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The Allure of Vanished Worlds

B.C's Jurassic Past: Provenance and Processes Explored

Canada's pre-glacial Amazon: Grand Canyon meets Great White North

Riding the Waves of Change - Halifax-2022 Field Trips

Passamaquoddy: Multicultural magmas meet and mingle in Nature's melting pot

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Cover Image: Remarkable modern landscapes from two areas that were once possibly connected by a vast pre-glacial river system in North America. The upper image is the famous Grand Canyon of the Colorado River (photo: A. Kerr) and the lower image shows Saglek Fiord in the Torngat Mountains National Park, Labrador (photo: Parks Canada). See the paper by Sears and Beranek (this issue) for more discussion.

EDITORIAL

The Allure of Vanished Worlds

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Over the years, it has become a tradition that the first issue of *Geoscience Canada* contains some sort of editorial piece. When the deadline looms in March, I regret that this precedent was ever established. What can I possibly write that has relevance and interest to readers? We are still here, obviously, and we plan to continue as best we can and serve our Geoscience Community in Canada. Surviving as a small scientific journal in a large pond has more than its fair share of challenges, but our long-term goal is to grow and prosper, not just to persist. Our ongoing efforts would not be possible without the support of volunteers and GAC members, and of course the invaluable work of managing editor Cindy Murphy. So let my first statement this year be one of sincere thanks to Cindy and to all who assist us every year in smaller ways to produce the journal.

In previous editorials, I have outlined some of the challenges that we face, and especially the need for the submission of good papers on diverse topics. This is the only viable route towards raising our profile and impact in a world dominated by corporate publishing. I have discussed the open-access concept, and its possible benefits to journals like us, even with the additional fiscal challenges that it implies. In 2020, I even ventured into the impact of the Covid-19 pandemic on the lives and work of Earth Scientists, mostly in an effort to find silver linings in a large bank of clouds. I doubt that many readers really want to hear more on that subject after two more years, as it is all too familiar. All of these topics are important to *Geoscience Canada*, and some are clearly vital, and many will come back in future years. Hopefully, Covid will not be in that latter group. So, the search for topics suited to a 2022 editorial seemed fruitless for quite some time. In the end, I decided to avoid all the obvious but well-worn subjects and will spend a few pages to instead contemplate the past. Not the recent past, or even some historical past, but the distant and mysterious geological past that lies at the very heart of our chosen calling. Those who read to the end of this might well feel that this is no more than an escapist flight into imagination, and perhaps just a diversion from the many serious issues confronting our world in the spring of 2022. There may be indeed some truth in this perspective.

The two technical papers featured in this first issue for 2022 have much in common, although this is certainly not by our design. Both articles focus on the use of detrital zircon U–Pb geochronology to solve geological problems, but they also share a deeper theme. Superficially, they include statistics, probability density charts and tables of data, but they are in the end delving into something more fundamental. Both papers seek to recreate *vanished worlds* - places that existed tens to hundreds of millions of years ago on an Earth that was simultaneously familiar and alien. Earth Scientists are uniquely privileged to be aware of a multitude of vanished worlds, to the extent that we may take them for granted. It is just part of geoscience thinking in the broad sense, and we do not often pause to contemplate the enormity of such concepts. But I believe it serves us well to indulge our fascination for this far greater picture. Like many of us, I started out intending to study something else in my teens, but then ended up in some first-year geology classes. I was lucky enough to encounter young and passionate instructors, and the heady combination of the *new global tectonics* and visions of long-vanished worlds that they gave me led to a different academic path. It was like being exposed to the speculative breadth of science fiction buried within the scope of a vast historical adventure, and fifty years later, I still feel exactly that way. Earth Science truly gives us multiple worlds to explore, although at times we wish for even more.

The paper by James Sears and Luke Beranek is built from measurements on thousands of nearly invisible zircon grains, but it transports us well beyond such details. It returns us to a pre-glacial North America that had a very different geography and climate, and a great river that rivalled our modern Amazon. Robert Bell of the Geological Survey of Canada speculated in 1895 that most of North America once drained into Arctic waters, before huge ice sheets remodelled our geography. The story of the "Bell River", as it later came to be called, is now stored in the sands and silts of a vast delta beneath the frigid Labrador Sea, and by scattered residual outcrops on the Great Plains. This concept is astonishing enough, but it seems that this vanished northern Amazon once had headwaters in the desert southwest of our continent, although it was likely not arid in those times. James and Luke suggest that the development of the Colorado Plateau, including the early Grand Canyon, might be part of the Bell River's long story. After 50 years, I still marvel at how Earth processes link such distant

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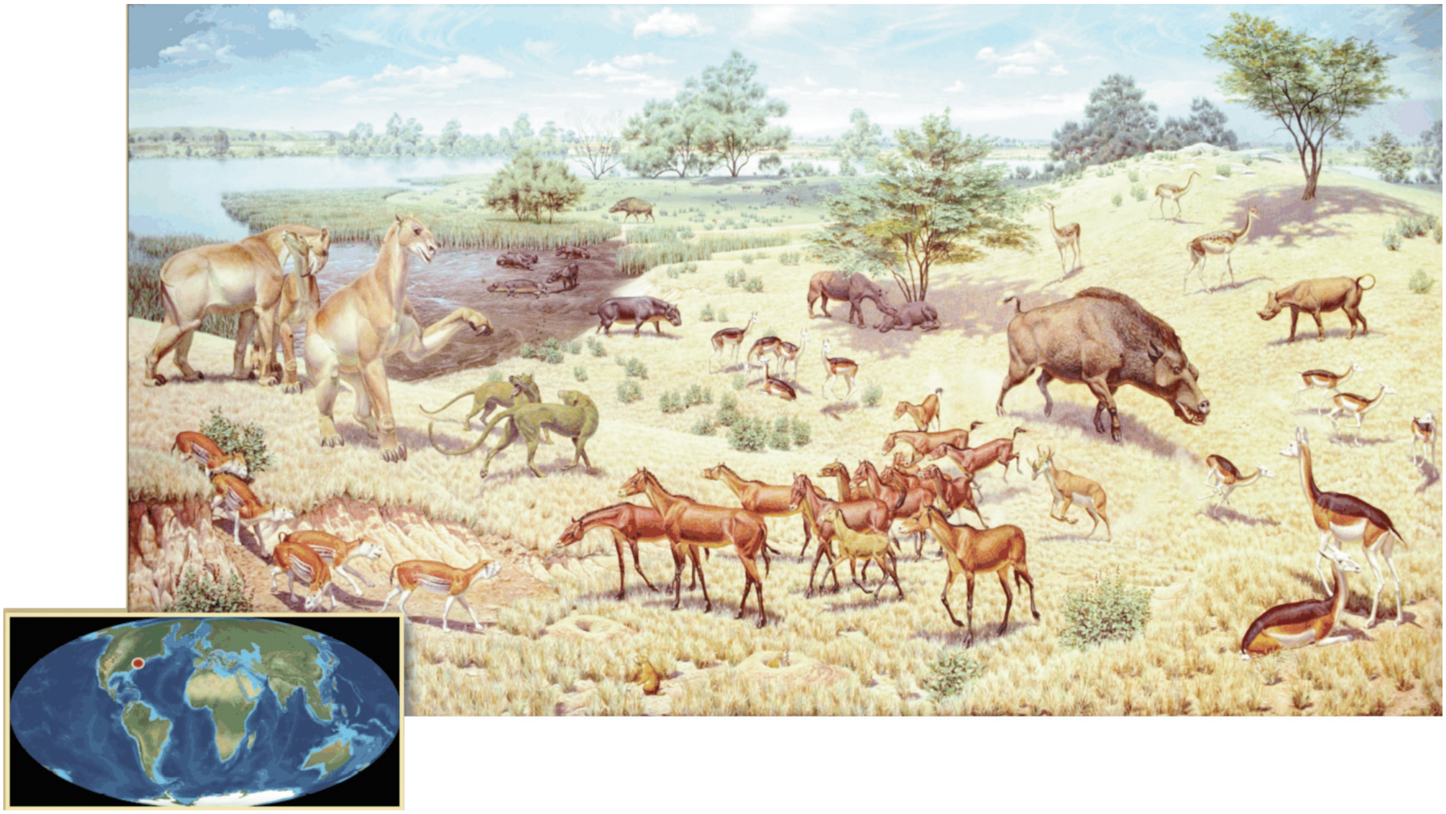

Figure 1. Artist's depiction of a Miocene landscape and fauna in North America, from the United States Geological Survey "Trail of Time" website (www.usgs.gov/youth-and-education-in-science). The painting depicts a wide waterway in the background, which can perhaps be thought of as the Bell River although (strictly speaking) this scene is intended to represent Virginia. The inset shows a global plate reconstruction for the Miocene Epoch, which broadly resembles the world map of today. Is this what the landscapes around the pre-glacial Bell River would have looked like?

and different places, even though it really should not surprise me. But when I read their paper as an editor, I wanted also to step beyond long-distance zircon transport and try to visualize this vanished world. This colossal drainage basin was initiated during one of the warmest climates in the geological record, so coal swamps existed in its delta, and as far north as present-day Ellesmere and Axel Heiberg islands. Forests flourished in landscapes we see today as ice-carved tundra. What other landscapes and environments existed across the land we now call Nunavut? During these warmer times, much of Ellesmere Island was probably covered by vegetation similar to modern Boreal forests, and pollens from vines and other semi-tropical plants are reported from other high-Arctic locations. What would it have been like to stand on a summit in the ancestral Torngat Mountains, and gaze across distant flatlands within a vast rift valley that would one day become an ice-choked sea? If only we could travel there, we could drift downstream with the waters of the Bell and see the remarkable mammals of the Paleogene and Neogene along its banks. We will never know all the details, but surely such a mighty river would be a vibrant ribbon of life, just like those of today. Artists have recreated many of the North American mammals of these times (see Figure 1; courtesy of the United States Geological Survey), and the image for the Miocene clearly includes a large waterway.

The paper by Dawn Kellett and Alex Zagorevski of the Geological Survey of Canada similarly uses geochronological and isotopic techniques to understand an ancient sedimentary basin now preserved within the mountains of present-day British Columbia and Yukon. But beyond its technical terms and data tables, it is an excursion to another vanished world - perhaps the real version of *Jurassic Park*. Visualizing this is a much greater leap than my imaginary voyage down the Bell River because there are only tenuous connections to our modern geography or topography. This long-vanished world was changed and moved by the power of tectonic orogeny, not just by the slow shift of global climates. As the Earth recovered from its catastrophic mass extinction at the end of the Permian, numerous Mesozoic island chains littered the ocean offshore from a stable continental shelf where the Rocky Mountains would eventually tower (Figure 2). We can only speculate about their sizes, shapes and geometries, and they bear only collective names today as "terranes" within the Cordilleran Orogenic Belt. We suspect that one of them, now called Yukon-Tanana, might have been larger, as it had a longer history, and was rifted away from North America in some earlier event. For the most part, these island networks of the Triassic and Jurassic *literally* vanished, as their volcanic peaks were eroded and dissected even as they erupted. The remains of a vanished archipelago remain in the folded and faulted sandstones

Figure 2. Reconstruction of North American paleogeography for the early Cretaceous period. The maze of islands located north and west of present-day British Columbia represents the area where the sedimentary rocks of the Laberge Group were deposited in an active tectonic environment during the Jurassic. The Rocky Mountains, which dominate the Canadian Cordillera, are just beginning to develop; over time their growth will rearrange continental drainage, to create the Paleogene and Neogene Bell River basin, which connected parts of the Cordillera to the Labrador Sea. The Labrador Sea is just beginning to develop on the opposite side of North America at this time. Original diagram by Ron Blakey, from the book *Four Billion Years and Counting*, published by the Canadian Federation of Earth Sciences.

and conglomerates of the Jurassic Laberge Group, which also preserves information on how this sedimentary basin was locally deformed and uplifted, even as other parts of it were still accumulating. Painting a picture of this vanished world reveals a much stranger place, but it does contain some characters familiar to most children, even if they do not have geologists in their families. This was another hothouse world, with no signs of polar ice, and inconspicuous mammals, which are generally portrayed as nervous oppressed victims of marauding dinosaurs. By our standards, it was a tropical environment, but likely very different from what we see today, particularly in terms of vegetation. Lush island slopes would have been dom-

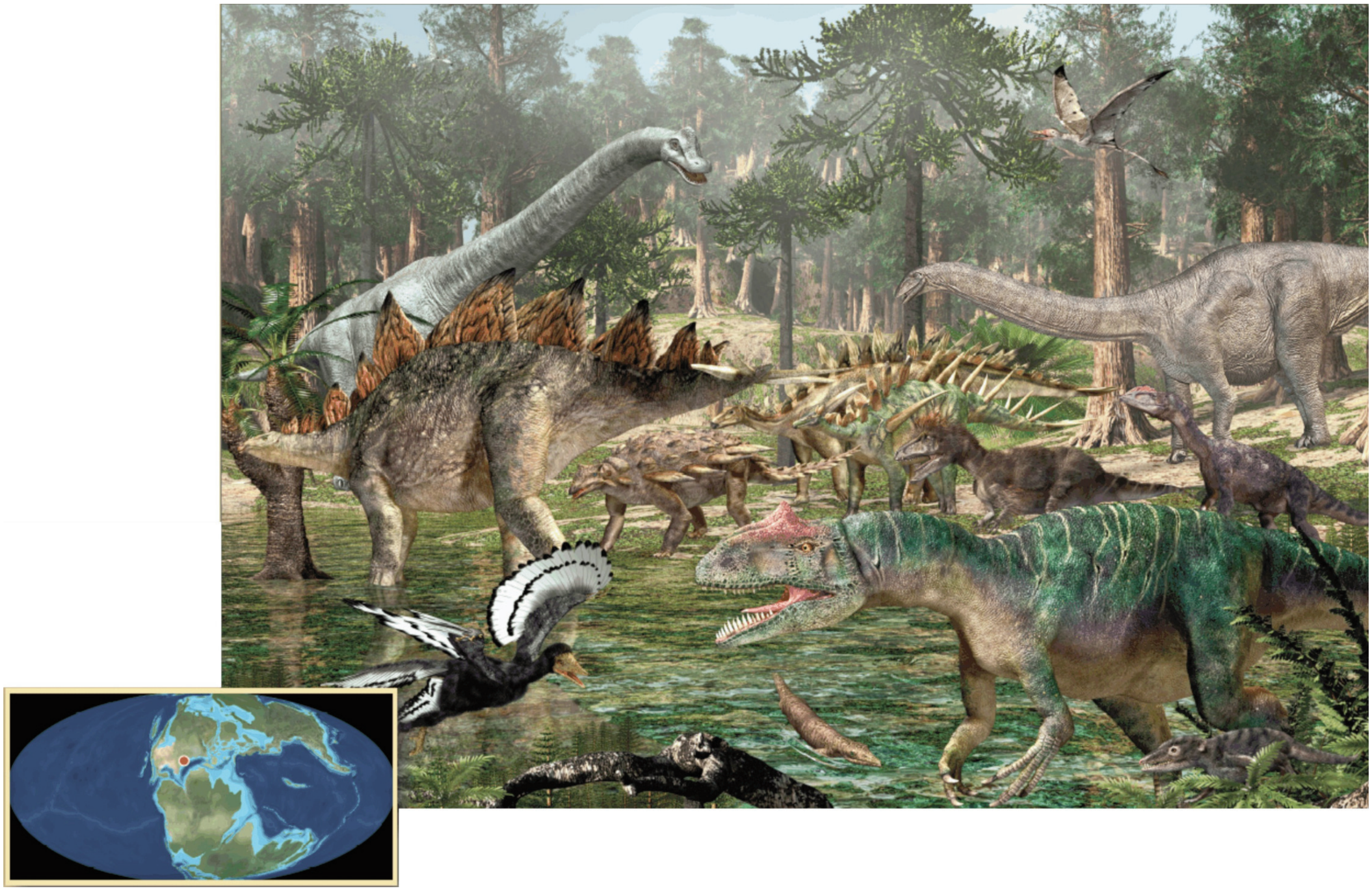

Figure 3. Artist's depiction of a Jurassic landscape and fauna in North America, from the United States Geological Survey "Trail of Time" website (www.usgs.gov/youth-and-education-in-science). The painting naturally depicts a wide variety of dinosaurs, some of which will be familiar. Although species might have differed in detail, some are probably representative of predators that lurked on the scattered islands of Jurassic British Columbia. Note that the vegetation is dominated by conifers and cycads, rather than the flowering trees of today's tropical regions. Inset shows Jurassic paleogeography, which is quite different from what we see on the world map of today.

inated by massive conifers and cycads - evergreen plants that resemble modern palms - and flowers (as we know them) had yet to evolve. What would it be like to go back in time and sail ancient turquoise seas in this Jurassic Eden, or to walk on its beaches of (presumably) black sand? We are told that the laws of physics will always forbid such excursions, but I feel sure that most geologists would jump at the chance if offered to them, even with the ever-present risk of being eaten by some sort of *Saurus*. Although the dinosaurian villains that populate the Hollywood version did not actually evolve until the Cretaceous, the reconstruction of Jurassic fauna provided by artists of the United States Geological Survey (Figure 3) implies that a variety of dangerous predators awaits any careless time-traveller.

Despite their contrasts, there is a thread of connection between the vanished worlds of Jurassic British Columbia and the Paleogene to Neogene Bell River. It was the development of the modern Cordilleran Orogenic Belt in late Mesozoic times that remodelled the drainage systems of North America and forced its inland sea to retreat through the corridor that would become the trunk route of the Bell River. Much later, geographic changes caused by tectonics in ancestral Central and South America may have set the stage for a transition to an icehouse climate and the great Pleistocene glaciations that would divert the Bell's course. These vanished worlds that we like to construct do not exist in isolation but are part of a continuum. Each is influenced by its ancestors and influences its descendants, just like the characters in a vast novel. A saga that Earth Scientists are uniquely privileged to understand and interpret.

I first learned about some of these vanished worlds in introductory geology courses, and they were an important influence on my decision to follow a career in Earth Sciences. I was even lucky enough to once teach a course on the topic, back in the days of blackboards and overhead projectors. I think that many readers had parallel experiences with learning historical geology as an integrated topic, but this is not necessarily the case for many Earth Science students in the 21st century. At Memorial University, there is no longer an introductory course devoted to Earth History, although it is still listed as "inactive" in formal documents. It has been that way for many years. There is, however, an excellent course entitled *Earth's Story*, but this is designed as an elective, without science prerequisites, placing some limits on its content and scope.

Although this course does not count as a credit towards an Earth Science degree, many students do complete it, and my colleague Sharon Deemer tells me that they find that it has much value in connecting diverse topics discussed in more specialized offerings. Given the immensity and breadth of the topic, and our modern view of the Earth as an "evolving planetary system", I find the absence of a dedicated core Earth History course more and more puzzling. To me, it provides a natural narrative to connect what we now know about the dynamic Earth and initially explore the many things that we still do not understand about it. Supercontinent cycles and the great mysteries of mass extinctions are just two of the most obvious examples, but Earth History also provides much insight into the controls of climates, atmospheric evolution and the profound influence of the biosphere on almost all aspects of planetary development. Vanished worlds also have relevance to our familiar world, and to less familiar worlds that our descendants may contend with. For example, the Paleocene–Eocene Thermal Maximum (PETM), which corresponds to the early times of the Bell River, provides a possible past analogue for today's rapid anthropogenic climate warming, although the rates of change then were orders of magnitude less than we are experiencing today.

It seems that Memorial University is not alone in devolving Earth History as a core component in its undergraduate program. An informal survey of other Earth Science departments across Canada suggests that many no longer offer such a course to students in their first or second years. Some do retain courses that include selected aspects of historical geology, but this is often associated closely with paleontology. There are of course many connections between these disciplines, and paleontology certainly defines many recent chapters in Earth's story, but I am sure that most paleontologists would agree that it is not the *only* story. Other departments follow Memorial's route in offering Earth History as a more generalized elective designed primarily for non-science majors or for related science majors. My survey was not detailed or comprehensive, and I did not get responses from all my queries, but it left me with a feeling that some of today's Earth Science students may be missing out on something fundamental and fascinating. I went on to look at available textbooks that explore this topic and I was surprised to find very few of recent vintage. The one I am most familiar with from my own use in teaching is *Earth System History*, by Steven Stanley and John Luczaj, last updated in 2015, which is a good combination of essential geoscience and a well-structured voyage through time. Beyond that there is not that much to choose from, although I was intrigued by Andrew Knoll's new book *A Brief History of Earth: Four Billion Years in Eight Chapters*, published just last summer. From its modest price, I think this must be a popular science book, and it is an obvious candidate for a review in some later issue this year. Robert M. Hazen's *The Story of Earth* (2012) is definitely in the popular science category, at half the price again, but still a very good read for non-geologists. I have always recommended it as supplementary reading to first-year classes, and hopefully some of them took that advice. Most other Earth History oriented texts seem to be second hand editions of older works – in sharp contrast to the general abundance and diversity of introductory Earth Science texts that emphasize physical geology. For readers in Canada, there is of course an excellent choice in *Four Billion Years and Counting*, published by the Canadian Federation of Earth Sciences, and this is almost a text in itself, but its historical focus is understandably very much on Canada.

I personally believe that this subject is one that all prospective Earth Scientists should encounter through an integrated treatment in the early stages of their program. For those who continue on to other aspects of Earth Science, it provides a framework to link and connect concepts and observations from other courses, including tectonics, paleontology, petrology, economic geology and even planetary science. For those who do not continue in mainstream Earth Science, but choose other paths, it provides an entirely new way of understanding the world that surrounds them, and the countless other worlds that preceded it. But most importantly, this remarkable 4.5 billion year saga surely has the narrative power to recruit those who may not yet realize that they are destined to become Earth Scientists. Those who simply cannot resist opportunities to explore vanished worlds and all their unanswered questions are surely needed as part of our profession's future.

