Structural-stratigraphic setting and U-Pb geochronology of Ni-Cu-Co-PGE ore environments in the central Cape Smith Belt, Circum-Superior Belt

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ABSTRACT

The economically important Cape Smith Belt of northern Quebec represents a key segment of the "Circum-Superior Belt", preserving a ~12–15 km thick record of Paleoproterozoic stratigraphy in a south-vergent, mostly north-dipping fold-thrust belt. The central part of this belt is only moderately deformed and experienced merely sub-biotite grade metamorphism. It hosts world-class Ni-Cu-Co-PGE mineralization in both extrusive and intrusive settings that, at present, form the basis for two integrated mining operations. Collectively, these attributes make this belt unique in Canada and the world.

A detailed, holistic understanding of this belt has been hampered, however, by conflicting interpretations on the degree of thrust stacking, and a lack of accurate and precise ages for critical elements of the stratigraphy. Here we report on new fieldwork and drill core observations—collected over several summers—that resolve many of the outstanding questions and provide a more detailed stratigraphic framework for the mineralization and the belt as a whole. We integrate these data and observations with new high-precision U-Pb ages for ~10 critical rock units, from the Cape Smith Belt and other parts of Circum-Superior Belt, as well as relevant parts of the overall craton-scale ore system.

We briefly describe the different ore settings of the Cape Smith Belt and place these in the structural-stratigraphic framework. We show that the central part of the Cape Smith Belt is more coherent and less imbricated by thrusts than previously interpreted. The important Nuvilik Formation of thinly bedded distal turbidites and sulphidic mudstones forms a stratigraphic unit at the top of the Povungnituk Group, reflecting a phase of basin formation and deepening following volcanism of the ca. 1959 Ma Cécilia Formation. Neither the lower contact nor the upper contact of the Nuvilik Formation is a regional thrust. At 1883–1882 Ma, the Nuvilik sulphidic mudstones formed the ambient seafloor across which high-volume, hot, Mg-rich lavas of the Chukotat Group were emplaced, which included high-flow rate, turbulent, channelized komatiite flows, thus bringing into direct contact the most dynamic magma system of the belt with a ubiquitous, prolific sulphur source. Although Chukotat magmas may have been at sulphur saturation on final ascent, thermo-mechanical erosion of the lava channels into underlying Nuvilik mudstones, and mixing and melting of sulphidic sediments into the channels, led to massive sulphur oversaturation and accumulation of net-textured and massive sulphides. Our ages show that all of this happened during the onset and climax phase of the Chukotat magmatic event, which lasted ~2 Myr and occurred at the same time as similar events more than 1500 km away, in Thompson, Manitoba. At Raglan, we describe one well preserved lava and ore channel where, in present coordinates, flow was demonstrably down-dip and to the north-northeast. This is the first observation of flow polarity. We prefer an overall model of several anastomosing, subparallel lava channels presently plunging down to the north-northeast, not a single, giant, meandering lava channel subparallel to the trace of the basal Chukotat lavas on the present erosion surface. The observed flow direction makes it feasible, if not likely, that the channelized komatiite flows were fed from an eruptive fissure system ~25 km to the south, which would suggest a "processing length" of ~25 km to achieve optimal mixing, sulphide saturation, and segregation at high R-factors.

At the craton scale, the overall model that best explains the rich spectrum of phenomena is that of a hot mantle upwelling ascending from a deep thermal boundary layer to impinge on the base of the lithosphere of the Superior craton, or rather its ancestral supercraton Superia, prior to final breakup. Rapid lateral flow of hot buoyant mantle to lithospheric "thin spots", such as active or pre-existing rifts or delamination scars, caused nearly synchronous, high-volume, ultramafic-mafic magmatism around what ultimately became the margins of a fully separated Superior craton. Although the overall magmatic event has a younger tail, to as young as 1878 Ma, and also a distinct younger pulse at ca. 1870 Ma, the early onset and climax phase of high-volume ultramafic-mafic magmatism is most prospective for economic Ni-Cu-Co-PGE mineralization.

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INTRODUCTION

The Paleoproterozoic Circum-Superior Belt (Baragar and Scoates, 1981), encircling the Archean Superior craton, represents one of Canada's principal mineral belts, particularly in terms of orthomagmatic Ni-Cu-Co-PGE sulphide ores and resources. It hosts both the ~100 Mtonne Thompson district in northern Manitoba and the ~30 Mtonne Raglan camp in the Cape Smith Belt of northernmost Quebec, as well as a number of significant prospects elsewhere, particularly in Manitoba and in the Labrador Trough. Less obvious is the connection of the Circum-Superior Belt with other mineral systems such as rare metal and industrial mineral (apatite) deposits in alkaline intrusions interior to the Superior craton, and the globally significant peak in Superior-type banded iron formations, all essentially of the same age at ca. 1880 Ma. The iron formations support the long active iron mining districts in Labrador, Minnesota, and Michigan, and their scale indicates that the ca. 1880 Ma Circum-Superior Belt magmatism affected the ocean-atmosphere system at the global scale.

Despite significant progress in the general understanding of this global mineral system, numerous key questions remained unresolved. Foremost among these were questions of detailed timing and regional- to deposit-scale stratigraphy in key belts, such as Raglan. Detailed timing of ore-forming processes, at the ~1 Myr scale, is essential for linking the various processes involved in the right time sequence: a cause must precede the effect. A correct interpretation of stratigraphy is equally essential for singling out key ore-forming processes, understanding the relationships among different rock units, subtracting out the interfering effects of later deformation, and correctly identifying ore horizons and where they may occur next. Many of these aspects were controversial at Raglan, particularly the question of detailed timing and the degree to which the ore-hosting stratigraphy is imbricated by thrust faulting, and thus which contacts are primary and which are structural (Bleeker, 2013; Bleeker and Ames, 2017; Bleeker and Kamo, 2018).

In this report, we present significant progress in resolving these questions, particularly for the Raglan camp of the central Cape Smith Belt in northern Quebec (Fig. 1). We show that the key magmatic pulse of komatiitic magmatism was short-lived at ca. 1882 Ma, with new U-Pb ages on ore-hosting units and on gabbro sills that immediately pre- and post-date the formation of major lenses of massive sulphide ore. We integrate these new data with structural and stratigraphic observations to arrive at a more refined understanding of the deposit- to regional-scale stratigraphy and the setting of the various ore-hosting environments. The stratigraphy at Raglan is more coherent than previously interpreted, and the ore-bearing "Raglan Horizon" resulted from the direct superposition, in space and time, of the most dynamic, high-volume part of the Chukotat magmatic system (large channelized komatiite flows; *see also* Lesher, 2007 and references therein) with the most prolific sulphur source in the belt, the sulphidic mudstones of the uppermost Nuvilik Formation. From Raglan and the Cape Smith Belt, we zoom out to the scale of the craton and the larger magmatic system of a hot mantle upwelling that ascended underneath the Archean lithosphere of the Superior craton, prior to final breakup of the ancestral craton. A number of predictions follow from this model. In an appendix, we explore interesting questions of correlation with the stratigraphy in the ~900 km long Labrador Trough of Quebec and Labrador.

STRATIGRAPHY OF THE CENTRAL CAPE SMITH BELT, RAGLAN

General Structural Considerations

The central Cape Smith Belt of northernmost Quebec (Low, 1902; Gunning, 1934; Bergeron, 1957, 1959; Stam, 1961; Taylor, 1982) preserves ~12 to 15 km of Paleoproterozoic lithostratigraphy across a number of structural panels in the core of an approximately east–west-trending synclinorium (Fig. 1, 2; Bergeron, 1957, 1959; Dimroth et al., 1970; Hynes and Francis, 1982). The belt forms an integral part of the Circum-Superior Belt (Baragar and Scoates, 1981), which extends all around the Ungava promontory of the northern Superior craton, and indeed around much of the craton. The southern part of the Cape Smith Belt, dominated by two major mafic volcanic sequences that have long been referred to as the mostly Fe-tholeiitic Povungnituk Group and the more Mg-rich Chukotat Group (Bergeron, 1959), respectively, is largely homoclinal and dipping moderately to the north. Some structural-stratigraphic repetition (e.g. Stam, 1961; Hynes and Francis, 1982) and a major north-dipping shear zone along the basal contact with the underlying granitoid gneisses of the Superior craton (Stam, 1961; St-Onge et al., 1992) indicate significant thrusting onto the craton in a generally south-vergent fold-thrust belt. Only a few small, fully autochthonous outliers of basal sedimentary rocks, lying unconformably on Archean crystalline basement, occur along the southern and eastern margin of the thrust belt (e.g. Taylor et al., 1982).

The first-order synclinorium that preserves the fold-thrust belt is ~50 km wide, being flanked by gently north-dipping basement to the south, and a major basement-cored antiformal ridge to the north, the Kovik Antifom (Fig. 1, 2). Archean granitoid gneisses of the Kovik Antiform are deformed into planar tectonites for ~1 km adjacent to the contact with the Paleoprotero-

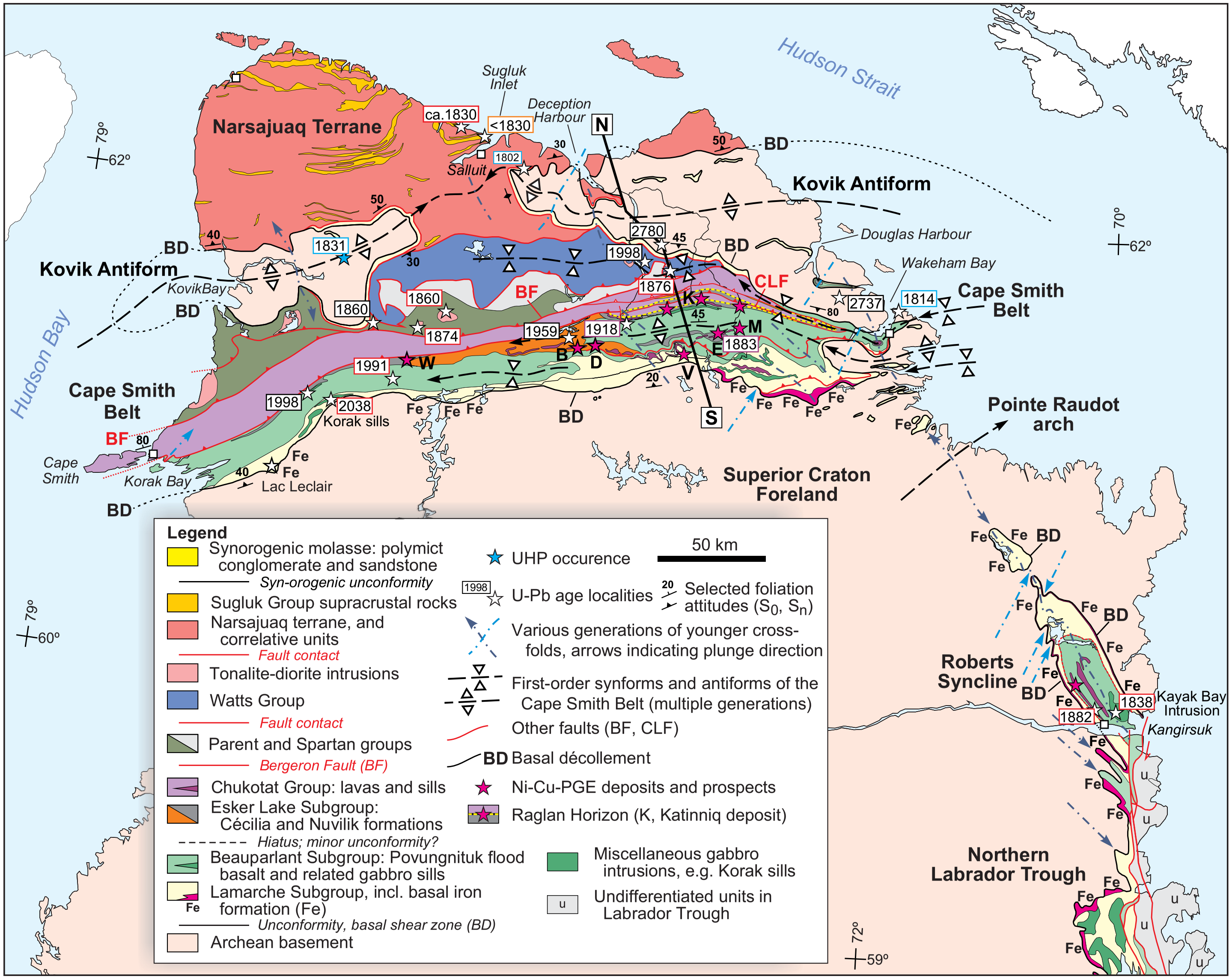

Figure 1. Generalized map of the Ungava promontory, northern Quebec, showing the Cape Smith Belt, Roberts Syncline area, and the northern Labrador Trough (*modified and simplified from* MRN (2002), St-Onge et al. (2006), and Lamothe (2007), with data from the present study). Only major faults are shown and most are thrusts, including early movement on the basal décollement (BD); however, faults that define the flanks of the major Kovik Antiform were reactivated as major extensional faults. The Cross Lake Fault (CLF) and Bergeron Fault (BF) are in red, with thrust teeth on their north side. Line S–N is the cross-section line discussed in the text (e.g. Fig. 2). Basal iron formations in the various belts are highlighted with "Fe". Stars indicate localities mentioned in the text, as well as previous U-Pb geochronology sites: Lac Leclair and Korak sills (white stars); UHP locality of Weller and St-Onge (2017) in Kovik Antiform (blue); main areas of mineralization (magenta): K = Katinniq deposit on the main Raglan Horizon; also shown along the main Raglan Horizon are the Kikialik deposit in the west, and Donaldson deposit in the east. Abbreviations: B = Bravo sill, D = Delta sill, E= Expo-Ungava, M = Mesamax, V = Lac Vaillant sill, W = West Raglan. U-Pb ages (in Ma) are colour-coded: black outline = plutonic and volcanic ages, red = intrusive and thus minimum ages for host rocks, purple = Chukotat ultramafic sills and dykes, orange = maximum depositional age from detrital zircon grains, blue = metamorphic ages. *See* the text for references.

