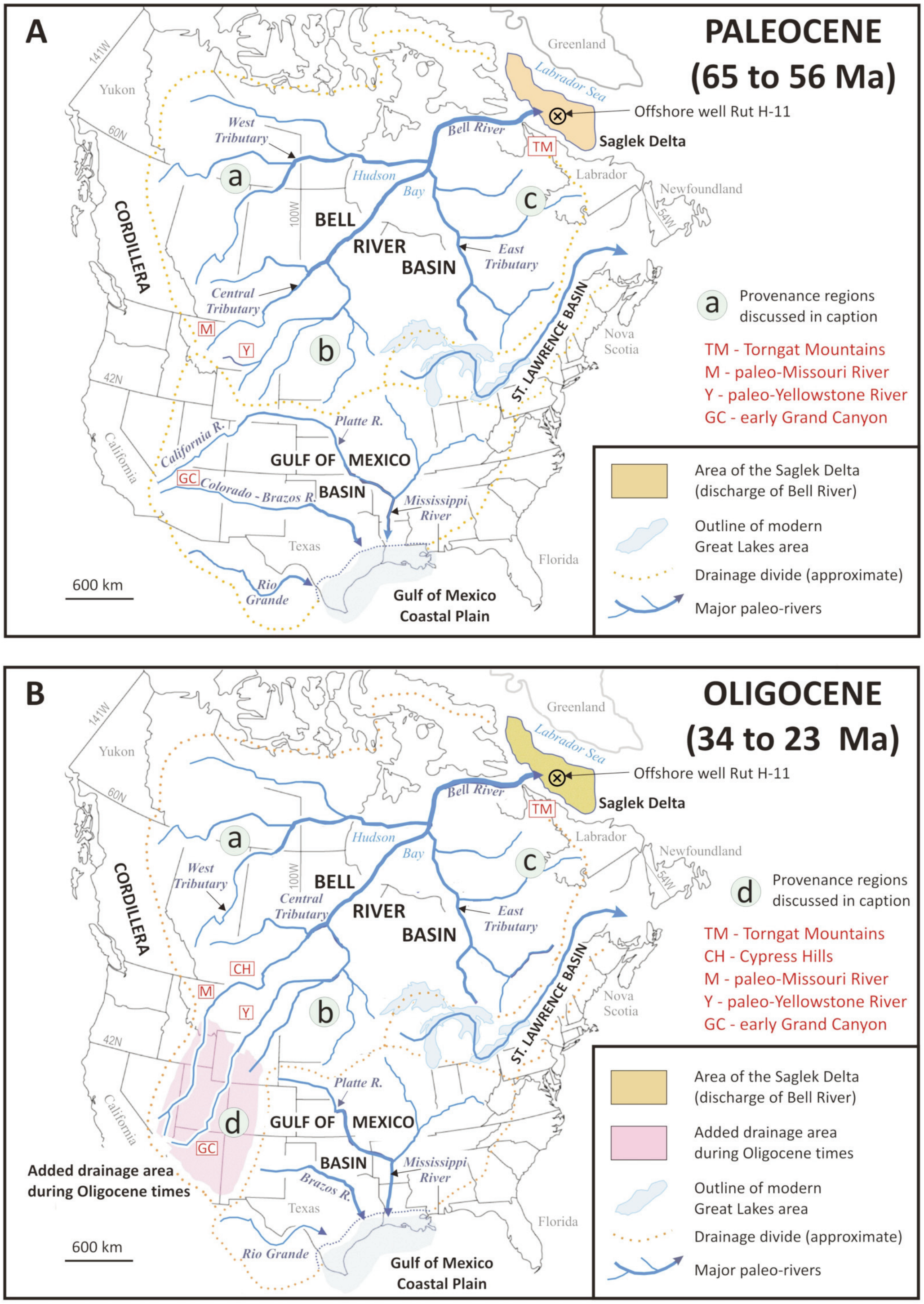

Figure 1. Summary maps depicting the evolution of North American drainage systems and the postulated extent and geography of the Bell River basin, after McMillan (1973), Balkwill et al. (1990), Duk-Rodkin and Hughes (1994), Sears (2013), Blum and Pecha (2014), Blum et al. (2017), Jackson (2018), and Corradino et al. (2022). A. Reconstruction for Paleocene times (~ 65 Ma to 56 Ma) in which three main tributaries of the Bell River meet in the region of modern-day Hudson Bay, and flow to the Saglek delta in the ancestral Labrador Sea. The three main detrital zircon provenance regions suggested are the Cordilleran foreland of Canada (label a), the Cordilleran foreland of the USA (label b) and the eastern Canadian Shield (label c). The California River of Davis et al. (2010) flows into the paleo-Platte River of Blum et al. (2017) beyond the southern extremity of the Bell River drainage basin. Note that Greenland is depicted in its present position for simplicity but would have been somewhat closer to Labrador during part of this period. B. Reconstruction for Oligocene times (~ 34 to 23 Ma) showing the same detrital zircon provenance regions and three main tributaries of the Bell River divide. Note that the central tributary system now extends over 1000 km to the south to include the southwestern USA and the early Grand Canyon region. The provenance region of the Colorado Plateau and Wyoming Rockies (label d) is suggested to have been captured by the Bell River basin upon truncation of the western Gulf of Mexico basin by the uplift of the New Mexico, Colorado, and Wyoming Rockies during the Oligocene. The California River of Davis et al. (2010), and other paleo-rivers that previously drained towards the Gulf of Mexico now represent the southern extremity of the Bell River basin. Note that the exact drainage courses of the Bell River and its tributaries are hard to establish because glaciation has removed most physical evidence.

River" in honor of Robert Bell, who first envisaged it (Bell 1895). Early palynological and mineralogical research on samples from exploration wells in the Saglek delta suggested that the Bell River had headwaters in the North American Cordillera and High Plains (Hiscott 1984; Williams 1986). Recycled Triassic and Carboniferous palynomorphs found in Saglek delta deposits suggest possible linkages to the southern Colorado Plateau (Sears 2013), as implied by Figure 1B.

McMillan (1973) and Balkwill et al. (1990) suggested that the Bell River had three major branches that joined in the Hudson Bay region and exited the Canadian Shield through a rifted trough along Hudson Strait (Fig. 1A). A western branch drained the northern Canadian Cordillera and its adjacent foreland basin; a central branch drained the northern U.S., southern Canadian Cordillera and adjacent foreland basin; and an eastern branch drained the eastern Canadian Shield. Our new data agree with that general interpretation, supported also by Corradino et al. (2022), but we propose that the central branch of the Bell River extended much farther into the southwestern U.S. during Oligocene–Miocene times. This is the interpretation depicted in Figure 1B and discussed in the final section of our paper.

Under the load of Pleistocene continental glaciers, the former lower reaches of the Bell River and its delta subsided below sea level, where they remain today. Glaciation removed most continental sedimentary deposits from the Bell River, although some possible remnants remain in the area of Saskatchewan, Alberta, and adjacent Montana (Cummings et al. 2012). Before its Pleistocene destruction, the Bell River basin closely matched the Amazon River basin, with a similar drainage area, headwaters in Cordilleran and cratonic uplands, a trunk stream gathering major tributaries across the continental interior, and discharge through a rift valley to a delta on the eastern seaboard.