In closing, I will of course suggest that *Geoscience Canada* could have some role to play in better understanding vanished worlds and bringing them to future generations. After all, no editor should ever pass up the opportunity to promote the preparation and submission of papers! The history of the Earth is not one smooth and continuous ride, but rather one of stops and starts, with times of rapid unidirectional change. I would not deny that some chapters are more interesting and controversial than others, but this view really depends on perspective. For example, the late Martin Brazier's famous characterization of the middle Proterozoic as *The Boring Billion* could never be endorsed by any economic geologist. Nevertheless, it is fair to say that some stretches of our long saga generate more debate than others, because the details, causes and effects of some fundamental changes in the Earth System remain obscure. The periodic mass extinctions of the Phanerozoic are perhaps the most obvious examples, but we can find many puzzles in the Precambrian depths. For example, what was the Hadean really like? Did it really live up to its name or, as some contend, was it actually as cold as Hell? Much still remains controversial in our understanding of the Great Oxidation Event(s) that define the earliest Proterozoic, leading to vast iron deposits that support our industrial civilization, and perhaps indirectly causing global glaciations. And what of the so-called *Canfield Oceans* that then persisted for nearly a billion years beyond those events, perhaps allowing the formation of other key metal resources that we now depend on? At the other end of the Proterozoic, the world-spanning glaciers returned again, but we are a long way from understanding the ultimate causes, or the links that might connect the *Snowball Earth* to suddenly increased atmospheric oxygenation and the first large multicellular organisms of the Ediacaran (Figure 4). What are the current views about the so-called *Cambrian Explosion* that later introduced familiar groups of organisms whose

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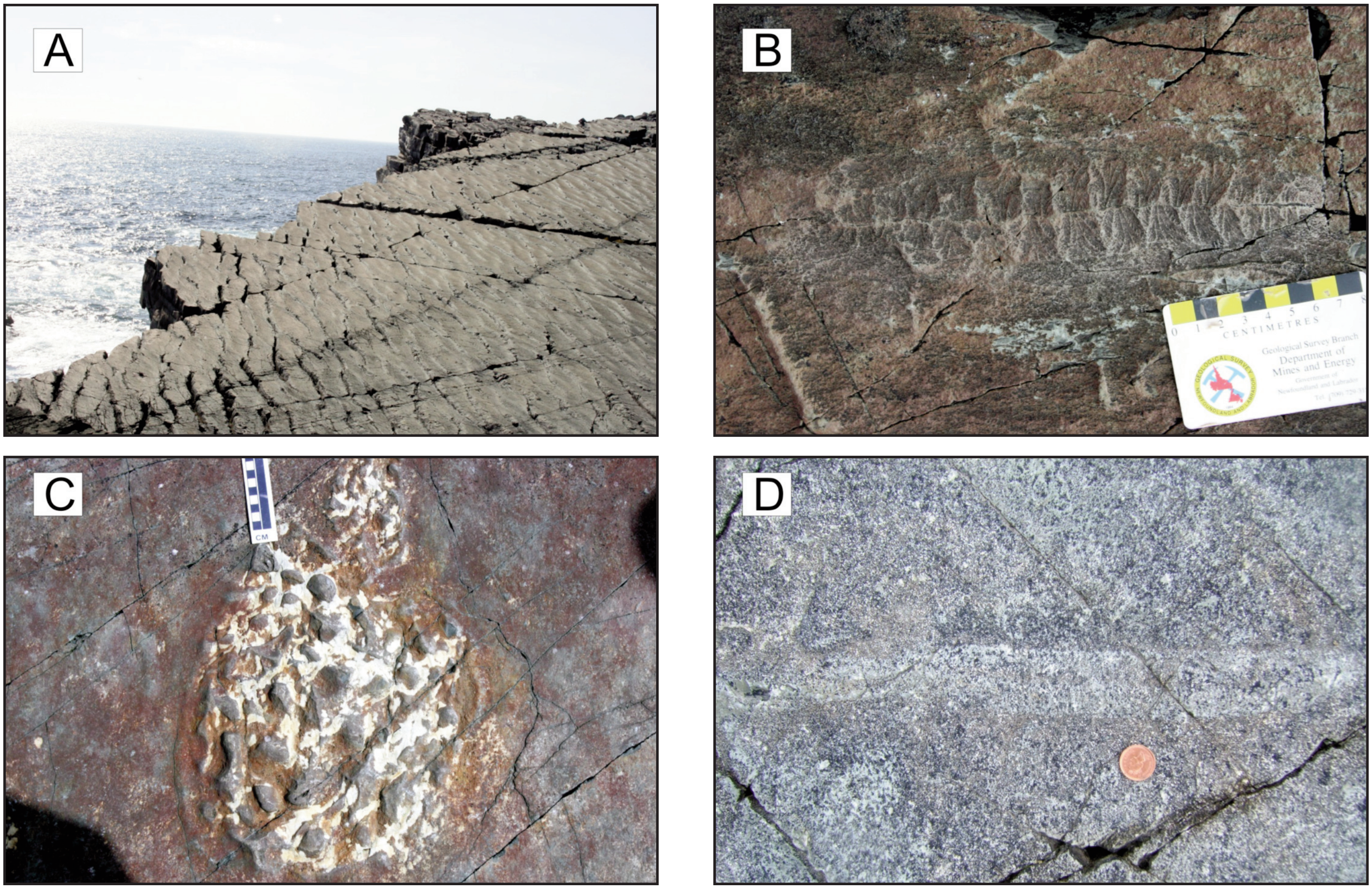
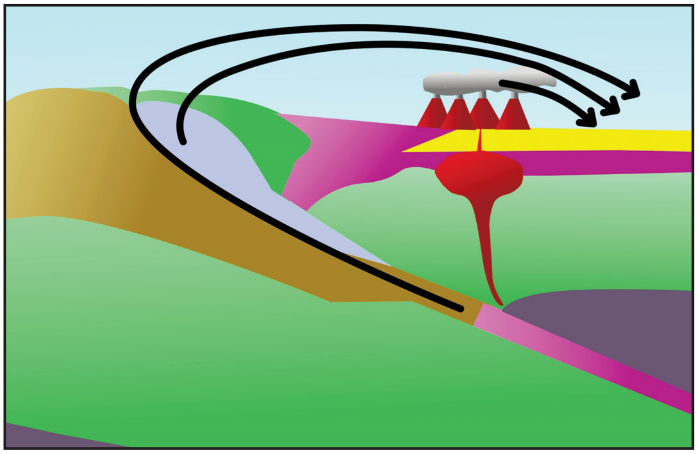


Figure 4. Images from Mistaken Point area, southeastern Newfoundland, a spectacular coastal location that is now a UNESCO World Heritage Site. A. General view of the "E Surface", which contains thousands of Precambrian fossils, even though they are not visible from a distance. The surface markings are not ripple marks, despite their suggestive appearance, but rather are structural features of the bedding plane. B. Exquisitely preserved frond-like fossil from the underlying "D Surface", which is probably the most famous area of the site. These elusive and beautiful survivors from a vanished world were preserved due to the deadly effects of volcanic ash, which forms the granular areas in the image. C. An interesting and very distinctive fossil known as *ivesheadia*, but invariably referred to as a "pizza disk" for obvious reasons. This was once thought to be a discrete organism of some strange type, but was later reinterpreted as the partially decayed remains of other creatures, which were left to the attention of bacteria, because this was a world that lacked megascopic predators or scavengers. D. An unusual linear trail on a bedding plane located tens of metres above the D and E surfaces, which is interpreted to represent the earliest trace fossil that can be ascribed to physical locomotion of an organism. The development of motility must surely be a prerequisite to the evolution of predatory behaviour, which was surely a critical control on evolution. Photos by A. Kerr, from several pilgrimages to this evocative site. For more information on the Ediacaran puzzles, see a previous article in Geoscience Canada by Liu and Matthews (2017; volume 44, p. 63–76). The Ediacaran period is one obvious candidate for a thematic review paper in a possible series to highlight critical chapters in Earth History.

evolution we can now trace for 540 million years? Moving forward through Paleozoic, Mesozoic and Cenozoic time, things seem almost familiar by comparison, but many puzzles remain for contemplation. Just look at *Four Billion Years and Counting* if you need an introduction to some of the more obvious examples, and do not forget the most recent, such as the PETM event and the nature and causes of Pleistocene glacial-interglacial cycles. So, perhaps we could consider starting a new thematic paper series entitled simply *Critical Chapters?* I am doubtless guilty of naïve optimism on this possibility, but optimism is surely something that we all need in this troubled spring of 2022.

ARTICLE



The Jurassic Laberge Group in the Whitehorse Trough of the Canadian Cordillera: Using Detrital Mineral Geochronology and Thermochronology to Investigate Tectonic Evolution

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SUMMARY

The Laberge Group is an Early to Middle Jurassic sequence of mostly siliciclastic sedimentary rocks that were deposited in a marginal marine environment in the northern Canadian Cordillera. It forms a long narrow belt with a total thickness of 3–4 km extending for more than 600 km across southern Yukon and northwestern British Columbia. These sedimentary rocks overlap the Yukon-Tanana, Stikinia and Cache Creek terranes that form the main components of the Intermontane superterrane. The Laberge Group contains a record of the erosion of some of these terranes, and also offers some constraints on the timing of their amalgamation and accretion to the Laurentian margin. The Laberge Group was deposited with local unconformity on the Late Triassic Stuhini Group (in British Columbia) and correlative Lewes River Group (in Yukon), both of which are volcanic-rich, and assigned to the Stikinia terrane. The Laberge Group is in turn overlain by Middle Jurassic to Cretaceous clastic rocks, including the Bowser Lake Group in B.C. and the Tantalus Formation in Yukon. Clast compositions and detrital zircon populations within the Laberge Group and between it and these bounding units indicate major shifts in depositional environment, basin extent and detrital sources from Late Triassic to Late Jurassic. During the Early Jurassic clast compositions in the Laberge Group shifted from sediment- and volcanic-dominated to plutonic-dominated, and detrital zircon populations are dominated by grains that yield ages that approach or overlap their inferred depositional ages. This pattern is consistent with progressive dissection and unroofing of (an) active arc(s) to eventually expose Triassic to Jurassic plutonic suites. Detrital rutile and muscovite data from the Laberge Group indicate rapid cooling and then exhumation of adjoining metamorphic rocks during the Early Jurassic, allowing these to contribute detritus on a more local scale. The most likely source for such metamorphic detritus is within the Yukon-Tanana terrane, and its presence in the Laberge Group may constrain the timing of amalgamation and accretion of the Yukon-Tanana and Stikinia terranes. Thermochronological data also provide new insights into the evolution of the Laberge Group basin. Results from the U–Th/(He) method on detrital apatite suggest that most areas experienced post-depositional heating to 60°C or more, whereas U–Th/(He) results from detrital zircon show that heating to more than 200°C occurred on a more local scale. In detail, Laberge Group cooling and exhumation was at least in part structurally controlled, with more strongly heated areas situated in the footwall of an important regional fault system. The thermochronological data are preliminary, but they suggest potential to eventually constrain the kinematics and timing of inversion across the Laberge Group basin and may also have implications for its energy prospectivity.

In summary, the Laberge Group is a complex package of sedimentary rocks developed in an active, evolving tectonic realm, and many questions remain about the details of its sources and evolution. Nevertheless, the available information demonstrates the potential of combined geochronological and thermochronological methods applied to detrital minerals to unravel links between regional tectonics, basin development and clastic sedimentation.

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RÉSUMÉ
Le groupe de Laberge est une séquence du Jurassique inférieur à moyen composée principalement de roches sédimentaires silicoclastiques qui se sont déposées dans un milieu marginomarin, dans le nord de la Cordillère canadienne. Il forme une longue ceinture étroite d'une épaisseur totale de 3 à 4 km s'étendant sur plus de 600 km à travers le sud du Yukon et le nord-ouest de la Colombie-Britannique. Ces roches sédimentaires chevauchent les terranes Yukon-Tanana, Stikinia et Cache Creek qui forment les principales composantes du superterrane Intermontagneux. Le groupe de Laberge contient un enregistrement de l'érosion de certains de ces terranes, et offre également certaines contraintes sur la datation de leur amalgamation et de leur accrétion à la marge laurentienne. Le groupe de Laberge a été déposé avec une discordance locale sur le groupe de Stuhini du Trias supérieur (en Colombie-Britannique) et le groupe corrélatif de Lewes River (au Yukon), tous deux riches en volcans et attribués au terrane de Stikinia. Le groupe de Laberge est à son tour recouvert de roches clastiques du Jurassique moyen à Crétacé, comprenant le groupe de Bowser Lake en Colombie-Britannique et la formation de Tantalus au Yukon. Les compositions de clastes et les populations de zircons détritiques au sein du groupe de Laberge et entre celui-ci, et ces unités limitrophes indiquent des changements majeurs dans l'environnement de dépôt, l'étendue du bassin et les sources détritiques du Trias supérieur jusqu'au Jurassique supérieur. Au cours du Jurassique inférieur, les compositions des clastes du groupe de Laberge sont passées d'une prédominance sédimentaire et volcanique à une prédominance plutonique, et les populations de zircons détritiques sont dominées par des grains qui donnent des âges qui se rapprochent ou chevauchent l'âge présumé de leur déposition. Ce modèle est cohérent avec la dissection progressive et le dévoilement d'un ou plusieurs arcs actifs pour éventuellement exposer les suites plutoniques du Trias au Jurassique. Les données sur le rutile détritique et la muscovite du groupe de Laberge indiquent un refroidissement rapide puis une exhumation des roches métamorphiques adjacentes au cours du Jurassique inférieur, permettant à celles-ci d'ajouter des débris à une échelle plus locale. La source la plus probable de ces débris métamorphiques se trouve dans le terrane Yukon-Tanana, et sa présence dans le groupe de Laberge peut apporter des contraintes sur la datation de l'amalgamation et de l'accrétion des terranes Yukon-Tanana et Stikinia. Les données thermochronologiques apportent également de nouveaux éclairages sur l'évolution du bassin du groupe de Laberge. Les résultats de la méthode U–Th/(He) sur l'apatite détritique suggèrent que la plupart des régions ont été soumises à des conditions de température post-dépôt de 60°C ou plus, tandis que les résultats U–Th/(He) sur zircon détritique montrent que des conditions de température de plus de 200° C se sont produites à une échelle plus locale. Dans le détail, le refroidissement et l'exhumation du groupe de Laberge étaient au moins en partie structurellement contrôlés, avec des régions plus fortement chauffées situées dans le mur d'un important système de failles régionales. Les données thermo-chronologiques sont préliminaires, mais elles suggèrent un potentiel pour éventuellement contraindre la cinématique et le moment de l'inversion à travers le bassin du groupe de Laberge et peuvent également avoir des implications sur sa capacité énergétique.

En résumé, le groupe de Laberge est un ensemble complexe de roches sédimentaires développées dans un domaine tectonique actif et en évolution, et de nombreuses questions demeurent quant aux détails de ses sources et de son évolution. Néanmoins, les informations disponibles démontrent le potentiel de la combinaison des méthodes géochronologiques et thermo-chronologiques appliquées aux minéraux détritiques pour démêler les liens entre la tectonique régionale, le développement du bassin et la sédimentation clastique.

Traduit par la Traductrice

INTRODUCTION
The Cordilleran Orogen of northwestern Canada developed through the successive accretion of discrete late Paleozoic and Mesozoic terranes against a long-lived active margin. Figure 1 shows the regional distribution of these terranes in British Columbia, Yukon and parts of Alaska, including the area of the research discussed in this paper. Five terranes, together comprising the Intermontane superterrane (i.e. Slide Mountain, Yukon-Tanana, Stikinia, Quesnellia and Cache Creek terranes) are of particular importance, as their accretion to the Laurentian margin has been considered to represent the initiation of the northern Canadian Cordillera orogen (Colpron et al. 2015; Monger and Gibson 2019). The exact geometry, timing and conditions of the accretion event(s) are not well established, and several outstanding questions are reviewed elsewhere (Zagorevski et al. 2017, 2021). Understanding the relative and absolute timing of these events is important in developing and improving the economic geology framework for the region (e.g. Logan and Mihalynuk 2014). The Late Triassic to Cretaceous sedimentary rocks in northern British Columbia (B.C.) and southern Yukon provide a record of changes in depositional environments and the evolution of those sedimentary basins through the time interval of progressive terrane accretion. This paper reviews the broader Late Triassic to Cretaceous evolution of this key segment of the orogen (Fig. 1) but focuses most of its attention on the Early–Middle Jurassic Laberge Group of the Whitehorse trough (Fig. 2; Wheeler 1961; Eisbacher 1974), and particularly recent and new data on sediment provenance, depositional constraints, and the timing and conditions of basin deformation. The principal tools that provide insight into the development of the Laberge Group are detrital geo- and thermochronology (U–Pb methods using zircon and rutile, and $^{40}Ar/^{39}Ar$ methods using muscovite and biotite) that constrain sediment source regions and low temperature thermochronological methods (U–Th/He on zircon and apatite) that illustrate aspects of basin evolution. The paper is an extension of a recent Geological Survey of Canada report (Kellett and Zagorevski 2021) and is intended to illustrate how diverse techniques can be applied together to understand the linked processes of tectonic accretion and basin development.

The Laberge Group is mostly found along the eastern flank of the Stikinia terrane, so Stikinia is the most likely source

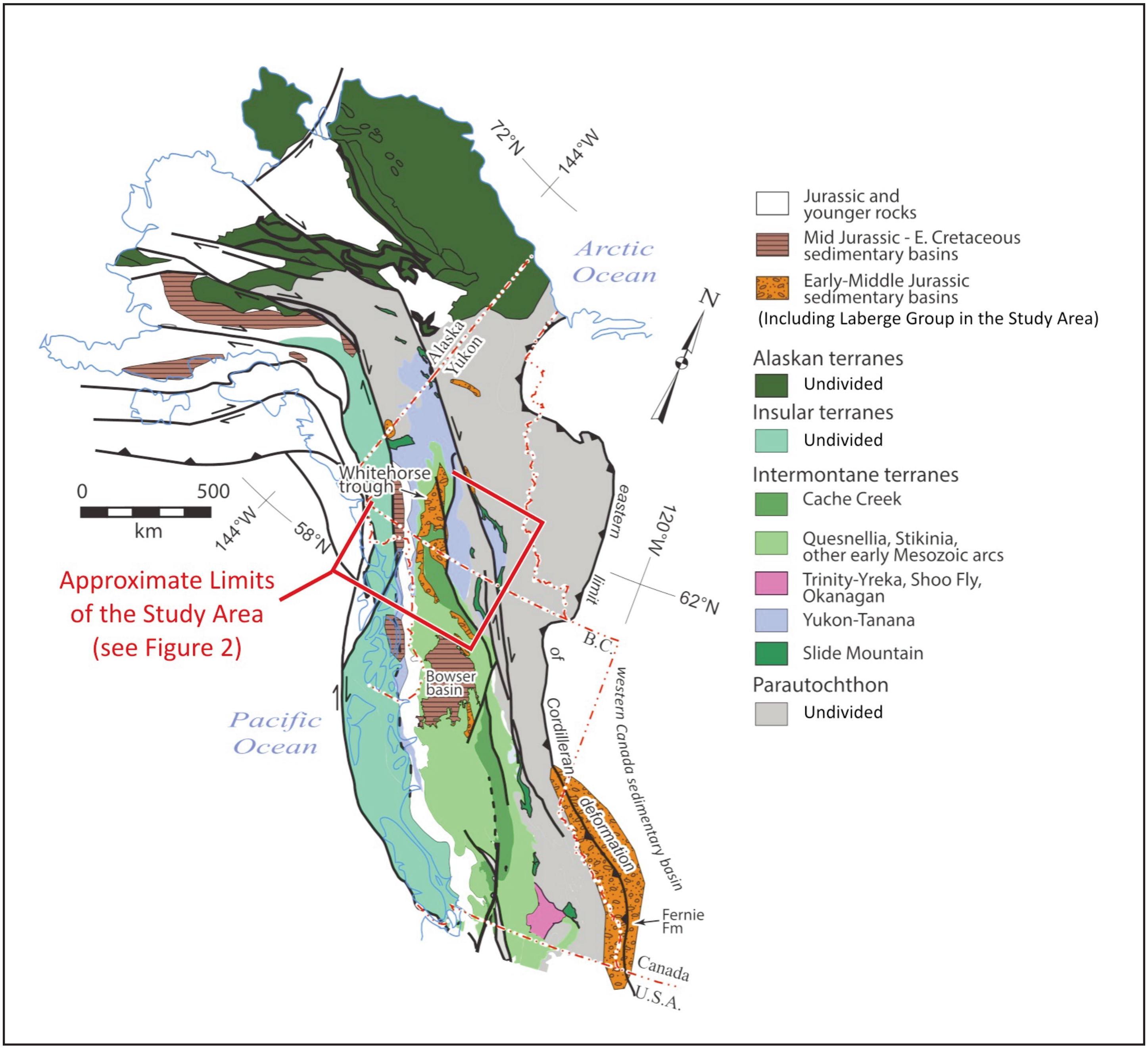

Figure 1. Terrane map of the Canadian Cordillera and adjacent regions of Alaska adapted from Colpron et al. (2015).

region for detritus entering the Laberge Group basin (e.g. Colpron et al. 2015; Fig. 2). Much of the research on Laberge Group sedimentary rocks has been focussed on provenance and identification of terrane-specific detritus that might constrain the timing of terrane amalgamation. Identification of detritus that could be derived from other now-adjacent terranes (e.g. the Yukon-Tanana or Cache Creek terranes; Figs. 1, 2) may provide a temporal constraint on their initial juxtaposition with Stikinia. However, the precise timing may be obscured if detritus is multicyclic. For example, sediment that was derived by erosion and recycling of an exhumed melange may significantly postdate the timing of accretion. In addition to timing of accretion, the nature of detritus in the Laberge Group sedimentary rocks can provide other critical constraints on the evolution of the orogen. The Laberge Group includes detritus of rock units that are either no longer exposed, or were removed completely by such erosion, providing 'snapshots' of the geological architecture of the Cordilleran Orogen throughout the Early Jurassic. Clast composition, such as clasts of high-pressure metamorphic rocks or mineral grains indicative of such conditions, can be diagnostic of specific tectonic settings, and provide insight into tectonic setting of the Intermontane terranes at a particular time. Overall, the range of source materials deposited into the Laberge Group basin pro-

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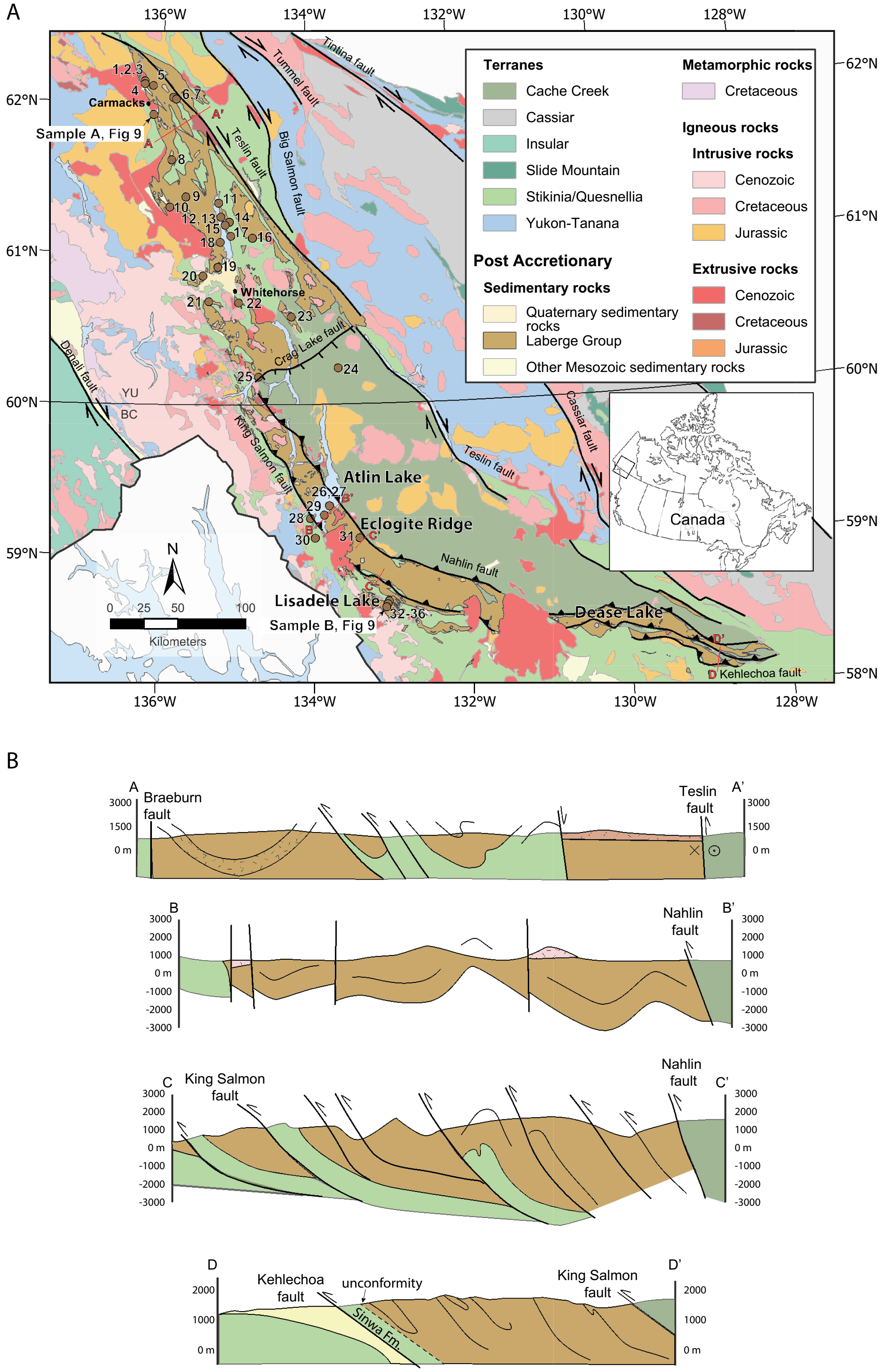

Figure 2. A. Terrane map of the study area highlighting post-accretionary units in the northern Cordillera, particularly the Early–Middle Jurassic Laberge Group. Map modified from Cui et al. (2017) and Colpron et al. (2016a). Numbers indicate detrital zircon U–Pb samples listed in Table 1 and reviewed in this study. Letters indicate detrital muscovite $^{40}Ar/^{39}Ar$ samples described in this study. B. Cross-sections through Laberge Group. Section lines are shown on the map. A–A' is redrawn from White et al. (2012). B–B' and C–C' are redrawn from English et al. (2005), and D–D' is redrawn from van Straaten and Bichlmaier (2018b).