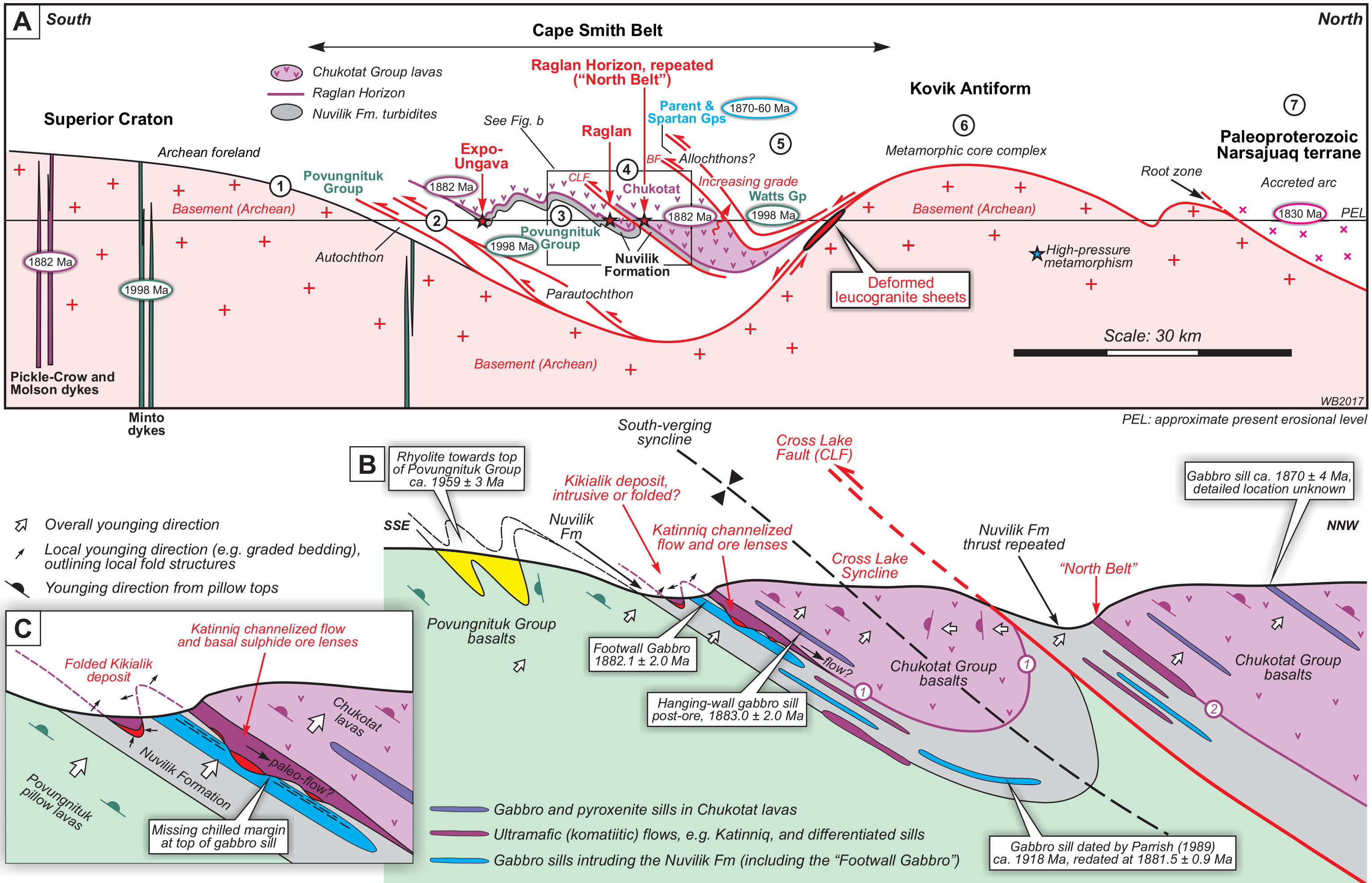

Figure 2. a) Generalized south-to-north regional-scale cross-section through the central Cape Smith Belt, northern Quebec. Circled numbers (1 to 7) refer to tectonostratigraphic domains: 1) the Archean foreland of the Superior craton; 2) parautochthonous thrust sheets of ca. 1998 Ma Povungnituk Group and its >2038 Ma basal units; 3) top of the Povungnituk Group and the overlying sedimentary rocks of the Nuvilik Formation (the latter in grey); 4) Chukotat lava flows exposed in a faulted syncline-anticline pair; 5) structurally higher thrust sheets in the core of the synform on the south side of the major Kovik Antiform; 6) the basement-cored Kovik Antiform; and 7) the younger Narsajuaq terrane. The mineralized "Raglan Horizon", in the well preserved north-dipping central part of the belt, is shown as a solid purple line, on the stratigraphic contact between turbiditic Nuvilik Formation mudstones and siltstones (in grey) and the overlying Chukotat Group lava flows. Ni-Cu-Co-PGE sulphide deposits and prospects are identified by red stars. **b)** Zoomed-in view of the central part of the Raglan belt, with the Katinniq orebodies at the base of channelized basal komatiite flows. The Kikialik deposit, situated in a tight fold structure, is also shown but off-section to the west. Some of the available high-precision ages are shown for reference. Note that the overall structure is that of a faulted syncline-anticline pair, the overturned limb of which has evolved into the Cross Lake Fault (CLF, in red), a fault of moderate displacement (reverse, north over south). The footwall syncline, a well defined structure in the belt, is known as the Cross Lake Syncline. The overall structure leads to repetition of the Raglan Horizon (1) across the Cross Lake Fault into the "North Belt" (2). **c)** Inset that zooms in further to highlight the stratigraphic and structural relationships of the Raglan Horizon at the Katinniq and Kikialik deposits. Note the localization of some of the larger sulphide lenses (red) at Katinniq in channels that have eroded down into the "Footwall Gabbro Sill" (gabbro sill in blue). A primary contact that formed by thermal erosion is indicated by a missing chilled margin at the top of the gabbro sill (*see* Bleeker and Ames, 2017).

zoic supracrustal rocks to the south, but become less tectonized in the core of the antiform. These gneisses host remarkably few major mafic dykes, which is one of several lines of evidence arguing against early views that the Cape Smith Belt developed in situ in a largely ensialic setting (cf. Dimroth et al., 1970; Hynes and Francis, 1982); rather, the entire fold-thrust belt of the Cape Smith Belt must have been transported over a basal décollement to the south into its current position (Hoffman, 1985), with a net displacement of >100 km, from a root zone well to the north. The complete set of arguments that favour significant structural transport of the thrust belt onto the craton, from a more northerly position towards to south, can be summarized as follows:

- A lack of "syn-rift" or synvolcanic basement-derived conglomerate-sandstone wedges in the Povungnituk and Chukotat lavas, which could indicate proximity to major rift fault scarps[1].
- No major, dense, mafic-ultramafic dyke systems in the nearby basement that could represent proximal feeder zones to the very thick lava sequences of the Povungnituk and Chukotat groups of the thrust belt. All such proximal feeder systems are contained within the thrust belt and thus transported with it.
- In most localities along the basal contact of the supracrustal thrust belt, there is a major shear zone hundreds of metres wide (e.g. Stam, 1961), involving complete transposition, i.e. a classic basal décollement, indicating very significant displacement (St-Onge et al., 1992).
- Crystalline basement of the Superior craton, and the décollement, can be mapped all around the eastern closure of the Cape Smith fold-thrust belt (Taylor, 1982), in what defines the broad hinge zone of a westerly plunging synclinorium (Lucas and St-Onge, 1992).
- Kinematic indicators and a general fold and thrust vergence that indicate structural transport towards the south.

This overall context for the supracrustal rocks of the central Cape Smith Belt is now generally agreed upon. What is more controversial, and worthy of debate, are the following aspects:

1. What is the nature of the uppermost thrust sheets (Fig. 2a), involving basaltic rocks, gabbros, and ultramafic cumulate rocks of the ca. 1998 Ma Watts Group? Do these rocks represent a fully allochthonous ophiolite assemblage as proposed by Scott et al. (1989, 1991, 1992)? The age of this assemblage remains problematic and, remarkably, it is identical to that of the Povungnituk Group basaltic rocks.
2. What is the nature of the ca. 1870–1860 Ma Parent Group volcanic rocks and the associated Spartan Group greywackes and intercalated volcanic rocks? Do they represent an accreted arc assemblage as per the various arc accretion models (Picard et al., 1989, 1990; St-Onge et al., 1992). If so, why then the apparently smooth age transition from the ca. 1883–1870 Ma Chukotat Group rocks into the 1870–1860 Ma Parent Group?
3. Where is the sediment prism representing the time between hypothesized basin opening (end Chukotat Group) and arc accretion? There is none and only the Parent and Spartan groups satisfy the constraints.
4. Which contact represents a suture, if any? Is it the basal contact of the Parent Group volcanic rocks, i.e. the Bergeron Fault (BF in Fig. 2)?
5. What is the nature of the major Kovik Antiform? Is it simply a basement-cored antiformal fold that formed as part of the early, progressive, deformation and shortening history ("D3" of Lucas and St. Onge, 1992; Hoffman, 1985), or do the significant scale and amplitude of this antiform indicate a different origin, i.e. as a late-stage core complex as proposed by Bleeker and Kamo (2018)? This important question is relevant to the major shear zone on its southern flank, which shows late-stage south-side-down kinematics and in which the entire thrust belt is reduced to narrow widths, including the complete pinching out of the Chukotat Group (Fig. 2).
6. And finally, what is the degree of internal thrust stacking (i.e. relative to normal stratigraphic superposition and some fold duplication) in the southern part of the fold-thrust belt?

Some of these questions will be touched upon later in this report. The last question, however, is immediately relevant to the stratigraphic understanding of the central Cape Smith Belt, and has important implications for understanding the Ni-Cu-Co-PGE ore system associated with its voluminous ultramafic rocks. As in any deformed belt with less than complete exposure and less than perfect age control, some degree of interpretation is involved in compiling the complete stratigraphic framework. In particular, the question of thrust

[1] Immature conglomerate units do occur in the Cape Smith Belt, but none are "syn-rift" in age and coeval with the thick lava sequences. They occur (1) at the very base of the stratigraphic sequence and thus are among the oldest of the preserved supracrustals; and (2) as thin panels of syn-orogenic conglomerates and sandstones within the Chukotat lavas, which are among the youngest rocks in the belt. *See* later in this report.

stacking pertains to which, and how many, of the sedimentary packages in the belt are unique, and part of regular depositional stratigraphic development, versus thrust repeats of the basal sedimentary section. It also pertains to what is the true thickness and geochemical evolution of the lava sequences of the Povungnituk and Chukotat groups.

Lithostratigraphy and Summary of U-Pb Ages

A synopsis of the lithostratigraphy of the southern homoclinal part of the Cape Smith Belt is shown in Figure 3. This figure contrasts previous understanding of the (tectono-) stratigraphy, based on the work of St-Onge et al. (1992, 2006) and St-Onge and Lucas (1993) (Fig. 3a), with our current understanding (Fig. 3b). The fundamental difference, other than significantly improved U-Pb age control, is that essentially all sedimentary packages in the north-dipping homoclinal belt were interpreted as thrust repeats of sedimentary units representative of the lower Povungnituk Group (i.e. Lamarche Subgroup, in the stratigraphic nomenclature of Picard et al., 1995). It is for this reason that all the various sedimentary intercalations in both the Povungnituk and also the Chukotat groups are "riding on top" of a thrust (Fig. 3a) in both the tectonostratigraphic interpretation and the mapping of St-Onge et al. (1992, 2006). This extreme interpretation also makes the important Nuvilik Formation, at the top of the Povungnituk Group, a thrust slice and its upper contact with the ore-bearing komatiites of the Chukotat Group a first-order, large-displacement thrust (Fig. 3a). Perhaps part of the motivation for this model was the early idea that there was a long-lived continuum in magmatic activity from the Povingnituk Group into the more magnesian lava flows of the Chukotat Group (e.g. Taylor, 1982[2]; Hynes and Francis, 1982), with the latter representing a more advanced stage of rifting and basin opening, and having been transported from a more northerly, outboard position. However, even as this end-member thrust model was being formulated, most other researchers considered the Nuvilik Formation greywackes and mudstones as the final stage of the Povungnituk Group (e.g. Coats, 1982; Moorhead, 1989) and essentially in place (relative to underlying and overlying lavas).

In the evolving understanding of the stratigraphy, a particularly problematic (apparent) age has been the baddeleyite upper intercept date for large mafic-ultramafic differentiated sills in the Nuvilik Formation, dated at ca. 1918 Ma (Parrish, 1989). We have previously reinterpreted those same data to reflect an age of ca. 1884 Ma (Bleeker, 2014), and, since then, reanalyzed zircon grains from this same sill[3]. The new data conclusively show this sill to be 1881.5 ± 0.9 Ma based on multiple concordant zircon analyses (Bleeker and Kamo, 2018). All currently available age data (Fig. 3b) thus show that flood basalts of the Povungnituk Group, representing a ~3–5 km thick lava sequence, are ca. 2000 to 1990 Ma, whereas Chukotat Group magmatism was initiated more than a 100 Myr later at 1883 to1882 Ma (Bleeker and Kamo, 2018). These two major magmatic events and lava sequences do not, therefore, represent a continuum but rather independent melting events below the northern Superior craton, and their lava sequences are stratigraphically stacked.

The sedimentary base of the Povungnituk Group stratigraphy, including platformal-type sedimentary rocks, overlain by finer grained sandy to silty semipelites, is locally intruded by gabbro sills that have a robust zircon age of ca. 2038 Ma (Korak sills, *see* Fig. 3b; Machado et al., 1993), thus indicating that basin formation on this part of the Superior craton (or rather its precursor, supercraton Superia; Bleeker, 2003, 2004; Bleeker and Kamo, 2018) had started well before this date of 2038 Ma and at least 40 Myr prior to eruption of the Povungnituk flood basalt sequence. Two other important deductions follow: 1) iron formation near the base of Povungnituk Group, which thickens eastward (Fig. 1), is older than 2038 Ma and likely correlates with the basal iron formation in the northernmost Labrador Trough, the Roberts Syncline area (Hardy, 1976; Madore and Larbi, 2001). It is therefore much older than the main ca. 1880 Ma Sokoman iron formation of the southern Labrador Trough; and 2) the basal part of the Povungnituk Group likely correlates in some ways with the older stratigraphy ("Cycle 1") of the Labrador Trough. These important issues are explored further in the Appendix.

Significantly post-dating the Povungnituk basaltic event, there was a flare-up of more localized alkalic volcanism, involving basanites, nephelinites, phonolites (Gaonac'h et al., 1989, 1992), and some rhyolites which have been dated at 1953 ± 3 Ma (Parrish, 1989). This is the Cécilia Formation, which is now complexly infolded into the rest of the Povungnituk Group (Fig. 1, 2), and, given its interesting makeup and importance stratigraphically, remains insufficiently documented. Besides volcanic and volcaniclastic rocks, the Cécilia Formation also involves minor carbonates and other shallow-water deposits. Early reports by Beall (1959) and Bergeron (1959) also mention conglomerates and

[2] In his more regional synthesis, Taylor (1982) saw little evidence for a break between the lower (Povungnituk) and upper (Chukotat) volcanic rocks and argued for discontinuing these two group names altogether. All of this work was undertaken prior to the first U-Pb ages in the belt.

[3] The thick lowermost differentiated sill in the Cross Lake area, also known as the "Romeo I" sill.

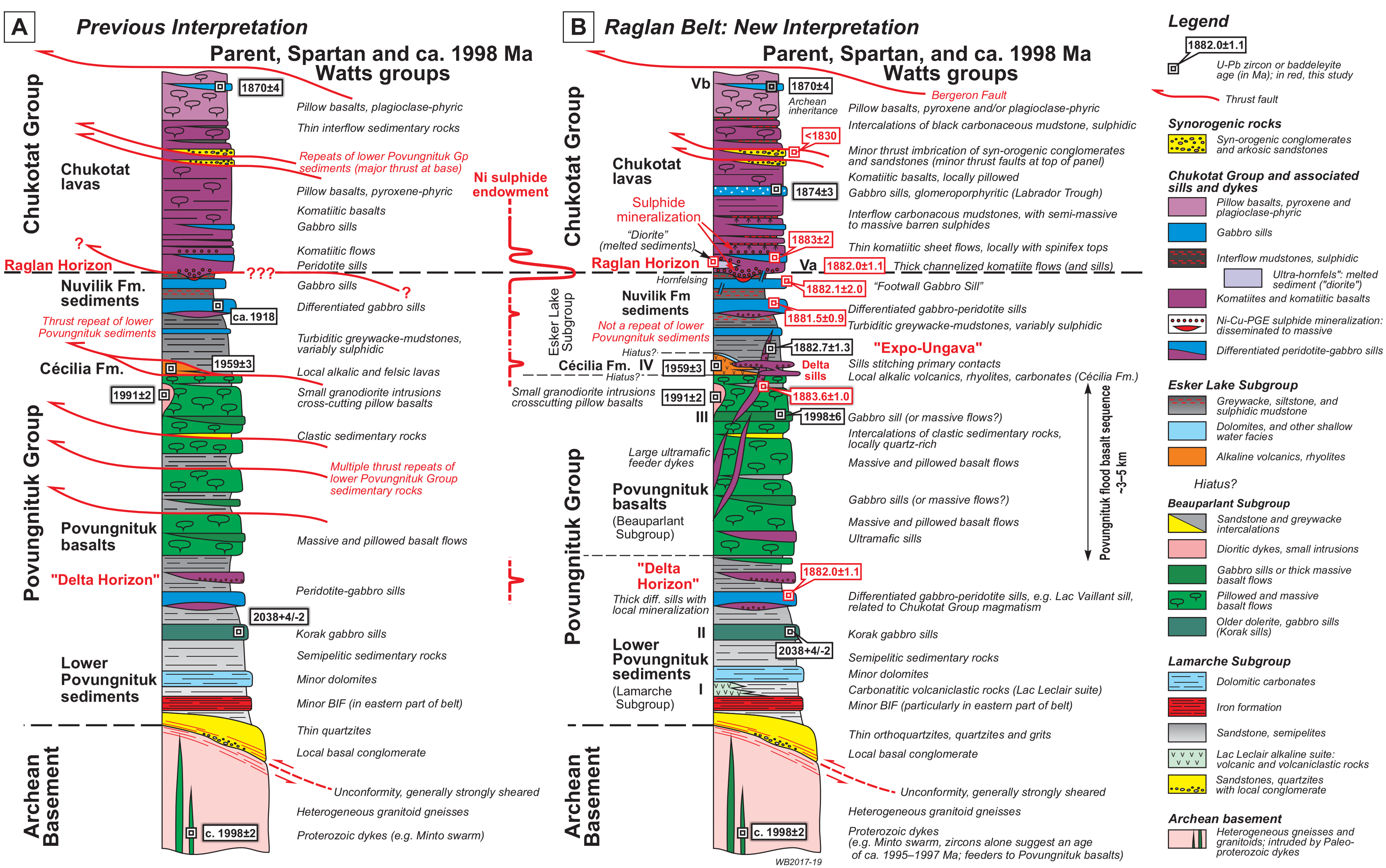

Figure 3. Lithostratigraphy of the Raglan belt. **a)** Previous interpretation, compiled from St-Onge et al. (1992) and St-Onge and Lucas (1993), with thrusts at the base of each sedimentary unit (based on a model of thrust imbrication and the repeated reappearance of lower Povungnituk sedimentary units). **b)** New interpretation based on this study, with far fewer thrust contacts. Most of the sedimentary members in the stratigraphy represent unique stratigraphic units rather than thrust repeats, in particular the important Nuvilik Formation. Conglomerate panels in the Chukotat Group are imbricated synorogenic clastic rocks. All available U-Pb ages (in Ma), as well as other details, are highlighted. Ages shown in red are from this study. *See* the text for references. Abreviations: BIF = banded iron formation, diff. = differentiated, Fm. = Formation, Gp = Group.

possibly some angular discordance with underlying Povungnituk basalts.