Paleogeographic maps of Slatterly et al. (2013) connected the Late Cretaceous–Early Paleocene Cannonball Sea of North Dakota and Saskatchewan with the northern Labrador Sea along the Hudson Seaway, through the present locations of Hudson Bay and Hudson Strait. Deposits of the Cannonball Sea have yielded marine fossils with affinities to northern European fossils that were adjacent to the Labrador Sea prior to post-Paleocene opening of the northern Atlantic Ocean. The main channel of the initial Bell River may have followed the pre-existing trough of the Hudson Seaway following the regression of the Cannonball Sea (Slatterly et al. 2013). Remnants of sedimentary deposits related to the Bell River also survive in Rocky Mountain and Mackenzie Mountains headwaters, and in fluvial channels buried beneath Pleistocene glacial drift on the High Plains of Canada and Montana (cf. Leckie 2006; Leckie and Cheel 1989; Dickie et al. 2011; Cummings et al. 2012; Corradino et al. 2022).

GEOLOGICAL BACKGROUND

Continental rifting between eastern Canada and Greenland began during the Early Cretaceous and resulted in Late Cretaceous to Paleocene opening of the Labrador seaway (e.g. Dickie et al. 2011; Fensome et al. 2016. Locally derived Lower Cretaceous to Middle Paleocene volcanic and sedimentary deposits filled initial rift grabens (Balkwill et al.1990; Thrane 2014). Seafloor spreading began by Middle Paleocene time and ended in the latest Eocene (Fensome et al. 2016). Sediments of the Saglek delta first began to accumulate in the Labrador Sea during the Late Paleocene. These overtopped rift-phase grabens and spread widely over thermally-subsiding ocean-floor basalt until the Pleistocene, at which time the Bell River basin was overridden by glaciation. Ice sheets cut off the Saglek delta from its sediment sources, and glaciers eventually scoured Hudson Strait to a depth of 250 m (Jauer and Budkewitsch 2010).

From Middle Paleocene to Pliocene times, the Saglek delta shelf formed a shallow marine to littoral coastal plain with a high content of coal and plant residue. The coal residue may have been partly derived from erosion of thick Paleocene and Eocene coal measures of the Cordilleran foreland. Natural gas sampled from delta wells was derived from Type III kerogen from coal residue in the delta (cf. Enachescu 2011).

The lithostratigraphy of the Saglek delta and underlying sequences is defined by criteria from well samples and well logs, but formational boundaries are not strictly timelines (cf. Fensome et al. 2016). The pre-deltaic units began with Lower Cretaceous facies of locally derived alluvial, lacustrine, lagoonal, and shallow marginal-marine strata with numerous internal unconformities (e.g. Balkwill et al. 1990). These pass upward into open-ocean, bathyal facies that continued from the Late Cretaceous into the Paleocene. From the base up, the deltaic lithostratigraphic units comprise the Cartwright, Kenamu, Mokami, and Saglek formations (Fig. 2). The Cartwright Formation is a sandstone unit of Middle and Upper Paleocene age (Selandian and Thanetian, 62–56 Ma). It correlates with final withdrawal of the Western Interior Seaway and Cannonball Sea, and establishment of the Bell River. The overlying Kenamu Formation comprises mostly deep-water shale. It spans latest Paleocene to latest Eocene times. The Oligocene–Pliocene Mokami Formation overlies the Kenamu Formation. It is mostly shale but includes lenses of sand. Sand increases in volume upward in the Mokami Formation. The base of the Oligocene–Pliocene Saglek Formation is defined at the appearance of 80% sand on lithologic logs. The Saglek Formation is a medium- to fine-grained clastic wedge which prograded in sandy channels across the delta plain into the subsiding basin. It is laterally equivalent to outboard shales of the Mokami Formation (Dickie et al. 2011). As discussed by Corradino et al. (2022), there is some inconsistency concerning the age ranges and facies equivalence of the Mokami and Saglek formations, as determined via micropaleontology and palynology. Their study calculated numerical ages based on Sr-isotope determinations (see below).

MATERIALS AND METHODS

Eight petroleum exploration wells were drilled in the Saglek delta in the 1970s and 1980s. Five of the wells were drilled near the head of the delta. We determined 819 concordant detrital zircon U–Pb dates from a total of 1200 analyses from four samples of Lower Oligocene and Lower Miocene sand from

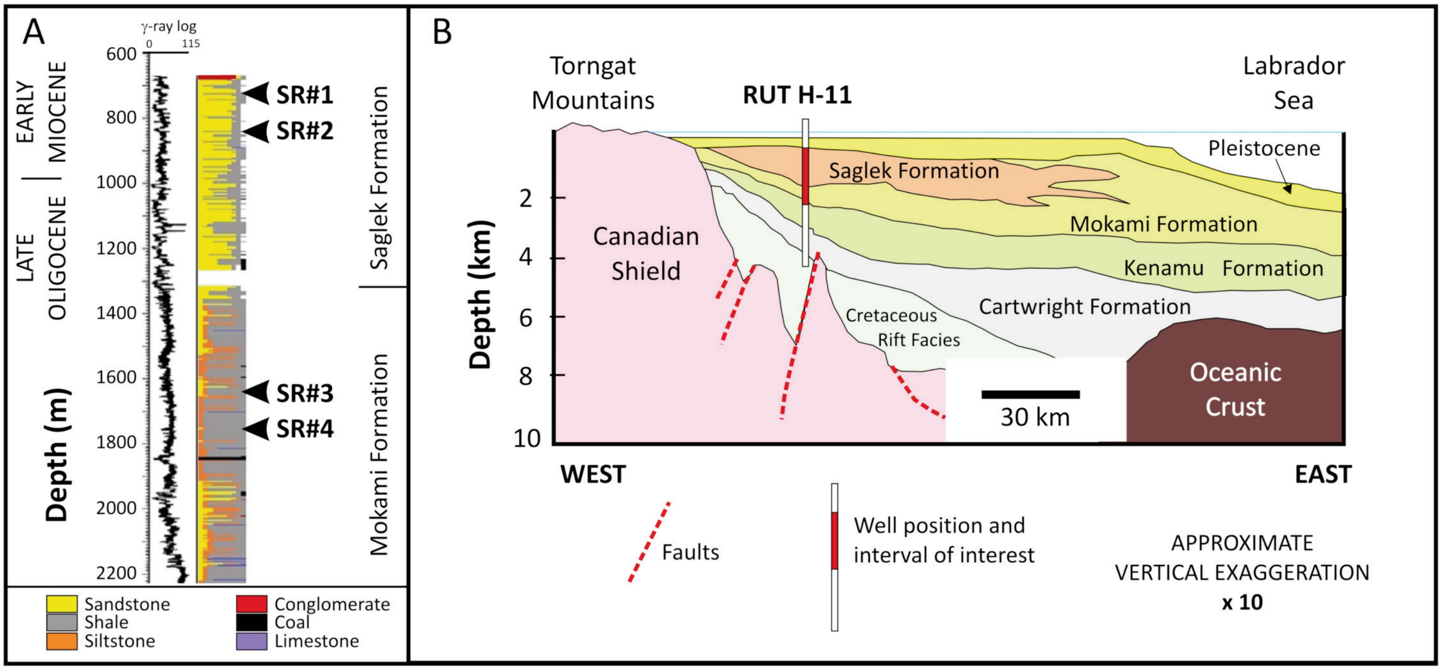

Figure 2 A. Rut H-11 well data from Fensome (2015). Our samples SR#1 and SR#2 are from Lower Miocene Saglek Formation sand. Samples SR#3 and SR#4 are from Lower Oligocene Mokami Formation sand. The sand was uniform in grain-size, texture, and composition. Fensome (2015) found abundant Cretaceous dinocyst clasts in these sands, derived from the Cordilleran foreland. B. Cross-section of Saglek basin, modified from Balkwill et al. (1990), and showing wider context of well Rut H-11, which was drilled in Cretaceous graben to 4450 m. Red box shows the sample interval for this study in well Rut H-11. For detailed information on drilling results, see Fensome et al. (2016).

well Rut H-11 (located on Fig. 1). Rut H-11 was drilled in a deep half-graben trough along the rifted Labrador shelf, near the interpreted mouth of the Bell River (Fig. 1A, B). Rut H-11 penetrated 4450 m of sediment, including 3100 m of Upper Paleocene through Lower Miocene delta units (Fig. 2A). It bottomed in 350 m of Upper Cretaceous–Lower Paleocene rift deposits and a diabase sill (Fensome et al. 2016). Lower Miocene deposits in the well are unconformably overlain by 700 m of Pleistocene glacial drift, but Pliocene deposits occur in a nearby well. A generalized cross-section through this part of the Saglek delta, including well Rut H-11, is shown in Figure 2B.