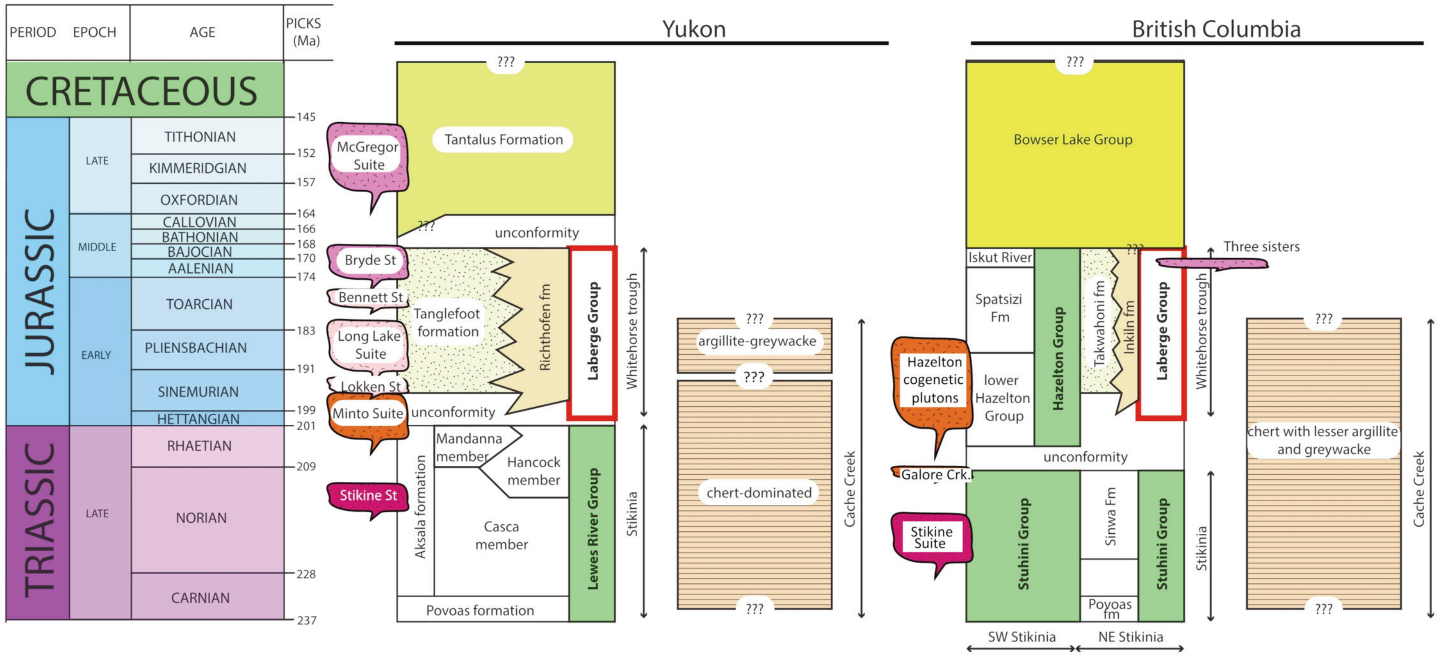

Figure 3. Comparative Upper Triassic to Lower Cretaceous lithological sections for Yukon (modified from Hutchison 2017; Sack et al. 2020 and references therein) and British Columbia (modified from Souther 1972; Shirmohammad et al. 2011; van Straaten and Bichlmaier 2017; Nelson et al. 2018; Mihalynuk et al. 2018 and references therein). Geologic Time Scale from Walker et al. (2018). Note that some units indicated here are not identified individually in Figure 2, and that some minor subdivisions of units referenced in the text cannot be represented in this summary diagram.

vides a record of vigorous erosion and deep incision of a young and evolving orogen.

TERMINOLOGY AND DATA SOURCES

The *Whitehorse trough* is a pre-plate tectonic term that was originally introduced to describe a linear belt of volcanic and sedimentary rocks in southern Yukon and northwestern B.C., including throughout the Whitehorse area (Fig. 3). Initially, the term was intended to include part or all of the Triassic Lewes River and Stuhini groups (located in the Yukon and B.C., respectively) and the Jurassic Laberge Group (in both areas), while more recent studies have also included the overlying Jurassic–Cretaceous Tantalus Formation in Yukon. The regional stratigraphic and geological relationships are summarized in the time–space diagram of Figure 3 (after Wheeler 1961; Hart 1997; Lowey 2008; Templeman-Kluit 2009), although not all components indicated on the figure are specifically discussed in this paper. A more restrictive definition of the Whitehorse Trough (Hutchison 2017) includes only the Laberge Group.

The Laberge Group extends from Carmacks in southern Yukon to Dease Lake in B.C. (Fig. 2). Regional mapping has resulted in two sets of formal nomenclature for geological units that are at least in part equivalent (Fig. 3). In this paper, the B.C. nomenclature is used for B.C. field areas, and Yukon nomenclature is used for Yukon field areas, with the probable equivalence identified where appropriate. This is done to aid the reader, but it should be noted that this may introduce some inconsistencies as the formal definitions of lithologically similar units are not necessarily identical.

The transition from the Lewes River and Stuhini groups into the Laberge Group was interpreted in both B.C. and the Yukon to represent a Hettangian (or younger) unconformity, above which the sedimentary environment changed markedly, and sedimentation rates increased (e.g. Johannson and McNicoll 1997; Shirmohammad et al. 2011; Colpron et al. 2015; Hutchison 2017; van Drecht and Beranek 2018). The boundary between the Laberge Group and the overlying Late Jurassic to Early Cretaceous Tantalus Formation in southern Yukon is a locally angular unconformity that also marks a significant change in sedimentary environment, and change in the extent of the sedimentary basin (Fig. 3; Colpron et al. 2015). The varied definitions of Whitehorse trough make this term ambiguous. In this contribution, rock units are mostly referred to using specific lithological or stratigraphic terminology, and, following Hutchison (2017), the term Whitehorse trough is used synonymously with the Laberge Group.

The Geological Survey of Canada's Geomapping for Energy and Minerals Program (GEM) included acquiring a range of new geochronological and thermochronological data from sedimentary rocks in the Cordilleran Orogen, under the GEM2 (2013–2020) Cache Creek and Yukon Tectonic Evolution activities. Recent work by the British Columbia Geological Survey and the Yukon Geological Survey has also generated significant new geochronological datasets for sedimentary rocks across the region shown in Figure 2. These new data add greatly to existing and new sedimentological (e.g. Hutchison 2017; van Drecht and Beranek 2018), biostratigraphic (e.g. Johannson et al. 1997; Golding 2018), and structural (e.g. English et al. 2002; White et al. 2006) information. Collectively, these multidisciplinary datasets allow improved understanding of the sedimentary evolution and later structural inversion of the Laberge Group. The following sections provide a brief regional overview of recent work.

GEOLOGICAL OVERVIEW

Tectonic Setting

The Canadian Cordillera is a long-lived and presently active accretionary orogen on the western margin of North America (Coney et al. 1980; Nelson et al. 2013). The oldest component of the orogen is a late Neoproterozoic to early Paleozoic passive margin sequence that developed on the Ancestral North American (or Laurentian) margin. The passive margin sedimentation was terminated by Devonian magmatism that has been interpreted to mark the initiation of east-directed (present coordinates) subduction beneath Laurentia (Mortensen 1992). The Devonian arc that formed on the Laurentian margin rifted away, becoming the Yukon-Tanana terrane and opening the intervening Slide Mountain ocean. During the Late Paleozoic, the Yukon-Tanana terrane and related island arc terranes (Stikinia and Quesnellia) developed outboard of Laurentia (Nelson et al. 2013; van Staal et al. 2018; Parsons et al. 2018). The Laurentian margin that was facing the Slide Mountain ocean resumed passive margin sedimentation (Monger 1977). The Yukon-Tanana, Stikinia and Quesnellia terranes (representing arc-type settings) and the adjacent Atlin, Cache Creek and Slide Mountain terranes were accreted to the Laurentian margin sometime between the late Paleozoic and the Middle Jurassic. This represents the first major accretionary event on the western Laurentian margin (Monger et al. 1982; Colpron et al. 2015; Monger and Gibson 2019). The Intermontane sedimentary record spanning this period of terrane amalgamation and superterrane accretion to the margin is relatively complete (Fig. 3), and provides a chronicle of the orogen's evolution through this critical time period.

Triassic Sedimentation

The Late Triassic Stikinia and Quesnellia terranes are characterized by arc-related volcanic and plutonic rocks. The Triassic sedimentary components of Stikinia are included in the Stuhini Group in B.C., and equivalent Lewes River Group in the Yukon, and in Quesnellia terrane's Shonektaw Formation (not separated in Fig. 3). By the Latest Triassic, magmatism had started to wane, and siliciclastic rocks became more abundant. These include the undivided Stuhini Group in B.C., the Mandanna Member of the Lewes River Group in Yukon, and the Nazcha Formation in Quesnellia, B.C. (not separated in Fig. 3). Then, limestone was deposited, forming the Sinwa Formation in B.C., and the Hancock Member of the Lewes River Group in Yukon (Templeman-Kluit 2009). The deposition of Late Norian to Rhaetian limestone is generally interpreted to mark the end of the Stuhini–Lewes River–Nicola arc (English and Johnston 2005 Long 2005; Shirmohammad et al. 2011; Logan and Mihalynuk 2014). As discussed previously, these rocks form the underlying strata upon which Laberge Group sediments were deposited. Late Triassic sedimentary rocks also occur in the adjacent Cache Creek terrane, where they include bedded radiolarian chert, siltstone and sandstone of the Kedahda Formation and its equivalents (Monger et al. 1991; Golding et al. 2016). The differences between Late Triassic sedimentary rocks in the Stikinia and Cache Creek terranes were previously interpreted to reflect different tectonic settings, i.e. arc-proximal for Stikinia versus subducting plate for Cache Creek (e.g. Mihalynuk et al. 2004; Colpron et al. 2015). Recent provenance studies of the Kedahda Formation in the Cache Creek terrane suggest that it was likely derived from Late Triassic Stikinia and/or Quesnellia terranes and overlaps all older Cache Creek terrane components (Monger et al. 1991; Zagorevski et al. 2016; 2018; 2021). Thus it is possible that Late Triassic siliciclastic rocks from the Stikinia terrane (Stuhini Group, Sinwa Formation, Aksala formation), the Cache Creek terrane (Kedahda Formation), and the Quesnellia terrane (Shonektaw Formation) represent a single overlapping sedimentary basin with internal facies variations (Zagorevski et al. 2018).

Early–Middle Jurassic Sedimentation – Laberge Group

Stikinia's Triassic rocks are overlain by the Early to Middle Jurassic siliciclastic rocks of the Laberge Group (Mihalynuk et al. 1995; Dickie and Hein 1995; Johannson et al. 1997). An angular unconformity locally defines this transition (Bordet et al. 2019) and it is associated with a marked change in the sedimentary environment, as discussed in the introduction. Southwest of the Laberge Group, volcanic and sedimentary rocks of the Hazelton Group were unconformably deposited on the Stuhini Group, representing a similar transition (Fig. 3; Marsden and Thorkelson 1992; Brown et al. 1996; van Straaten and Nelson 2016; Hutchison 2017; Nelson et al. 2018). The Hazelton Group is at least partially equivalent to the Laberge Group (Fig. 3).

The Laberge Group comprises 3–4 km of siliciclastic sedimentary rocks (Dickie and Hein 1995; Johannson et al. 1997; Shirmohammad 2006) that can be traced for ~ 600 km along strike, from near Carmacks, Yukon to ~ 100 km east of Dease Lake, B.C. (Figs. 2, 3). It is structurally complex, because it is located within a regional fold and thrust belt, which disrupted and repeated the original stratigraphy through translation and imbrication (Fig. 2B). Major structures that affect the Laberge Group include the King Salmon, Nahlin and Kehlechoa faults (e.g. Mihalynuk et al. 1995; Gabrielse 1998; English et al. 2002; Mihalynuk et al. 2017; van Straaten and Gibson 2017; van Straaten and Bichlmaier 2018a, b; Fig. 2B). It is also dissected by younger major dextral strike-slip faults including the Teslin and Big Salmon faults (Fig. 2A, B; Gabrielse et al. 2006; Colpron 2011). Consequently, it is difficult to reconstruct the complete stratigraphy of the Laberge Group in many areas, but it is locally well-preserved, notably at Lisadele Lake (Mihalynuk et al. 1995; 2004; Shirmohammad et al. 2007; 2011). The good preservation of diagnostic fossils also allows precise biostratigraphic control in other regions, which assists in reconstructing the wider stratigraphic sequence (e.g. Johannson et al. 1997).

The Laberge Group includes two coeval units; a more distal, turbiditic unit, and a more proximal, coarse clastic unit, collectively representing a tidal- and fluvial-influenced coastal depositional environment (Colpron and Friedman 2008; Shirmohammad et al. 2011; White et al. 2012; Hutchison 2017). It also includes intercalated Pliensbachian volcaniclastic horizons and rare porphyritic dacite to andesite (Nordenskiöld facies). The distal unit, referred to as the Richthofen formation in Yukon and the Inklin formation in B.C., is a graded siltstone to very fine-grained sandstone with minor conglomerate, volcaniclastic and limestone layers (Lowey 2008). These strata are interpreted to have formed as mass flows, submarine fans and turbidites (Lowey 2008; Hutchison 2017). The more proximal member, referred to as the Tanglefoot formation in Yukon, includes coal-bearing sandstone, mudstone, conglomerate and volcaniclastic rocks, with minor limestone, interpreted to represent shallow marine, deltaic, and fluvial settings (Lowey 2008; Hutchison 2017). The Tanglefoot formation was considered to be a potential source rock for petroleum accumulations (Lowey and Long 2006). The Takwahoni formation in B.C., which is broadly equivalent to the Tanglefoot formation, comprises conglomerate, tuff and laminated greywacke and shale (Gabrielse 1998). As discussed above, recent investigations of the Laberge Group suggest that the Richthofen and Tanglefoot formations in the Yukon and the Inklin and Takwahoni formations in B.C. respectively represent distal and proximal facies within a common depositional system. Consequently, distinguishing between the units can be challenging (Hutchison 2017; Mihalynuk et al. 2017). Recent Yukon-based investigations of the Laberge Group concluded that it was deposited only on the Stikinia terrane and is everywhere in tectonic contact with rocks of the Cache Creek terrane (e.g. Bickerton et al. 2013). However, recent mapping in the Sinwa Creek area of B.C. indicates that the Inklin formation was also deposited on late Permian to Middle Triassic rocks of the Kutcho arc (not separated on Fig. 3), which is assigned to the Cache Creek terrane (Mihalynuk et al. 2017). Similar relationships are described in the Kutcho area, where the Sinwa Formation and southernmost Laberge Group stratigraphically overlie the Kutcho arc assemblage (Gabrielse 1998; Schiarizza 2011).

Early–Middle Jurassic Sedimentation External to Laberge Group

Southwest of the mapped extent of the Laberge Group, Pliensbachian to Aalenian sandstone, siltstone and shale of the Spatsizi Formation forms part of the Hazelton Group in northern B.C, which is interpreted as part of the Stikinia terrane (Fig. 3; Gagnon et al. 2012; Nelson et al. 2018). The Spatsizi Formation is thought to have been deposited during thermal subsidence that marked the decline of the older Hazelton arc (Gagnon et al. 2012). East of the Laberge Group, a sequence of Early Jurassic chert to argillite–greywacke was deposited above chert-dominated Triassic sedimentary rocks in the northern Cache Creek terrane (Fig. 3; Cordey et al. 1991; Gordey and Stevens 1994; Colpron et al. 2015).

The Hettangian to Tithonian Fernie Formation of southeastern British Columbia, which was deposited at the western edge of the Western Canada sedimentary basin, is also age-equivalent to the Laberge Group. The Fernie Formation records Early–Middle Jurassic passive margin sedimentation followed by Late Jurassic initiation of the Western Interior foreland basin (Pană et al. 2019). Paleomagnetic reconstructions place the Laberge Group at about the latitude of southern Alberta during the Early Jurassic (Kent and Irving 2010 and references therein), suggesting that the Laberge Group and Fernie Formation depocentres were closer to each other than their current positions would imply. Other small, isolated Early Jurassic basins in Yukon are reviewed in Colpron et al. (2015) and are not discussed here.

Middle Jurassic to Early Cretaceous Sedimentation

Sedimentary rocks that postdate the Laberge Group in southern Yukon are represented by conglomerate of the Bathonian(?) to Upper Cretaceous Tantalus Formation (Bostock 1936; Colpron et al. 2015; van Drecht and Beranek 2018). The Tantalus Formation unconformably overlies the Laberge Group, and represents a major shift in depositional setting, from shallow marine to fluvial. The transition is marked by a shift from the abundant volcanic and igneous lithic clasts in the Laberge Group to chert, quartz and silicified mudstone clasts in the Tantalus Formation (Long 2005). The Tantalus Formation is interpreted to have been deposited in restricted (confined) mountainous river valleys and is notable for its coal deposits near Tantalus Butte, which were mined historically (Long 2015; Colpron et al. 2015).

In north-central B.C., the Bowser Lake Group forms the main component of the extensive Late Jurassic to Mid Cretaceous Bowser basin (Tipper and Richards 1976; Evenchick and Thorkelson 2005; Fig. 1). In its type area, the Bowser Lake Group was deposited on the Spatsizi Formation of the Jurassic Hazelton Group (Fig. 3). Unlike the Tantalus Formation, the Bowser Lake Group was deposited in a marine setting, progressing to non-marine in the uppermost strata (Evenchick and Thorkelson 2005). The wider Bowser basin is interpreted to be the west-facing foreland basin of a doubly vergent Jurassic orogenic system, with the Western Canada sedimentary basin forming the other flank (Fig. 1; Evenchick et al. 2007). Bajocian to Lower Cretaceous siliciclastic strata that sit unconformably on Laberge Group strata in northern B.C., southwest of the King Salmon fault and structurally lower Kehlechoa fault (Figs. 2, 3), have been correlated with the Bowser Lake Group. These include rocks at Lisadele Lake (Shirmohammad et al. 2011) and south of Dease Lake (van Straaten and Gibson 2017; van Straaten and Bichlmaier 2018a). Correlative strata have not been reported from the hanging wall of the King Salmon fault (Fig. 2). This may be because they were removed by erosion in this area, or because the fault juxtaposes distinct sub-basins.

Both the Tantalus Formation and the Bowser Lake Group differ markedly from the underlying strata of the Laberge Group. They contain far fewer volcanic and plutonic clasts, and their clast populations are dominated by chert and silicified mudstone. In both cases, these chert-dominated clast populations have been interpreted as derived from the Cache

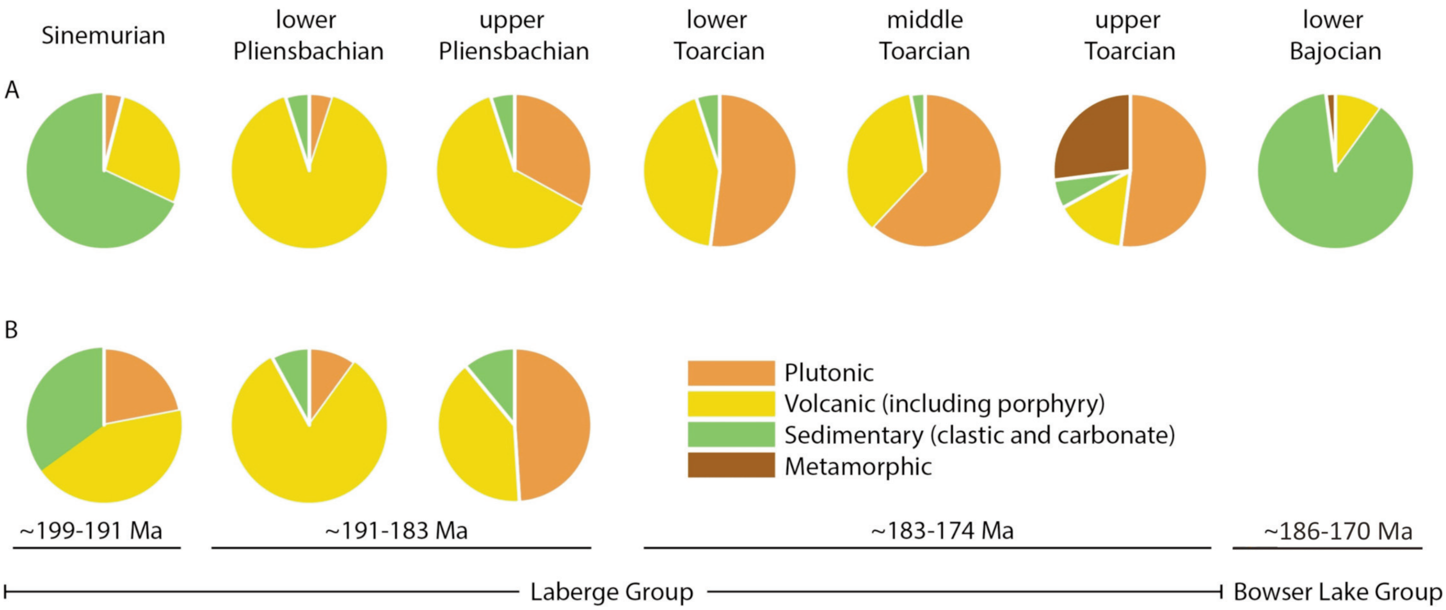

Figure 4. Clast composition distribution for Laberge Group and lower Bajocian Bowser Lake Group conglomerates. A) Lisadele Lake area (Shirmohammad 2006); and B) Atlin Lake area (Johannson et al. 1997).

Creek terrane, based on their Early Permian to Triassic ages. This shift in provenance was interpreted to record the juxtaposition of Stikinia and Cache Creek terranes (Cordey et al. 1991; Cordey 1992; Mihalynuk et al. 2004; Evenchick and Thorkelson 2005; Colpron et al. 2015). However, chert is also common in the Paleozoic–Triassic Stikinia terrane, including the Stikine assemblage (Logan et al. 2000; Mihalynuk et al. 2012), the Tsabayhe Group (Read 1984) and the Sinwa Formation (Mihalynuk et al. 2017) as well as in the Slide Mountain terrane (e.g. Harms and Murchey 1992). The presence of chert detritus in the Tantalus Formation and Bowser Lake Group thus may not be diagnostic of a Cache Creek source (see also Long 2015).

LABERGE GROUP – DETRITUS TYPES AND AGES

Laberge Group Clast Populations

Clast types and proportions in conglomerate beds of the Laberge Group in both southern Yukon and northern B.C. show clear trends related to stratigraphy (Dickie and Hein 1995; Hart et al. 1995; Johannson et al. 1997; Shirmohammad et al. 2011). These are summarized for the strata of northern B.C. in Figure 4 (Johannson, 1994; Shirmohammad et al. 2011). At the base of the Laberge Group, Sinemurian strata at both Lisadele Lake and Atlin Lake (B.C.) contain mostly volcanic and sedimentary clasts, with the latter thought to be largely derived from the underlying Stuhini Group. In overlying lower Pliensbachian strata, volcanic and subvolcanic clasts dominate whereas sedimentary and plutonic clasts are rare. From upper Pliensbachian into middle Toarcian strata there is an increase in the proportion of plutonic clasts to > 60%, largely at the expense of the volcanic clasts.

A regional compilation from the Laberge Group in southern Yukon (Dickie and Hein 1995) illustrates a similar pattern. There is a dominance of sedimentary and volcanic clasts in the basal strata, presumably derived from the older Lewes River Group, and then a shift to > 60% plutonic clasts (largely granite) in Pliensbachian and younger strata. The shifting proportions of volcanic, plutonic and sedimentary clasts through the Laberge Group stratigraphy is interpreted as a shift in the tectonic setting of the source regions. The earlier Sinemurian strata are thought to record flank uplift of the Triassic arc, while the later strata record arc and dissected arc sources through the late Pliensbachian and early Toarcian. The Middle Jurassic arrival of chert-dominated sedimentary clasts in post-Laberge Group strata is interpreted to signal a return to flank uplift (Fig. 4; Dickie and Hein 1995; Johannson et al. 1997; Shirmohammad et al. 2011).

Metamorphic rocks provided discrete, short-lived sources of detritus for the Laberge Group, but two well-described occurrences in B.C. are important. A diverse range of metamorphic clasts and minerals were identified in upper Pliensbachian to lower Toarcian strata at Eclogite Ridge (Fig. 2), including eclogite, granulite, amphibolite, mica schist and garnet peridotite (Canil et al. 2006; Kellett et al. 2018). Upper Pliensbachian strata containing abundant garnet near Janus Point (within Atlin Lake; Fig. 2) are thought to represent the same stratigraphic horizon (Canil et al. 2006; Kellett et al. 2018). Higher in the Laberge Group, metamorphic clasts form a major component of upper Toarcian conglomerate at Lisadele Lake (Fig. 4), where they are mostly quartzofeldspathic schist and gneiss (Shirmohammad 2006). The Lisadele Lake section sits in the footwall of the King Salmon fault, and Toarcian conglomerate in the equivalent setting at the foot of the Llewellyn glacier (Atlin Lake) also contains gneiss clasts (Mihalynuk et al. 2006; Kellett and Iraheta-Muniz 2019). Metamorphic clasts are less commonly reported from the Laberge Group in the Yukon, but they do form a minor component (< 5%) in probable Middle Jurassic strata west of Whitehorse.