The important Nuvilik Formation is mostly younger than the Cécilia Formation and represents renewed basin formation and general basin deepening. Its lower part may interfinger with Cécilia Formation volcanic rocks, and locally includes tuffs (J. Moorhead, pers. comm., 2020). To some extent the two formations may be lateral facies equivalents. The Nuvilik Formation is overall upward fining and its upper part is characterized by thinly bedded distal turbidites and black, carbonaceous, sulphidic mudstones that formed in a below-storm wave-base setting. We have grouped the Cécilia and Nuvilik formations in an upper "Esker Lake Subgroup" to set them apart from the two lower, previously defined subgroups of the Povungnituk Group (Fig. 3b). The Esker Lake Subgroup spans a minimum of 75 Myr, from the single Cécilia Formation rhyolite age to the onset of the Chukotat event, and there could well be an important time hiatus in this part of the stratigraphy, perhaps at the base of the Cécilia Formation and (or) near its top (Fig. 3b).

All current data indicate a rapid and sudden onset of Chukotat high-volume ultramafic-mafic magmatism at ca. 1883–1882 Ma, and much of the ~3–4 km Chukotat lava pile could have developed within 1–2 Myr, as essentially all the high-precision ages overlap within uncertainty.

In summary then, no continuum exists between the magmatic evolution of the Povungnituk Group and that of the Chukotat Group. These major lava sequences are separated in time by more than 100 Myr. Just the Cape Smith Belt section of the Circum-Superior Belt experienced at least five discrete magmatic events (*see* Roman numerals I to V in Fig. 3b): early alkaline magmatism of the Lac Leclair suite (Baragar et al., 2001); Korak sill mafic magmatism at 2038 Ma (Machado et al., 1993); 2000–1990 Ma Povungnituk flood basalt eruption (Machado et al., 1993; Kastek et al., 2018) and intrusion of Minto dykes in the distal foreland (Buchan et al., 1998); ca. 1959 Ma Cécilia Formation alkaline and bimodal volcanism (Gaonac'h et al., 1989; Parrish, 1989); and the ca. 1883–1882 Ma onset of the Chukotat magmatic event (Bleeker and Kamo, 2018; this study). All of these events and the resulting stratigraphy (Fig. 3b) can be tied to Superior craton basement and/or its margin.

Returning to the issue of thrust repetition of basal Povungnituk sedimentary rocks, in the field the evidence for discrete thrust faults at the base of sedimentary panels is absent or at least ambiguous. We have walked through a number of these interpreted thrust panels and found no obvious thrust fault at their base. Many of the key contacts are stitched by synvolcanic intrusions and are thus primary. Some thrust repeats likely exist in the southernmost part of the belt (St-Onge et al., 1992, 2006), but much of the central part of the belt lacks major thrusts. Instead, many of the sedimentary intercalations of siliciclastic rocks, and the Nuvilik Formation in particular, represent regular stratigraphy. Both the lower and the upper contact of the Nuvilik Formation are stitched by mafic-ultramafic sills and dykes (Fig. 3b). A typical traverse across the transition from the Povungnituk Group to the Chukotat Group shows intense hornfelsing of uppermost Nuvilik Formation silt- and mudstones by hot, thick, basal ultramafic flows and sills of the Chukotat Group, without significant shearing, thus tying both groups together (*see also* Coats, 1982; Lesher, 1999, 2007 and references therein). This contact between the Nuvilik sulphidic silt- and mudstones and the overlying Chukotat komatiites, which defines the main ore-bearing "Raglan Horizon", is therefore a primary stratigraphic contact (Bleeker and Ames, 2017; Bleeker and Kamo, 2018). It is locally defined by thermo-mechanical erosion channels (Lesher, 1999, 2007) where hot komatiite lava flows eroded down into the Nuvilik Formation substrate and into marginally older footwall gabbro sills (Fig. 2c, 3b). Many of these channels host Ni-Cu-Co-PGE sulphides near the base of the komatiite flows, and some of the largest ore lenses occur within the deepest lava channels, on a footwall of gabbro sills that lack their upper chilled margin (e.g. Bleeker and Ames, 2017).

Higher in the stratigraphic section, several coarse clastic panels are observed within the Chukotat lavas. The fact that they consist solely of polymict conglomerate and arkosic sandstone, without also bringing Povungnituk basalts back into the section, rules out the possibility that they represent thrust repeats ramped up from the base of the Povungnituk Group. They are significantly deformed, however, and we therefore proposed that they represent synorogenic clastic wedges that were shed from a northerly source across the developing fold-thrust belt, and then captured by later, minor thrust faults, along the top of the panels (north side). These minor thrusts imbricated them within the Chukotat section (Bleeker and Kamo, 2018)[4]. We have tested this by dating detrital zircon grains, which indeed indicate that these conglomerates are younger than ca. 1830 Ma (*see* geochronology section *below*).

[4] The same explanation may equally apply to other reported occurrences of conglomerate in the belt, but we have not had an opportunity to test this for such occurrences other than the ones discussed here. The young polymict conglomerates discussed here were interpreted in some early reports (e.g. Bergeron, 1959; Beall, 1977) to indicate a significant unconformity at the base of the Chukotat Group.

U-Pb GEOCHRONOLOGY

In this section we briefly review and discuss existing geochronological data, in addition to introducing half a dozen new ages for units associated with the onset of the Chukotat magmatic event. We also present detrital zircon data for young synorogenic conglomerate panels interleaved within the Chukotat Group lavas. Ages will be discussed from oldest to youngest and going up stratigraphy, with reference to Figure 3b. A selection of the new age data are shown by means of concordia diagrams in Figures 4 and 5.

Lac Leclair Suite (Magmatic Event I)

Baragar et al. (2001) described the interesting occurrence of the alkaline (carbonatitic) volcaniclastic rocks of the Lac Leclair suite, in the same general area as the Korak sills, western Cape Smith Belt (Fig. 1). No age is available for this early magmatic suite, but it must be considerably older than 2038 Ma. Considering other magmatic events in the northern Superior craton (e.g. Ernst and Bleeker, 2010), it could be as old as ca. 2170 Ma or 2216 Ma and could perhaps assist in clarifying correlations with Cycle 1 stratigraphy of the Labrador Trough.

Korak Gabbro Sills (Magmatic Event II)

Machado et al. (1993) determined a crystallization age of 2038 +4/-2 Ma for the Korak gabbro sills, from near the base of the western Cape Smith Belt (Fig. 1). This sill was intruded towards the top of the Lamarche Subgroup. The age is based on three concordant to slightly discordant air-abraded zircon analyses and is robust within the quoted uncertainty. It demonstrates that much of the Lamarche Subgroup sedimentary units are older than 2038 Ma.

Povungnituk Flood Basalt Sequence and Minto Dyke Swarm (Magmatic Event III)

An upper intercept age of 1991 ± 2 Ma was determined for a small granodiorite intrusion or dyke cutting across pillow basalts of the Povungnituk flood basalt sequence, again by Machado et al. (1993). This age is based on three slightly discordant but collinear fractions of air-abraded zircon grains, with a near zero-age lower intercept, and is therefore robust. It probably indicates the end stage of Povungnituk basaltic volcanism. Recently, this age was confirmed by a baddeleyite upper intercept age of 1998 ± 6 Ma for a massive doleritic unit within the uppermost Povungnituk basalt sequence (Kastek et al., 2018). Well to the south, intruding Archean basement of the Superior craton, large northwest-trending mafic dykes, referred to as the Minto swarm (Buchan et al., 1998), have yielded a similar upper intercept age of ca. 1998 Ma. These dykes likely represent a major dyke swarm associated with the Povungnituk basaltic magmatism and may point to a magmatic centre in the Hudson Bay area (Ernst and Bleeker, 2010). This age was partly defined by a cluster of slightly discordant zircon fractions and we are currently refining the age of these zircons using chemical abrasion techniques. Preliminary results indicate an age that may be marginally younger but within error of the result of Buchan et al. (1998). Thus, all these Povungnituk ages cluster between 2000 and 1990 Ma and there is currently no evidence for Povungnituk basaltic volcanism to have continued to much younger ages. As dating methods have improved, protracted basaltic flood volcanism spanning tens of millions of years is rare, if not absent, in the modern record. We thus view the alkaline volcanism of the Cécilia Formation as a discrete younger magmatic pulse after a ~30 Myr hiatus.

We note that ages for the Watts Group basalts and ultramafic cumulate rocks, along the northern margin of the fold-thrust belt, also fall within the same 1990 to 2000 Ma interval as that of the Povungituk basaltic volcanism. It seems likely that this age equivalence points to a connection that yet remains to be fully understood. Could the Watts Group represent a northern rifted margin of essentially Povungnituk basaltic units, including layered ultramafic rocks?

Cécilia Formation Volcanism (Magmatic Event IV)

The interesting Cécilia Formation (Gaonac'h et al., 1989, 1992; Picard et al., 1990) remains insufficiently documented. It occurs in the central part of the Cape Smith Belt, overlying and infolded with the Povungnituk Group. It is described as alkaline and comprising mostly volcaniclastic rocks. A rhyolite associated with this volcanic package has been dated at 1959 ± 3 Ma (Parrish, 1989), but data remain unpublished.

Onset of the Chukotat Event, Lac Vaillant Sill and Expo-Ungava Dyke (Magmatic Event Va)

Differentiated gabbro-peridotite sills with thick lower sections of ultramafic rocks occur at various levels within the stratigraphy (Fig. 3b). These have long been correlated with the Mg-rich Chukotat lava sequence based on geochemical similarity (e.g. Hynes and Francis, 1982). We have dated gabbros from near the top of the ~400–500 m thick "Lac Vaillant sill"[5], exposed immediately east of Lac Vaillant in the southern part of the belt, at 1882.0 ± 1.1 Ma (Fig. 4a). This age is based on several chemically abraded single zir-

[5] This large sill east of Lac Vaillant also goes by the name "Gulf Sill" (M. Houlé, pers. comm., 2020).

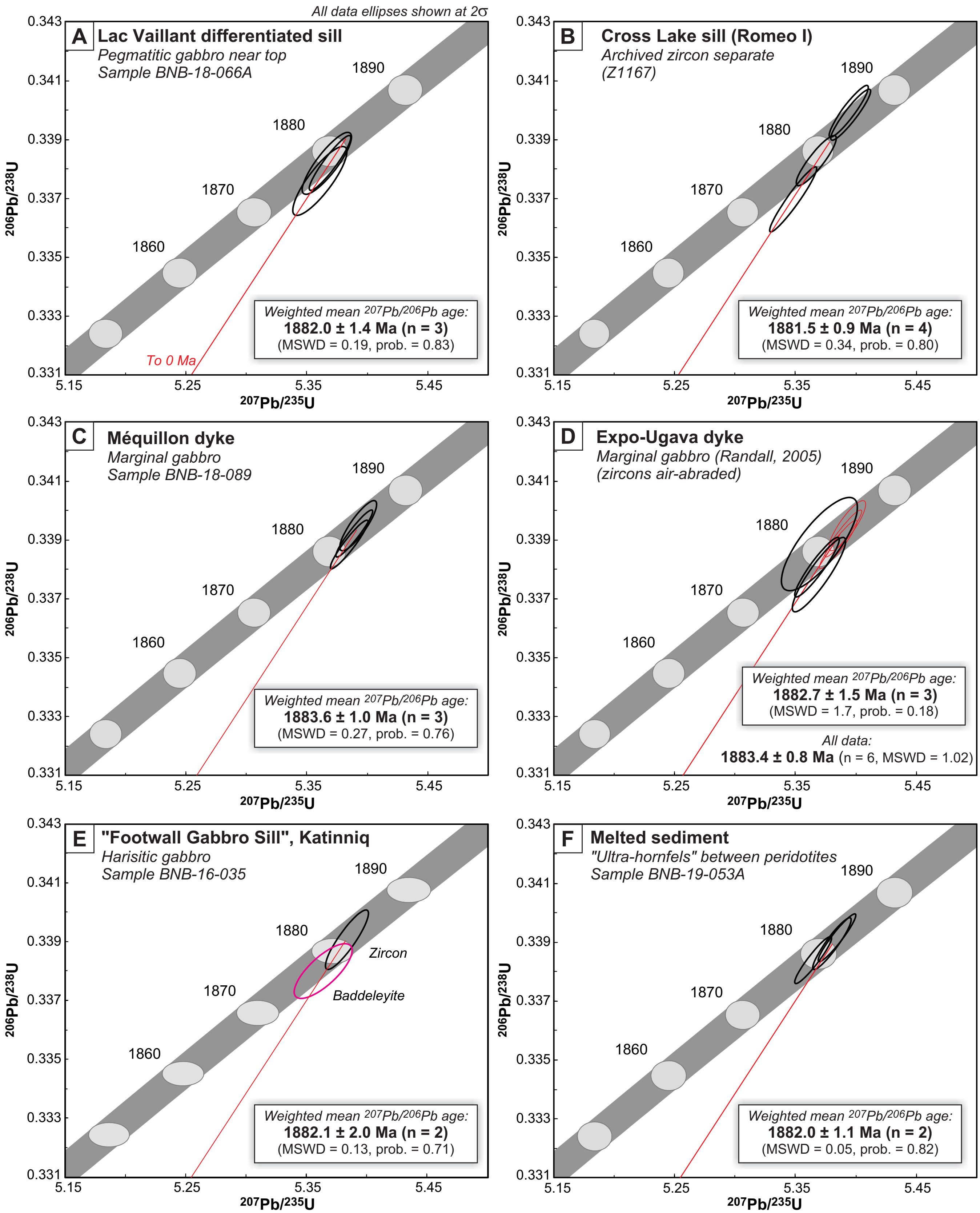

Figure 4. U-Pb concordia diagrams for selected results from this study. All data are from chemically abraded zircons and mostly single crystals, unless otherwise indicated. Abbreviations: MSWD = mean square weighted deviation, prob. = probability.