We collected our samples at the Canada-Newfoundland and Labrador Offshore Petroleum Board Core Storage and Research Centre in St. John's, Newfoundland and Labrador. The sampled intervals are listed in Table 1. Samples SR#1 and SR#2 (Saglek Formation) represent the interval from 720 m to 890 m below the sea floor, which also included five samples examined by Corradino et al. (2022). Samples SR#3 and SR#4 (Mokami Formation) represent intervals deeper than 1590 m below the sea floor, older than the sampling range of Corradino et al. (2022).

The samples were weakly-consolidated cuttings of well-rounded, fine- to medium-grained light-grey quartz sandstone. They contained minor feldspar, coal fragments, and detrital kyanite and zircon. The Saglek and Mokami sandstone samples were similar in texture and composition. The Storage Centre cuttings were bagged in 70- to 100- m intervals. We sampled from contiguous intervals in the Saglek (720–790 m, 795–890 m) and Mokami (1590–1690 m, 1695–1790 m) formations to ensure robust detrital zircon recovery.

Detrital zircon grains were separated from cuttings and analyzed for U–Pb geochronology at the Arizona LaserChron Center, University of Arizona. Sample processing and laboratory methods followed the laser ablation ICP-MS (inductively coupled plasma-mass spectrometry), data reduction, and data evaluation protocols of Gehrels and Pecha (2014). Further information on analytical procedures is available on the Arizona LaserChron Centre website: https://sites.google.com/laserchron.org/arizonalaserchroncenter/home. Detrital zircon age results and full isotopic U–Pb data are provided as Microsoft Excel spreadsheets in the Data Repository.

The U–Pb results are shown in normalized probability density plots (Figs. 3, 4, 5, 6) that all contain the same area under the curve and were made with an Excel macro developed at the Arizona LaserChron Center (e.g. Gehrels et al. 2011). Corradino et al. (2022) estimated Late Oligocene (25.6 Ma) through Early Miocene (18.0 Ma) depositional ages of their sampled interval from well Rut H-11, by correlation of fossil bivalves with the LOWESS 5 marine $^{87}Sr/^{86}Sr$ curve. Our samples SR#3 and SR#4 must be older than 25.6 Ma, as they are stratigraphically below the deepest samples examined by Corradino et al. (2022).

RESULTS

Figure 3 shows normalized probability density plots of our four samples. The Mokami Formation samples were from 700 to 900 m deeper in the well than the Saglek Formation sam-

Table 1. Detrital zircon U–Pb provenance groups (percent) from Rut H-11 and Raleigh N-18, Saglek basin, Labrador Sea. Samples SR#1 to SR#4 are from this study.

Source Age (Ma)	SOURCE REGION	Rut H-11 SR#1, SR#2 (720–890 m) ~ 18 Ma Early Miocene Saglek Formation *n* = 380	Rut H-11 SR#3, SR#4 (1595–1790 m) ~ 34–29 Ma? Early Oligocene Mokami Formation *n* = 439	Raleigh N-18 Thrane (2008) ~ 58 Ma Late Paleocene Cartwright Formation *n* = 492	Rut H-11 Corradino et al. (2022) (735–1410 m) ~ 26–18 Ma Late Oligocene to Early Miocene Saglek Formation *n* = 2366
	US CORDILLERAN ARC				
50–34	Late Eocene	0.8	0.0	0.0	0.3
86–51	Late Cretaceous–Eocene	5.5	2.5	1.4	3.7
125–87	Mid-Cretaceous	3.2	1.8	1.0	3.0
145–126	Magmatic gap	0.8	0.2	0.3	0.1
250–146	Triassic–Jurassic	5.3	2.7	1.4	3.2
	Total	**15.5**	**7.2**	**4.1**	**10.3**
	CORDILLERAN FORELAND				
542–251	Paleozoic	1.6	1.3	2.2	1.8
950–543	Neoproterozoic	0.5	0.7	0.9	0.7
1700–1601	Mazatzal orogen	5.8	4.3	6.1	4.5
1800–1701	Yavapai orogen	6.8	5.9	8.2	8.4
2000–1801	Trans-Hudson orogen	13.4	11.6	10.8	14.6
	Total	**28.2**	**23.8**	**28.2**	**30.0**
	CANADIAN SHIELD & CORDILLERAN FORELAND				
1300–951	Grenville orogen	8.2	22.8	8.6	7.1
1600–1301	Anorogenic	9.7	14.4	12.4	10.8
2300–2000	Wopmay orogen	3.4	2.1	2.6	4.7
2500–2301	Early Proterozoic	1.8	1.4	3.5	3.3
3200–2501	Neoarchean	31.8	27.6	36.9	32.4
4000–3201	Paleoarchean	1.3	0.7	3.7	1.4
	Total	**56.3**	**69.0**	**67.7**	**59.7**

ples. Background colours highlight ages of probable ultimate source terranes, i.e. the Canadian Shield, the Cordilleran orogen, and its foreland.

Mokami Formation

Lower Oligocene (cf. Fensome 2015, ~ 34–32 Ma?) sand collected from 1695–1790 m depth in well Rut H-11 (sample SR#4, Fig. 3) mostly yielded Mesoproterozoic (1593–1011 Ma; 42%), Paleoproterozoic (2433–1628 Ma; 23%), and Neoarchean (2794–2502 Ma; 25%) detrital zircon grains with main age peaks at ca. 1060, 1150, 1380, 1835, and 2720 Ma. Paleozoic (533–337 Ma), Mesozoic (218–79 Ma), and Cenozoic (62 Ma) ages are typically single-grain occurrences that together comprise only 7% of the data.

Lower Oligocene (cf. Fensome 2015, ~ 32–29 Ma?) sand collected from 1690–1595 m in well Rut H-11 (sample SR#3, Fig. 3) generally contained Mesoproterozoic (1598–1034 Ma; 31%), Paleoproterozoic (2482–1612 Ma; 29%), and Neoarchean (2800–2521 Ma; 26%) detrital zircon grains with main age peaks at ca. 1070, 1160, 1460, 1790, 1890, and 2720 Ma. Paleozoic (451 Ma), Mesozoic (217–68 Ma), and Cenozoic (55–52 Ma) detrital zircon grains together comprise 11% of the data and include groupings of three or more ages from 178–174, 96–87, 80–71, and 55–52 Ma.