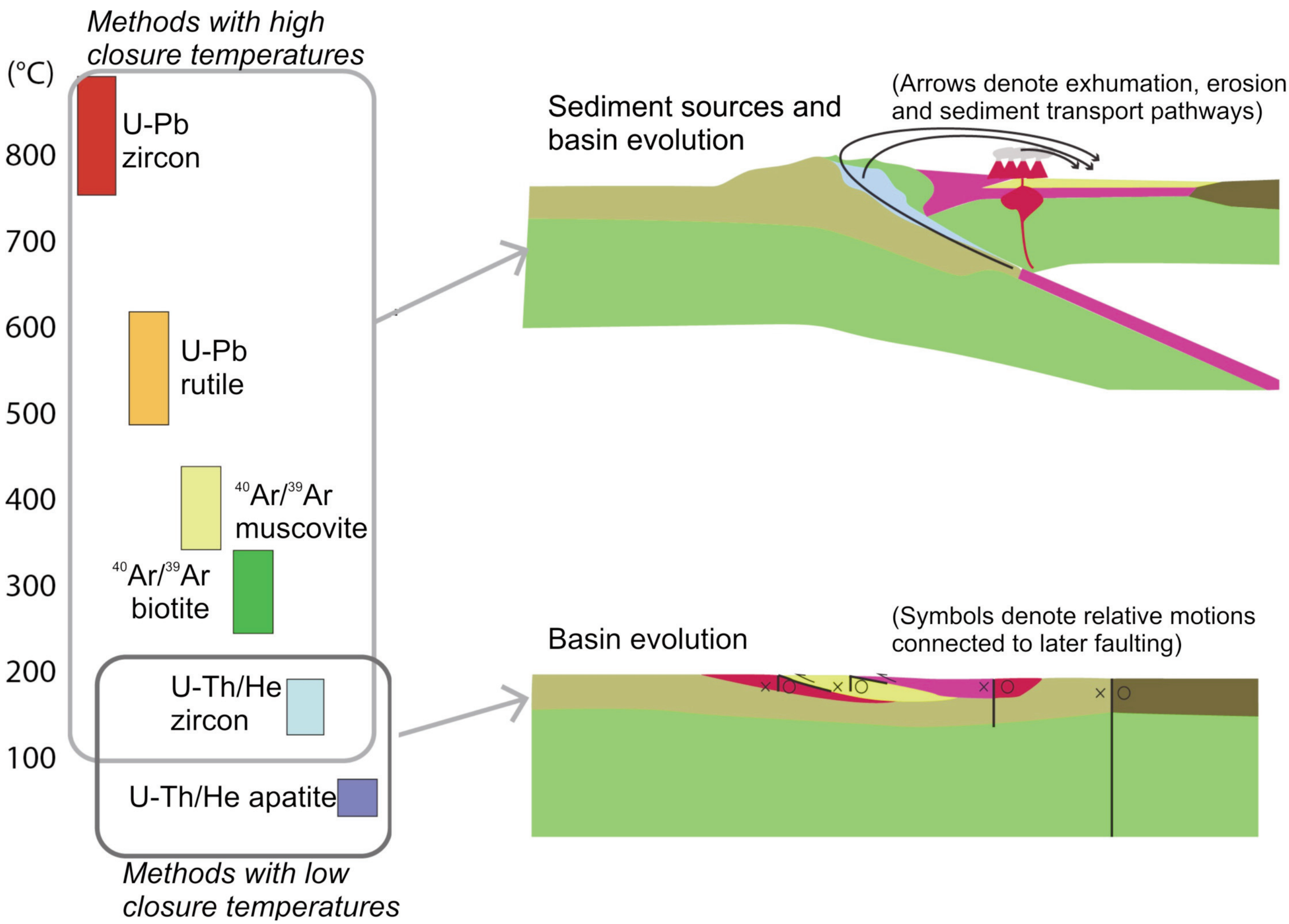

Figure 5. Approximate closure temperatures for geo- and thermochronometers mentioned in this review, based on Harrison et al. (1985); Cherniak (2000); Cherniak and Watson (2001); Farley and Stockli (2002); Reiners (2005); Harrison et al. (2009).

The clast rock types include quartzite, quartz–mica schist, chlorite schist, orthogneiss and marble (Hart et al. 1995). Possible eclogite clasts were reported from exposures in the northernmost Laberge Group (Colpron et al. 2015). Metamorphic clasts were also recognized in the argillite–greywacke units of the Cache Creek Terrane (Mulligan 1963; see Fig. 3). In all these cases, the source of the metamorphic clasts is uncertain (e.g. Hart et al. 1995), but new geochronological data from detrital minerals (discussed below) now provides better constraints.

Geochronology and Thermochronology of Detrital Minerals

Techniques and Their Applications

Geochronological and thermochronological studies of detrital minerals, either as free grains or in relationship to other minerals within rock clasts, provide valuable information for the study of sedimentary basins and their complex links to evolving tectonic processes. Geochronology uses the measurement of radioactive isotopes to yield the 'age' of a particular mineral, but this age is not always the time at which the dated mineral formed. Some mineral decay systems, (e.g. production of ^{40}Ar via decay of ^{40}K in muscovite or biotite) are open systems at geologically high temperatures, such that the daughter products of radioactive decay are not retained (i.e. the radiometric 'clock' doesn't start) until the material reaches a temperature range at which thermal diffusion of daughter elements becomes energetically unfavourable. In such cases, the radiometric age provides data on when the mineral cooled below its 'closure' temperature, rather than when it first formed. These temperature-sensitive mineral decay systems are called *thermochronometers* and they can illustrate the influence of tectonic events, e.g. by providing estimates of exhumation rates. In this section of the paper, geochronological and thermochronological data from the Laberge Group are reviewed and discussed, with emphasis on recent studies. The main methods include the U–Pb geochronometer applied to detrital zircon and rutile grains, and the ^{40}Ar/^{39}Ar thermochronometer, applied to detrital muscovite and biotite. Preliminary information from the (U–Th)/He system applied to zircon and apatite is also reviewed. As indicated in Figure 5, these systems vary widely

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in their trapping (or 'closure') temperatures. For example, in the case of zircon, the closure temperature ranges from < 200°C for the (U–Th)/He system to > 750°C for the U–Pb system. Systems with higher closure temperatures that have remained closed since the exhumation and erosion of source regions are useful in investigating the sources of sedimentary detritus. Systems that have low closure temperatures may undergo resetting (open system behaviour, a reset of the radiometric clock) following the deposition of the host rocks, so these are more useful in understanding later processes such as sediment burial and basin inversion. In an active setting such as the Jurassic basins of the northern Canadian Cordillera, the depositional and structural histories of sedimentary basins are closely linked, so both approaches are valuable.

U–Pb on Detrital Zircon

U–Pb data from detrital zircon grains in the Laberge Group are available for the entire length of the basin, and some data are also available from older (Stuhini and Lewes River groups) and younger strata (Tantalus Formation and Bowser Lake Group). The compiled information is listed in Table 1 and illustrated in Figures 6 and 7 (information from Shirmohammad et al. 2011; Colpron et al. 2015; Kellett et al. 2018; Kellett and Iraheta-Muniz 2019).

The ages derived from detrital zircon grains in a sample do not automatically provide information on the depositional age of a sample, but since all grains formed in precursor source rocks, they provide a maximum possible age of sedimentation. There are different methods to estimate the maximum depositional age (MDA) of a stratigraphic layer based on its spectrum of U–Pb detrital zircon ages. A robust and widely used approach is to calculate the weighted mean age of all grains within 1σ error of the youngest dated grain, and this is applied in cases where it is anticipated that some zircon grains formed shortly before deposition (Dickinson and Gehrels 2009; Coutts et al. 2019). The abundance of volcanic and plutonic clasts in the Laberge Group strata attests to nearby active magmatic systems that would provide a continual source of contemporary zircon. The weighted mean age method outlined above is applied, following previous U–Pb studies of detrital zircon in these rocks (e.g. Colpron et al. 2015). Whereas MDAs may not be true depositional ages, evidence suggests that they are a useful measure in studies of the Laberge Group. Direct comparison of U–Pb data from detrital zircon at Lisadele Lake with local biostratigraphic constraints demonstrated that the MDAs for Laberge Group samples approach their true depositional ages, as expected for sedimentation close to an active

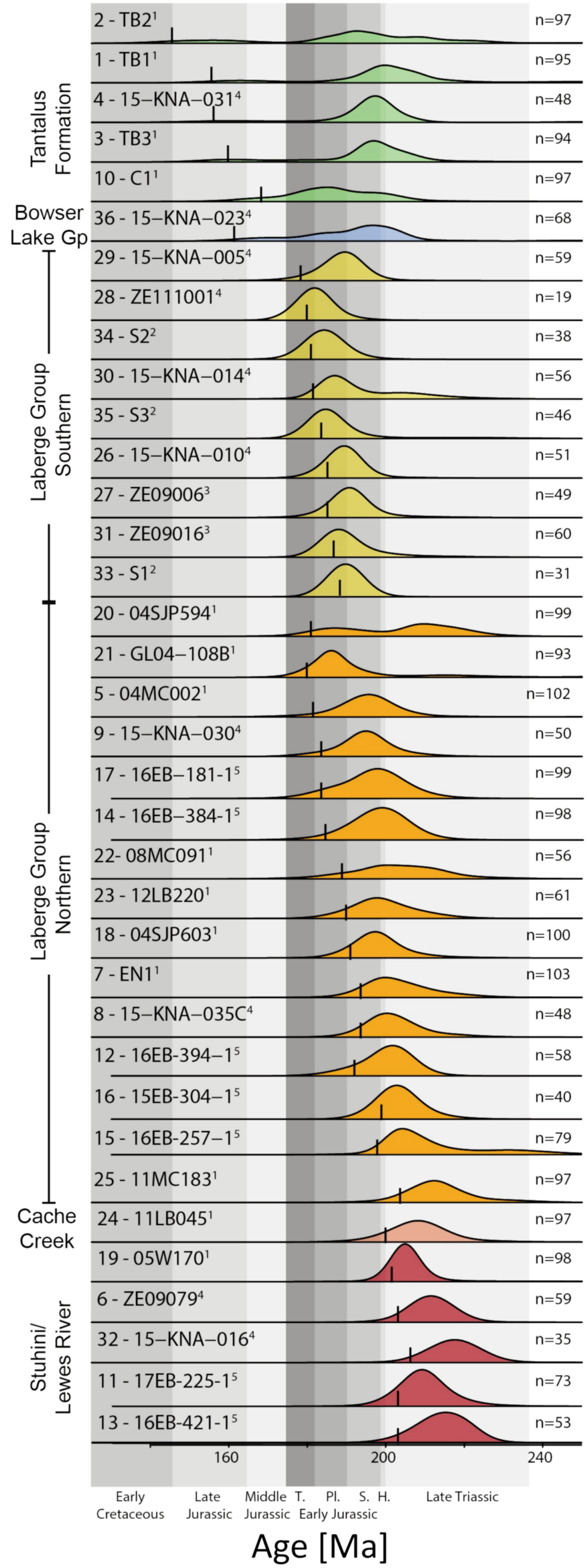


Figure 6. (*opposite*) Kernel density estimates (KDE) for all detrital zircon U–Pb data ($^{206}Pb/^{238}U$ ages), grouped by formation, with northern (Yukon) Laberge Group samples separated from southern (B.C.) Laberge Group samples, and sorted within each group by maximum depositional age. For clarity, only age determinations of < 250 Ma are shown. Tick marks indicate maximum depositional ages as listed in Table 1. Samples are numbered, and those numbers refer to sample locations on Figure 1. Data sources are indicated with superscripts: 1, Colpron et al. (2015); 2, Shirmohammad et al. (2011); 3, Kellett et al. (2018); 4, Kellett and Iraheta-Muniz (2019); 5, Bordet et al. (2019). KDE plots were constructed using IsoplotR (Vermeesch 2018). H = Hettangian; S = Sinemurian; Pl = Pliensbachian; T = Toarcian.

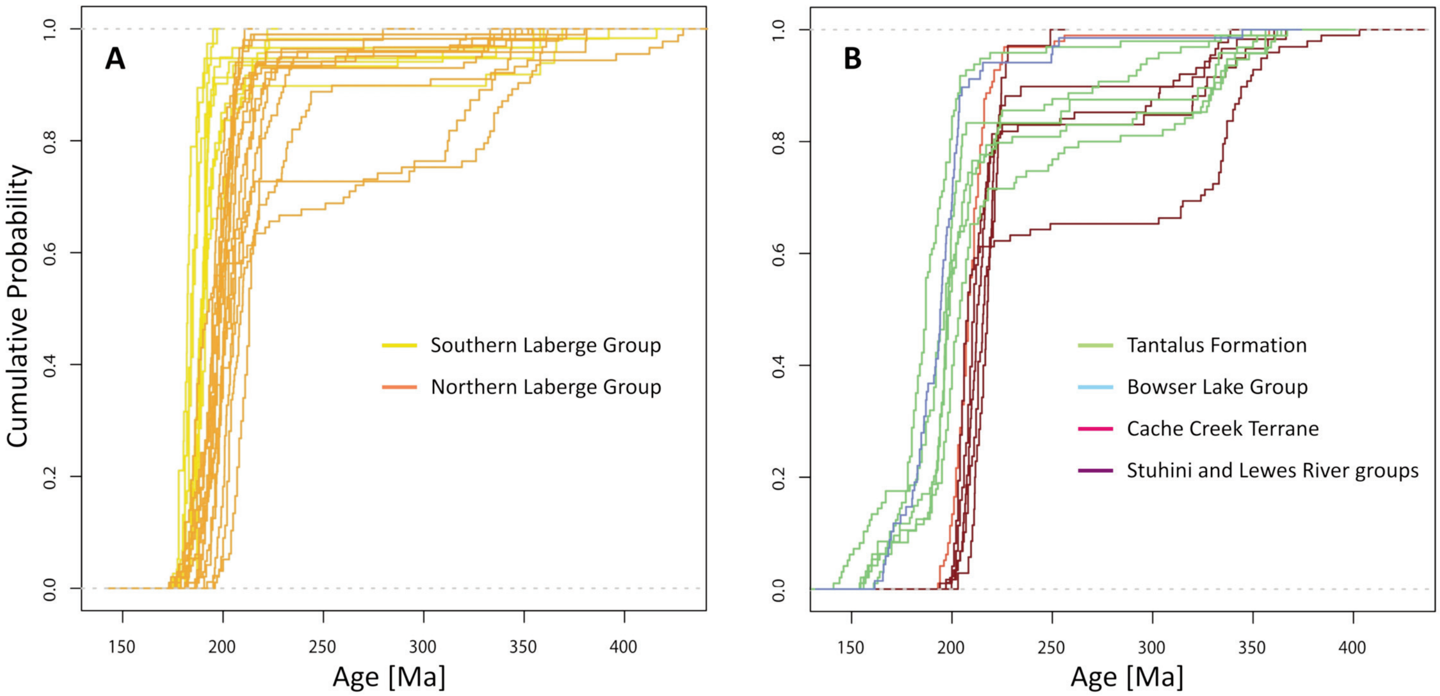


Figure 7. Cumulative age distribution (CAD) plots showing data from Figure 6 coloured by formation. Laberge Group age distributions are shown in A, and younger and older stratigraphic units are shown in B. CAD plots were constructed using IsoplotR (Vermeesch 2018).

arc (Table 1; Shirmohammad et al. 2011). MDAs determined in this way are also very close to the youngest age peaks in all Laberge Group samples and are generally within ± 2% of precise U–Pb ages derived using chemical abrasion thermal ionization mass spectrometry (CA–TIMS) ages for the youngest zircon grains (Table 1; Colpron et al. 2015; Bordet et al. 2019). These two criteria are appropriate methods to assess the relevance of MDA estimates based on detrital zircon ages. Collectively, the U–Pb isotopic data from the Laberge Group and their correspondence with biostratigraphic constraints indicate that the reported maximum depositional ages (MDA) represent a reliable and useful parameter.

The U–Pb data from detrital zircon in the Laberge Group and associated rock units that predate and postdate the Laberge Group reveal interesting spatial and temporal patterns that suggest variations in source terranes and depositional ages. To illustrate those trends, northern Laberge Group results (Yukon) are separated from southern Laberge Group (B.C.) in Figure 6, which shows the maximum depositional age and the age distributions for all dated samples. The MDAs for the northern Laberge Group range from ca. 204–181 Ma compared to frequency maxima between 212–186 Ma, whereas the MDAs for the southern Laberge Group range from ca. 188–178 Ma, compared to frequency maxima between 191 and 182 Ma.

This pattern of maximum depositional ages may suggest that deposition of the Laberge Group progressed southward from Yukon to B.C over a period of some 30 million years. However, the situation may be more complex than it appears from Figure 6. First, the MDA is not necessarily equivalent to a true depositional age, although the evidence presented above suggests broad equivalence. Second, several of the samples from Yukon were selected specifically to represent basal strata of the Laberge Group (Colpron et al. 2015; Bordet et al. 2019), whereas none of the B.C. samples specifically represent this part of the succession. The oldest MDA for the southern Laberge Group, sample S1 from Lisadele Lake, was collected ~ 250 m stratigraphically above the base of the Laberge Group (Shirmohammad et al. 2011). This sampling bias may explain the apparent transgression and should be tested by further research in B.C. aimed specifically at basal Laberge Group strata.

All southern Laberge Group samples are dominated by Pliensbachian zircon (191–183 Ma), but only two of the southernmost samples from Yukon captured significant zircon of this age (04SJP594 and GL04-108B, localities 20 and 21 in Fig. 2), with the remaining 9 samples being dominated by Norian to Sinemurian zircon (228–191 Ma), even though a few have MDAs young enough that they could feasibly have captured Pliensbachian zircon (04MC002, 15-KNA-030, localities 5 and 9 in Fig. 2). The Nordenskiöld tuff units, which are interbedded with the Laberge Group in Yukon are of Pliensbachian age (Templeman-Kluit 2009), so some zircon of this age range could be expected. The lack of Pliensbachian zircon suggests either some sampling bias, or that source catchments for the Laberge Group were locally restricted, perhaps due to the topography of the underlying Lewes River Group (van Drecht and Beranek 2018). In terms of potential igneous zircon sources, it appears that the youngest zircon populations from the northern Laberge Group zircon samples (from Rhaetian through Pliensbachian strata) are similar in age to igneous rocks of the Minto and Texas Creek plutonic suites (Fig. 3). A

Table 1. Summary of detrital zircon U–Pb data for Laberge Group and spatially associated sedimentary rocks of the Cache Creek, Stuhini Group, Bowser Lake Group, Tantalus and Aksala formations.

Map Locality	Sample Number	Latitude dd.dddd	Longitude ddd.dddd	Stratigraphic Unit	Youngest age peak (Ma)	Maximum depositional age* (Ma)	Youngest Zircon (CA-TIMS; Ma) or stratigraphic age	Reference
1	TB1	62.1422	-136.2662	Tantalus Fm.	162	156	159.20 ± 0.08	Colpron et al. (2014)
2	TB2	62.1422	-136.2662	Tantalus Fm.	155	146	148.51 ± 0.06	Colpron et al. (2014)
3	TB3	62.1230	-136.2639	Tantalus Fm.	160	160		Colpron et al. (2014)
4	15-KNA-031	62.1233	-136.2652	Tantalus Fm.	197	157		Kellett and Iraheta-Muniz (2019)
5	04MC002	62.1117	-136.1491	Laberge Gp. (N)	196	182		Colpron et al. (2014)
6	ZE09079	62.0240	-135.8219	Aksala fm.	212	203		Kellett and Iraheta-Muniz (2019)
7	EN1	62.0238	-135.8226	Laberge Gp. (N)	200	194		Colpron et al. (2014)
8	15-KNA-035C	61.6212	-135.8777	Laberge Gp. (N)	200	194		Kellett and Iraheta-Muniz (2019)
9	15-KNA-030	61.3765	-135.6744	Laberge Gp. (N)	195	184		Kellett and Iraheta-Muniz (2019)
10	C1	61.3424	-135.9727	Tantalus Fm.	185	168		Colpron et al. (2014)
11	17EB-225-1	61.3364	-135.2227	Aksala fm.	210	208	211.33 ± 0.01	Bordet et al. (2019)
12	16EB-394-1	61.2503	-135.1888	Laberge Gp. (N)	201	199	199.78 ± 0.06	Bordet et al. (2019)
13	16EB-421-1	61.2439	-135.1910	Aksala fm.	215	214	214.75 ± 0.07	Bordet et al. (2019)
14	16EB-384-1	61.2106	-135.0755	Laberge Gp. (N)	199	190	186.38 ± 0.07	Bordet et al. (2019)
15	16EB-257-1	61.1909	-135.1328	Laberge Gp. (N)	205	202	203.46 ± 0.14	Bordet et al. (2019)
16	15EB-304-1	61.1042	-134.7580	Laberge Gp. (N)	203	202	202.4 ± 1.5	Bordet et al. (2019)
17	16EB-181-1	61.0994	-135.0755	Laberge Gp. (N)	197	189	186.22 ± 0.09	Bordet et al. (2019)
18	04SJP603	61.0761	-135.1965	Laberge Gp. (N)	197	191		Colpron et al. (2014)
19	05W170	60.8476	-135.3738	Lewes River Gp.	205	202		Colpron et al. (2014)
20	04SJP594	60.8527	-135.4326	Laberge Gp. (N)	187	181		Colpron et al. (2014)
21	GL04-108B	60.6997	-135.3737	Laberge Gp. (N)	186	180		Colpron et al. (2014)
22	08MC091	60.6653	-134.9095	Laberge Gp. (N)	201	189		Colpron et al. (2014)
23	12LB220	60.5083	-134.1222	Laberge Gp. (N)	198	190		Colpron et al. (2014)
24	11LB045	60.2585	-133.6483	Cache Creek	208	200		Colpron et al. (2014)
25	11MC183	60.1838	-134.6850	Laberge Gp. (N)	212	212		Colpron et al. (2014)
26	15-KNA-010	59.3272	-133.7708	Laberge Gp. (S)	189	185		Kellett and Iraheta-Muniz (2019)
27	ZE09006	59.3271	-133.7721	Laberge Gp. (S)	191	185		Kellett et al. (2018a)
28	ZE111001	59.2793	-134.0748	Laberge Gp. (S)	182	180		Kellett and Iraheta-Muniz (2019)
29	15-KNA-005	59.2653	-133.8401	Laberge Gp. (S)	188	178		Kellett and Iraheta-Muniz (2019)
30	15-KNA-014	59.1136	-133.9623	Laberge Gp. (S)	187	183		Kellett and Iraheta-Muniz (2019)
31	ZE09016	59.1102	-133.3873	Laberge Gp. (S)	188	187		Kellett et al. (2018a)
32	15-KNA-016	58.6887	-133.0308	Stuhini Gp.	212	206		Kellett and Iraheta-Muniz (2019)
33	S1	58.6825	-133.0384	Laberge Gp. (S)	190	188	Pliensbachian	Shirmohammad et al. (2011)
34	S2	58.6757	-133.0429	Laberge Gp. (S)	184	181	Lower Toarcian	Shirmohammad et al. (2011)
35	S3	58.6695	-133.0489	Laberge Gp. (S)	184	184	Upper Toarcian	Shirmohammad et al. (2011)
36	15-KNA-023	58.6491	-133.0671	Bowser Lake Gp.	170	162		Kellett and Iraheta-Muniz (2019)

*Maximum depositional age determined as the weighted mean age of grains within 1σ of youngest grain (see explanation in text of the paper). Both youngest age peaks and calculated maximum depositional age are shown rounded to nearest m.y.: two-sigma errors for calculated MDAs are typically 1%. Where CA-TIMS ages for youngest zircon grains are available, they are listed for comparison with the calculated MDA, with their 2σ errors. Where precise biostratigraphic constraints are available, they are also listed for comparison. Biostratigraphic age (Shirmohammad et al. 2011). See sample locations on the map in Figure 2. For methods and laboratories, see original references.

comparison of MDA against youngest zircon age peak, show the interval between crystallization of those zircon grains and their deposition is 5–15 million years (Fig. 8). In contrast, the youngest zircon populations from the southern Laberge Group samples (Pleinsbachian strata) are similar in age to igneous rocks of the Texas Creek and Long Lake plutonic suites (Fig. 3) and were deposited within 10 million years of crystallization (Fig. 8). Note that this inference depends on the assumption that the MDA estimates approximate true depositional ages.