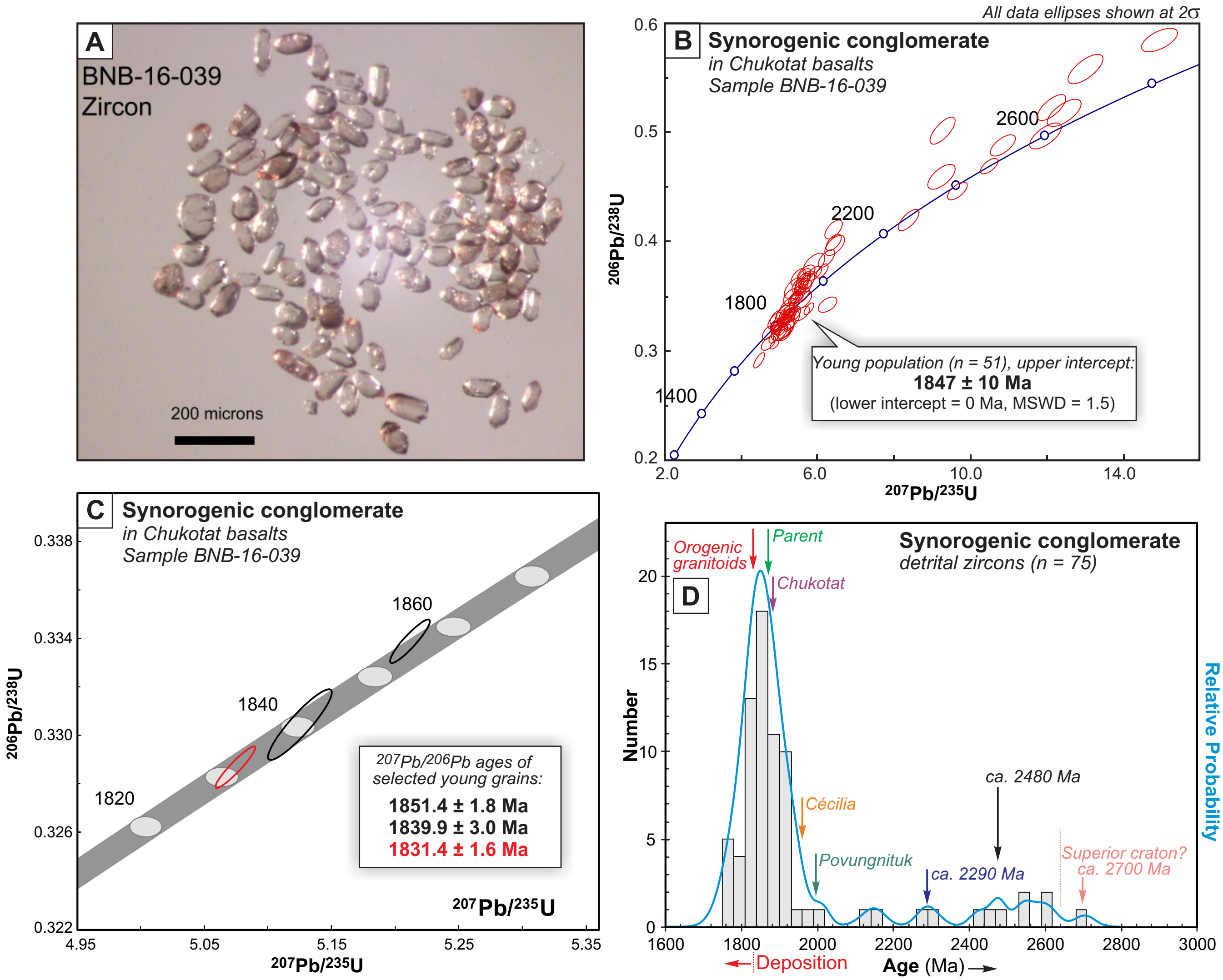

Figure 5. U-Pb results for ~80 detrital zircons from the synorogenic clastic rocks imbricated in the Chukotat lavas. **a)** Image of zircon grains selected for laser ablation analysis. The selection was more or less random but favoured clearer grains to optimize chances for good results. **b)** Summary of the laser ablation data presented on a standard Wetherill U-Pb concordia plot; note the dominant young population and the relative absence of grains >2650 Ma that would indicate a Superior basement source. **c)** CA-ID-TIMS results for three selected grains from the young population, with the youngest concordant zircon analysis indicating a maximum depositional age of 1831 Ma. **d)** Relative probability plot of all the laser ablation data showing the dominant young "orogenic" population and relative absence of Superior basement-derived grains. Abbreviation: MSWD = mean square weighted deviation.

con grains, all of which are concordant. This high-precision age confirms the connection with the Chukotat event.

Higher in the stratigraphy, linear outcrops of ultramafic rocks, with an overall west-southwest trend, define a large, steeply dipping, dyke-like body that can be followed for several tens of kilometres (e.g. Mungall, 2007; *see* Fig. 1). It is the host of disseminated Ni-Cu-PGE sulphide mineralization, including the Expo and Ungava orebodies which have been mined by open pit, as well as several other prospects. Randall (2005) presented an age of 1882.7 ± 1.5 Ma[6] for this dyke based on air-abraded zircon analyses on a sample of marginal gabbro from the Expo area (Fig. 4d). We have dated a second sample from the western continuation of this locally >300 m wide dyke in the Méquillion area[7]. This sample also contained zircon. Using modern chemical abrasion (CA) ID-TIMS methods[8], these zircon grains yield a crystallization age of 1883.6 ± 1.0 Ma (Fig. 4c), within error of the previous result presented by Randall

[6] Mineral separation and U-Pb analyses done at the Jack Satterly Lab, University of Toronto, by S. Kamo.

[7] A sample of coarse-grained gabbro was collected from the northern margin of the dyke at the Méquillon showing by M. Houlé.

[8] Chemical abrasion-isotope dilution-thermal mass spectrometry (CA-ID-TIMS).

(2005). Combining six data points from these two data sets of the same overall body, and all done at the same laboratory, these data defines a weighted mean $^{207}Pb/^{206}Pb$ age of 1883.4 ± 0.8 Ma (Fig. 4d).

Given the size and steep attitude of this very large differentiated dyke (~30 km long, steep, and at high angles to stratigraphy), and that it intrudes across the Povungnituk Group and into the base of the Nuvilik Formation, it is very likely to have reached the surface at the time of intrusion. Thus, it likely acted as a major fissure-like feeder to the lowermost Chukotat komatiite lava flows.

Although at the limit of what we can currently resolve, there is a hint in the overall U-Pb data set that this well dated dyke, at least its margin, with a crystallization age of 1883.4 ± 0.8 Ma, is among the oldest Chukotat-related units and that it is marginally older than the precisely dated Cross Lake sill with an age of 1881.5 ± 0.9 Ma (Fig. 4b; *see below*). It is possible therefore that many of the ultramafic sills are marginally younger, and that the Chukotat event was initiated by dyke intrusion and eruption of high-volume komatiite flows. As the lava pile thickened, silling may have become more important.

Footwall Gabbro Sills (Magmatic Event Va, continued)

The Nuvilik Formation is intruded by numerous gabbro and differentiated gabbro-peridotite sills. One of these large differentiated sills, at Cross Lake, near the western end of the Raglan belt proper, produced the earlier 1918 +9/-7 Ma upper intercept age interpretation of Parrish (1989). Using modern CA-ID-TIMS methods, we have redated the remaining zircon grains from this same sample, showing it to be 1881.5 ± 0.9 Ma (Bleeker and Kamo, 2018; Fig. 4b). We have also dated several other gabbro sills, including the main "Footwall Gabbro Sill" below the main komatiitic lava channel at Katinniq, which forms the immediate footwall to some of the larger ore lenses (e.g. Barnes et al., 1982; Lesher, 2007). The sample from this sill returned an age of 1882.1 ± 2.0 Ma (Fig. 4e). All of these sills are metamorphosed and the zircons recovered from these samples vary in quality, abundance, and how they respond to the chemical abrasion pre-treatment, a procedure that is critical to achieving concordance by removing open system domains (Mattinson, 2005). Some of the minor dispersion among the various dating results is therefore, in all likelihood, largely a function of this variability in zircon quality. All the ages overlap within uncertainty. In some samples we also recovered baddeleyite, but in most cases they display minor secondary zircon overgrowths and generally returned more complex data than those zircon grains that could be successfully treated with chemical abrasion.

Melted Sediments Interleaved with Main Komatiite Flows and Sills

From the many hundreds of exploration drillholes that intersect the lowermost Chukotat Group, in search of and to delineate the lenses of basal sulphide mineralization, some holes intersect anomalous rocks of igneous aspect but of more intermediate composition than the komatiites. Some of these intersections have been logged as "diorite" or "leucogabbro" (Raglan exploration staff, pers. comm., 2019), and in some cases can be shown to be grading into high-temperature hornfelsed sedimentary rocks of the Nuvilik Formation between thick peridotite bodies. Their mineralogy is dominated by randomly orientated, zoned, plagioclase crystals, granophyre with K-feldspar but little quartz, dark mica (both biotite and stilpnomelane), and accessory minerals such as titanite, zircon, and disseminated sulphides (Fig. 6). They clearly represent in situ melting and subsequent crystallization of siltstone and mudstone between thick (~100 m), hot, peridotite bodies—most likely a thick komatiite lava channel above and a sill-like invasive flow below. Heat input from both sides led to wholesale melting of the silt- and mudstones; we like to refer to this distinctive rock type as "ultra-hornfels". One of the intersections of such ultra-hornfels studied in detail contained newly crystallized zircon crystals of sufficient size to be separated, thus allowing dating of the actual mineralized komatiite lava channels. Zircon cystals from this sample yield an age of 1882.0 ± 1.1 Ma (Fig. 4f).

Hanging-wall Gabbro Sills (Magmatic Event Va, continued)

Gabbro sills also intrude the komatiite flows above the basal contact of the Chukotat Group, and above some of the lowermost sulphide lenses. One such gabbro sill showed chilled margins against both underlying and overlying komatiite flows, and must have intruded some time after the effusion of the lowermost komatiite lava flows and, therefore, after the formation of the basal ore lenses. Pegmatitic gabbro from near the top of this sill returned a zircon age of 1883.0 ± 2.0 Ma, somewhat less precise but within uncertainty of all the other dated gabbro-peridotite sills (and dykes).

Gabbro Sills at Higher Stratigraphic Levels (Magmatic Event Vb)

At yet higher stratigraphic levels, one gabbro sill has returned a reported age of 1870 ± 4 Ma based on preliminary zircon analyses (R. Parrish, unpubl. data; mentioned in Lucas and St-Onge, 1992; *see* Fig. 3b). Interestingly, this sample was reported to also contain inherited Archean zircon crystals. We have not yet independently confirmed this younger age. We do note, however, that at the larger scale of the Circum-Superior

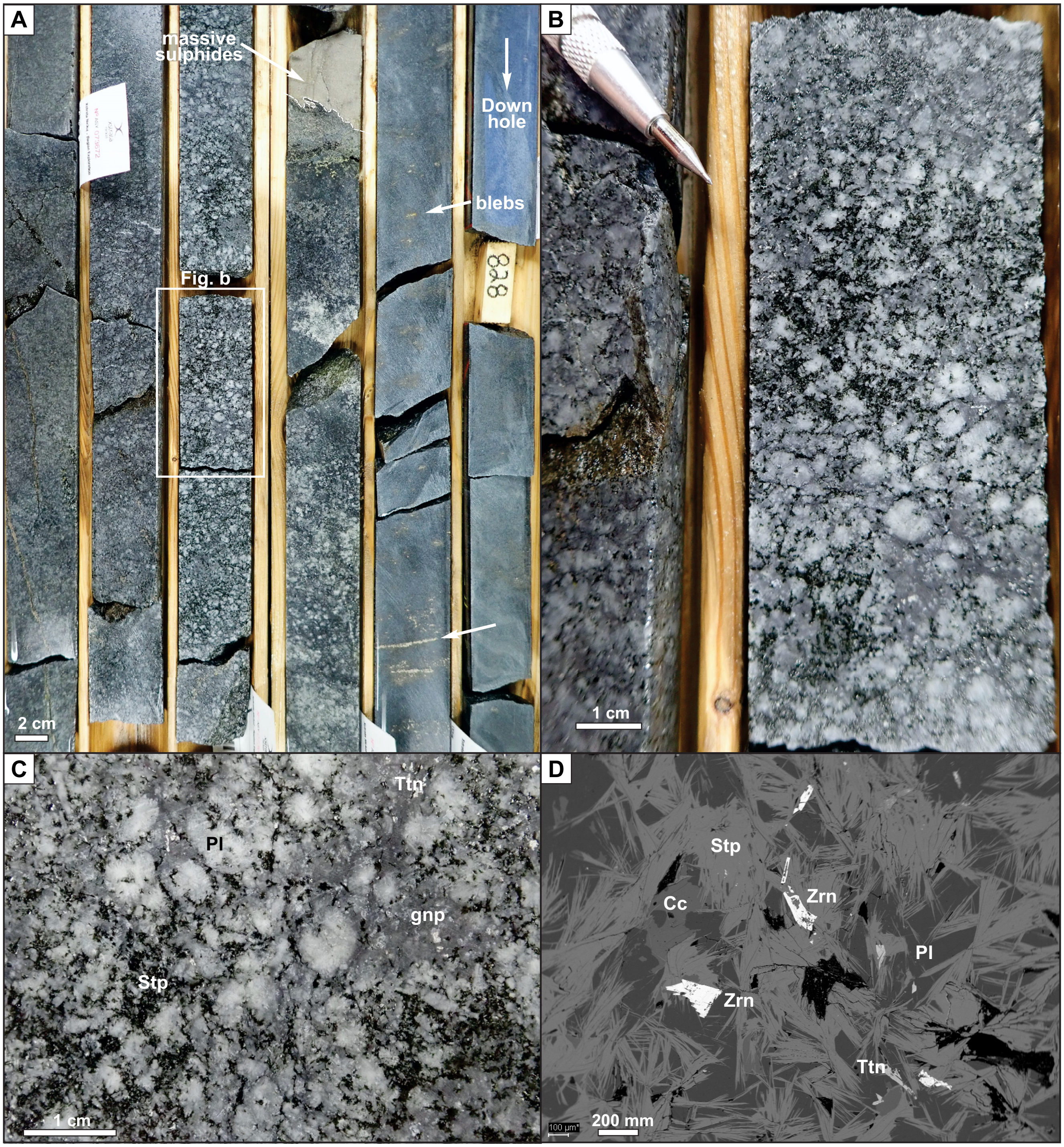

Figure 6. Images of the melted sedimentary units between large peridotite channels or sills. **a)** Overview of drill core through the base of a komatiite channel with basal sulphide blebs (~829.5 m) in contact with the melted sedimentary unit at ~831.0 m. The contact is characterized by ~5 cm of massive sulphide on the underlying unit, with the sulphides having infiltrated down to some extent. Note the pseudo-porphyritic texture in the melted sedimentary unit, in the middle of the image, which is shown in detail in (b). **b)** Close-up of the melted sedimentary "ultra-hornfels", which is dominated by feldspar (white to grey) and stilpnomelane (black) in a randomly orientated texture. **c)** Further close-up with minerals identified. **d)** Backscattered-electron image showing the skeletal morphology of zircon crystals that were used for dating. Also note the fan-like sheaves of stilpnomelane. Abbreviations: Cc = calcite; gnp = granophyric intergrowth of plagioclase and K-feldspar; Pl = plagioclase; Stp = stilpnomelane; Ttn = titanite; Zrn = zircon.