Saglek Formation

Lower Miocene sand (~ 21–18 Ma, Corradino et al. 2022) collected from 795–890 m in well Rut H-11 (sample SR#2, Fig. 3) yielded predominantly Mesoproterozoic (1595–1006 Ma; 20%), Paleoproterozoic (2478–1603 Ma; 32%), and Neoarchean (2793–2531 Ma; 26%) detrital zircon grains with main age peaks at ca. 1140, 1280, 1435, 1650, 1800, 1870, 2575, and 2720 Ma. Paleozoic (434–359 Ma), Mesozoic (224–67 Ma), and Cenozoic (65–35 Ma) detrital zircon grains together comprise 15% of the data and include groupings of three or more ages from 198–187, 172–166, 148–142, 108–102, 82–77, and 65–61 Ma.

Lower Miocene sand (~ 18 Ma, Corradino et al. 2022) collected from 720–790 m in well Rut H-11 (sample SR1, Fig. 3) largely contained Mesoproterozoic (1475–1027 Ma; 12%), Paleoproterozoic (2395–1661 Ma; 30%), and Neoarchean (2766–2540 Ma; 27%) detrital zircon grains with main age peaks at ca. 1400, 1790, 1835, and 2720 Ma. Paleozoic (521–266 Ma), Mesozoic (192–71 Ma), and Cenozoic (62–34 Ma) ages are typically single-grain occurrences that together comprise 16% of the data with notable groupings of three or more grains from 115–107, 77–71, and 62–58 Ma.

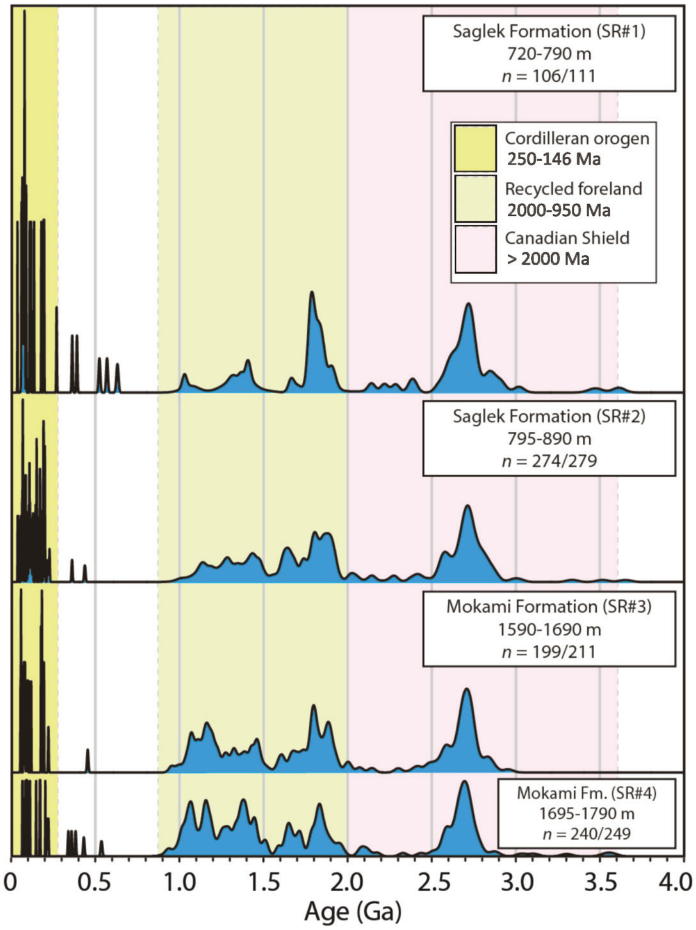

Figure 3. Stacked normalized probability plots and detrital U–Pb results for SR#1 (Lower Miocene Saglek Formation: 720–790 m), SR#2 (Lower Miocene Saglek Formation: 795–890 m), SR#3 (Lower Oligocene Mokami Formation: 1590–1690 m), and SR#4 (Lower Oligocene Mokami Formation: 1695–1790 m) samples from Rut H-11. Data show generally consistent probability peaks from Early Oligocene to Early Miocene time, but with increasing percentages of Cordilleran magmatic arc zircon grains with time. The total number of analyses is presented with the results; for example, *n* = 240/249 indicates that 249 analyses for sample SR#4 yielded 240 ages that passed the discordance filter of Gehrels and Pecha (2014) and were used for interpretation.

CORRELATIONS OF DETRITAL ZIRCON POPULATIONS WITH POSSIBLE SOURCE AREAS

Archean and Proterozoic (3650–567 Ma) age populations comprise 87% of the detrital zircon grains in Rut H-11 (Fig. 3) and are interpreted to have provenance from Precambrian basement rocks of the Laurentian craton and (or) their cover sequences. Archean detrital zircon grains in Mokami and Saglek formation strata generally match the ages of felsic igneous rocks and metamorphic derivatives in the basement provinces ('cratons') of North America (Superior, Nain, Wyoming, and others; e.g. Hoffman et al. 1989), whereas most of the younger contributions indicate derivation from rock units in late Paleoproterozoic and Mesoproterozoic orogenic belts (Trans-Hudson, New Quebec, Torngat, Mazatzal, Yavapai, Grenville, and others; e.g. Whitmeyer and Karlstrom 2007). Precambrian detrital zircon grains are abundant in Proterozoic and younger siliciclastic strata of North America

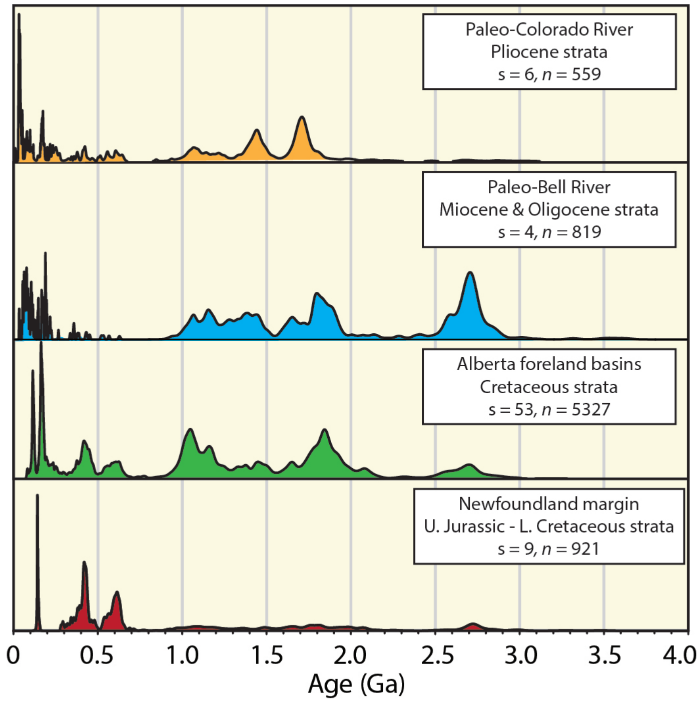

Figure 4. Stacked normalized probability density plots for selected Jurassic to Neogene drainage systems, including Pliocene paleo-Colorado River sediment from Kimbrough et al. (2015), Oligocene and Miocene paleo-Bell River from this study, Cretaceous Alberta foreland basin strata from Leier and Gehrels (2011), Raines et al. (2013), Blum and Pecha (2014), Benyon et al. (2016), Quinn et al. (2016), and Upper Jurassic to Lower Cretaceous strata of the Newfoundland margin from Hutter and Beranek (2020). s = number of detrital zircon samples, *n* = number of detrital zircon grains used for interpretation.