Based on the available data, there is little to no gap in MDA between the Stuhini and Lewes River Group rocks and the Laberge Group sedimentary rocks, at least for the northern part of the study area. The MDAs for samples 05W170 and ZE09079 (Lewes River Group and Mandanna member, respectively, localities 19 and 6 in Fig. 2) overlap with those calculated for Laberge Group sample 11MC183 (locality 25 in Fig. 2). The data suggest a gap of ~ 10 m.y. between the latest Laberge Group deposition and deposition of Bowser Lake Group and Tantalus Formation. Other work has suggested that deposition of the Bowser Lake Group began in the Bajocian (Evenchick et al. 2010; Shirmohammad et al. 2011), so there is little to no time gap between the Laberge Group and these rocks at the regional scale.

Only one sample from sedimentary rocks of the Cache Creek Terrane provides U–Pb data from detrital zircon grains.

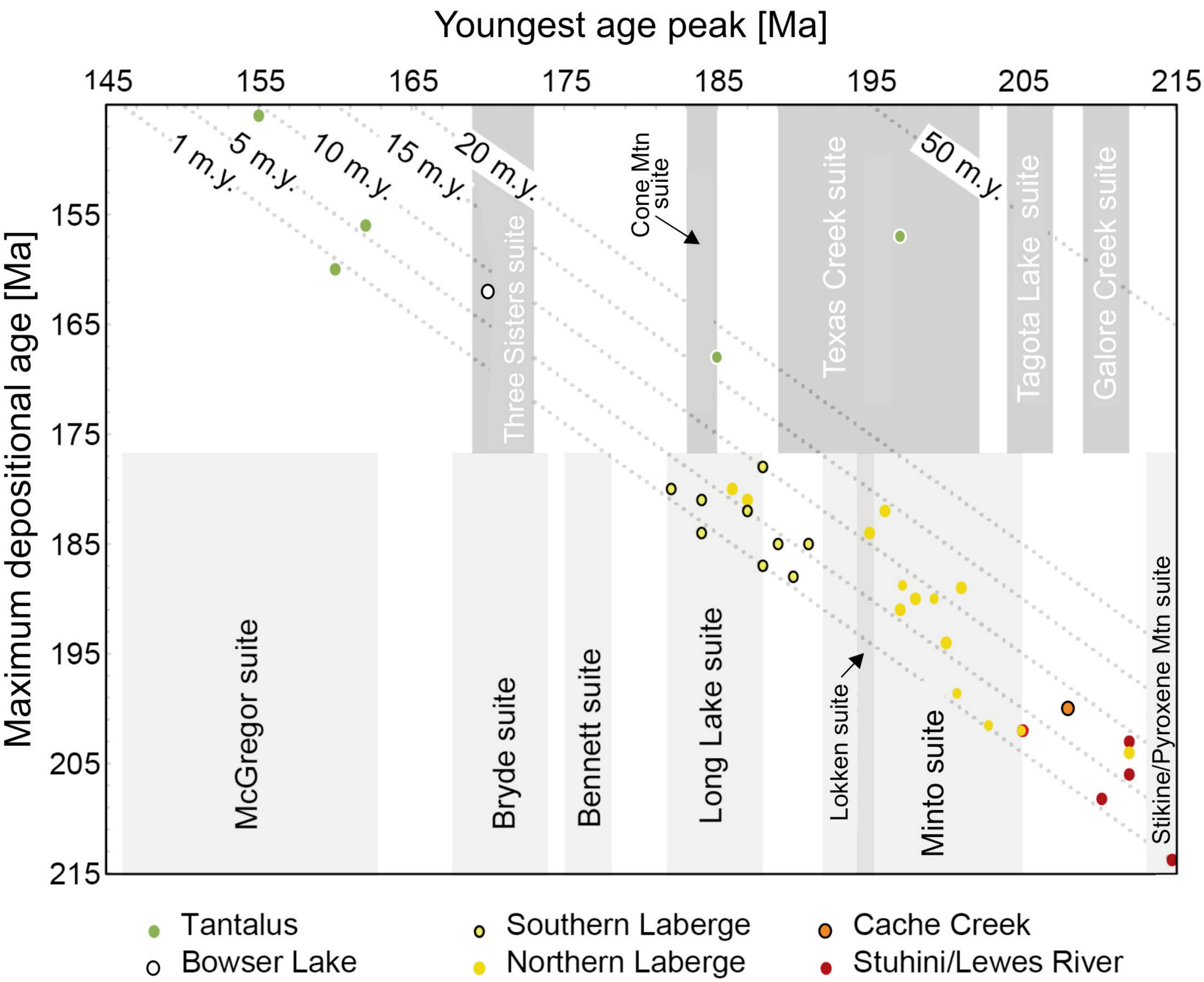


Figure 8. Plot of maximum depositional age vs. youngest age peak for detrital zircon data illustrated in Figures 6 and 7. Dashed lines show lag times in m.y. Light shaded boxes indicate age ranges of plutonic suites of southern Yukon from Figure 3: Stikine/Pyroxene Mountain suite (217–214 Ma), Minto suite (205–194 Ma), Lokken suite (195–192 Ma), Long Lake suite (188–182 Ma), Bennett suite (178–175 Ma), Bryde suite (174–168 Ma) and McGregor suite (ca. 163–146 Ma) (Colpron et al. 2016b; Sack et al. 2020). Dark shaded boxes indicate age ranges of plutonic suites for northern B.C. from Figure 3: Stikine suite (229–216 Ma), Galore Creek suite (212–209 Ma), Tatogga Lake suite (207–204 Ma), Texas Creek suite (202–189 Ma), Cone Mountain suite (185–183 Ma) and Three Sisters suite (173–169 Ma) (van Straaten et al. BCGS Open House presentation 2018).

Sample 11LB045 (locality 24 in Fig. 2) is closest in MDA to Stuhini sample 05W170 (locality 19), and has a younger MDA than the 'oldest' Laberge Group sample (11MC183; locality 25). Its detrital zircon population is similar to both of these samples (Figs. 6, 7).

Cumulative probability plots (Fig. 7) show that the Laberge Group samples contain fewer Paleozoic grains compared to samples from the older units of the Stuhini and Lewes River groups, and younger strata of the Tantalus Formation. However, there are older grains present in some Laberge Group samples. The most likely explanation for the contrast is that the detritus arriving to form the Laberge Group was dominated by erosion products from the nearby Stikine arc, consistent with the pattern shown by clast compositions (Fig. 4). Other zircon grains derived from older sources would simply have been swamped by material derived from the young adjacent arc terranes (e.g. Colpron et al. 2015).

Detrital zircon has also been isolated from igneous clasts in conglomerate of the Laberge Group in southern Yukon, and in the Lisadele Lake region. U–Pb dating of multigrain zircon fractions from clasts in the Yukon samples by TIMS yielded ages from 215 to 208 Ma (Hart et al. 1995), suggesting derivation from members of the Late Triassic Stikine plutonic suite, such as the Willison Bay pluton near Atlin (Mihalynuk et al. 2006) and the Tally Ho leucogabbro in southernmost Yukon (Hart 1996). TIMS dating of zircon in clasts from Lisadele

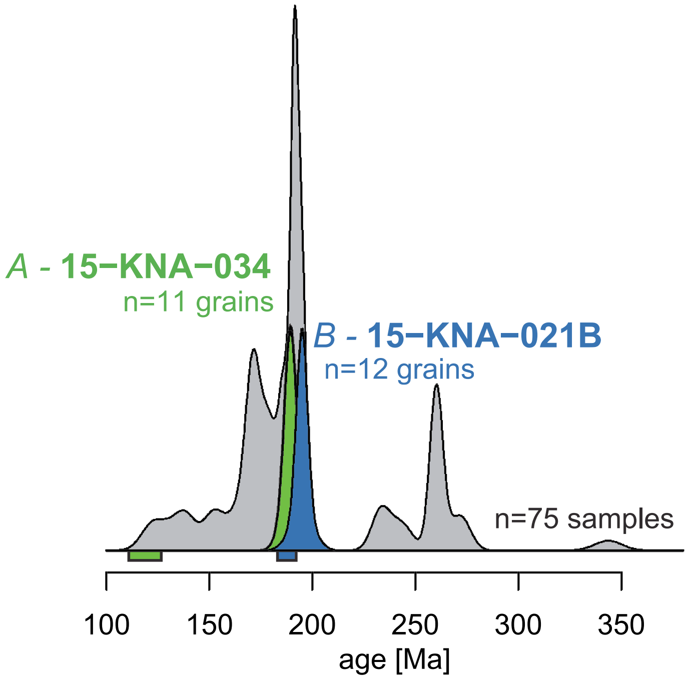


Figure 9. Kernel density estimate (KDE) plot for single crystal step heating detrital muscovite ages from samples 15-KNA-034 (Tantalus Formation) and 15-KNA-021B (a clast in Toarcian strata of Laberge Group). Sample locations are identified in Figure 2 as A and B, respectively, and their geographic coordinates are listed in the text. Note that data are overlain on a KDE that compiles all published muscovite $^{40}Ar/^{39}Ar$ metamorphic cooling ages from southern Yukon (Yukon Age Database 2006; Joyce et al. 2015). Bars beneath KDE plot show maximum depositional ages coloured by sample, as discussed in text.

Lake samples yielded crystallization ages of 186.6 ± 0.5 Ma and 221 ± 1 Ma (Shirmohammad et al. 2011). The older age coincides with the age of the Stikine plutonic suite, but the younger age is not represented in igneous rocks of northern B.C. However, an age of ca. 187 Ma overlaps the age range of the Hazelton Group (Cutts et al. 2015) and the Long Lake plutonic suite of southern Yukon (Colpron et al. 2016b; Sack et al. 2020).

U–Pb on Detrital Rutile

Pliensbachian Laberge Group strata at and south of Atlin Lake, including at Eclogite Ridge, contain minerals associated with high-grade metamorphism and discrete metamorphic rock clasts (English et al. 2002). These strata are the likely source of micro-diamonds captured in nearby stream sediment surveys (Canil et al. 2005). Metamorphic clasts within this horizon include eclogite, granulite, amphibolite and mica schist. These rock types are accompanied by porphyry, volcanic and granitic clasts that are more typical in the Laberge Group. The geochemistry of detrital garnet, spinel and pyroxene indicates that sources include ultra-high pressure (> 2.8 GPa) garnet peridotite (MacKenzie et al. 2005; Canil et al. 2006). Recent detailed studies of pristine eclogite clasts suggested peak temperature and pressure conditions of ≥ 800°C and ≥ 2.2 GPa, with U–Pb dating of rutile indicating that samples cooled through about 610°C during the Early Jurassic (182 ± 15 Ma; Kellett et al. 2018). In order for these clasts be deposited into the Laberge Group by the latest Pliensbachian, the source rocks must have been exhumed from depths of about 80 km depth at a mean vertical rate of at least 4 km/m.y. during the Early Jurassic (Kellett et al. 2018). This rapid rate of exhumation is typical for rocks exhumed at active subduction zones (e.g. Baldwin et al. 2004), and the eclogite clasts are interpreted to have been carried in a subduction channel between the Yukon-Tanana and Stikinia terranes (Kellett et al. 2018).

$^{40}Ar/^{39}Ar$ on Detrital Mica

Detrital muscovite is rare in the Late Triassic to Early Cretaceous sedimentary rocks of the northern Canadian Cordillera, likely because the Triassic to Early Jurassic magmatic rocks that contributed most detritus are generally sub-greenschist facies. However, muscovite is abundant in potential metamorphic source rocks such as the Snowcap assemblage of Yukon-Tanana terrane which may have contributed detritus to the Laberge Group (e.g. Piercey and Colpron 2009). Thus, although detrital muscovite is rare in Laberge Group samples, it is an important data source that provides information about exclusively metamorphic sources that are difficult to identify using detrital zircon. The nominal closure temperature for Ar in muscovite is ~ 400°C (Fig. 5). Muscovite from a strongly foliated and lineated quartz–feldspar schist clast in an Upper Toarcian horizon of the Laberge Group at Lisadele Lake, B.C. (Sample B in Fig. 2; latitude 58.6714N, longitude 133.0471W) was dated by Kellett and Iraheta-Muniz (2019). The depositional age for this location is constrained by biostratigraphy (Shirmohammad et al. 2011). Matrix detrital muscovite from a horizon of the Tantalus Formation along the Klondike Highway in the southern Yukon (Sample A in Fig. 2; latitude 61.75N; longitude 136.00W) was also dated by Kellett and Iraheta-Muniz (2019). This location has a Cretaceous (Aptian) mean depositional age (van Drecht, L., pers. comm. 2017).

Step heating results of individual muscovite crystals from the two sampled horizons indicate homogeneous $^{40}Ar/^{39}Ar$ age populations for these samples (Fig. 9). The clast from Lisadele Lake (locality B in Fig. 2, sample 15-KNA-021B) yielded a muscovite cooling age of ca. 195 Ma, and detrital grains from the Tantalus Formation (locality A in Fig. 2, sample 15-KNA-034) yielded an age peak of ca. 190 Ma. Both these results match $^{40}Ar/^{39}Ar$ age populations that are documented in metamorphic rocks from the Yukon-Tanana terrane in southern Yukon (Fig. 9). The age overlap between these detrital muscovite populations and bedrock metamorphic muscovite ages in southern Yukon suggests that Yukon-Tanana terrane metamorphic rocks are a likely source for horizons including metamorphic detritus in the Laberge Group and the Tantalus Formation. The data also indicate that the metamorphic source rock for the muscovite-bearing clasts in the Laberge Group must have been exhumed rapidly. Using a nominal closure temperature for metamorphic or igneous muscovite of 400°C, a 25°C/km geothermal gradient, and a depositional age of ca. 180 Ma, a source rock containing muscovite with 195 Ma cooling age would need to be exhumed at a mean rate of about 1 km/m.y. during the Early Jurassic.

Detrital biotite grains from two metamorphic clasts within Upper Toarcian Laberge Group strata at Lisadele Lake, B.C.

Table 2. Summary of preliminary zircon and apatite U–Th/He data for Laberge Group and spatially associated sedimentary rocks of the Lewes River Group, Bowser Lake Group and Tantalus Formation.

Map Locality*	Sample	Stratigraphic Unit	Latitude dd.dddd	Longitude ddd.dddd	ZHe* (Ma)	Number of grains	Age Dispersion	AHe* (Ma)	Number of grains	Age Dispersion
2	TB2	Tantalus Fm.	62.1422	-136.2662				56.2	3	
4	15KNA031	Tantalus Fm.	62.1233	-136.2652	203–170	5				
5	04MC002	Laberge Gp.	62.1117	-136.1491				47.4	5	
	15KNA032	Laberge Gp.	62.0347	-135.8619	156.7	7		43	5	Y
6	ZE09079	Lewes River Gp.	62.024	-135.8219	223–185	7	Y	39.3	2	Y
7	EN1	Laberge Gp.	62.0238	-135.8226				64.8	5	
	15KNA034	Tantalus Fm.	61.75	-136.00	176–152	4		40.4	5	
8	15KNA035C	Laberge Gp.	61.6212	-135.8777	150.1	5	Y	50.2	6	
9	15KNA030	Laberge Gp.	61.3765	-135.6744	111.3	6		51.2	4	Y
	15KNA029	Laberge Gp.	61.077	-135.1981	82.3	4				
	15KNA028	Laberge Gp.	60.9783	-135.1835	72.4	8		26.5	7	Y
	15KNA027	Laberge Gp.	60.9116	-135.2304	148.5	5	Y	41.9	5	
	15KNA025	Laberge Gp.	60.2676	-134.7457				43.1	5	
25	11MC183	Laberge Gp.	60.1838	-134.685				72.3	5	
26	15KNA010	Laberge Gp.	59.3272	-133.7708	198–173	4	Y	43.7	5	
27	ZE09006	Laberge Gp.	59.3271	-133.7721	205–180	7	Y			
28	ZE111001	Laberge Gp.	59.2793	-134.0748	61.5	7				
29	15KNA005	Laberge Gp.	59.2653	-133.8401	117.2	6		32.5	6	
	15KNA012	Laberge Gp.	59.2435	-134.0198	109.7	4		41.5	4	
30	15KNA014	Laberge Gp.	59.1136	-133.9623	103.4	5				
31	ZE09016	Laberge Gp.	59.1102	-133.3873	207–165	8				
32	15KNA016	Stuhini Gp.	58.6887	-133.0308				37.4	4	
35	S3	Laberge Gp.	58.6695	-133.0489	97.8	6	Y			
36	15KNA023	Bowser Lake Gp	58.6491	-133.0671	89	3	Y			

*Locality numbers in Figure 2 where indicated; otherwise, sample locations in Figure 10.

were dated with $^{40}Ar/^{39}Ar$ (Shirmohammad 2006) and yielded hump-shaped spectra generally indicative of partial Ar loss, in this case likely after deposition, and potentially a minor excess ^{40}Ar contribution (i.e. ^{40}Ar not produced by decay within the biotite) (Shirmohammad 2006). The final heating steps in these samples yielded poorly defined ca. 220 Ma and ca. 195 Ma ages which were interpreted by Kellett and Zagorevski (2021) to broadly represent maximum cooling ages.

In summary, cooling ages of metamorphic detritus in the Laberge Group indicate (a) source region(s) that experienced Early Jurassic Barrovian to high-pressure metamorphism that was quickly followed by rapid exhumation, erosion and deposition. The evidence for widespread Early Jurassic metamorphism in the Yukon-Tanana terrane (Currie and Parrish 1993; Dusel-Bacon et al. 2002; Berman et al. 2007; Morneau 2017) and other evidence for rapid exhumation and cooling (Johnston and Erdmer 1995; Johnston et al. 1996; Joyce et al. 2015) suggest it is the most likely source for the metamorphic detritus (e.g. Canil et al. 2006; Kellett et al. 2018).

(U–Th)/He on Detrital Zircon

Radiogenic He is a by-product of alpha decay of U, Th and Sm, and the decay chain from ^{238}U to ^{206}Pb, for example, produces 8 ^{4}He atoms. The nominal closure temperature for trapping and accumulating He atoms in zircon is ~ 180°C (Reiners 2005), but can vary significantly depending on cooling rate, grain size and radiogenic content (Whipp et al. in press). The U–Pb age of zircon generally (but not always) provides the timing of zircon crystallization, but the (U–Th)/He age of a zircon grain (ZHe) records the time when the crystal last cooled through ~ 180°C. Depending on thermal conditions in the sedimentary basin, ZHe ages of detrital zircon grains may provide either a record of source exhumation ages (i.e. they give ages *older* than depositional age) or a record of the basin's thermal history (i.e. ages *younger* than depositional age). The resetting of the U–Th/(He) ages in the second scenario could be related to sedimentary and structural burial, contact metamorphism, local hydrothermal fluid circulation or influences from nearby tectonic events.

Preliminary results from ZHe and (U–Th)/He dating of apatite (AHe) from Laberge Group and associated rocks are presented in Table 2 and Figure 10. ZHe dating was performed on zircon from 14 Laberge Group samples. These data are augmented by three matrix samples from the Tantalus Formation and one matrix sample from the Bowser Lake Group, representing younger Cretaceous strata. Two matrix samples from the Triassic Lewes River and Stuhini groups represent units older than the Laberge Group and were collected close to basal Laberge strata (Kellett et al. 2017). Five of these samples were double-dated, that is, U–Pb and He dates were obtained from the same individual zircon crystals (Table 2; Fig. 11). Double-dating of detrital zircon is a powerful approach for studying sediment provenance (Reiners et al. 2005).

The ZHe ages of detrital zircon from the northernmost Laberge Group and from the area between the King Salmon and Nahlin faults, are slightly older than or within error of

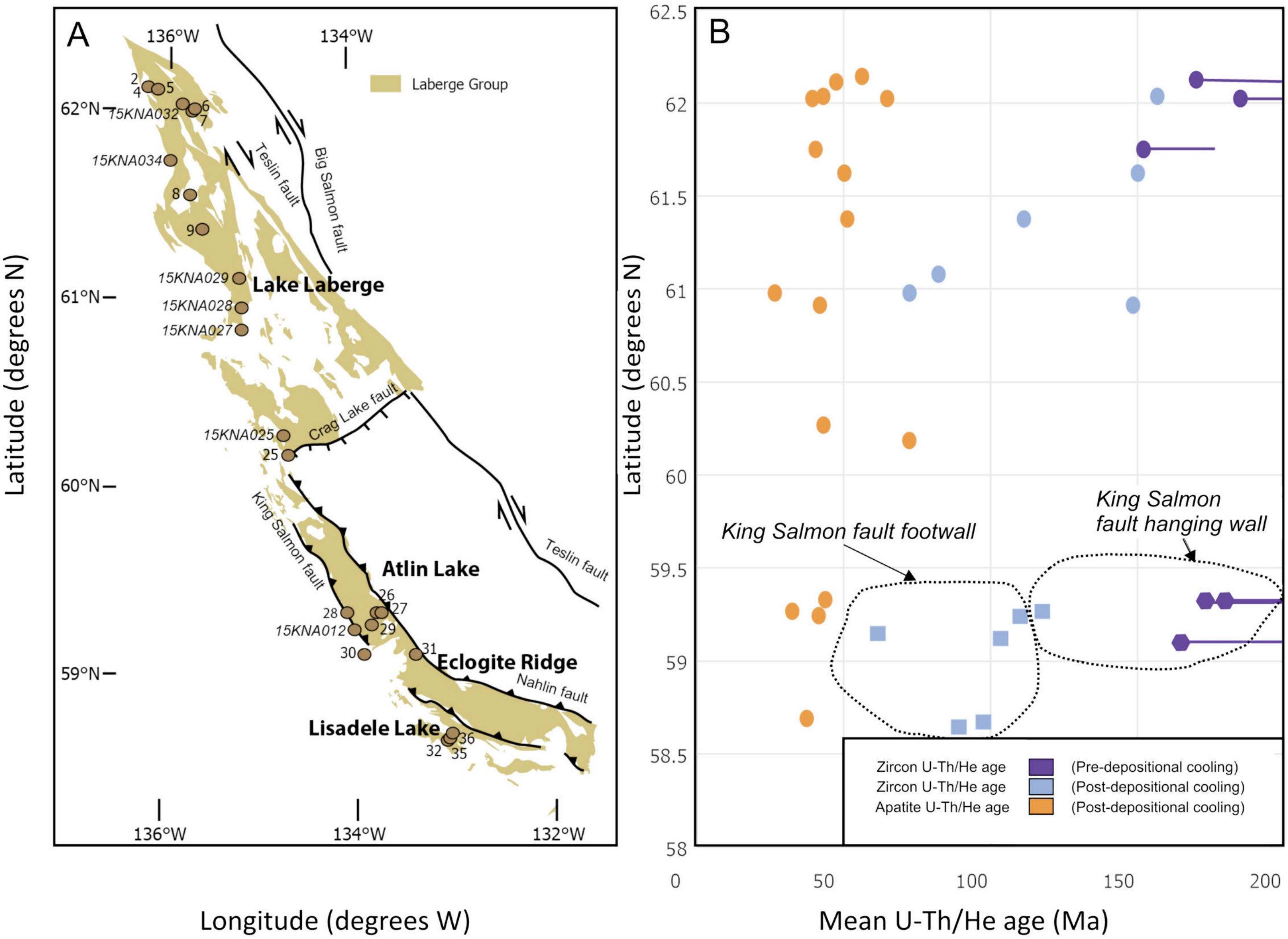


Figure 10. A. Laberge Group map footprint extracted from Figure 2 showing locations of U-Th/He samples. Short locality numbers correspond to samples shown in Figure 2 and listed in Table 1, and longer sample numbers represent additional analyses listed in Table 2. These additional samples do not have corresponding detrital zircon data. Map modified from Cui et al. (2017) and Colpron et al. (2016a). B. Mean U–Th/He ages for zircon and apatite from Table 2 plotted against sample latitude, as a proxy for along-strike position in the basin. Hexagonal ZHe data points are from the hanging wall of the King Salmon thrust, while square ZHe data points are from the footwall. Horizontal blue bars indicate range of detrital ZHe ages.