Belt, there occur a number of well dated dykes and sills in this same time interval of 1874 to 1870 Ma (Fig. 7). Hence there was a discrete younger magmatic pulse at the tail end of the Chukotat event. One such younger gabbro sill is the Haig Sill on the Belcher Islands (Hamilton et al., 2009). Another example occurs in the

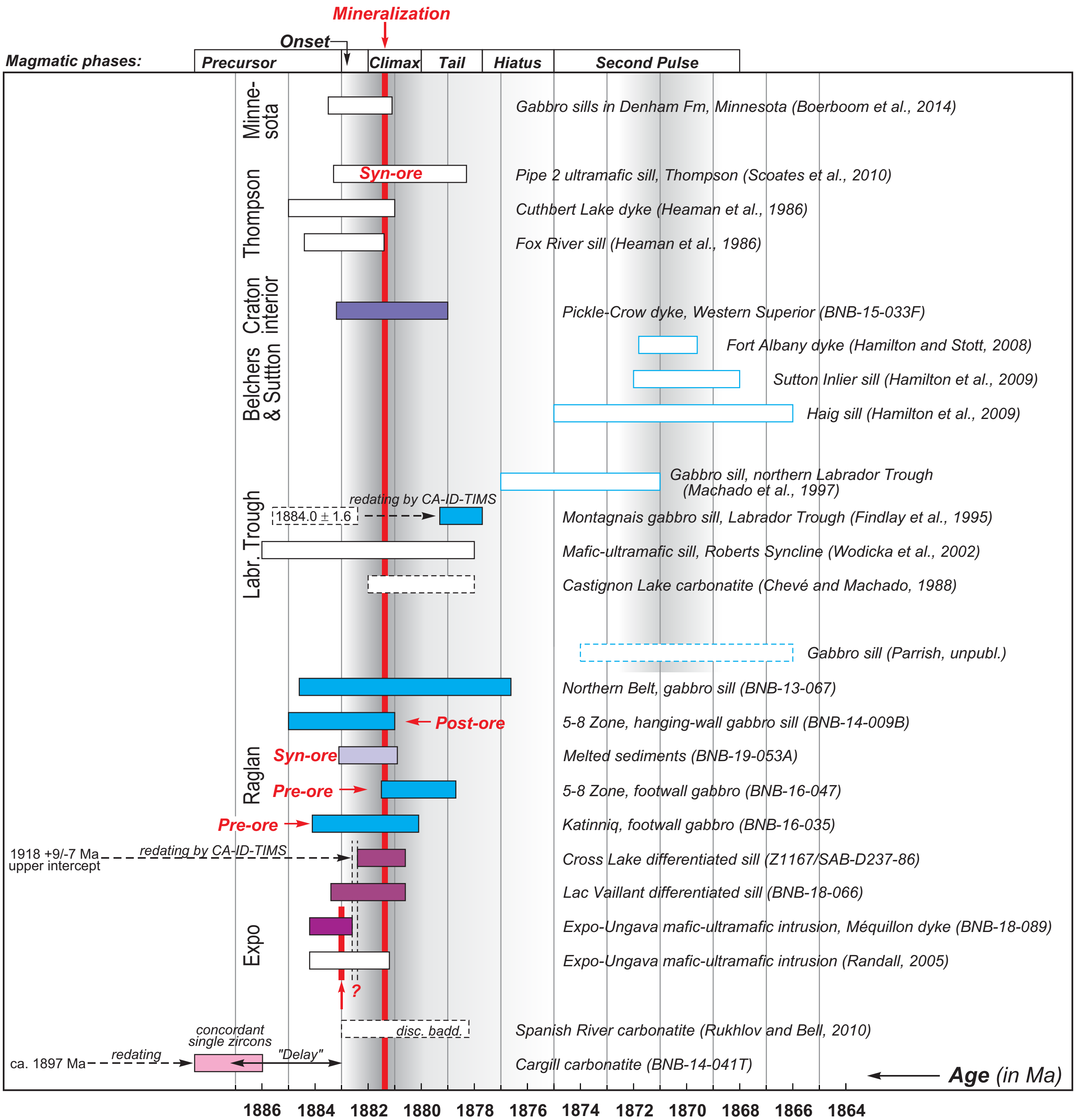

Figure 7. Summary of selected U-Pb zircon ages for Raglan and other segments of the Circum-Superior Belt. New data that were obtained as part of the present study are represented by the coloured (filled) age bars; others are referenced to the original publication as indicated. Units specifically redated for this study are identified and discussed in the text. Dates that explicitly bracket ore formation are highlighted (pre-, syn- and post-ore). The large igneous province-scale event started at 1883 Ma or shortly thereafter, and, at Raglan, peak komatiite effusion and ore formation (mineralization) occurred at 1882 ±1 Ma. The "Chukotat magmatic event" can be divided into several magmatic phases as shown at the top of the diagram. Data for a number of units across the Superior craton also indicate a distinct younger pulse at ca. 1870 Ma. Abbreviations: CA-ID-TIMS = chemical abrasion-isotope dilution-thermal ionization mass spectrometry; disc. badd. = age based on discordant baddeleyite; Fm = Formation; Labr. = Labrador.

northern Labrador Trough, where Machado et al. (1997) dated one of the glomeroporphyritic gabbro sills intruding the Hellancourt Formation, which can likely be correlated with the Chukotat Group. This sill returned a zircon age of 1874 ± 3 Ma (Fig. 3b). Further south in the Labrador Trough, we have refined the age of one of the type samples of these glomeroporphyritic "Montagnais" gabbro sills to 1878.6 ± 0.8 Ma (Bleeker and Kamo, 2018; *see* Findlay et al., 1995, for original date of 1884 Ma). These plagioclase porphyritic gabbro sills are therefore clearly younger and more evolved than the earlier komatiitic magmas at the onset of the Chukotat event (*see* Appendix for regional correlations with the Labrador Trough).

Synorogenic Conglomerates and Sandstones Structurally Interleaved within the Chukotat Group

Several panels of polymict conglomerate and pink arkosic sandstone occur within the Chukotat Group (St-Onge et al., 2006). These panels are deformed with a composite cleavage fabric compatible with north-over-south deformation. As essentially all other sedimentary intercalations in the Chukotat Group lavas consist of either sulphidic mudstone or komatiitic-basaltic volcaniclastic material (the latter interpreted as proximal debris flows of reworked lava flows), these polymict conglomerates and sandstones appear distinctly out of place. As these panels do not bring back other Povungnituk Group rocks, we can rule out that they are brought up by thrusts from the very base of the sequence (cf. St-Onge et al., 1992). An alternative possibility is that these panels are lenses of synorogenic clastic rocks that were shed across the fold-thrust belt in alluvial fans and subsequently imbricated within it by later thrust movement. We have tested this prediction by investigating the detrital zircons from one of these panels. A selection of ~80 whole zircon grains was mounted on tape and analyzed by laser ablation to determine approximate ages, without destroying most of the grains[9]. We then analyzed a selection of the youngest grains by CA-ID-TIMS, with the youngest grains being ca. 1831 Ma (Fig. 5). These grains must indeed have been derived from orogenic granitoid rocks towards the north, with the compositionally immature conglomerate representing an apron of molasse being shed to the south across the Cape Smith fold-thrust belt. That the conglomerate now occurs imbricated within the Chukotat lavas indicates that there was a renewed, late, thrusting event, younger than 1830 Ma, most likely associated with the uplift of the Kovik Antiform core complex (Bleeker and Kamo, 2018).

INTEGRATING STRATIGRAPHY AND STRUCTURAL DEVELOPMENT

Here we elaborate on the structural development of the Cape Smith fold-thrust belt, and in particular the setting of the Raglan Horizon in the central part to the thrust belt. A generalized cross-section was already introduced in Figure 2.

All observations support the interpretation that the Cape Smith Belt represents a fold-thrust belt that was transported to the south onto the craton, and preserved by down-folding into a broad synclinorium on the south side of the Kovik Antiform. In Figure 8, we explain in more detail some of the key features of the structural development, again using a cross-sectional perspective.

Figure 8a shows a south-to-north model cross-section of the Cape Smith Belt, with ~7 main thrust sheets, stacked in a moderately north-dipping homoclinal thrust stack. Key features are the flexed-down basement of the northern Superior craton in the south, the main shear zone (basal décollement), across which progressively more transported thrust slices were emplaced onto the craton, the progressive thickening of the thrust stack towards the north, and the potentially allochthonous thrust sheets at the highest structural level (structural panels 6 and 7). The inset shows the general stratigraphic template of the imbricated cover succession, which was implicit to earlier interpretations, with a single sediment package at the base of the stratigraphic sequence. Importantly, each major thrust sheet is marked by the reappearance of basal Povungnituk sedimentary rocks in the section.

Figure 8b shows a more detailed version of this same cross-section, which is essentially the end-member interpretation proposed by St-Onge et al. (1992) and St-Onge and Lucas (1993). In this section, going from south to north, each sedimentary panel is interpreted as riding on a thrust that ramped up basal Povungnituk sedimentary rocks. No less than 13 major thrust sheets are required by this interpretation. The sedimentary unit between the Povungnituk and Chukotat volcanic sequence is incorporated in this section, and St-Onge et al. interpreted yet another major thrust fault at the base of this unit (thrust fault #5 in Fig. 8b). As the Chukotat sequence was seen as a more outboard (distal) volcanic package, perhaps in part oceanic (following Hynes and Francis, 1982), and emplaced on these sediments, a major thrust was also introduced at the top of this sediment package (fault #6), going against such field observations as sills stitching contacts and hornfelsing that clearly tie these units together stratigraphically.

At Raglan (*see* arrow indicating the position of the Katinniq orebody), it is easy to demonstrate, based on numerous pillow top directions, that the Chukotat lavas sit in a south-vergent synclinal fold that is truncated on its north side by a fault (fault #7, the Cross Lake Fault) and thrust over by north-facing siltstones and mudstones (e.g. Coats, 1982), followed again by north-dip-

[9] Laser spot size of ~25 µm, and pits of ~15 µm deep; we estimate that, on average, only ~20 vol.% of the analyzed zircon grain is consumed during this process, and therefore much of the grain remains available for follow-up CA-ID-TIMS analysis.

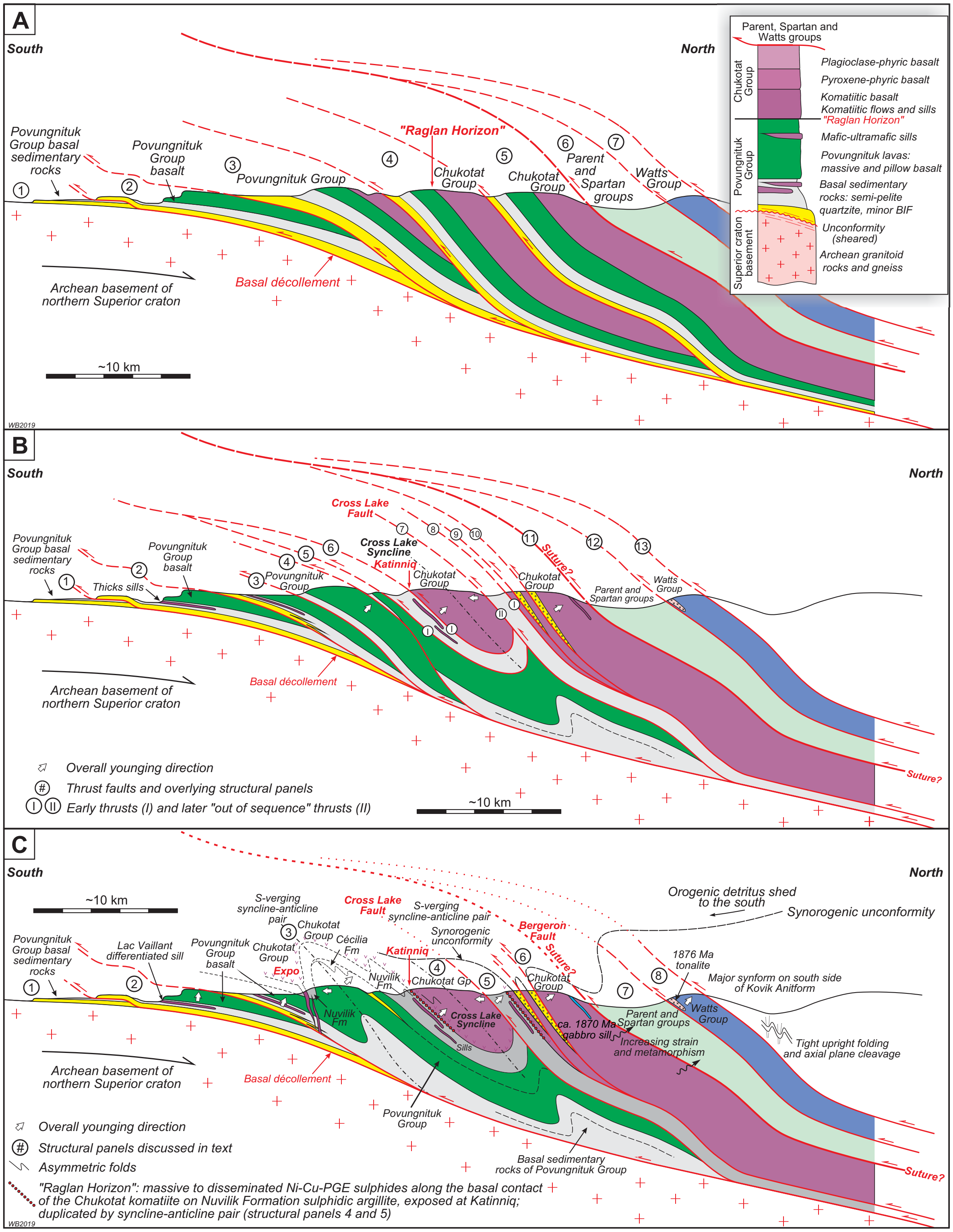

Figure 8. Model section (a) and more detailed cross-sections (b, c), all south to north, across the central Cape Smith Belt; compare with Figure 2. Many of the details are not to scale. **a)** Model section of the north-dipping homoclinal part of the Central Cape Smith Belt, using the interpretation that is implicit in the model of St-Onge et al. (1992), in which each panel of sedimentary rocks was identified as representing units ramped up from the base of the sequence (Lamarche Subgroup), following the stratigraphic template as shown in the inset. **b)** Section similar to (a) but incorporating the sedimentary unit between the Povungnituk and Chukotat lavas (i.e. the Nuvilik Formation), also bounded by thrusts. *See* the text for discussion. **c)** Reinterpretation of the same section (b) based on the present study. In this section the important Nuvilik Formation is a stratigraphic unit that marks the transition from the Povungnituk Group to the Chukotat Group, with primary depositional contacts. The upper contact with the Chukotat komatiites defines the “Raglan Horizon”. The central part of the section has far fewer thrusts and is more coherent. Two major syncline-anticline pairs define key parts of the section.

ping and north-younging Chukotat lava flows. Hence, as the Cross Lake Fault clearly cuts the Nuvilik Formation upper and lower contacts, two ages of thrust faults (I and II, *see* Fig. 8b) were hypothesized to maintain this overall model (Lucas and St-Onge, 1992; St-Onge et al., 1992).

Abundant evidence, summarized in earlier sections, argues against many of these thrust faults, and specifically against the thrust faults at the base and top of this sedimentary package, i.e. the Nuvilik Formation that separates the Povungnituk and Chukotat lava sequences. Hence, Figure 8c shows a more accurate cross-section that honours the field observations obtained as part of the current study. Other than significantly less thrust duplication, another key feature is that the mostly north-dipping fold-thrust belt incorporates two significant syncline-anticline pairs that repeat and thicken both the Povungnituk and Chukotat lava sequences. The first of these exposes the main Povungnituk basalt belt in an asymmetric anticlinal core, and brings back the Nuvilik Formation in the Expo-Ungava area to the south (*see also* Mungall, 2007). The second syncline-anticline pair involves the Cross Lake Syncline and duplicates the Raglan Horizon from Katinniq into what is known as the "North Belt" (*see also* Fig. 2). Given the stratigraphic linkages and the nature of this overall syncline-anticline pair, with the Cross Lake Syncline representing a "footwall syncline" and the Cross Lake Fault representing merely a faulted overturned limb, the net displacement on the Cross Lake Fault is probably on the order of one to a few kilometres, rather than many tens or a hundred kilometres as in the model proposed by St-Onge et al. (1992). Figure 8c also shows, in context, the position of the dated Lac Vaillant gabbro-peridotite sill in the south; the major ultramafic dykes that host the Expo and Ungava orebodies, also dated; orebody-scale asymmetric folds at Raglan (Katinniq) that repeat the Raglan Horizon on a mine scale and, off-section to the west, host the Kikialik deposit (Bleeker, 2013; *see* Fig. 2b,c); the synorogenic conglomerate panels in the Chukotat Group, in the hanging wall of the Cross Lake Fault (*see* panel #6); the required synorogenic unconformity across which molasse-type deposits were shed to the south; and the possible suture at the base of panel #7, the Bergeron Fault[10], which brings in the Parent Group volcanic rocks and associated Spartan Group greywackes.

In Figure 9, the cross-section is completed by adding the Kovik Antiform to the north and drawing attention to the major shear zone on its southern flank that eliminates much of the thrust belt. Shear fabrics along the basement-cover contact on this southern flank indicate late-stage, south-side down kinematics (Fig. 9d) and we interpret this overall structure as being due to uplift of a metamorphic core complex (the broad domal Kovik Antiform), and extensional thinning of the thrust belt on its uplifted southern flank. Extension and core complex uplift may also be related to the exhumation of high-pressure rocks in the core of the antiform further west (Weller and St-Onge, 2017; *see* Fig. 1 for location). Thin orthoquartzite units on the contact of the Kovik Antiform must be all that is left of the basal part of the Povungnituk Group, whereas prominent kilometre-scale peridotite knobs just above this contact are likely the highly extended leftovers of Lac Vaillant-equivalent sills.

At the highest structural level, peridotitic, dunitic, and pyroxenitic layered cumulates of the Lac Watts Group overlie basaltic units and may well be facing down (Fig. 9a, structural panel #9). The exact age equivalence of the Watts Group with the Povungnituk flood basalt sequence argues for these units being related, perhaps in the sense of the Watts Group being derived from a northernmost rift-type basin, and perhaps of transitional oceanic character. A key question is whether the peridotites of the Watts Group represent true mantle rocks, versus perhaps the lower cumulate parts of a layered intrusion associated with a northern extent of the Povungnituk Group. If indeed the latter, it would require significant revision of the various arc collision models (Picard et al., 1989; St-Onge et al., 1992).