(Rainbird et al. 2017), including continental margin rocks involved in the Cordilleran, Innuitian, and Appalachian orogenic systems (e.g. Gehrels and Pecha 2014; Gibson et al. 2021; Kuiper and Hepburn 2021). Proterozoic detrital zircon grains in the Mokami and Saglek formations are likely mostly polycyclic and record long-term sediment recycling processes prior to deposition in the Saglek basin.

Paleozoic (533–266 Ma), Mesozoic (224–67 Ma), and Cenozoic (65–34 Ma) detrital zircon grains represent 13% of the total well Rut H-11 population (Fig. 3) and show consistent Late Triassic to Early Jurassic, Late Jurassic, mid- to Late Cretaceous, and Paleocene to Eocene age subpopulations. Paleocene magmatism is important in western Greenland, and intermittent Late Triassic to Early Cretaceous magmatism is recognized in Atlantic Canada (e.g. Pe-Piper et al. 2008; Hutter and Beranek 2020). However, the occurrences of mid-Cretaceous to Oligocene detrital zircon grains in the Mokami and Saglek formations are unlikely to be representative of local mafic sources, which typically lack zircons. These mid-Cretaceous to Oligocene zircon grains are more consistent with derivation from Mesozoic magmatic arc and foreland basin sedimentary rocks, and Cenozoic ignimbrite successions of the Canadian and U.S. Cordilleran orogen (Corradino et al. 2022). Sources of this age are widespread in the northern Rocky Mountains, the Basin and Range province, and the Colorado Plateau in the U.S. (e.g. Dickinson 2004; Nelson et al. 2013; DeCelles and Graham 2015).

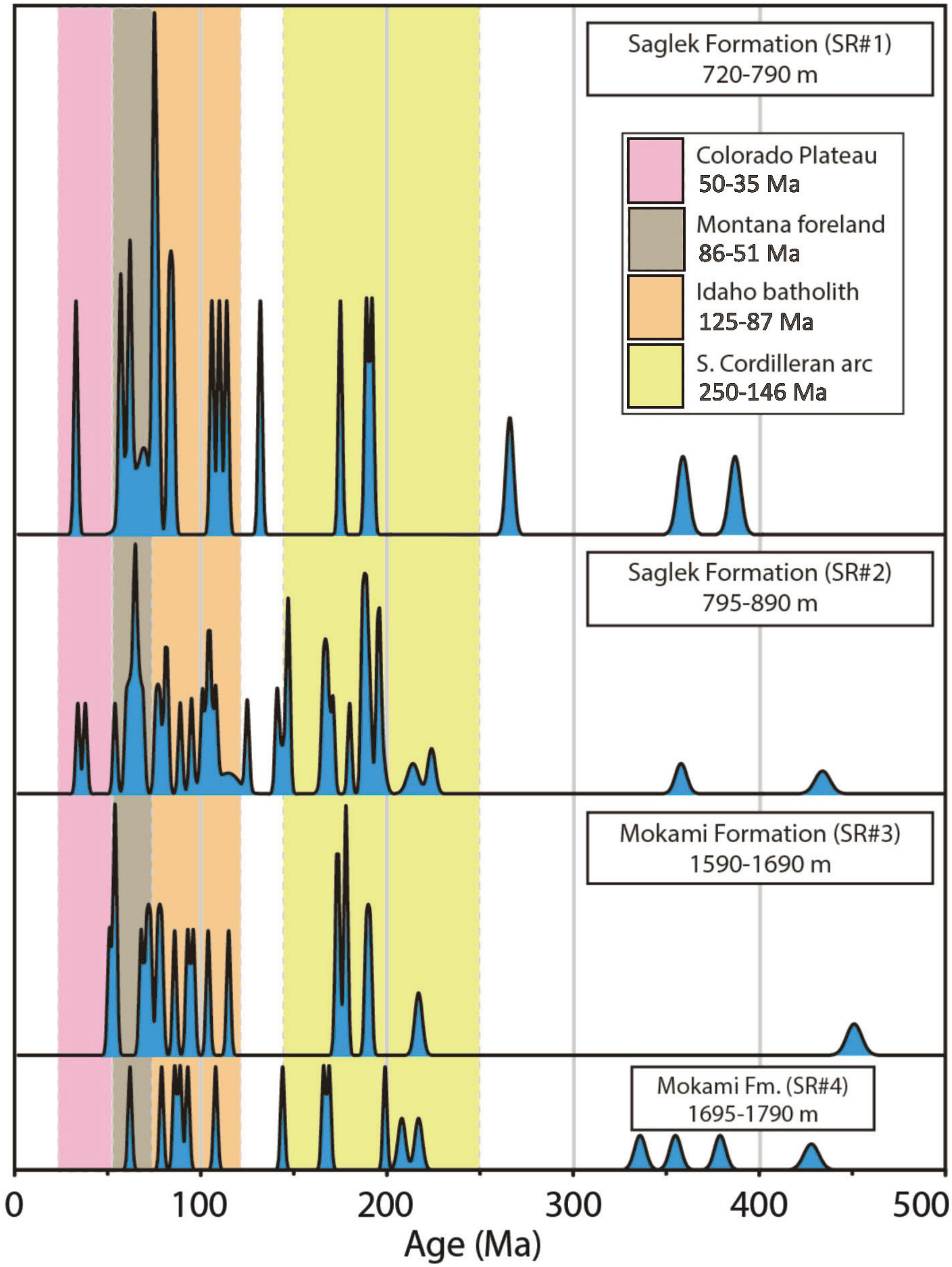

Figure 5. Stacked normalized probability density plots of < 500 Ma detrital zircon grains from this study. The 250–146 Ma detrital zircon grains (yellow) may indicate derivation from the southern Cordilleran arc and foreland basin. The 125–87 Ma detrital zircon grains (orange) link to the Idaho batholith. The 86–51 Ma detrital zircon grains (brown) correlate with Montana batholiths and foreland basin deposits. The 50–35 Ma detrital zircon grains (pink) correlate with southern Cordilleran Eocene and Oligocene arcs of the Colorado Plateau and the Great Basin.