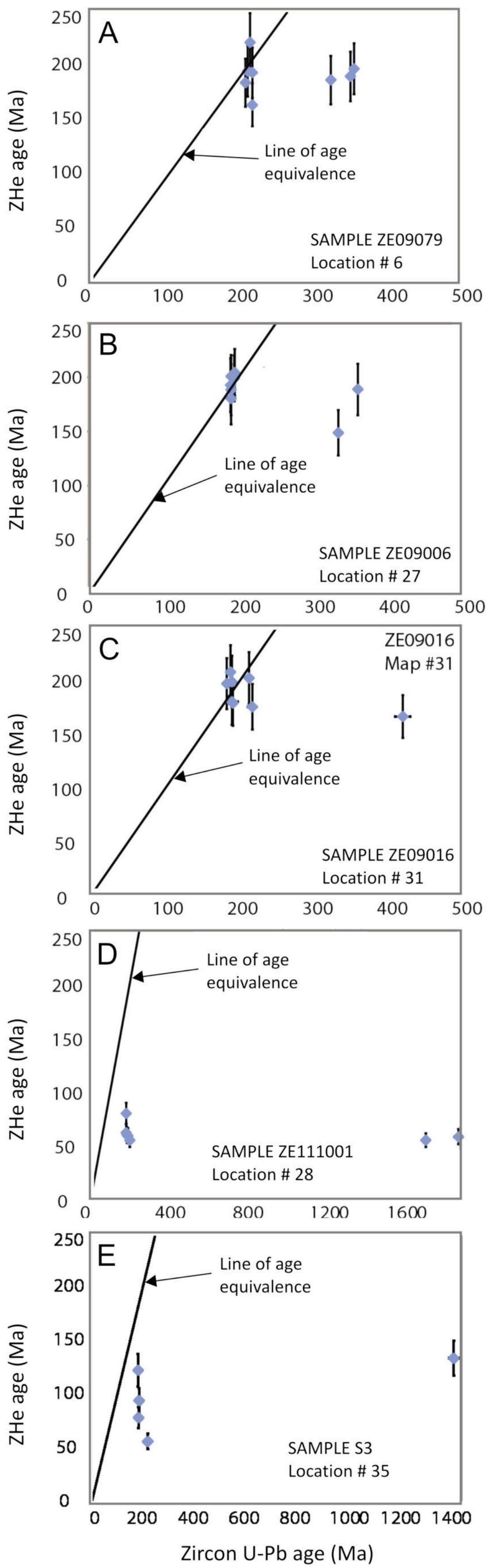
their depositional ages indicating that they preserve information about the exhumation and cooling history of their source rocks (Fig. 10). The similarity between U–Pb ages and ZHe ages, as demonstrated clearly in double-dated samples ZE09006, ZE09016 and ZE09079 (Fig. 11; localities 27, 31 and 6 in Fig. 2), indicates that those rocks did not experience post-depositional temperatures higher than ~ 180°C. In contrast, there are two regions where ZHe dates have been reset by post-depositional heating (i.e. ZHe ages are significantly younger than depositional ages; Figs. 10, 11). Samples collected northwest and southwest of Lake Laberge yielded post-depositional ZHe dates between ~ 150 and 80 Ma. Finally, all samples collected from the footwall of the King Salmon thrust yielded post-depositional ZHe dates of 110 Ma or younger (Figs. 10, 11). These include samples collected from units older than the Laberge Group (e.g. 15KNA016; locality 32), and younger sedimentary rocks of the Bowser Lake Group (15KNA023; locality 36).

(U–Th)/He on Detrital Apatite

Compared to He in zircon, He in apatite has a significantly lower nominal trapping temperature, ~60°C (Farley and Stockli 2002). Thus, apatite grains are more likely to be reset during burial or heating events than zircon grains, i.e. AHe ages are expected to be young than depositional ages, and younger than ZHe ages from the same samples. All AHe dates obtained to date from Mesozoic sedimentary rocks range from late Cretaceous to Oligocene, significantly postdating deposition of their host strata (Fig. 10). These results indicate that final cooling and exhumation of the post-accretionary basins following basin inversion mostly occurred during the Paleogene.

DISCUSSION

The Jurassic sedimentary strata of the Laberge Group in northern British Columbia and southern Yukon provide an impressive record of basin development linked to progressive tectonic evolution and coeval arc magmatism. The earliest



Laberge Group strata were deposited unconformably on late Triassic volcanic-dominated sequences of the Lewes River Group in Yukon and in the Stuhini Group in B.C., both of which belong to the arc-related Stikinia terrane. During Sinemurian to Toarcian times (199 Ma to 174 Ma) the Stikinia terrane was uplifted and incised through erosion of its supracrustal rocks, which locally reached its plutonic roots. This process is revealed by changes in clast proportions in the Laberge Group sequence, which received detritus from the still active but eroding arc terranes. At the same time, older rocks of the adjacent Yukon-Tanana terrane were metamorphosed under Barrovian and (locally) high-pressure conditions, and were then rapidly exhumed and eroded. This metamorphic detritus, representing all crustal levels and including possible subduction-zone eclogite, was also deposited in the Laberge Group, but such contributions were minor compared to those from volcanic and plutonic rocks. Nevertheless, its presence as a minor component suggests that the Stikinia and Yukon-Tanana terranes were amalgamated (or re-amalgamated) during the Early Jurassic, with the Yukon-Tanana terrane representing the lower plate. The relationship between the Stikinia and Cache Creek terranes during the Early Jurassic remains enigmatic, yet the potential for correlation between Late Triassic and Early Jurassic clastic and volcanoclastic units within them suggests that more detailed studies could clarify this problem.

By the Bajocian (Middle Jurassic, 170 to 168 Ma) deposition of the Laberge Group was nearly complete, some of these strata were eroded, and successor Late Jurassic and Cretaceous sequences of the Tantalus Formation and the Bowser Lake Group developed. The abundance of chert clasts in these strata and the paucity of volcanic or plutonic detritus indicate an important shift in sediment sources. The shift from a marine depositional setting in the Laberge Group to a restricted fluvial depositional setting in the Tantalus Formation, and the widespread contribution of chert debris could suggest the closure and inversion of a marine basin.

The Laberge Group, the Bowser Lake Group and correlative rocks were eventually inverted and shortened into a west-facing fold and thrust belt that includes the King Salmon fault (Tipper 1978; English et al. 2002; see Fig. 2). The locally angular unconformity between the Laberge Group and the overlying younger units suggests that more than one phase of folding and thrusting occurred during the Jurassic, before and after the younger sequences were deposited. Any westward overthrusting of the Cache Creek terrane onto the Stikinia terrane (and the Laberge Group) must have been limited, as U–Th/(He) data indicate that Laberge Group rocks lying in the footwall of the Nahlin fault were not buried sufficiently to

Figure 11. (*opposite*) Double dating of detrital zircon crystals. U–Pb ages are from Kellett and Iraheta-Muniz (2019) (A, D), Kellett et al. (2018) (B, C) and Shirmohammad et al. (2011) (E), while ZHe ages for the same crystals are preliminary data. Sample numbers and locality numbers correspond to those listed in Table 2 and shown in Figures 2 and 10. Points that plot on the line of age equivalence have identical U-Pb and ZHe ages within error. Error bars are at the 1σ level for both U–Pb and ZHe data.

reach ~ 180°C (~ 7 km for a geothermal gradient of 25°C/km). However, Laberge Group rocks in southernmost Yukon and west of the King Salmon fault in northern B.C. were heated to more than 180°C during Late Jurassic to Early Cretaceous, before eventually cooling, likely by being exhumed into the shallow crust. Movements on post-accretionary structures such as the King Salmon, Nahlin and Teslin faults may have contributed to regional differences in exhumation and cooling rates throughout the Cretaceous, and to a lesser extent during the Paleogene.

CONCLUSIONS

Information from multiple isotopic systems, including U–Pb studies of detrital zircon and rutile, $^{40}Ar/^{39}Ar$ studies of detrital muscovite and biotite, and U–Th/(He) investigations of zircon and apatite, provide valuable information about the geological history of the Laberge Group and associated rocks, and these data also provide directions for future studies. U–Pb data from detrital zircon show that the Laberge Group was sourced largely from Mesozoic volcanic and plutonic rocks, which in most cases were only slightly older than the documented and inferred depositional ages of the sedimentary rocks. Older Triassic sedimentary rocks in the region, and a few younger Late Jurassic to Cretaceous sedimentary rocks contain higher proportions of older (Paleozoic) zircon grains than typical Laberge Group samples, suggesting that they had more diverse source terranes. The contribution of nearly contemporary or slightly older volcanic and plutonic rocks to the Laberge Group basin seems to have generally swamped other sediment sources, which is consistent with sources in the arc-related rocks of the Stikinia Terrane, with very few older contributions. Maximum depositional ages (MDA) calculated from the detrital zircon data hint at regional age variations within the Laberge Group, with older strata in the north and deposition progressing southward, but these patterns may be influenced by sampling bias. Nevertheless, the close correspondence between calculated MDA for Laberge Group samples and the peak age ranges for detrital zircon implies that it provides a useful measure of depositional age, and the calculated MDA are at least locally consistent with biostratigraphic evidence.

Preliminary data for U–Th/(He) studies of selected Laberge Group samples, combined with constraints on depositional ages from detrital zircon U–Pb data, allow the definition of at least five broad domains within the basin that have contrasting thermal histories. Some parts of the Laberge Group basin retain ZHe ages that correspond to or are slightly older than calculated maximum depositional ages, whereas others seem to have experienced post-depositional heating above about ~ 180°C. There is also a contrast between the ZHe and AHe ages, with the latter being completely reset, indicating post-depositional heating to 60°C or more occurred almost everywhere. The regions that show greater heating to ~ 180°C are at least in part structurally controlled, as some are associated with the location of an important regional structure known as the King Salmon fault.

Further analyses are required to explore whether the other thermal history domains are also structurally controlled, and to what degree these data can be used to constrain the timing and kinematics of slip on the intervening structures. The regional extent of contrasting thermal history domains within the Laberge Group may be significant for evaluation of the basin's petroleum potential. The domains where ZHe data indicate heating above ~ 180°C are likely to be overmature for oil and gas, but the data on the timing of heating may assist in the identification of possible traps for migrating oil and gas in areas where ZHe and AHe data indicate lesser degrees of post-burial heating.

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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-

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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

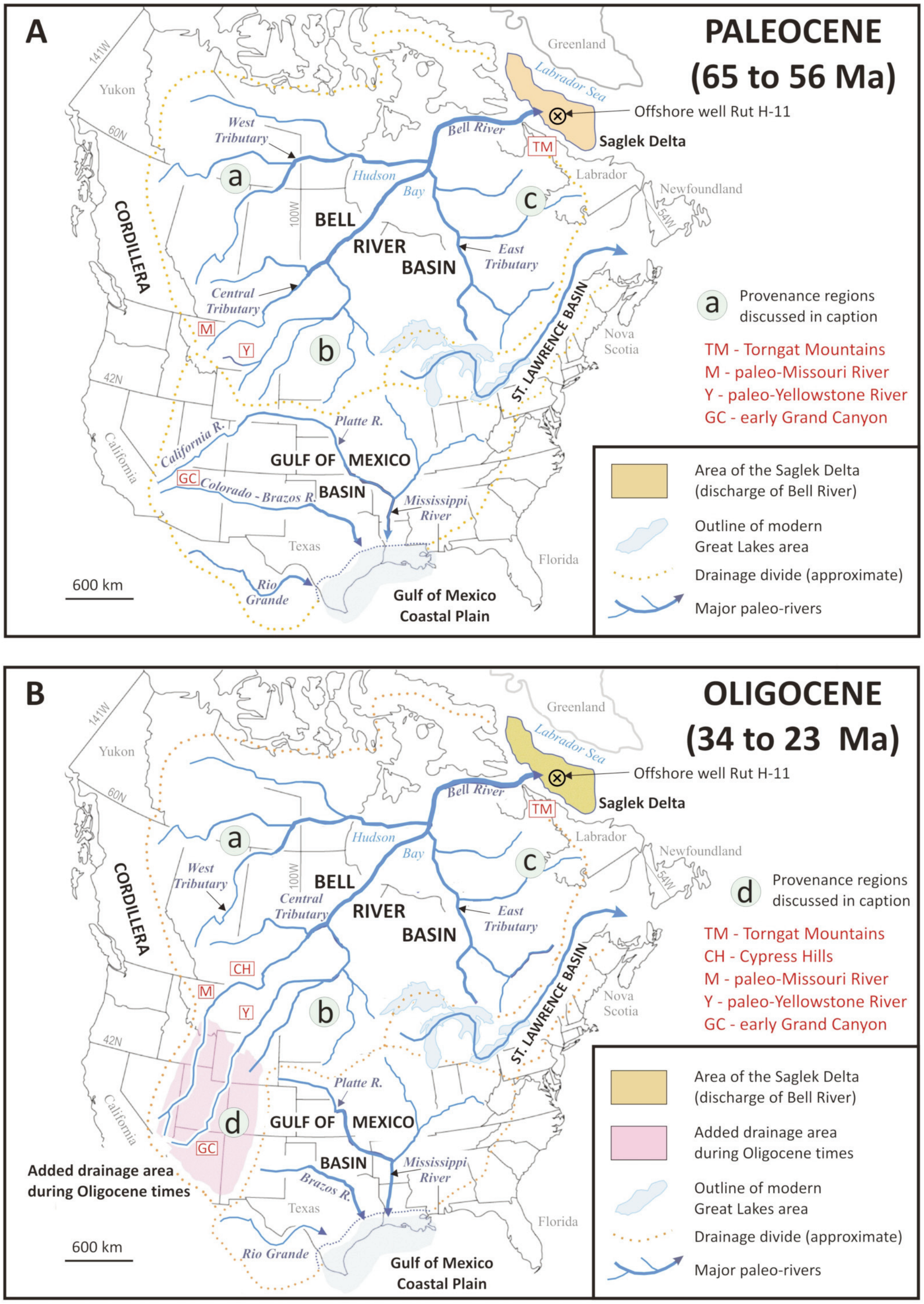

Figure 1. Summary maps depicting the evolution of North American drainage systems and the postulated extent and geography of the Bell River basin, after McMillan (1973), Balkwill et al. (1990), Duk-Rodkin and Hughes (1994), Sears (2013), Blum and Pecha (2014), Blum et al. (2017), Jackson (2018), and 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.

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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

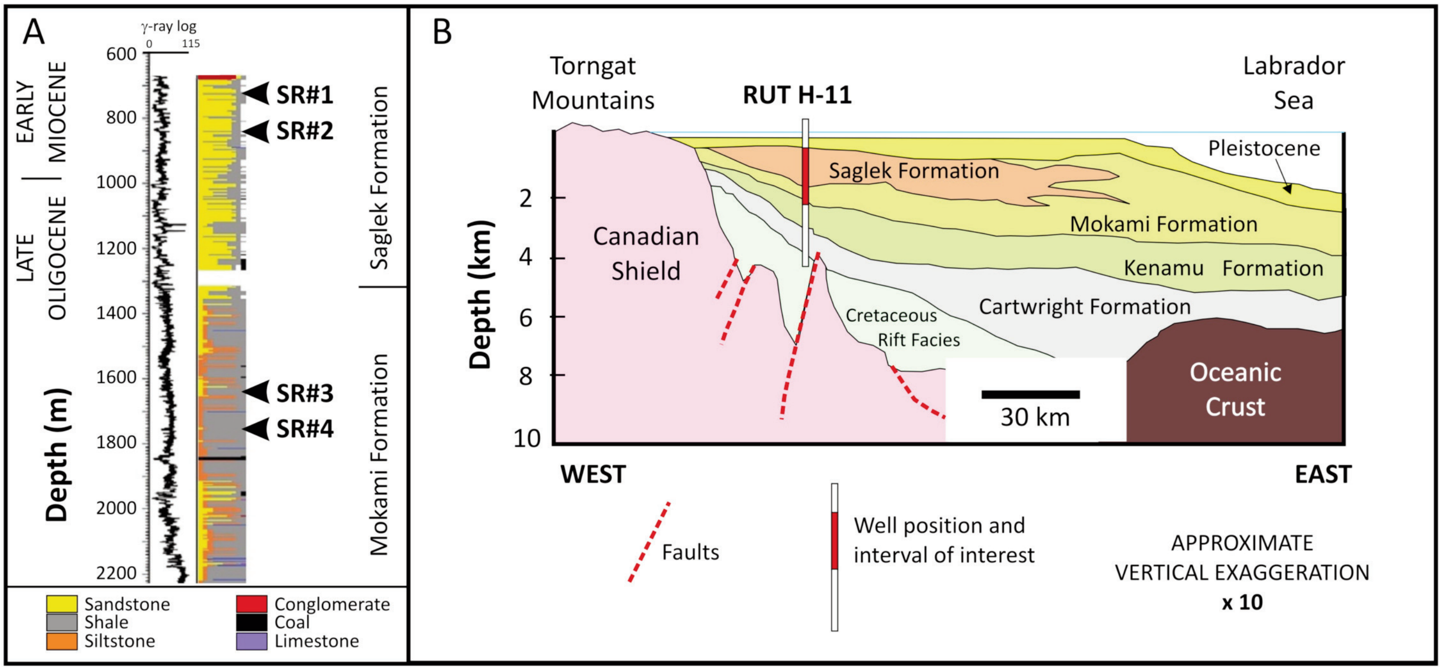

Figure 2 A. Rut H-11 well data from Fensome (2015). Our samples SR#1 and SR#2 are from Lower Miocene Saglek Formation sand. Samples SR#3 and SR#4 are from Lower Oligocene Mokami Formation sand. The sand was uniform in grain-size, texture, and composition. Fensome (2015) found abundant Cretaceous dinocyst 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.

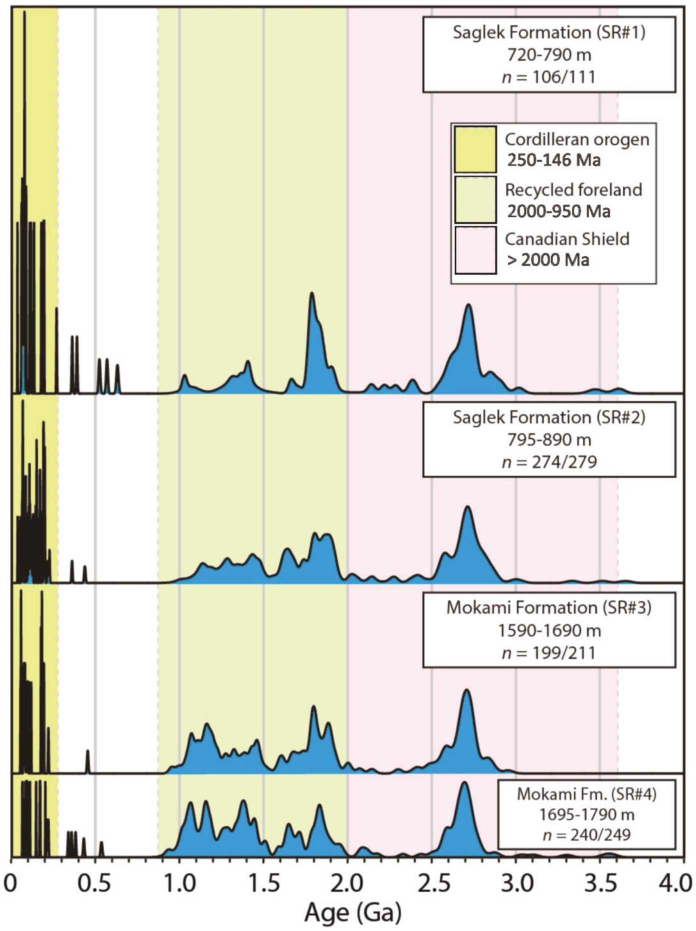

Figure 3. Stacked normalized probability plots and detrital U–Pb results for SR#1 (Lower Miocene Saglek Formation: 720–790 m), SR#2 (Lower Miocene Saglek Formation: 795–890 m), SR#3 (Lower Oligocene Mokami Formation: 1590–1690 m), and SR#4 (Lower Oligocene Mokami Formation: 1695–1790 m) samples from 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

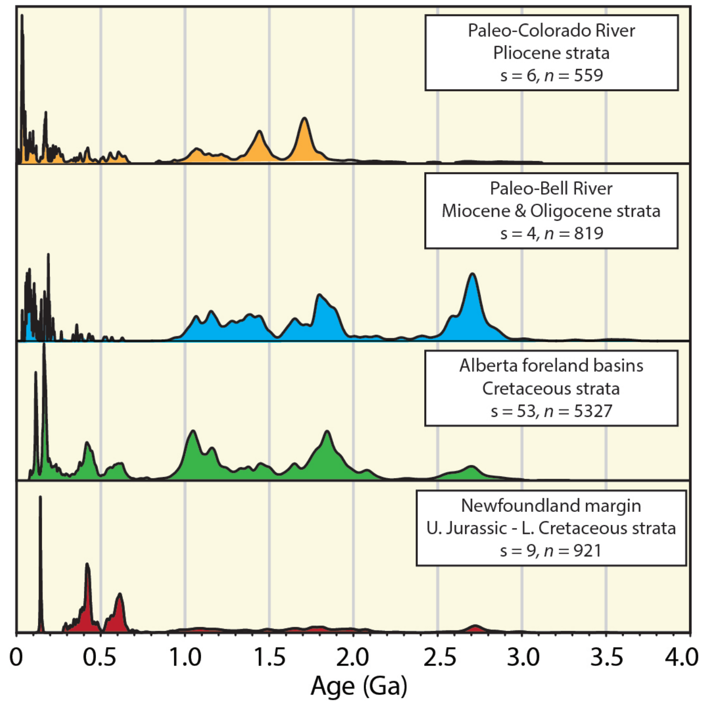

Figure 4. Stacked normalized probability density plots for selected Jurassic to Neogene drainage systems, including Pliocene paleo-Colorado River sediment from Kimbrough et al. (2015), Oligocene and Miocene paleo-Bell River from this study, Cretaceous Alberta foreland basin strata from Leier and Gehrels (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).

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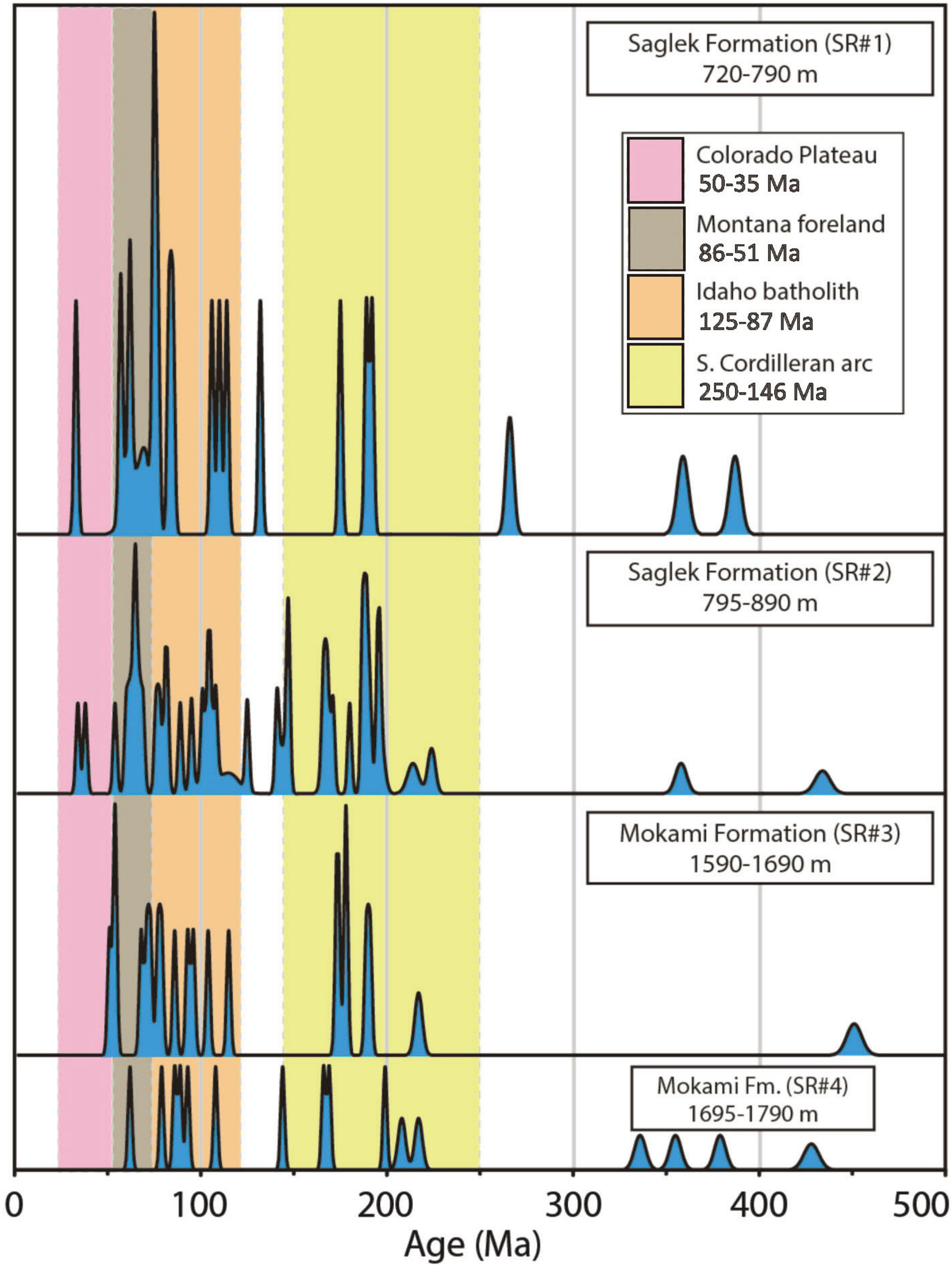

Figure 5. Stacked normalized probability density plots of < 500 Ma detrital zircon grains from this study. The 250–146 Ma detrital zircon grains (yellow) may indicate derivation from the southern Cordilleran arc and foreland basin. The 125–87 Ma detrital zircon grains (orange) link to the Idaho batholith. 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.