Figure 9 also draws attention to some other intriguing aspects that are relevant to any accurate interpretation of these uppermost thrust sheets and what they mean in terms of a tectonic model. Near the top of the Chukotat Group (panel #6), a gabbro sill has been dated at 1870 ± 4 Ma (R. Parrish, unpubl. data) and is reported to contain inherited Archean zircon grains, suggesting a link to Archean basement even at this stratigraphic level and relative (original) position on the Superior margin. As final Chukotat magmatism, at ca. 1870 Ma, must still represent an overall extensional setting, and basin opening rather than closing, thrusting must have started well after 1870 Ma.

At approximately the same time, small tonalitic intrusions were intruded into the Watts Group (Fig. 9, panel #8). Parrish (1989) reports ages for several of these, which overlap with the tail end of Chukotat magmatism. One specifically has been dated at ca. 1876.1 ± 1.5 Ma. It seems fortuitous to link this to random events in an offshore arc, particularly as the mafic host rocks of the Watts Group already have an exact age

[10] Named after R. Bergeron, whose early mapping in the 1950s identified this major fault structure (Bergeron, 1957a,b, 1958, 1959).

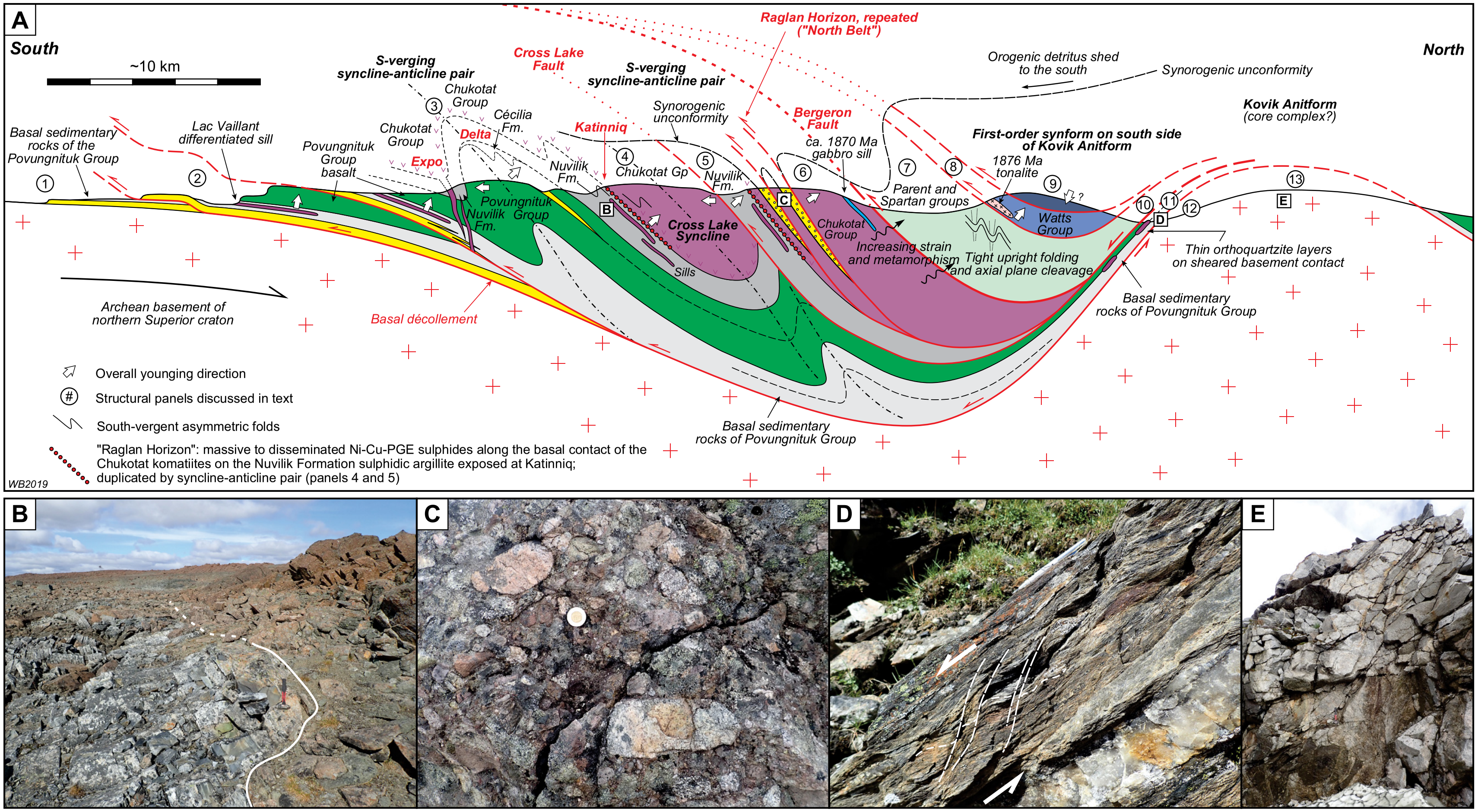

Figure 9. a) Final cross-section, incorporating the first-order basement-cored Kovik Antiform that flanks the north side of the Cape Smith Belt. Structural panels in the section are (1) Autochthonous foreland with local outliers of lowermost sedimentary rocks overlying Archean basement. 2) Parautochthonous belt of lower Povungnituk Group rocks, with some thrust repeats. 3) The central part of the belt is dominated by the Povungnituk flood basalt sequence, outlining a major south-verging syncline-anticline pair. 4) Cross Lake Syncline hosting Chukotat flows and sills that stratigraphically overlie the Nuvilik Formation. 5) Thrust repeat of Nuvilik Formation and overlying Chukotat lavas. Panels 4, 5, and 6 define a south-verging, faulted syncline-anticline pair. 6) Uppermost Chukotat panel with imbricated synorogenic clastic rocks (*see* Fig. c). Note also the gabbro sill dated at 1870 ± 4 Ma near the top. 7) Upper thrust sheet of possible arc rocks, the Parent and Spartan groups. The major fault at the base of this panel is the Bergeron Fault. 8) Watts Group basalts, gabbros and dykes, with ca. 1876 Ma tonalite intrusions. 9) Upper panel of the Watts Group comprising ultramafic rocks, perhaps facing down? 10) More strongly deformed and metamorphosed Spartan and Parent group rocks on the flank of the Kovik Antiform. 11) Highly deformed amphibolites and schists, including quartzites, overlying tectonized Archean basement; likely thinned and highly deformed equivalents of Povungnituk Group rocks. Kilometre-scale peridotite boudins occur in this belt, which are remnants of some of the large sills. 12) Tectonized Archean basement gneisses. 13) The less tectonized core of the Kovik Antiform. Note the remarkable thinning of the fold-thrust belt on the flank of the Kovik Antiform. We interpret the Kovik Antiform as a metamorphic core complex that was uplifted and exhumed at a late orogenic stage, perhaps at ca. 1820–1790 Ma. **b)** Basal contact of the Romeo I sill, cutting across but subparallel to hornfelsed thinly bedded wackes of the Nuvilik Formation, indicating a primary contact; view to the west. Hammer for scale. **c)** Polymict synorogenic conglomerate panels imbricated in Chukotat lavas. Diameter of the coin for scale is 28 mm. d) Late, south-side-down, extensional shear zone on the south flank of the Kovik Antiform; view to the west. Pencil for scale is 15 cm. **e)** Heterogeneous Archean gneisses and granitoid rocks in the core of the Kovik Antiform. Hammer for scale.

match to the Povungnituk basalts. More likely perhaps, Chukotat magmatism led to melting of Povungnituk/Watts group units, locally producing tonalitic magmas. More detailed work on the zircon populations in these various units may help solve these questions.

In summary, in the stratigraphic framework as currently understood (Fig. 3b), the entire Chukotat Group appears tied to the Povungnituk Group and, in turn, to Archean basement. This basement was likely thinned by synmagmatic extension, providing the lithospheric thin spot that allowed large-scale decompression melting. Even the MORB-like upper Chukotat lava flows cannot be fully oceanic, as hypothesized by earlier authors (Hynes and Francis, 1982; St-Onge et al., 1992). This link to basement is supported by inherited Archean zircon grains in the youngest gabbro sills with ages of 1870 ± 4 Ma. As Chukotat magmatism was still active at 1870 Ma, thrusting (and subduction?) must have started much later, not prior to 1870 Ma (cf. Lucas and St-Onge, 1992). Late re-imbrication occurred after 1830 Ma.

The presence of an accreted arc and a true suture, indeed most likely at the base of the Parent Group (the fault at the base of panel #7, the Bergeron Fault), depends entirely on an accurate interpretation of the Parent and Spartan groups. In the model of St-Onge et al. (1992), these units represent the leading edge of the Narsajuak Arc, and the boundary between panels #6 and #7 would be the remnants of a north-dipping subduction interface.

As is clear from this brief review, a number of observations remain to be explained and significantly complicate the details of published arc collision models. Resolution of some of these issues could greatly benefit from a more detailed follow-up, using SHRIMP, on the various archived zircon populations of such samples as the late gabbro sills and the tonalite/diorite intrusions, as well as various Watts and Parent group units. A full review of these issues is beyond the scope of this report and best deferred to a later date when such data are available.

THE SETTING OF MINERALIZATION

Ni-Cu-Co-PGE Ore Systems

With a more refined stratigraphic and structural framework, we can now return to the detailed setting of Ni-Cu-Co-PGE mineralization. In previous publications, the mineralization has often been discussed as occurring along two different belts or trends: 1) a main northern belt at Raglan, i.e. the “Raglan Horizon” (e.g. the Katinniq orebody shown in Fig. 8, 9; *see also* Fig. 1, 3b), and 2) a southern belt associated with various ultramafic sills, particularly the Delta sill and thus generally referred to as the “Delta Horizon” (e.g. Giovenazzo et al., 1989; St-Onge and Lucas, 1994). It is evident from the stratigraphic and structural sections shown here that this view needs some modification.

The “Raglan Horizon” is clearly structurally duplicated by the faulted syncline-anticline pair involving the Cross Lake footwall syncline and Cross Lake Fault, with the northern structural repeat of the Raglan Horizon referred to as the “North Belt” by exploration staff at Raglan Mine. The southern “Delta Horizon” is a collection of different ultramafic sills, not all at the same stratigraphic level. The Delta sill *sensu stricto*, intruding the Cécilia Formation, is just one of these sills, but other sills such as the large Lac Vaillant sill occur lower in the lithostratigraphy (Fig. 1, 3b). None of these have been mined to date. The Delta sill, specifically, has received attention for PGE mineralization (Picard et al., 1995).

Finally, the Expo, Ungava, and Cominga orebodies, and other showings such as Kehoe and Méquillon (*see* Mungall, 2007; McKevitt et al., 2020) are associated with the major ultramafic feeder dyke system in the south, with variable amounts of disseminated sulphides occurring in parts of this ~30 km long dyke. Examples of this mineralization are shown in Figure 10. This dyke cuts at high angles through Povungnituk Group units, reaching up into the southern synclinal outlier of the Nuvilik Formation (Fig. 2, 3b, 8c, 9). Therefore, it is very likely to have acted as one of the feeders to the Chukotat lava flows. No other potential feeder dyke system is known in the belt.

From all these different settings, the main Raglan Horizon, along which major, very hot, high-volume and high flow-rate channelized komatiite lavas flowed out across a substrate of sulphidic sediments of the Nuvilik Formation, is by far the most dynamic setting and, consequently, hosts the largest amount of high-grade sulphide ore (Fig. 11, 12). It is this stratigraphic ore horizon that elevates the Cape Smith Belt to a world-class Ni-Cu-Co-PGE district with several operating mines (~30 Mtonnes of ore). Large komatiite lava flows will inevitably channelize (gravity!), and thus thermo-mechanically erode into their footwall or substrate due to very high temperatures and turbulent flow (Huppert et al., 1984; Lesher et al., 1984; Huppert and Sparks, 1985; Williams et al., 1998), and thus necessarily interact with proximal sulphide sources (i.e. the Nuvilik deep-water mudstones). Such interaction is much less predictable in sill or dyke settings, if any occurs at all. Many of the sills are devoid of sulphide mineralization and appear to represent less dynamic magma inflation events, perhaps just a single pulse, followed by in situ differentiation and crystallization (*see also* Lesher, 2007).

Sulphide-bearing mudstone of the uppermost Nuvilik Formation, the stratigraphic substrate (ambient seafloor) across which the Chukotat komatiite flows

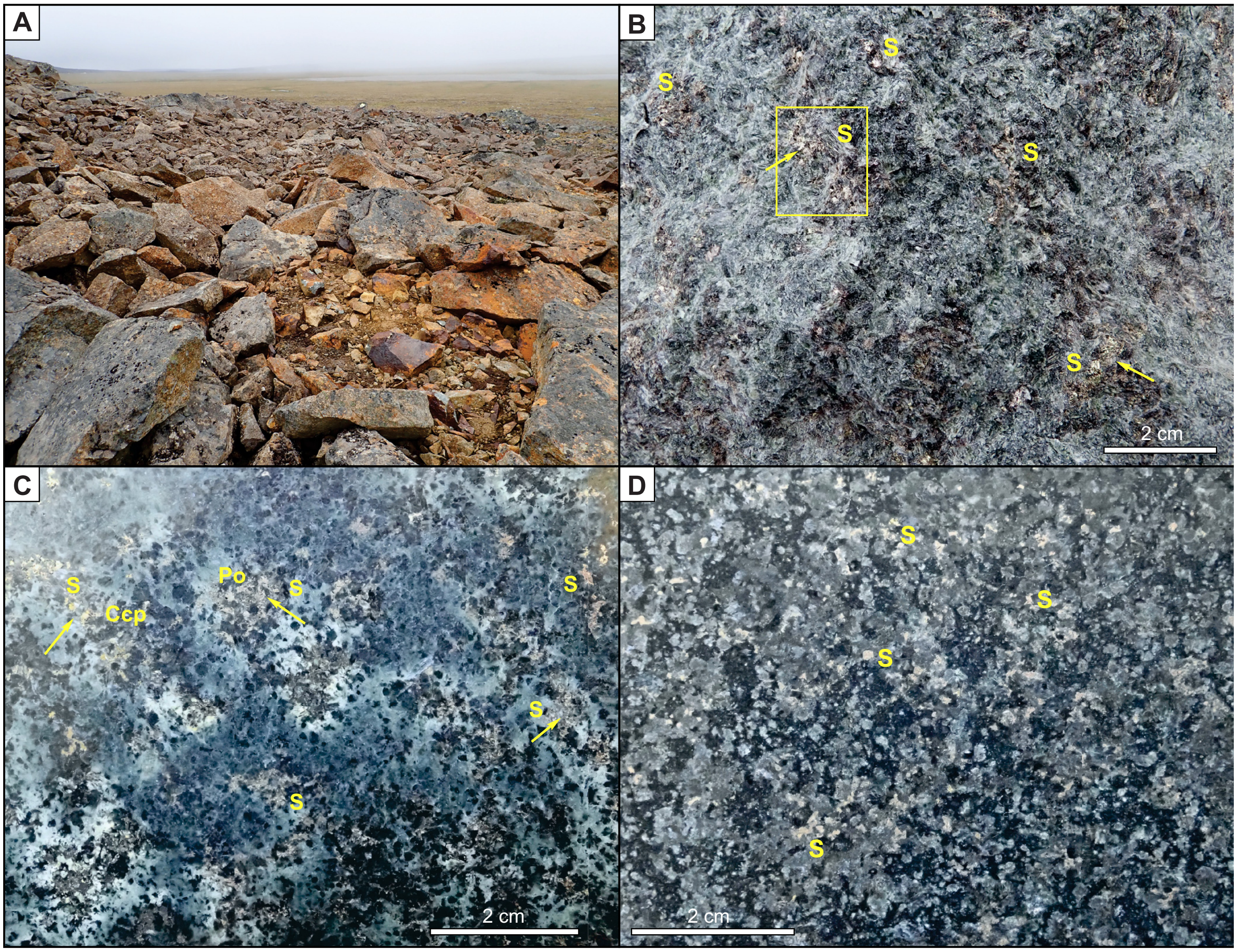

Figure 10. The ore environment of the Expo-Ungava ultramafic dyke system. **a)** Field photograph along the northern margin of the large ultramafic-mafic dyke intrusion, Kehoe showing; view towards the west. Note the gossanous blocks among the frost-heaved material. **b)** Fresh surface of one of the gossanous blocks showing ~5–10% sulphides in amphibole-altered pyroxenitic host rock. Sulphide aggregates (S) are highlighted. **c)** Polished slab from the same locality. Sulphide aggregates (S) show both chalcopyrite (Ccp) and Fe-Ni sulphides (Po), with an overall grade of ~2 wt% combined Ni and Cu. **d)** More olivine-rich rock, further into the dyke, with ~3–5 wt% disseminated sulphides.

were emplaced, acted as a proximal sulphide source for the Raglan Ni-Cu-Co-PGE sulphide orebodies, as has long been surmised empirically (Barnes et al., 1982; Coats, 1982;). This is supported by S isotopic data (Lesher, 2007). The numerous mafic-ultramafic differentiated sills, now all dated to the same short-lived event and spatially correlated with the komatiite flows on a regional scale, must be part of a complex and extensive feeder system that tapped into a deeper trans-lithospheric plumbing system (e.g. Fig. 13b) somewhere in the northern root zone of the thrust belt. Dynamic parts of this feeder system could host economic mineralization, such as in the Expo-Ungava dyke setting, but the base of the komatiite lava pile, in direct contact with Nuvilik Formation sulphidic mudstones, is more prospective and predictable.