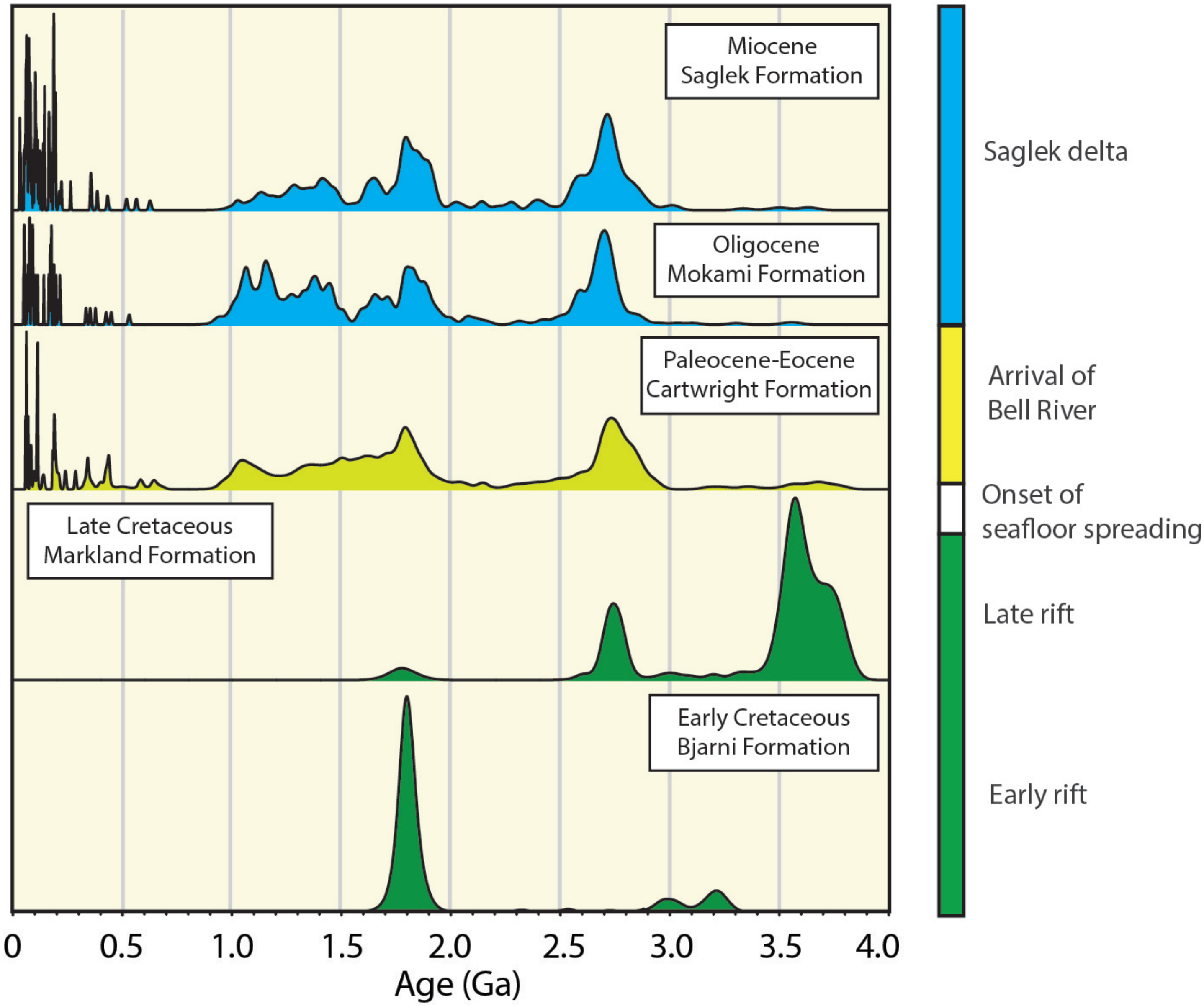

Figure 6. Stacked normalized probability density plots for Cretaceous and Neogene strata of the Saglek basin. Lower Cretaceous Bjarni and Upper Cretaceous Markland formations and Paleocene–Eocene Cartwright Formation results from Thrane (2014). Oligocene Mokami Formation and Miocene Saglek Formation results from this study. The dramatic change between Cretaceous (dark green) and Paleocene (light green) samples records the withdrawal of Western Interior Seaway and arrival of the Bell River in the Labrador Sea. Note the loss of locally derived > 3500 Ma grains of Labrador rift margin and addition of Cordilleran foreland and magmatic arc detrital zircon grains in the younger sequences.

PROVENANCE INTERPRETATIONS

Our U–Pb detrital zircon ages agree with the inferences of Balkwill et al. (1990) that the Bell River had three main tributary drainages that met in the Hudson Bay region (Fig. 1A, B). The eastern tributary drained the eastern Canadian Shield, the western tributary drained the Canadian Cordillera and High Plains, and the central tributary drained the U.S. Cordillera and High Plains. The detrital zircon signatures recorded in the Saglek delta are blends of these three regions. Figure 4 shows the patterns from the Saglek delta as compared to several regions of particular interest.

Canadian Shield

Figure 3 shows a large proportion of detrital zircons correlative with Precambrian-age domains of the Canadian Shield (see also Table 1). The relative proportions of 2000–1801 Ma, 2300– 2001 Ma, 2500–2301 Ma, and 4000–3201 Ma detrital zircons correspond broadly to areal proportions of those domains exposed on the Canadian Shield. Although the Hudson Bay basin is a large Paleozoic domain in the center of the Canadian Shield, and was once crossed by the Bell River, as shown in Figure 1A and B, it mostly contains marine carbonates with little siliciclastic material and likely did not contribute significantly to the Saglek delta detrital zircon population.

The relatively high proportions of 1600–951 Ma detrital zircons in the Saglek delta could imply that the Grenville Province and large anorogenic intrusions in the headwaters of rivers in northeastern Quebec contributed disproportionately to the Canadian Shield detrital zircon population in the river's discharge region. The Quebec-Labrador region was uplifted into mountainous relief on the west shoulder of the Labrador Sea rift system during the late Mesozoic and would have provided abundant sources of this age.

Cordilleran Foreland

A significant proportion of Proterozoic-aged detrital zircons could have been recycled from Cordilleran foreland basins (Fig. 4). The 1600–951 Ma age range is well represented in recycled detrital zircon populations of the Cretaceous strata of the Alberta foreland basins (Fig. 4), and in recycled detrital zircon populations of Paleozoic strata of the Colorado Plateau (Gehrels et al. 2011). The U.S. Cordillera has higher proportions of 1800–951 Ma detrital zircons than the Canadian Cordillera (Dickinson and Gehrels 2008; Laskowski et al. 2013; Corradino et al. 2022). The 2000–1801 Ma detrital zircon grains typically occur in higher proportions in Canada than the U.S. (Laskowski et al. 2013; Quinn et al. 2016). The large spike in Archean detrital zircons in the Saglek delta samples, compared with the smaller proportion in the Alberta foreland suggests derivation of the Archean grains mostly from the eastern Canadian Shield, rather than by recycling from the foreland.

U.S. Cordilleran Arc

The U.S. Cordilleran foreland basin system has abundant detrital zircon grains that match the ages of adjacent Cordilleran magmatic arcs (250–34 Ma) (Laskowski et al. 2013; Dickinson and Gehrels 2008). Figure 5 shows the < 500 Ma zircon populations for the Saglek delta samples. Mesozoic and Cenozoic detrital zircon grains increase in abundance upward in the stratigraphy. Figure 6 shows the zircon populations of the Saglek and Mokami formations (our data) compared to those of the Upper Paleocene Cartwright Formation (Thrane 2014). Overall, the abundance of < 500 Ma zircon grains increases from 4% to 16% of individual sample detrital zircon populations between Paleocene and Miocene times (Figs. 5 and 6). Of particular relevance is the 250–146 Ma population of detrital zircon grains shown in Figure 5. These ages correlate well with primary zircon sources in the magmatic arcs of southern California, Arizona, and northern Mexico, as well as with abundant detrital zircons of Upper Jurassic and Lower Cretaceous foreland basin formations of the Colorado Plateau and Rocky Mountain orogenic plateau (Dickinson and Gehrels 2008; Blum and Pecha 2014; Blum et al. 2017). This suggests that the ultimate sources for this zircon subpopulation lie in the southwestern U.S. Cordillera, rather than in more northern regions, including those in Canada. Detrital zircon grains of 125–87 Ma age are also present, and these closely correlate with the Idaho batholith. Similarly, detrital zircons of 86–51 Ma age correlate with the Boulder batholith and associated plutonic rocks, volcanic rocks, and bentonites of the Montana foreland (Laskowski et al. 2013). Detrital zircon grains of 50–34 Ma age correlate with plutonic and volcanic rocks of the Colorado Plateau and U.S. Rockies. The Coast Mountains batholith of British Columbia also contains grains of these ages (Gehrels et al. 2009; Cecil et al. 2018).