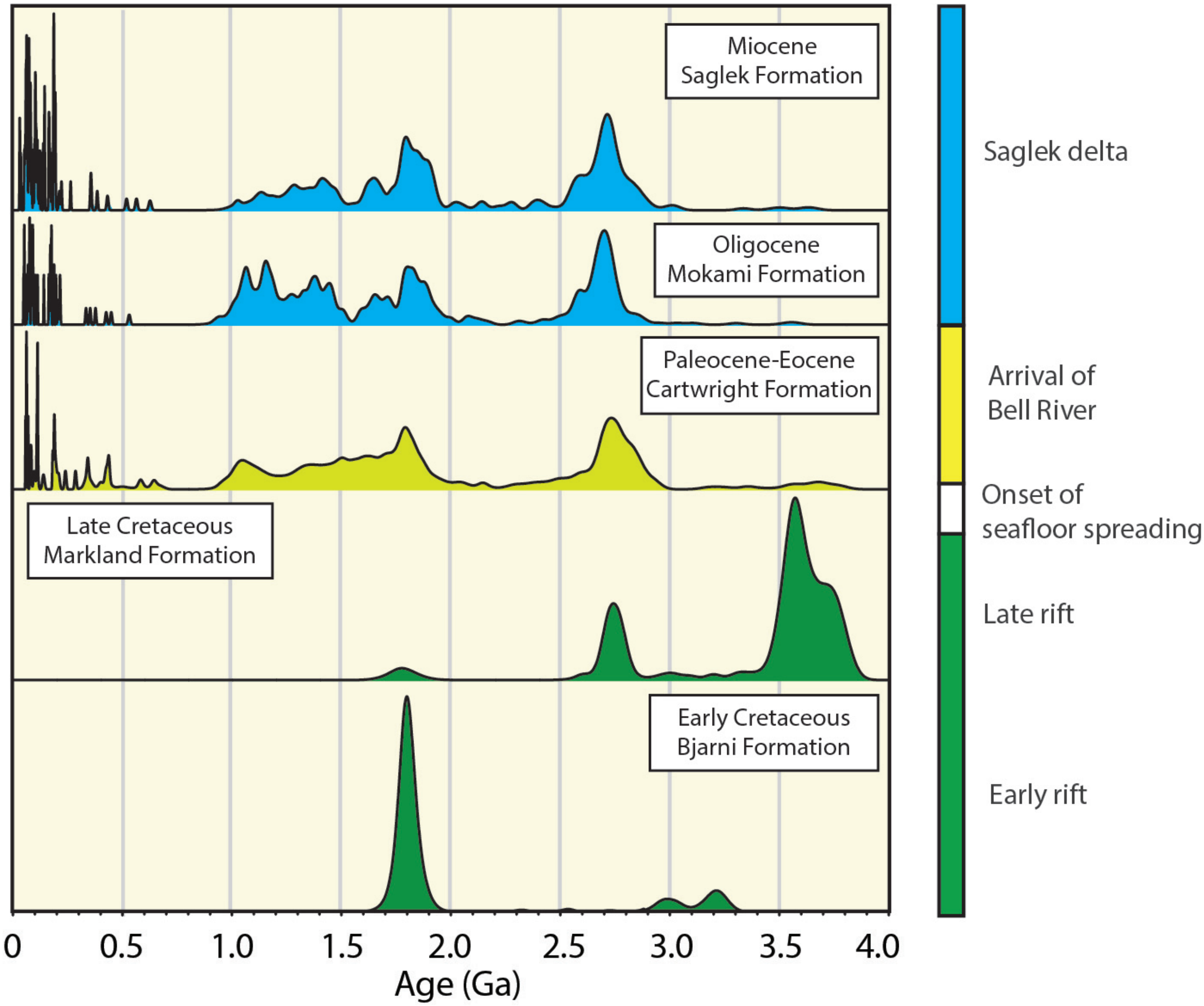

Figure 6. Stacked normalized probability density plots for Cretaceous and Neogene strata of the Saglek basin. Lower Cretaceous Bjarni and Upper Cretaceous Markland formations and Paleocene–Eocene Cartwright Formation results from Thrane (2014). Oligocene Mokami Formation and Miocene Saglek Formation 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

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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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For access to the Sears and Beranek (2022) Supplementary Data Files, SR#1, SR#2, SR#3, and SR#4, providing detrital zircon age results and U–Pb isotopic data, please visit the GAC's open source GC Data Repository at: https://gac.ca/gc-data-repository/.

GAC-MAC: FIELD GUIDE SUMMARY

Halifax 2022: GAC–MAC–IAH-CNC–CSPG Joint Annual Meeting Field Trips

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HALIFAX 2022 FIELD TRIPS OVERVIEW

This year the 2022 GAC–MAC Annual Meeting returns to 'Canada's Ocean Playground' in the gleaming new convention centre located in the heart of downtown Halifax. Partnered with the Canadian Society of Petroleum Geologists (CSPG) and International Association of Hydrogeologists (IAH-CNC), the meeting also coincides with the 50th anniversary of the Atlantic Geoscience Society (AGS). What better way to celebrate Atlantic geoscience by attending one of the many field trips on offer from a variety of organizations!

Delegates have a total of 12 trips to choose from with a bonus free self-guided walking tour of the geology of the historic Dartmouth Commons that will be offered to all conference participants. Trips range from several hours to multiple days to suit a wide variety of interests and budgets.

Folded Lower Carboniferous Horton Group at Split Rock, spectacularly exposed on the sea cliffs wave-cut platform of the macrotidal Bay of Fundy. Photo: John Waldron.

Benjamin Bridge Vineyards, view looking northeast over the Gaspereau Valley. Photo: Denise Brushett.

Pre-Conference Field Trips

On May 12th, join John Waldron on a trip to several spectacular Nova Scotian coastal sites during "*Salt tectonics along a late Paleozoic transform fault, Nova Scotia*". This 2 ½ day trip will take you across Nova Scotia and focus on Carboniferous rocks of the Maritimes Basin that were deposited and deformed in a transform-fault setting during the assembly of Pangea. Visits to the Joggins Fossil Cliffs, Cliffs of Fundy Geopark and the Pictou Coalfield will provide an opportunity to discuss the complex interaction among sedimentation, strike-slip tectonics, and salt movement.

Kick back and explore how climate, the local geology, soil characteristics and groundwater influence local wines during "*Geology, Groundwater and Wines of the Annapolis Valley, Nova Scotia*", a single day outing offered on May 15th. Field trip leaders will guide participants across a selection of wineries to learn about (and taste) the wide diversity of geological settings that form the distinctive terroir of the Annapolis Valley.

The CSPG sponsored "*3-D Virtual Book Cliffs Tour, Coal Creek and Deadman Canyons, Utah; Sequence Stratigraphy and Sedimentology of Coastal plain, Shoreface and Offshore Successions of the late Cretaceous Castle gate, Blackhawk and Mancos Shale Formations*" will be offered on May 13th for those interested in the application of Unmanned Aerial Vehicles (UAVs) to 3-D modelling of normally inaccessible and treacherous vertical canyons. This virtual field trip is offered by knowledgeable guides in a live session and includes a comprehensive summary document and video recording for participants.

From May 12th to 15th, Nancy Van Wagoner, Les Fyffe, and Dave Lentz will lead participants on a 4-day field trip exploring the "*Volcanism of the Late Silurian Eastport Formation of the Coastal Volcanic Belt, Passamaquoddy Bay, New Brunswick*". This trip will provide a detailed look at several stunning exposures of a Late Silurian bimodal volcanic and sedimentary sequence, many sites of which are located along the picturesque Bay of Fundy (see Van Wagoner et al. 2022, this Issue).

Post-Conference Field Trips

As part of the International Geoscience Programme (IGCP)

Geoscience Canada, v. 49, https://doi.org/10.12789/geocanj.2022.49.185 pages 43–44

Bedded and cross bedded felsic lithic-crystal-tuff and lapilli tuff of cycle 2 interpreted to be surge, flow and minor airfall deposits, distal to source. Photo: K. Dadd.

Coastal exposure of volcaniclastic rocks of the Main-à-Dieu Group near the Fortress of Louisburg, Cape Breton Island. Photo: D. van Rooyen.

project IGCP 683, Sandra Barr, Yvette Kuiper, Deanne van Rooyen, and Chris White are offering at 5-day field trip examining the *"Geological comparisons and correlations among crustal blocks of eastern North America, northwest Africa, and western Europe"*. From May 19th to 23rd, the field trip will take participants around Nova Scotia to examine the unique geology of the Meguma terrane, the diversity of Avalonian rocks in the Cobequid Highlands, and the contrasts between rocks of the Mira and Bras d'Or terranes on Cape Breton Island. Other areas (southern NB and SE and coastal New England) will be highlighted during evening 'virtual' field trips.

From May 18th to 21st, Jim Walker, Aaron Bustard and Dustin Dahn will lead participants through "*Stratigraphy and tectonic setting of the Bathurst Mining Camp, New Brunswick*". This 4-day field trip will whisk you away from Halifax to northern New Brunswick to examine the stratigraphic and structural setting of the volcanogenic massive sulphide deposits of the Bathurst Mining Camp. Focus will first be on the Tetagouche Group including the Brunswick Horizon and its associated deposits, followed by a closer look at the California Lake Group and its deposits.

Stretching across the northern Minas Basin and Bay of Fundy of Nova Scotia, *The Cliffs of Fundy Geopark* was officially designated as a UNESCO Global Geopark in 2020. Beginning on May 19th, Caleb Grant and colleagues will host a 3-day traverse through the Geopark with "*Telling the story of the Cliffs of Fundy UNESCO Global Geopark, Nova Scotia: linking geoheritage, indigenous heritage and culture*". This trip will take participants to several stunning localities within the Geopark and demonstrate the importance and interplay of geological features from cultural, scientific, and indigenous heritage perspectives. Louise Leslie's Field Trip FT- B7 also explores the wonders of the Cliffs of Fundy Geopark but lasts only for a single day and is exclusively for teachers.

Join Grant Wach and colleagues on May 19th for a 2-day excursion examining "*Paleozoic Petroleum, CO_2, and Geothermal Systems of the Maritimes Basins*". This trip will visit the Joggins UNESCO World Heritage Site to have a closer look at a salt-withdrawal basin where rates of accommodation were so rapid that trees of the Carboniferous forest were preserved upright. On day 2, the group will descend on the Stellarton Drill Core Library to examine basin complexities in cores analogous to outcrops visited on Day 1.

Crisscrossing the Carboniferous in Nova Scotia and New Brunswick, the field trip "*The Geological Setting of Romer's Gap: in memoriam of Jenny Clack*" will examine the environments where tetrapod evolution occurred during and after Romer's Gap. This 3-day trip beginning on May 18th led by Adrian Park, Steven Hinds, Matt Stimson, and Olivia King, will examine tetrapod fossils and footprints and the stratigraphy in which they are hosted. No tour of the Carboniferous is complete without a stop at the Joggins UNESCO World Heritage Site followed by an opportunity to get up close and personal with a late Pennsylvanian trackway at the Tatamagouche Creamery Square Heritage Centre.

Rich in knowledge of the Nova Scotia goldfields, Rick Horne, Dan Kontak and Mitch Kerr are offering a 5-day field trip examining "*Gold Deposits*" of the Meguma Supergroup. Beginning on May 19th, the field trip will take participants to several deposits in production and near-term development including the Moose River (Touquoy) Mine, Aureus East (Dufferin) and Goldboro properties, as well as examining a recently discovered epithermal gold project in the Antigonish Highlands. Several additional localities will further augment and challenge the understanding and unresolved issues surrounding Meguma gold deposits.

On top of all the exciting field trips across Nova Scotia and New Brunswick, be sure to give yourself enough time to hop on the ferry from downtown Halifax and travel across the harbour to explore the *"Geology and History of the Dartmouth Commons"* using Tim Fedak's online self-guided tour. Details of the walking tour will be provided in the conference registration package.

Further information and registration details can be found at the Halifax 2022 website:
https://halifax2022.atlanticgeosciencesociety.ca.

GAC-MAC: FIELD GUIDE SUMMARY

Volcanism of the Late Silurian Eastport Formation of the Coastal Volcanic Belt, Passamaquoddy Bay, New Brunswick

GAC–MAC Halifax 2022 Pre-Meeting Field Trip

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SUMMARY

This field trip is an excursion through the exquisite, nearly pristine exposures of a Silurian, felsic-dominated bimodal volcanic and sedimentary sequence exposed in the Passamaquoddy Bay area of southwestern, New Brunswick (Eastport Formation). These rocks form the northwest extension of the Coastal Volcanic Belt that extends from southwestern New Brunswick to the southern coast of Maine. The sequence is significant because it is part of a large bimodal igneous province with evidence for supervolcano-scale eruptions that began to form during the close of the Salinic Orogeny (about 424 Ma), and continued into the Acadian Orogeny (421–400 Ma). The geochemical characteristic of the rocks can be explained by extension related volcanism but the specific drivers of the extension are uncertain. The Passamaquoddy Bay sequence is 4 km thick and comprises four cycles of basaltic-rhyolitic volcanism. Basaltic volcanism typically precedes rhyolitic volcanism in Cycles 1–3. Cycle 4 represents the waning stages of volcanism and is dominated by peritidal sediments and basaltic volcanics. A spectrum of eruptive and emplacement mechanisms is represented ranging from the Hawaiian and Strombolian-type volcanism of the basaltic flows and pyroclastic scoria deposits, to highly explosive sub-Plinian to Plinian rhyolitic pyroclastic eruptions forming pyroclastic density currents (PDC) and high grade rheomorphic ignimbrites. During this field trip we will examine key exposures illustrating this spectrum of eruptive and emplacement processes, and their diagnostic characteristics, along with evidence for the interaction between mafic and felsic magmas and a variety of peperitic breccias formed as a result of emplacement of flows on wet peritidal sediments. The constraints the depositional setting and voluminous bimodal volcanism places on tectonic models will also be considered.

RÉSUMÉ

Cette sortie sur le terrain est une excursion à travers les magnifiques affleurements pratiquement non altérés d'une séquence volcanique et sédimentaire bimodale silurienne à dominance felsique exposée dans la région de la baie de Passamaquoddy, au sud-ouest du Nouveau-Brunswick (Formation d'Eastport). Ces roches forment le prolongement nord-ouest de la Ceinture volcanique côtière qui s'étend du sud-ouest du Nouveau-Brunswick à la côte sud du Maine. La séquence est importante car elle fait partie d'une grande province ignée bimodale comprenant des preuves de super éruptions volcaniques qui ont commencé à se former à la fin de l'orogenèse salinique (environ 424 Ma) et se sont poursuivies pendant l'orogenèse acadienne (421–400 Ma). La caractéristique géochimique des roches peut être expliquée par le volcanisme lié à l'extension, mais les facteurs spécifiques de l'extension sont incertains. La séquence de la baie de Passamaquoddy a une épaisseur de 4 km et comprend quatre cycles de volcanisme basaltique-rhyolitique. Le volcanisme basaltique précède généralement le volcanisme rhyolitique dans les cycles 1–3. Le cycle 4 représente les stades décroissants du volcanisme et est dominé par des sédiments péritidaux et des roches volcaniques basaltiques. Une variété de mécanismes éruptifs et de mises en place est représentée, allant du volcanisme de type hawaïen et strombolien des coulées basaltiques et des dépôts de scories pyroclastiques, aux éruptions pyroclastiques rhyolitiques hautement explosives sous-pliniennes à pliniennes formant des courants de densité pyroclastiques et des ignimbrites rhéomorphes à haute teneur. Au cours de cette visite sur le terrain, nous examinerons les affleurements clés illustrant cette gamme de processus éruptifs et de mises en place, et leurs caractéristiques

diagnostiques, ainsi que les preuves de l'interaction entre les magmas mafiques et felsiques et une variété de brèches pépéritiques formées à la suite de la mise en place de coulées sur des sédiments péritidaux humides. Les contraintes que le contexte de dépôt et le vaste volcanisme bimodal imposent aux modèles tectoniques seront également examinées.

Traduit par la Traductrice

INTRODUCTION

This field trip is a geotraverse through the exquisite, nearly pristine exposures of the Late Silurian, bimodal (basaltic-rhyolitic) volcanic and sedimentary sequence of the Eastport Formation in the Passamaquoddy Bay area of southwestern New Brunswick. These rocks form the northern extension of the Coastal Volcanic belt that extends south from southwestern, New Brunswick to the southern coast of Maine. Together with the bimodal Central Magmatic Belt of Maine (formerly the Piscataquis volcanic belt), and the Tobique Volcanic Belt in central New Brunswick and Quebec (Fig. 1), the Eastport Formation is part of a large bimodal igneous province with evidence for super volcano-scale eruptions (Seaman et al. 1999, 2019). These rocks, their geochemistry, eruptive styles and depositional settings, place constraints on the Late Paleozoic tectonic history of the northern Appalachians and provide insights into the evolution of large bimodal volcanic systems.

The age of the Eastport Formation is based on two dates, 421 ± 3 Ma and an informal age of 423±1 Ma (Mohammadi et al. 2019 and Van Wagoner and Dadd 2003, respectively), which corresponds to the age range of the Coastal Maine bimodal complexes of 424–420 Ma (Seaman et al. 1995, 2019; McLaughlin et al. 2003; Churchill-Dickson 2004; Turner and Burrow 2018). In contrast, two age groups of bimodal volcanism are recognized in the northern and central part of the Tobique Volcanic Belt; 422–419 Ma and 417–407 Ma (Wilson et al. 2017; Sánchez-Mora et al. 2021). The ages of magmatism in the Central Volcanic Belt of Maine, are 407-406 Ma (Rankin and Tucker 1995; Bradley et al. 2000) corresponding only with the younger of the two age groups of the Tobique. The combination of age dates, though limited, indicates that bimodal volcanism across the three belts was active for about 17 million years from 424 to 407 Ma with a possible hiatus of 2.2 Ma during that period (e.g. Wilson et al. 2017; Seaman et al. 2019). Volcanism apparently began at the same time in the Coastal and Tobique belts, but persisted longer, into the Devonian in the Tobique and Central Volcanic belts.

This time period encompasses the end of the Silurian Salinic Orogeny (440–423 Ma) and the Late Silurian–Early Devonian Acadian Orogeny (421–400 Ma) (e.g. van Staal and Barr 2012). All three of the bimodal volcanic belts were interpreted to have formed on the Ganderia terrane, which accreted to the eastern margin of Laurentia during the Salinic orogeny (e.g. van Staal 2009; Wilson et al. 2017). The geochemical characteristics of the rocks (e.g. bimodal, within plate geochemical affinities) can be explained by extension-related volcanism within an intra-arc rift and backarc on the margin of Ganderia/Laurentia situated above the northwest directed oceanic subducting plate of Avalonia as it approached Ganderia to close the Acadian Seaway (e.g. Fyffe et al. 1999; Van Wagoner et al. 2002; van Staal et al. 2009, 2014; van Staal and Barr 2012). However, the specific drivers of the extension remain uncertain (e.g. Piñán Llamas and Hepburn 2013; Seaman et al. 2019).

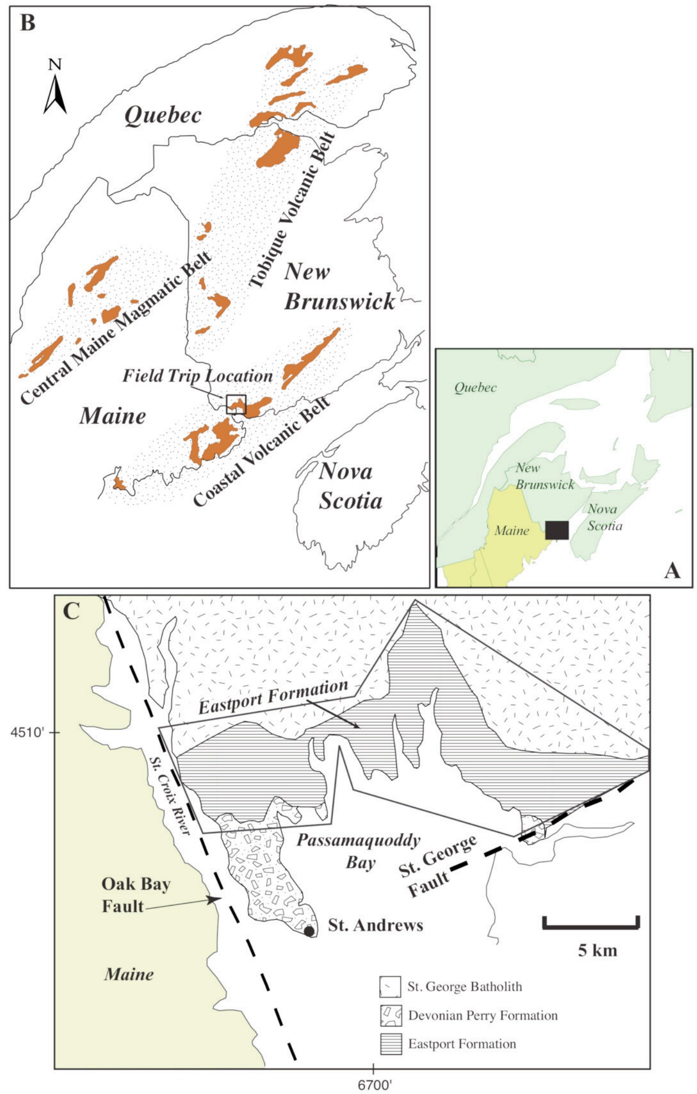

Figure 1. a) Black box shows the geographic setting of the field trip. b) Location of the Coastal, Central, and Tobique volcanic belts (after Dostal et al. 1989 and Seaman el al. 2019). The patterned areas show the locations of the belts and dark areas show exposures of volcanic rock. c) The location of the Eastport Formation in New Brunswick, (the Passamaquoddy Bay Volcanic Sequence) (after Fyffe and Fricker 1987). The striped area is detailed in Figure 2.