Raglan is perhaps unique, certainly in Canada, in terms of the scale and preservation of the komatiite lava channels (e.g. Lesher, 1999, 2007). It bears many similarities to the Thompson camp (~100 Mtonnes), northern Manitoba, generated by komatiitic magmatism of identical age (see Fig. 7) and resulting from the same overall large-scale magmatic event, but where many of the primary relationships have been destroyed by intense polyphase deformation and high-grade metamorphism (Bleeker, 1990a,b,c). Lessons from Raglan may change some of the interpretations of the Thompson geology, and perhaps the role of large, deeply eroding komatiitic lava channels has been under-estimated at Thompson. Worldwide, some of the best developed komatiitic lava channels and associated Ni-Cu-PGE mineralization occur, of course, in the late Archean greenstone belts of the Yilgarn craton, particularly at Kambalda and Perseverence, where the critical concept of lava channels and dynamic interaction with sulphidic footwall rocks was first recognized and

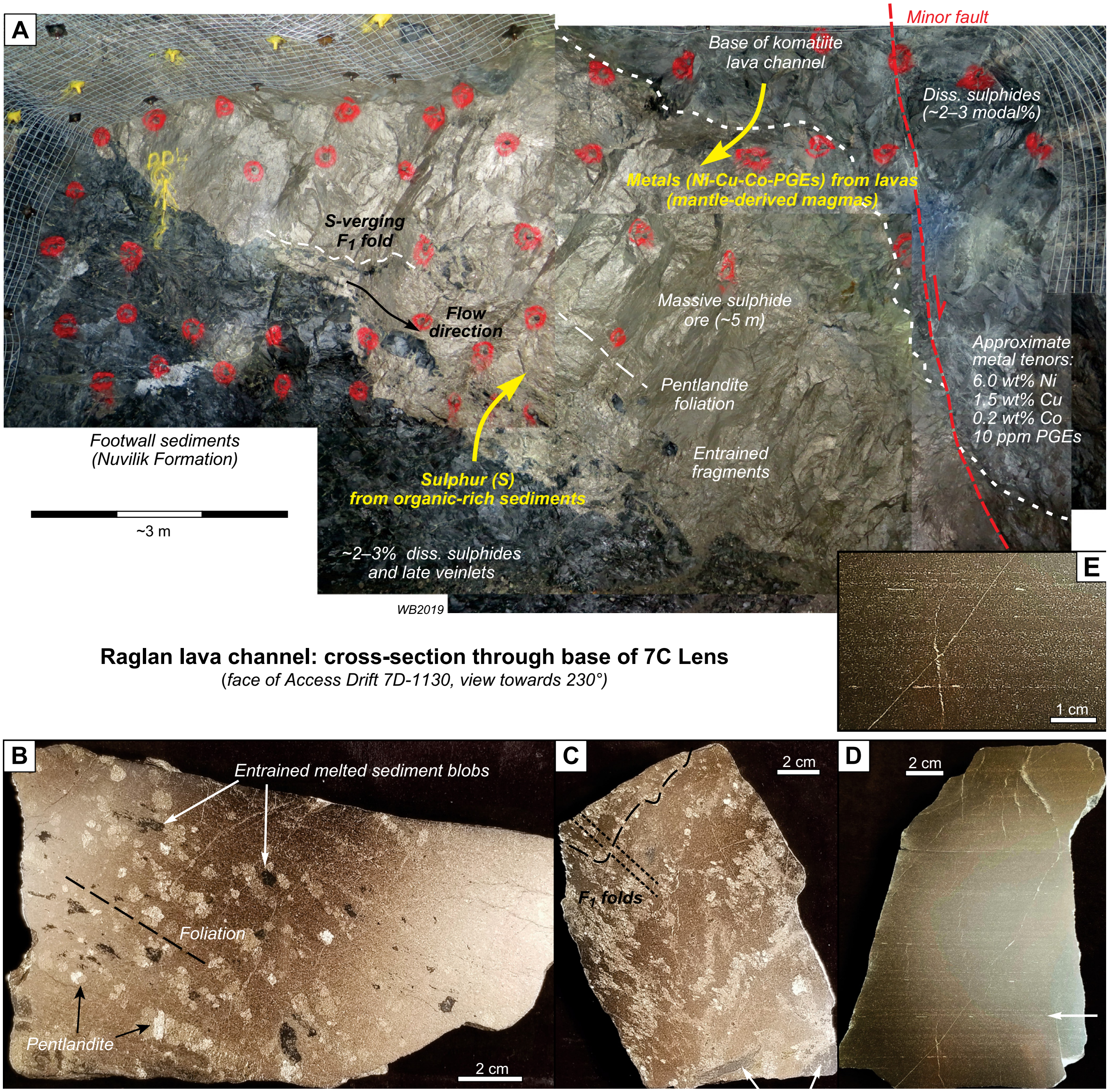

Figure 11. Cross-sectional view of one of the main komatiite lava channels with thick basal sulphide accumulation at Raglan, at the base of the 7C Lens, Qakimajurq deposit (5-8 Zone). **a)** A nearly 5 m thick massive sulphide zone occurs at the base of a thick komatiite lava channel, overlying and interacting with sulphidic, graphitic, footwall sedimentary rocks (black) of the uppermost Nuvilik Formation. Note entrainment of fragments of the footwall sedimentary rocks into the sulphide ore, indicating an original flow direction in the channel to the north (to the right in photo). The ore lens shows minor south-vergent folding (F_1), and is offset by a minor fault on the right side. **b)** Massive sulphide ore from this ore lens, showing entrained blobs of sedimentary rocks in the process of melting into the ore. Bright blotches are pentlandite ($(Fe,Ni)_9S_8$) crystals. The ore contains considerable graphite, which tracks the high degree of footwall assimilation. **c)** Massive ore with the pentlandite foliation being folded by minor south-verging folds, with development of a new foliation. **d)** A polished slab of Nuvilik Formation sulphidic mudstone, highlighting the considerable sulphide content of finely disseminated barren sulphides (pyrrhotite) along the primary bedding and lamination. **e)** Zoomed-in view of the sulphide lamination of the mudstone, showing 2–3 modal% barren sulphides along the lamination. Some remobilization of sulphides can be seen along late fractures, some of which may be originating from the overlying ore lens.

described (Gresham and Loftus-Hills, 1981; Marston et al., 1981; Lesher et al., 1984; Barnes et al., 1988; Gole et al., 1989; Lesher, 1989; *see also* Naldrett, 2005).

Interestingly, as at Raglan, the recognition of eroding lava channels at Kambalda, and thus of a somewhat more distal volcanic setting, came in several steps. At

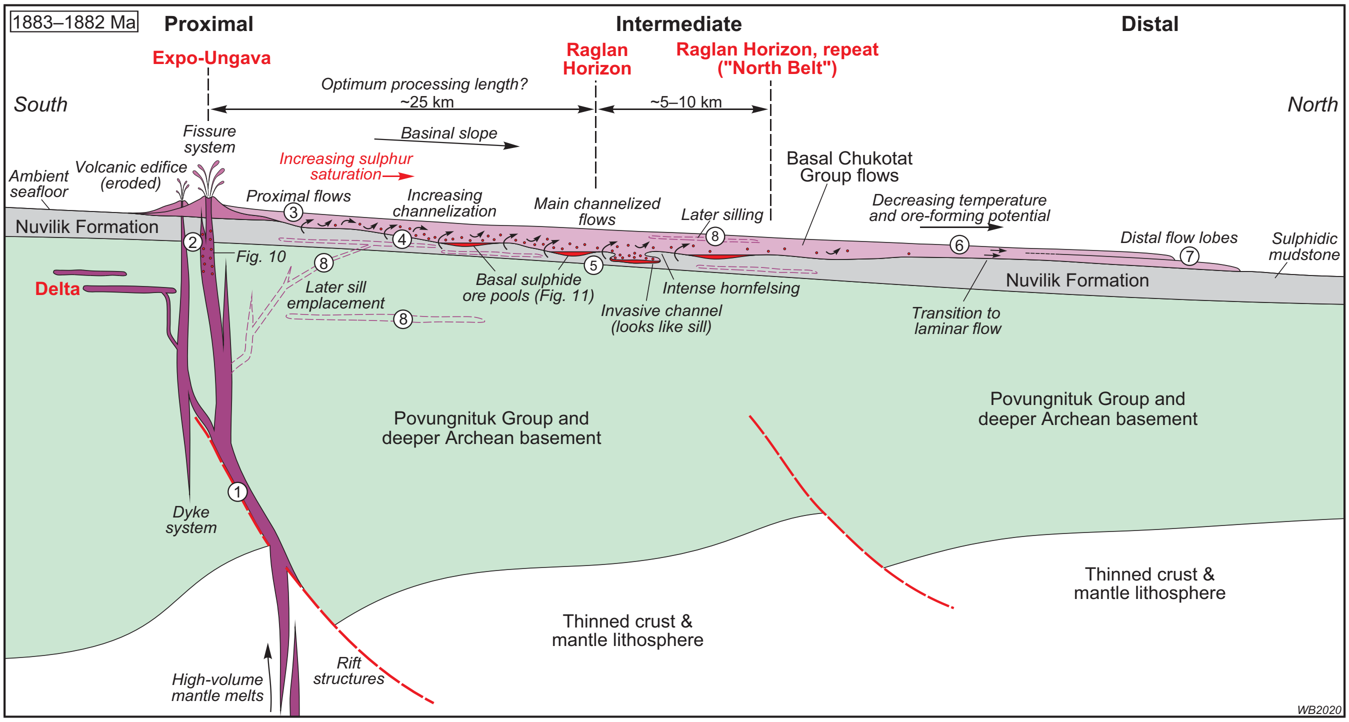

Figure 12. Key elements of the Chukotat magmatic system that generated the Raglan Horizon, in south-to-north cross-sectional view; details are not to scale. A major ultramafic feeder dyke system intruded in the south, guided by rift faults (1), resulting in a fissure system from which komatiite flows were erupted (2). These high-volume lavas flowed down a weak basinal slope in a northerly direction (3), and progressively channelized (4), while thermo-mechanically eroding into the underlying substrate of Nuvilik Formation mudstone. Channelization, erosion, and efficient mixing led to massive oversaturation of sulphides, with sulphide ore pooling out in embayments along the channel floor (5). The current position of the Raglan Horizon is indicated at a horizontal distance of ~25 km north-northeast of the fissure system. Downstream from Raglan, at an unconstrained distance, the lava flow field became less channelized (6) and terminated in lower temperature distal flow lobes of komatiitic basalt (7), devoid of mineralization. As the lava pile thickened, after multiple eruptive pulses, the emplacement mechanism transitioned to a mode where dense ultramafic magmas were emplaced as sills (8). The approximate position of the Delta sills is also shown, as are the locations of Figures 10 and 11.

first, the mineralized peridotite bodies were universally interpreted as sills and the ore environment was seen as proximal and intrusive. As spinifex textures and flow-top breccia units were recognized, the realization grew that the mineralized bodies were likely komatiite lava flows rather than sills (e.g. Barnes and Barnes, 1990 in the case of Raglan). Yet, the footwall troughs were still seen as primary topographic features filled in by the komatiite flows (Gresham and Loftus-Hills, 1981; Lesher et al., 1984; Barnes and Barnes, 1990), and a link to proximal feeding sills was maintained. A growing understanding of hot komatiite lavas, and the modelling of their turbulent flow (Huppert et al., 1984; Huppert and Sparks, 1985), and modern volcanological studies of lava channels in places such as Hawaii, finally led to the critical insight that the basal trough shapes and the elimination of flanking stratigraphy (thin sulphide-rich shale and iron formation at Kambalda; sulphidic Nuvilik mudstone at Raglan) were entirely a product of thermo-mechanical erosion. This important realization thus allows the ore-forming environment to occur in an entirely distal volcanic environment of hot channelized lava flows, decoupled from proximal feeder sills (e.g. Lesher, 2007).

This critical change in perspective naturally leads to several important next-level questions: how big can these channels be; how deep can they erode; what is their cross-sectional shape; and how far can they flow and remain prospective for sulphide mineralization? The Raglan camp may provide partial answers to these questions. If indeed the Expo-Ungava dyke and fissure system acted as the feeder system to the channels at Raglan, the basal komatiite flows occur ~25 km downstream (corrected for fold structures) from their feeder system, allowing direct interaction with sulphidic Nuvilik mudstone for part of that "processing length" (Fig. 12). Cross-sectional shapes of the channels may be complex (Huppert et al., 1984; Huppert and Sparks, 1985), perhaps locally leading to "invasive flows" that eroded laterally into the footwall strata for a limited distance. In typical drill core intersections, or in terrain of incomplete exposure, these invasive flows would be easily misinterpreted as shallow sills.

Other Ore Systems

A number of other ore systems may be represented in the Cape Smith Belt, among them various types of base metal mineralization, as well as orogenic gold mineralization (e.g. Orford Mining's Qiqavik project, *see* https://orfordmining.com/projects/qiqavik/). The refined cross-section of Figure 9 certainly draws attention to the association of a potentially deep-reaching fault zone or suture (Bergeron Fault), multiply deformed and metamorphosed volcano-sedimentary rocks (Parent-Spartan assemblages), synorogenic magmatism, and a synorogenic unconformity and associated clastic rocks that are imbricated in the thrust belt. This overall setting bears strong similarities to Archean settings of major lode gold systems (e.g. Bleeker, 2015).

SOME REGIONAL CORRELATIONS

The stratigraphy of the Cape Smith Belt, and specifically the Raglan belt in terms of mafic-ultramafic sills with an age of 1882 Ma, can be followed further east into the northern Labrador Trough, specifically the Roberts Syncline around the northern hamlet of Kangirsuk (Hardy, 1976; Madore and Larbi, 2001; *see* Fig. 1). There, Wodicka et al. (2002) dated a differentiated mafic-ultramafic sill at 1882 ± 4 Ma (Fig. 7). This same sill, somewhat further north along the syncline, was drilled for low-grade Ni-Cu sulphide mineralization. The entire Roberts Syncline with its basal sedimentary units, including iron formation, and a thick upper sequence of massive and pillowed flows, equivalent to the Povungnituk basalts and intruded by Chukotat age sills, represents a straightforward continuation of the Cape Smith stratigraphy (*see also* Taylor, 1982), less so of the typical cyclic Labrador Trough stratigraphy described much further south (e.g. Dimroth et al., 1970; Rohon et al., 1993; Findlay et al., 1995; Clark and Wares, 2006). Where and how the transition to more typical Labrador Trough stratigraphy occurs, somewhere well south of Kangirsuk, remains to be resolved in detail (*see* Appendix).

ZOOMING OUT TO THE SCALE OF THE CRATON

Most of the U-Pb data for units associated with the Raglan Horizon, from the northern Labrador Trough to the western Cape Smith Belt, suggest a short-lived, large igneous province-scale magmatic event that initiated at 1883–1882 Ma (*see also* Ernst and Bleeker, 2010). As far as can currently be resolved (~1–2 Myr), this age is identical to that of komatiitic magmatism along the western margin of the Superior craton (Thompson, Manitoba: Bleeker, 1990 a,b,c; Scoates et al., 2017), and to the age of large intra-cratonic dykes that intruded the craton (Molson swarm: Heaman et al., 1986, 2009; Pickle-Crow dyke: Bleeker and Kamo, this study). Recently, 1882 Ma gabbro sills have also been documented from the southern margin of the Superior Craton, in Minnesota (Boerboom et al., 2014). Many of the key ages have been summarized in Figure 7.