DISCUSSION

Cretaceous to Neogene Evolution of the Saglek Basin

Detrital zircon U–Pb investigations are critical to constrain the provenance of siliciclastic units and to reconstruct the paleogeography of continental margin basins (e.g. Gehrels 2014). Detrital zircon studies of Saglek basin strata therefore have the potential to test and develop new models for the Cretaceous to Neogene development of both the Labrador Sea margin and the ancient interior landscape of North America.

Lower Cretaceous syn-rift strata of the Bjarni Formation and overlying Upper Cretaceous strata of the Markland Formation exclusively yield Paleoproterozoic (1800–1700 Ma) and Archean (2800–2700, 3600–3000 Ma) detrital zircon grains that indicate derivation from rock units of the nearby Makkovik and Grenville provinces and the Archean North Atlantic craton in Labrador (Fig. 6; Thrane 2014). These results are consistent with an extensional plate-tectonic setting and proximal source regions that provided sediment in a geographically restricted distribution system (e.g. Cawood et al. 2012). Paleocene strata of the Cartwright Formation show the delivery of significant Mesoproterozoic to late Paleoproterozoic (1650–1000 Ma), late Neoproterozoic (670–585 Ma), Paleozoic (500–288 Ma), Mesozoic (242–66 Ma) and Cenozoic (64–60 Ma) detrital zircon grains to the Saglek basin at ~ 58 Ma (Fig. 6; Thrane 2014). The arrival of these detrital zircon grains from far outside Atlantic Canada supports the onset of thermal subsidence by Paleocene time and indicates that a regional- to continental-scale drainage area with subtle relief fed the developing Labrador Sea passive margin system (e.g. Cawood et al. 2012). New results from our study confirm that the overlying Mokami and Saglek formations were also derived from a large Oligocene–Miocene drainage basin network that included the Canadian Shield, Paleozoic to Mesozoic orogenic systems, and Paleocene to late Eocene magmatic rocks likely from southwestern North America. The youngest age populations became more abundant with time. The percentage of Triassic and younger grains generally increases from the Cartwright Formation (4%; Thrane 2014) to the Mokami Formation (5% in SR#4 and 10% in SR#3) to the Saglek Formation (15% in SR#2 and 16% in SR#1), suggesting that new drainage areas were organized during the Oligocene–Miocene.

Implications for Oligocene–Miocene Erosion of the Grand Canyon and Denudation of the Colorado Plateau

The detrital zircon data from the Labrador Sea delta constrain Cenozoic paleogeographic and drainage models for North America and add to previous inferences by Corradino et al. (2022). The detrital zircon data of Blum and Pecha (2014) and Blum et al. (2017) from the U.S. Gulf of Mexico coastal plain augment the data from the Saglek delta and allow a test of the hypothesis that the Bell River headwaters reached into the southwestern U.S. in Oligocene and Miocene times, which may have initiated the cutting of the Grand Canyon and associated denudation of the Colorado Plateau (Sears 2013).

The early incision of the Grand Canyon was accompanied by 1 to 2 km of erosional denudation of the Colorado Plateau surface (Flowers et al. 2008; Cather et al. 2008; 2012; Flowers and Farley 2012; Lee et al. 2013) during the age range of our sampled interval in the Saglek delta. The Colorado River did not carve the deeper Inner Gorge of the Grand Canyon until the early Pliocene (< 5.3 Ma; Dorsey et al. 2005), which is when the river first flowed into the newly opened Gulf of California (Lucchitta 1972; Karlstrom et al. 2008; Lucchitta et al. 2011). Wernicke (2011) and Young (2008) suggested that parts of early Grand Canyon were instead carved by some combinations of north-flowing rivers. Davis et al. (2010) used detrital zircon data to propose that their "California River" flowed from southern California through the southwestern Colorado Plateau to northern Utah (Fig. 1A). Sears (2013) proposed that the large mass of sediment eroded from the Colorado Plateau in Oligocene–Miocene times was transported farther northward into the Bell River basin and is now buried in the Saglek delta.

Figure 4 compares detrital zircon data from the Bell River to data from deposits associated with the Pliocene Colorado River, the Cretaceous Alberta foreland basins, and the Atlantic offshore margin of Newfoundland. The Bell River and Pliocene Colorado River data match, aside from the absence of a prominent Neoarchean peak in the Colorado River data. This indicates that the source regions for the Bell and Colorado paleo-rivers had similar geological architecture, but that the Bell River derived more abundant material from the Canadian Shield, including cratonic blocks. The Pliocene Colorado River was mainly sourced from the Colorado Plateau and Wyoming Rockies, so it would not have had the same access to older Precambrian sources.

The Bell River and Cretaceous Alberta foreland basins share similar detrital zircon age peaks, except that the Bell River has a more prominent Neoarchean peak representing the Canadian Shield, and also includes some significantly younger detrital zircon populations. However, the depositional ages of the sediments that contain the detrital zircons differ, and therefore the Cretaceous foreland basins in Alberta clearly cannot contain Cenozoic zircons because those sources did not exist at the time of deposition. Paleozoic and Mesozoic detrital zircons grains in the Saglek delta could in part be derived from recycling of material from the Alberta foreland basins, and (or) the Bell River and the Alberta foreland basins had primary source regions with similar geological architecture. Comparison of the detrital zircon data for the Bell River and the Newfoundland Atlantic margin indicates that they are very different. This suggests that the Bell River delta was not fed by rivers flowing north from the Canadian Maritimes. The signature of the Newfoundland Atlantic margin is largely that of the paleo-St. Lawrence River (Fig. 1A, B).

Our results demonstrate that Saglek delta sands may have had some provenance in the Cordilleran magmatic arc, although this distal component was greatly diluted by older zircon grains from the Canadian Shield. Our results are consistent with the detrital zircon data of Corradino et al. (2022), who also sampled some intervals from well Rut H-11 but did not differentiate among Cordilleran sources. The detailed view of Paleozoic and Mesozoic data shown in Figure 5 indicates that detrital zircon subpopulations from well Rut H-11 correlate with: 1) the U.S. Cordilleran arc and foreland basin (250–146 Ma); 2) the Idaho batholith (115–87 Ma); 3) the magmatic arc and foreland basin of Montana (86–51 Ma); and 4) the Eocene–Oligocene magmatic provinces of the Colorado Plateau and Great Basin (50–35 Ma). This combination of age provinces appears to be unique within the wider potential catchment area for the Bell River in North America.

Blum and Pecha (2014) and Blum et al. (2017) mapped North American drainage re-organizations from Early Cretaceous through Oligocene time. Their detrital zircon data indicates that the Late Paleocene–Late Eocene drainage divide between the Gulf of Mexico and Bell River basins trended westward across the north central U.S. (Fig. 1A). In Montana, that drainage divide intersected the Pacific drainage divide, which trended southward along the Cordillera from Canada to southern California. The situation changed during Oligocene times (Fig. 1B), when there was uplift of the New Mexico, Colorado, and Wyoming Rockies across the western headwaters of the Gulf of Mexico drainage basin. This shifted the Gulf of Mexico divide eastward (Blum et al. 2017), but according to Best et al. (2013) the Pacific divide remained in Nevada and southern California. The California River may have been captured by the southern headwaters of the Bell River in Wyoming. The Colorado Plateau region would thus have transferred from the Gulf of Mexico basin to the Bell River basin during the Oligocene. That transfer would have increased the catchment area of the Bell River basin by about 7.5%, from ~ 8.6×10^6 km^2 to ~ 9.3×10^6 km^2. (Fig. 1 A, B). Blum et al. (2017) found that the western facies of the Upper Paleocene–Lower Eocene Wilcox sand wedge of the Gulf of Mexico basin contained significant percentages of southern Cordilleran magmatic arc detrital zircons, but that these diminished in the western facies of the Oligocene Vicksburg-Frio sand wedge. The stratigraphic distribution of submarine fans in the Gulf of Mexico indicates that drainage areas in the western part of its basin diminished in extent at the same time as the detrital zircon provenance changed (Blum et al. 2017).