The Passamaquoddy Bay sequence of the Eastport Formation, the subject of this field trip, has a minimum thickness of about 4 km, and preserves at least four cycles of basaltic and rhyolitic volcanic rocks, and sedimentary rocks (Figs. 2 and 3) (McNeil 1989; Baldwin 1991; Van Wagoner et al. 1994). The most recent, comprehensive report of the volcanism of the Passamaquoddy Bay Sequence of the Eastport Formation is by Van Wagoner et al. (1994). They identified 63 units mappable at the 1:10,000 scale and interpreted the model of eruption and deposition for each unit. This field guide is based largely on that work and theses of Baldwin (1991) and McNeil (1989). Subse-

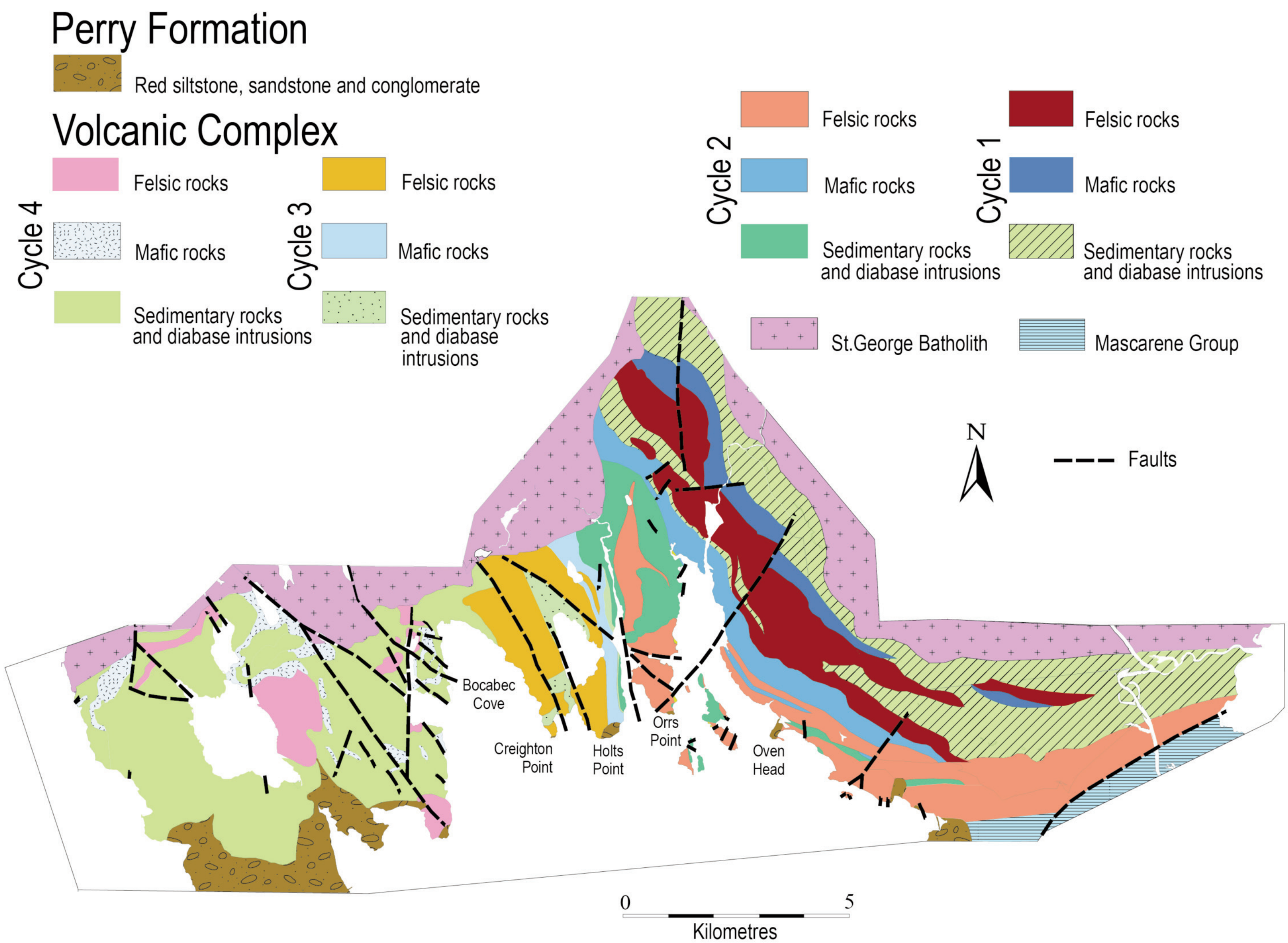

Figure 2. Generalized map of the Passamaquoddy Bay Volcanic Sequence (Eastport Formation in New Brunswick), showing the volcanic cycles; Cycle 1 is the oldest, and Cycle 4 is the youngest (modified after Van Wagoner et al. 2001, 2002).

quently, major construction produced an abundance of new outcrops, mapped by Les Fyffe which improved the accuracy of previous work.

This sequence was correlated with the Eastport Formation in Maine based on the similarity of volcanic and sedimentary rocks, and faunal assemblages (Pickerill and Pajari 1976), but the precise correlation has not been established, and there are lithologic distinctions (between the formation in Maine and New Brunswick (Lodge 2004; Van Wagoner et al. 2005; Lodge et al. 2005). The lower part of the Eastport Formation was intruded by the Saint George Batholith (Fig. 1) obscuring older portions of the Eastport such that the initiation of bimodal volcanism is unknown. The middle and parts of the sequence are overlain unconformably by the alluvial clastic rocks of the Late Devonian Perry Formation. Flow directions and the lack of clear vent facies for most of the felsic pyroclastic units suggests that the preserved sequence is somewhat distal to the source, and therefore does not represent a maximum thickness nor a complete sequence as the locus of emplacement of volcanic rocks would be expected to change.

The basaltic rocks were interpreted to be mantle melts modified by crustal contamination and mantle metasomatism from a previous subduction event. There is a trend toward more primitive mafic compositions upward in the section. The rhyolitic rocks were interpreted to be crustal melts, modified by crystal fractionation (Van Wagoner et al. 2002).

Basaltic volcanism typically precedes episodes of rhyolitic volcanism in the cycles 1–3 (Fig. 3). The presence of juvenile basaltic ejecta in some of the felsic pyroclastic units is an indication of coeval and co-spatial basaltic and rhyolitic volcanism (Fig. 4a). Enclaves of mafic rocks in felsic flows and intrusive sequences have been observed elsewhere in large igneous provinces associated with some of the world's largest eruptions (e.g. Cimarelli et al. 2008; Bryan et al. 2010). This relationship is consistent with the injection of mafic magma triggering felsic eruptions (Van Wagoner et al. 2002). Rhyolitic units are the most voluminous in the first three cycles. The final cycle represents the waning stages of volcanism with basaltic volcanic rocks being more abundant than rhyolitic, and sedimentary rocks predominating (Van Wagoner et al. 1994).

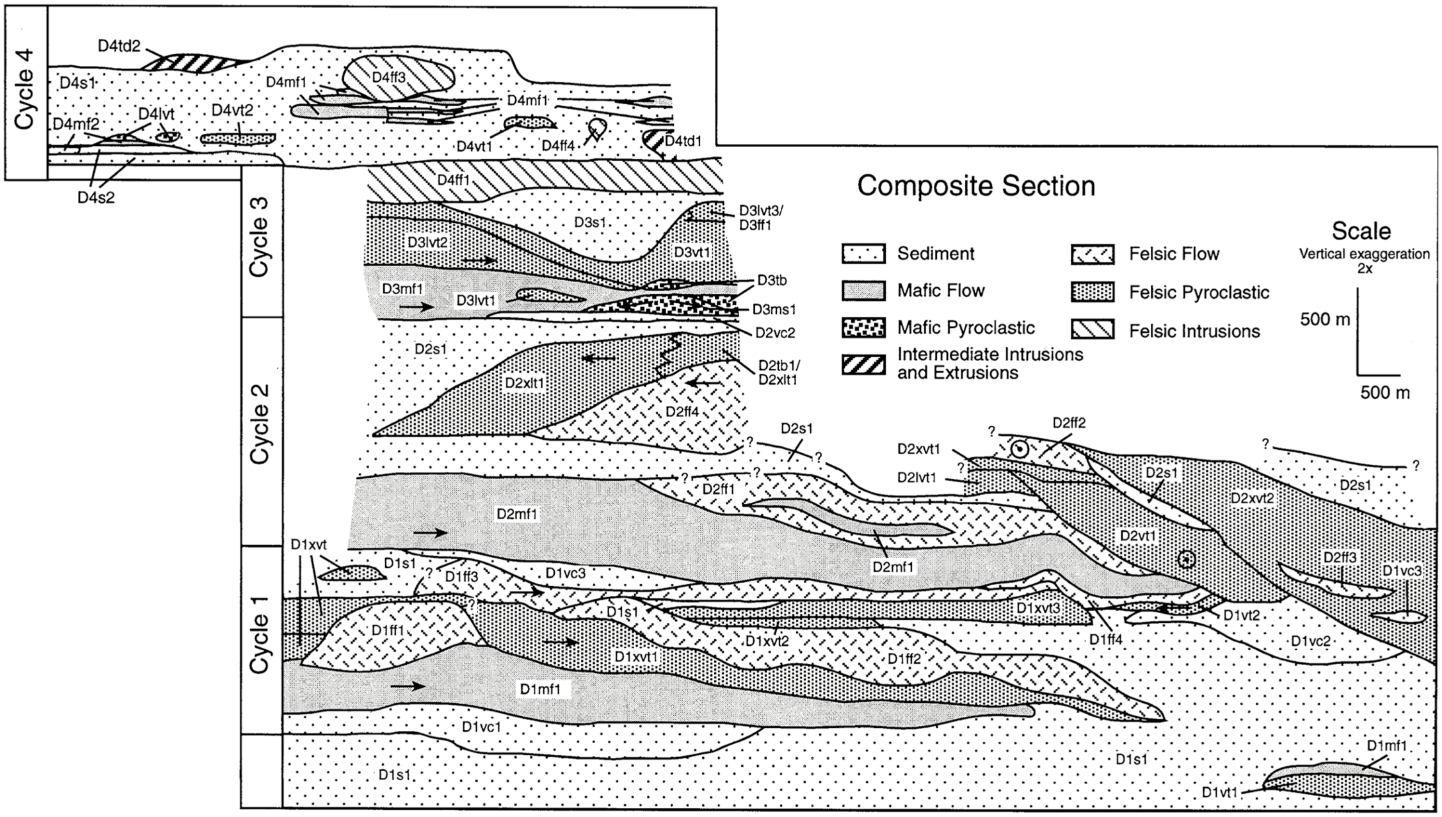

Figure 3. Composite section of the Passamaquoddy Bay Sequence of the Eastport Formation in New Brunswick. The four cycles of mafic-felsic volcanism are indicated on the left. Arrows indicate the major component of flow direction in the plane of the section. Circled dots indicate flow direction perpendicular to the page. Lithological codes: D=Silurian, s=sedimentary rock, c=conglomerate, vc = volcaniclastirock, mf = mafic flow, ms = mafic scoria deposit, tb = tuff breccia, f = felsic flow or dome, td = trachydacite dome, v = vitric, l = lithic, t = tuff. From Van Wagoner et al. 1994; Dadd and Van Wagoner 2002.

The sedimentary facies and fossils (Pickerill and Pajari 1976) indicate deposition in a peritidal environment comprising tidal flats and channels interbedded upward in the sequence with alluvial fan sediments (cycles 3 and 4). There are three periods of relative volcanic quiescence or non-deposition separating cycles of paired mafic-felsic volcanism (Fig. 3). The flows, both basaltic and rhyolitic, interacted with wet sediment to form a variety of peperitic breccias (Fig. 5a, b) (Dadd and Van Wagoner 2002).

A spectrum of eruptive and emplacement mechanisms is represented ranging from the Hawaiian and Strombolian-type volcanism of the basaltic flows and pyroclastic scoria deposits, to highly explosive sub-Plinian to Plinian rhyolitic pyroclastic eruptions forming pyroclastic density currents (PDC) and high grade ignimbrites. Basaltic flows are pahoehoe-type flows (Fig. 6a) that thin to the south and are interpreted to have had a source in the northern part of the map area. A basaltic scoria cone deposit (Fig. 6b) and evidence for such deposits in the clasts of volcaniclastic units in Cycle 3 represent Surtseyan-type volcanism.

The Passamaquoddy Bay volcanic sequence also includes a significant component of rhyolite lava flows which are typically banded, and primarily though not exclusively crystal poor. Hydrous mineral phases are notably absent throughout the sequence. Though most of the rhyolite flows are subaerial, there is evidence for subaqueous rhyolite flows associated with marine sediments in Cycle 2.

The felsic pyroclastic rocks are among the most varied and complex rocks in the section, and comprise weakly to strongly welded vitric, crystal and lapilli tuff and tuff breccias. Some of the densely welded tuffs have a eutaxitic foliation that is complexly folded typical of rheomorphic high-grade pyroclastic density currents (e.g. Brown and Andrews 2015) and are difficult to distinguish from rhyolitic lava flows. Despite the availability of external water in the peritidal environment, most of the explosive volcanism was driven by magmatic volatiles. An exception is a sequence of bedded accretionary lapilli tuffs (Fig. 4b) and tuffs containing other ash aggregates (e.g. Brown et al. 2010) interpreted to have been formed by phreatomagmatic eruptions.

This combination of volcanic deposits, particularly the apparently large volume rhyolite lava flows, intensely welded rheomorphic ignimbrites, ash deposits with abundant ash aggregates and accretionary lapilli, and the associated pahoehoe-style basaltic flows were interpreted by Van Wagoner et al. (1988, 1994) to be most akin to Snake River-type volcanism (e.g. Branney et al. 2008; Knott et al. 2016).

FIELD TRIP ITINERARY

Key exposures will be examined to show how the Pas-

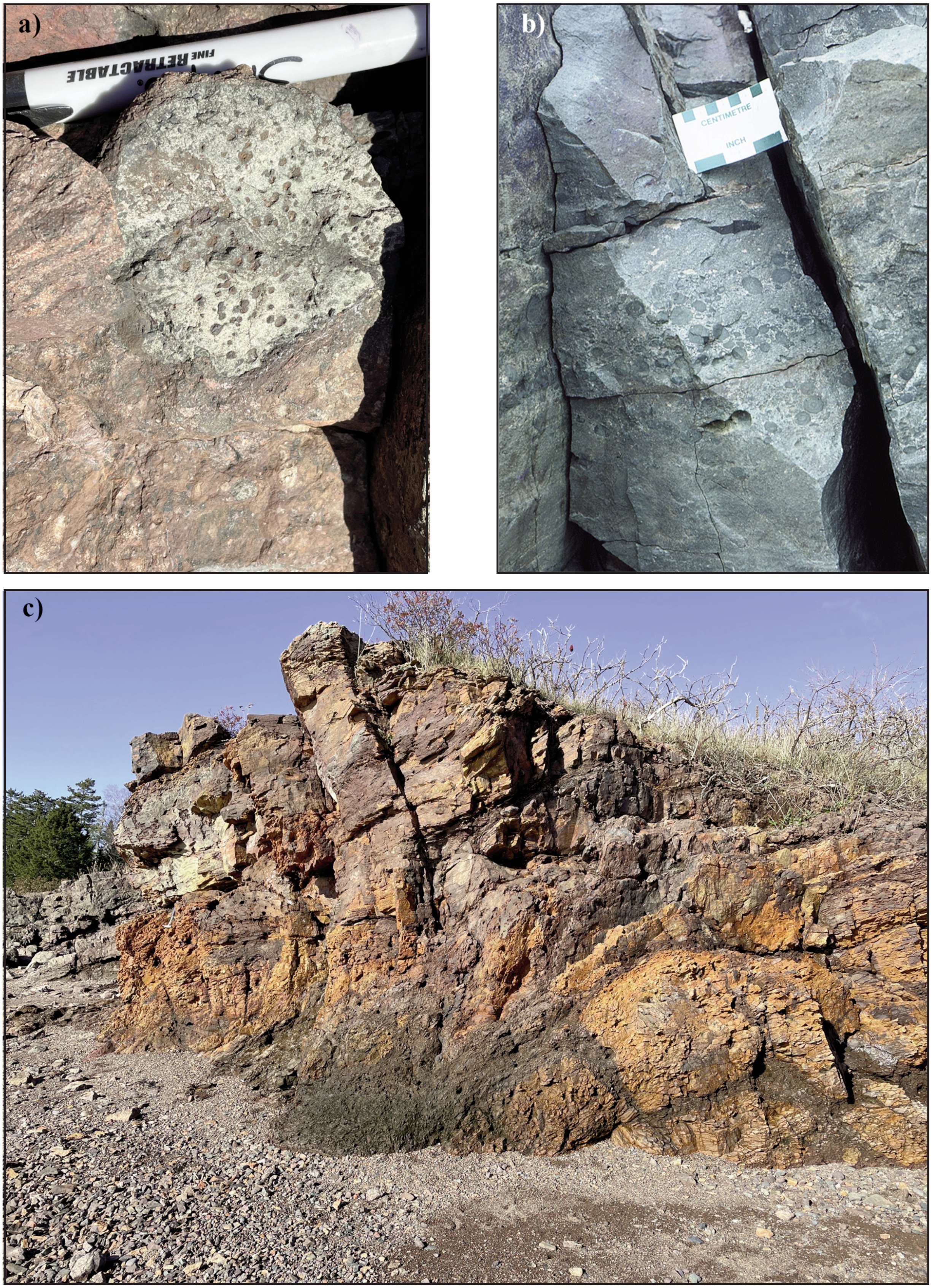

Figure 4. Cycle 2 felsic pyroclastic rocks at Oven Head on the Passamaquoddy Bay coast. a) Juvenile mafic pyroclast in a felsic welded heterolithic lapilli tuff and tuff breccia. b) Accretionary lapilli in a sequence of bedded tuff and lapilli tuffs. c) Hydrothermally altered and brecciated rheomorphic pyroclastic flow. Photo credit: N. Van Wagoner.

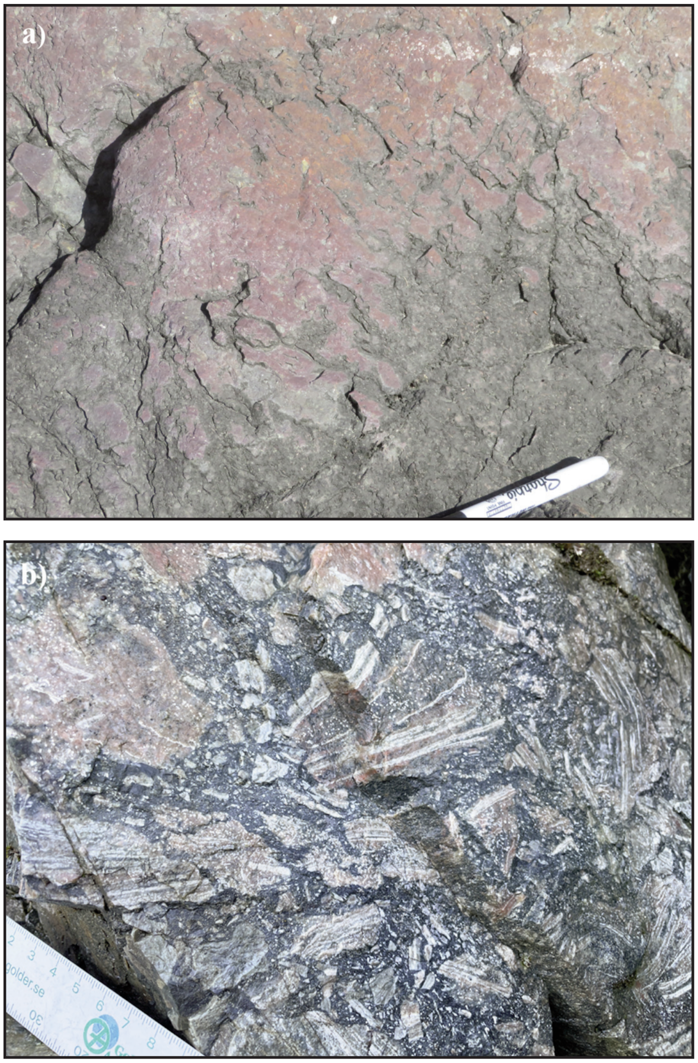

Figure 5. Two contrasting textures of peperitic breccias. a) In this basaltic peperitic breccia the lava flow has mingled with the underlying sediment to form globular shapes in the sediment. b) This photo shows the breccia at the margin of a rhyolite flow. In contrast to the basaltic peperite, the rhyolitic brecciated fragments are angular and blocky. Spherulites are visible in some of the fragments. Photo credit: N. Van Wagoner.

samaquoddy Bay volcanic sequence evolved through time and the range of eruptive and emplacement processes. Diagnostic features observed in outcrop will be viewed simultaneously with textures visible in photomicrographs, and the geochemical characteristics of the rocks. The tentative schedule follows but adjustments may be required to accommodate time and weather.

Day 1 will be spent in transit from Halifax to St. Andrews, New Brunswick. Before heading to our accommodation at the Huntsman Marine Science Centre, a stop is planned along the Passamaquoddy Bay coast where the Devonian Perry Formation is in unconformable contact with the underlying medium-bedded pyroclastic rocks of Cycle 2 of the Eastport Formation. These rocks, were formed by pulses of PDCs. They are interbedded with shallow marine sediments near the upper part of the sequence and overlain by a rhyolite lava flow.

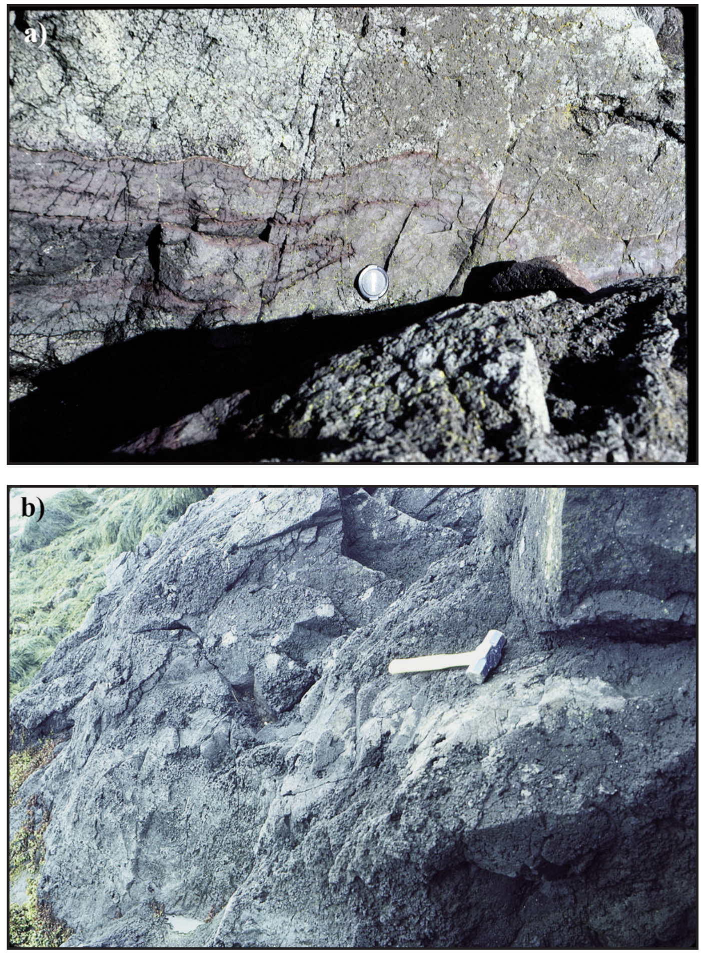

Figure 6. Cycle 3 basaltic volcanism. a) Pahoehoe toes with oxidized selvages. b) Large bomb just below the rock hammer in a scoria deposit. Photo credit: N. Van Wagoner.

Day 2 will start at an inland section along a road cut that traverses through cycles 1 and 2 including maroon marine sedimentary rocks, the peperitic breccias at the margin of a rhyolitic flow, basaltic lapilli tuffs and amygdaloidal flows, and ending at a fault contact between cycles 2 and 3. With low tide in the afternoon, the tour of Cycle 2 will continue along the coast where a spectacular deposit of bedded accretionary lapilli tuffs (Fig. 4b), interpreted to be formed by silicic phreatomagmatic volcanism, are exposed at a tombolo. These rocks are underlain by a densely welded and rheomorphic heterolithic tuff to tuff breccia that includes both felsic and mafic juvenile pyroclasts (Fig. 4a), that is hydrothermally altered in places (Fig. 4c). The day will end at a coastal exposure to the east at the margin of a massive rhyolite flow of Cycle 4, and the underlying Cycle 3 fluvial sedimentary rocks and bedded tuffaceous PDCs also with rhyolitic and basaltic juvenile pyroclasts as observed in Cycle 2.

Day 3 will start with a visit to two inland sections; a rhyolitic subaerial lava flow of Cycle 1 and the overlying mafic lava flows of Cycle 2 and their associated peperitic breccias, and the exposure of rhyolitic pillow flow and associated mafic volcaniclastic rocks, also of Cycle 2. As the tides recede the rest of the day will be spent traversing a coastal section of Cycle 3, from the lowermost contact with Cycle 2 fossiliferous shallow marine sedimentary rocks, through a sequence of volcaniclastic rocks, and continuing up section through mafic tuffs and tuff breccias interpreted to be scoria cones, overlain by mafic pahoehoe flows (Fig. 6), and then into the overlying felsic vitric tuffs and felsic flows. If time permits there will be one last stop in the thick sequences of sedimentary rocks and basaltic lava flows of Cycle 4 that represent the waning phases of volcanism. A special tour of the Huntsman Marine Aquarium is planned for the evening.

Day 4 will be spent in transit back to the GAC–MAC 2022 Halifax conference in time for the opening events in the evening.

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