The data presented in this paper show that detrital zircon assemblages with a distinctive Cordilleran arc signature from the southwestern U.S. first appeared in the Saglek delta of the northern Labrador Sea at ~ 34–32 Ma, at about the same time as they diminished in the Gulf of Mexico drainage basin. The Bell River system may thus have linked southern Colorado Plateau sources to the Saglek delta from Oligocene to Miocene times, which is also when 1 to 2 km of the Colorado Plateau was removed by erosion (Cather et al. 2008, 2012).

Comparison of Oligocene–Miocene detrital zircon data with Thrane's (2014) results from the Upper Paleocene Cartwright Formation in Saglek basin well Raleigh N-18 (Fig. 6) reveals a dramatic change in provenance between Late Paleocene and Early Oligocene time. Detrital zircon percentages attributed to recycled Paleozoic and Cordilleran foreland basin sources (2000 Ma to 251 Ma) and Canadian Shield sources (3000–2000 Ma) remained relatively constant between the Paleocene and Upper Oligocene/Lower Miocene samples, but the proportion of zircon grains possibly representing Cordilleran magmatic arc sources (251– 60 Ma) increased with time. The data of Corradino et al. (2022) show a similar pattern for the Late Oligocene–Early Miocene Bell River drainage compared to earlier times.

Davis et al. (2010) interpreted detrital zircon patterns in Paleocene–Eocene units of the Uinta basin in the northern Colorado Plateau as due to northward fluvial transport by the California River (Wernicke 2011), which flowed northward from southern California to northern Utah. In the interpreted paleogeography for Late Paleocene times (Fig. 1A), the California River joins the paleo-Platte River near the Bell River divide to flow southeastwards to the Gulf of Mexico. The California River thus provides a mechanism for Late Paleocene fluvial transport northward from the southern Colorado Plateau, but the ultimate destination for detritus at that time was the Gulf of Mexico. The Cypress Hills of the Alberta and Saskatchewan High Plains provide a second example of northward fluvial transport of detrital zircon grains (CH, Fig. 1B). Middle Eocene through Lower Miocene fluvial beds of the Cypress Hills were derived from the south on tributaries of the Bell River that were upstream of other major branches that drained the northern Canadian Cordillera and eastern Canadian Shield (Leckie 2006). The beds contain only minor proportions of Archean detrital zircon grains and moderate proportions of Proterozoic detrital zircon grains, but they contain abundant detrital zircon grains that match Cordilleran arc sources (Corradino et al. 2022). The detrital zircon assemblages of the Cypress Hills are similar to those of the California River (cf. Davis et al. 2010). These two lines of evidence suggest that north-flowing rivers could have linked the Colorado Plateau with the Bell River basin if the California River was captured by the Bell River during the Oligocene, and no longer fed the Gulf of Mexico basin (Fig. 1B).

The Archean and Proterozoic detrital zircons were likely recycled from the Cordilleran foreland basin, and the Cordilleran arc detrital zircons may have been recycled from foreland basin deposits or may have been derived directly from primary igneous sources in the Colorado Plateau and Great Basin areas.

Although capture of the western headwaters of the Gulf of Mexico basin would have increased the area of the Bell River drainage basin, the proportions of Precambrian detrital zircon grains in the Saglek delta stayed much the same, because zircons of that age were present in the foreland basin and Canadian Shield sources and were recycled downstream along with young zircons from magmatic arc sources. Detrital zircon grains from the Cordilleran arc were progressively diluted by detrital zircons from the foreland basin and Canadian Shield *en route* to the Saglek delta and so account for smaller proportions in the delta than in either the Cypress Hills or the Uinta basin, as discussed by Corradino et al. (2022).

An interesting exception to the provenance signal is an unusual spike in Grenville-aged detrital zircon grains in the Mokami Formation (24.4%) relative to background proportions in the underlying Cartwright Formation (8.6 %, Thrane 2014 and overlying Saglek Formation of 8.1%). This may reflect denudation of Mesozoic eolianites along the southern rim of the Colorado Plateau in Arizona that have high proportions of Grenvillian detrital zircon grains (Gehrels et al. 2011). The Colorado Plateau was widely denuded beginning in Oligocene time (Flowers et al. 2008). Southwest to northeast progression of unroofing parallel to the Plateau margin may have spiked the Grenvillian detrital zircon content of paleo-rivers that flowed north to the Saglek delta. Upon stabilization of the erosional surface, these Grenvillian detrital zircons contributions ceased, and their proportions returned to the background levels contributed by the Cordilleran foreland basin and Canadian Shield.

The north-flowing rivers that initiated erosion of the Grand Canyon and denuded the southern Colorado Plateau may have drained into the paleo-Missouri or paleo-Yellowstone rivers (see Fig. 1B). These were known southern tributaries of the Bell River before Pleistocene continental glaciation diverted them into the modern Mississippi River basin (Howard 1958; Leckie and Cheel 1989; Leckie 2006; Galloway et al. 2011). The paleo-Missouri River may have drained along a rift valley in the Great Basin region (Sears 2013), whereas the paleo-Yellowstone River may have drained from the Colorado Plateau and Wyoming Rockies. Our results support the fluvial connection between Oligocene–Miocene erosion of the Grand Canyon and deposition of derived sediment in the Labrador Sea, but they do not differentiate between flow into the paleo-Missouri or the paleo-Yellowstone rivers. Nevertheless, through one route or another, we suggest that the California River discussed by Davis et al. (2010) made its way into the central branch of the Bell River, and so established a long-distance connection between the southwestern part of what is now the U.S., and land that is now submerged in the northeastern Arctic and Subarctic regions of Canada.

CONCLUSIONS

Our U–Pb detrital zircon results, in conjunction with information presented by Corradino et al. (2022) and other past research, link Oligocene–early Miocene sediment deposition in the submarine Saglek delta of the Labrador Sea to sources in the Cordilleran orogen. These sources reached at least as far south as Montana and Idaho, and possibly beyond, into the Colorado Plateau and the Great Basin. We suggest that the headwaters of the Bell River, a system comparable in size to the modern Amazon River, could have reached as far south as the Grand Canyon, as hypothesized by Sears (2013). It remains possible that some detrital zircon grains in the Saglek delta that came from these distant regions could have been recycled from farther north in the Cordilleran foreland. However, the evidence from contemporaneous paleo-drainage systems related to the Colorado Plateau and the Gulf of Mexico basin suggests that the arrival of far-travelled detritus in the Saglek delta corresponds in time with continental-scale changes in drainage patterns. Further research may refine the correlations between deposition in the Saglek delta and erosion in the many headwaters of the Bell River basin. In particular, detrital zircon data from Pliocene sediments in the Saglek delta could provide further tests of these ideas.

The story of this pre-glacial Amazon River and the very different world that it drained and watered still has many missing chapters, but it provides a powerful illustration of how geological processes can connect events in locations separated by truly immense distances.

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