The overall scale and volume of this magmatic event, its short-lived nature of ~1–2 Myr, its synchroneity at the craton scale, and the involvement of initial high-temperature magmas compares well to modern large igneous provinces. Consequently, we interpret the overall geodynamic setting in terms of a hot mantle upwelling, possibly a deep-seated mantle plume, that impinged on the base of the Superior craton's subcontinental lithosphere (Fig. 13). The initial ascent of this mantle upwelling may have been somewhat slower (tens of millions of years; *see* Davies, 1999; Fig. 13a), but accelerated in the uppermost mantle with overall lower viscosities. A buoyant plume head, first flattening and then rapidly spreading (~1–2 Myr) underneath thick cratonic lithosphere (Fig. 13b), flowed to "thin spots" in the lithosphere where high-volume decompression melting led to the large-scale emplacement of mafic and ultramafic magmas, and ultimately ore formation. This overall model (*see* Sleep (1997) and Griffin et al. (2013) for more background) most easily explains the rich spectrum of phenomena at the scale of the Superior craton, in particular the nearly contemporaneous emplacement of mafic-ultramafic magmatic rocks along the entire length of the Circum-Superior Belt (Baragar and Scoates, 1981).

The model also makes many predictions, a few of which are highlighted below:

- Alkaline complexes, possibly including early kimberlite clusters, were likely one of the first manifestations of the impingement of a hot mantle upwelling underneath ancient Superior craton subcontinental lithosphere (Fig. 13a; *see also* Fig. 7). Indeed, kimberlitic rocks of this age are known in the Castignon area (Chevé and Machado, 1988).
- Precise ages of such alkaline complexes (e.g. David et al., 2006; Rukhlov and Bell, 2010; this study), at the scale of the craton, may provide information on the earliest interaction and potentially outline a plume track across the Superior craton as the Superior plate (i.e. supercraton Superia: *see* Bleeker, 2003, 2004) migrated over the mantle upwelling. This could be a rich avenue of further investigation and, at a global scale, will help to identify which cratonic blocks represent the conjugate margins to specific segments of the Circum-Superior Belt (Bleeker and Ernst, 2006).
- The markedly linear trend of large, ca. 1880–1890 Ma, alkaline and carbonatite complexes across the centre of the Superior craton from James Bay to Lake Superior, and following the Kapuskasing Structural Zone (Sage, 1991), must be related to this overall event and our model (Fig. 13b) provides a context for it. This trend must have initiated as a rift zone in cratonic lithosphere just prior to 1883 Ma. We have obtained a new, concordant,

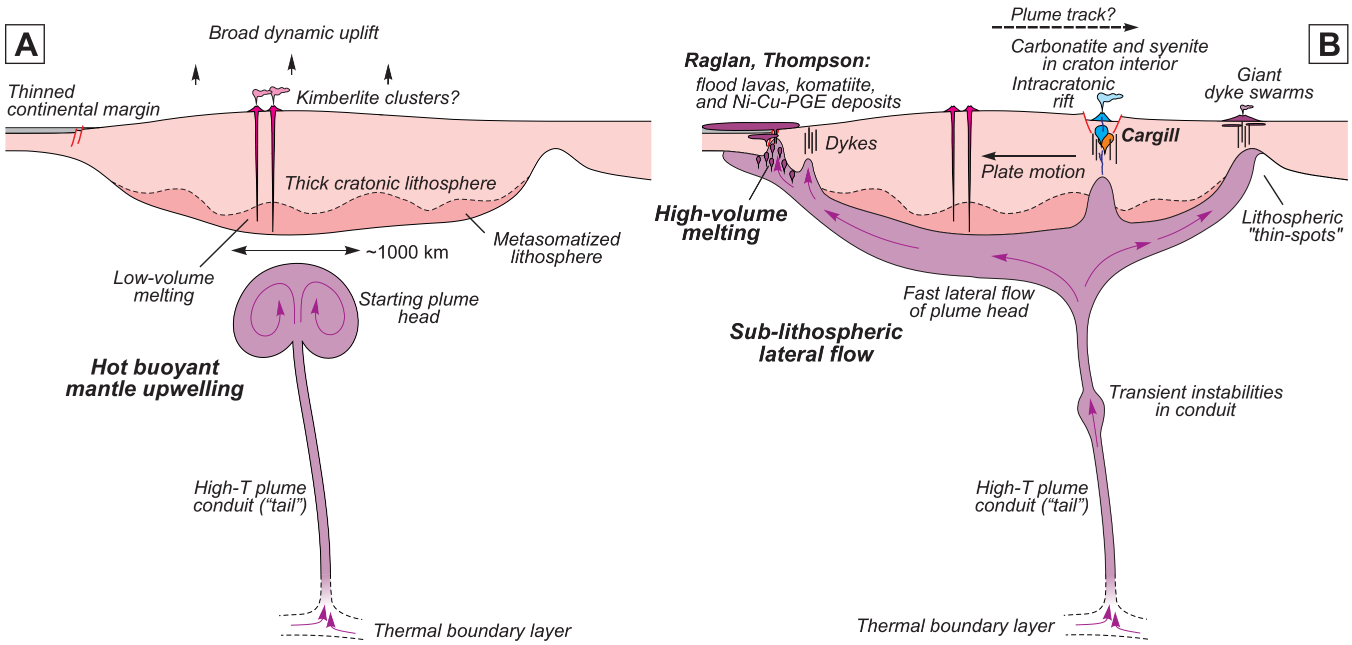

Figure 13. Interpreted geodynamic setting of the Chukotat magmatic event, at Raglan, and the broader Circum-Superior Belt magmatism. **a)** Initial slow rise of a hot mantle upwelling, possibly a mantle plume from a deep thermal boundary layer, below ancient continental lithosphere of the Superior craton. The latter was likely still part of a larger Superia plate at the time. The initial manifestations of the arrival of the hot upwelling or plume were broad uplift, possibly localized rifting, and low-volume melting of metasomatized lithosphere. **b)** Flattening and rapid spreading of the hot, buoyant, plume head below the subcontinental lithosphere and lateral flow to "thin spots", where large-volume decompression melting led to LIP-scale volumes of ultramafic and mafic magmatic rocks. Elsewhere, carbonatite complexes intruded into local rift structures in the craton interior, and giant dyke swarms intruded into fracture patterns in the crust. Events can be essentially contemporaneous on the craton scale, over a ~1 to 2 Myr interval. Transient instabilities in the plume conduit may have led to new arrivals of hot ultramafic magmas in younger pulses (e.g. Waterton et al., 2017). Overall, the spectrum of phenomena is suggestive of a continental breakup setting rather than a back-arc tectonic environment.

high-precision age of 1887 Ma for the large Cargill Complex along this zone (Fig. 7), suggesting intracratonic rifting and carbonatite magmatism preceded high-volume mafic magmatism by ~4–5 Myr, a similar delay as is seen between the Phaloborwa (2060 Ma) and Bushveld (2056 Ma) complexes in South Africa (Heaman, 2009; Mungall et al., 2016). This rifting provided the preparation and weakening for the later intra-cratonic thrusting documented along the Kapuskasing Zone (e.g. Percival and West, 1994), which was probably driven by collisions along the margin of the craton at ca. 1830–1800 Ma. This modified rift was later reactivated, again with intrusion of alkaline complexes, during ca. 1.1 Ga Midcontinent rifting (e.g. Bleeker et al., 2020).

- The overall geodynamic setting as portrayed in Figure 13 is more suggestive of a continental breakup setting than one of subduction-driven back-arc magmatism and associated upper mantle flow. Attempts to explain the ca. 1883–1882 Ma Circum-Superior Belt events in the latter context (i.e. back-arcs) may be misguided (cf. Corrigan et al., 2007, 2009). Not only are there no arcs built on the Circum-Superior margins, but arcs in general cannot explain the remarkable synchroneity of mafic-ultramafic magmatism around the Superior craton. We thus suggest that along some segments of the Circum-Superior Belt final breakup of supercraton Superia was delayed until about 1880–1878 Ma, after which the Superior craton fragment was finally isolated as an independently drifting plate.

CONCLUSIONS

We have resolved some of the persistent problems and contradictions in the stratigraphic and structural interpretation, and geochronology, of the central Cape Smith Belt, thus providing a more accurate context for the setting of world-class Ni-Cu-Co-PGE mineralization along the Raglan Horizon on the contact between the sulphidic Nuvilik Formation and the overlying Chukotat Group lavas. Neither the lower contact nor the upper contact of the important Nuvilik Formation is a thrust. Instead this formation of distal, thinly bedded turbidites and sulphidic mudstone defines the transition from the Povungnituk Group to the komatiitic Chukotat Group and represents the substrate and ambient seafloor across which the basal Chukotat komatiite flows were erupted and channelized. The Nuvilik sulphidic mudstones provided a proximal sulphur source for the komatiitic lava channels, invasive flows, and sills.

We have dated differentiated gabbro sills, both below and above the critical contact at ca. 1883–1882 Ma, showing that the onset of the high-volume and high-temperature Chukotat magmatic event occurred at that age. To this we have now added precise zircon ages from melted sedimentary rocks ("ultra-hornfels") sandwiched between thick komatiite channels and their invasive flows, thus dating the channels and mineralization themselves. This age is 1882.0 ± 1.1 Ma based on two overlapping, concordant single zircon analyses. Our observations on one of the lava channels with thick basal sulphide ore (7C lens, Fig. 11) also provide the first robust indication of flow direction (polarity) in the channel: down-dip to the north-northeast. This important observation, together with the new ages, allows for the following scenario (*see* Fig. 12): (1) A major ultramafic feeder dyke system, perhaps guided by deep-reaching rift faults, intruded well to the south of Raglan; (2) these dykes, with a precise age at 1883.4 ± 0.8 Ma, formed an eruptive fissure system that fed the hot basal komatiite flows. From there, the high-volume komatiite lavas flowed down a gentle basinal slope in a northerly direction (3), and progressively channelized (4), while thermo-mechanically eroding into the underlying substrate of Nuvilik Formation mudstone. Channelization, erosion, and efficient mixing led to massive oversaturation of sulphides, with sulphide ore pooling out in embayments along the channel floor (5). A horizontal flow distance of ~20 to 25 km to Raglan, downstream to the northeast, may have provided an ideal "processing length" to achieve large degrees of assimilation, sulphur saturation, turbulent mixing, and final sulphide segregation and pooling, at high R-factors[11], to form the main high-grade ore lenses of the Raglan Horizon. Downstream from Raglan, at an unconstrained distance, the lava flow field became less channelized (6), and terminated in lower temperature distal flow lobes of komatiitic basalt (7), devoid of mineralization. As the lava pile thickened, after multiple eruptive pulses, the emplacement mechanism transitioned to a mode where dense ultramafic magma was emplaced mainly as sills (8), with the most precisely dated sill being emplaced at 1881.5 ± 0.9 Ma. The Raglan Horizon likely represents several subparallel lava channels, each with a cross-sectional width of ~1 km. Typical channel depths are ~100 to 150 m, and lateral erosion of the channels into the Nuvilik Formation may have taken place locally on a similar scale. In typical drill sections, such lateral expansions of the channels ("invasive flows") are likely to be misinterpreted as shallow sills.

The lithostratigraphy of the central Cape Smith Belt is more coherent and less disrupted by numerous thrusts than previously interpreted, simplifying the overall structural-stratigraphic interpretation. Clearly there are some thrusts in the belt, however, and one of these, the Cross Lake Fault just north of Raglan, duplicates the Raglan Horizon into the "North Belt". This thrust is a relatively minor reverse fault that evolved from the overturned limb of what was originally a south-vergent syncline-anticline pair. Thrust displacement on this fault is probably on the order of one to a few kilometres, rather than many tens or hundreds of kilometres. Another south-vergent syncline-anticline pair duplicates and thickens the stratigraphy further south, particularly the main belt of Povungnituk basalts and the infolded Cécilia Formation and Delta sills.

It appears the entire stratigraphy of Povungnituk and Chukotat groups, as shown in Figure 3b, is coherent and tied to the basement of the Superior craton or its margin, perhaps with some lateral offset in the sense of the youngest, uppermost lavas of the Chukotat Group being concentrated along a more extended northern margin. Whether a short-lived basin opened towards the end of the Chukotat Group deposition, at ca. 1875–1870 Ma, and to what extent the Parent-Spartan and Watts groups are allochthonous remain problematic issues. The ca. 1870–1860 Ma Parent Group and the associated sedimentary rocks of the Spartan Group represent the fill of this basin, which may simply reflect a volcano-sedimentary rift basin on thinned Superior craton crust. Ages of the Watts Group are remarkably similar to those of the Povungnituk flood basalts and may suggest a link to the Superior craton, rather than indicating some exotic, outboard, oceanic crust.

The Kovik Antiform likely reflects late uplift of low-density sialic basement from below the thickened thrust belt, as a metamorphic core complex, resulting in the formation of a major extensional shear zone on its flank and necking of nearly the entire fold-thrust belt. This uplift also drove significant re-imbrication of the thrust belt, with slices of synorogenic molasse deposits, with detrital zircon grains as young as 1831 Ma, being captured in the thrust belt. The age of this re-imbrication could be as young as ca. 1820 to 1790 Ma.

At the scale of the craton, the concept of a Circum-Superior Belt, envisioned by Baragar and Scoates (1981) almost four decades ago, is coming into focus. The new high-precision ages demonstrate essentially synchronous magmatic activity across the craton and

[11] The R-factor is defined as the mass ratio of silicate magma to sulphide magma (Campbell and Barnes, 1984). Intimate interaction and mixing of segregated sulphides with a large volume (mass) of host silicate magma (i.e. high R-factors) leads to higher grade (tenor) ores, particularly of the more chalcophile elements.

around its (present) margins at ca. 1883–1882 Ma. This magmatism is best explained by a model of a mantle plume impinging on the base of the lithosphere of supercraton Superia, prior to final breakup, with initial alkaline magmatism as early as 1887 Ma (e.g. Cargill carbonatite), followed by lateral flow of hot mantle to lithospheric thin spots, and the essentially synchronous onset of high-volume mafic-ultramafic magmatism at 1883–1882 Ma. The overall context is one of final continental break-up, with possible arc accretion and fore-deep deposition occurring much later, after ca. 1850 Ma.

A wide variety of mineral deposits can be linked to this likely globally significant event, from rare metal and apatite deposits associated with early alkaline intrusions, to the Ni-Cu-Co-PGE magmatic ore systems at 1882 Ma, and the return of major Superior-type iron formation deposition at ca. 1880 Ma, all around the Superior craton (*see* Appendix). If indeed these processes are linked, it indicates that the ca. 1882 Ma Circum-Superior magmatism was of a scale sufficient to affect the global ocean-atmosphere system. At Raglan and Thompson, high-volume ultramafic magmatism caused the direct juxtaposition of dynamic hot magma systems with a prolific, crustal, and proximal sulphur source in the form of carbonaceous sulphide-rich mudstone, resulting in some of the largest Ni-sulphide deposits in Canada and the world.

FUTURE RESEARCH

An important remaining question relevant to the Raglan Horizon is the overall shape and flow direction of the komatiite lava channels (or channel?). Did the various deposits form in a single, giant, meandering lava channel, subparallel to the present surface trend of the horizon (Fig. 14b), as has been suggested by some authors (Green and Dupras, 1999; Osmond and Watts, 1999)? Or were there several subparallel anastomosing channels, now plunging, in present day coordinates, in a north- to northeasterly direction (Fig. 14c). The magnetic image that suggests that the various deposit areas are connected in a single giant west-to-east meandering channel (Fig. 14a,b), although spectacular, very likely is an artefact of more magnetic komatiite channels dipping to the north underneath a thickening hanging wall of less magnetic flows, with the magnetic anomalies merging to depth and then fading out. Our preferred interpretation is of multiple, subparallel, anastomosing lava channels flowing in an overall northeasterly direction (i.e. Fig. 14c).

Equally important, what was the flow direction in the main lava channels? In other words, what was (and is) downstream and upstream in these channels, and in terms of magmatic assimilation processes and evolving compositions? Currently, few data on flow direction are available from any of the channels or ore lenses; merely long axes of main ore lenses, which generally plunge to the northeast to north. Our observation of flow direction in the channel of Figure 11, down-dip to the north, is the first hard observation of this kind, but similar observations are needed for other key channels. These questions are relevant to how the structurally repeated North Belt relates to the main Raglan trend, and thus to its prospectivity. If the paleo-flow direction in the channels was to the north or northeast, as we indeed observed in the 7C ore lens, the North Belt would be ~5–10 km downstream from the main deposits such as Katinniq and Qakimajurq (5-8 Zone), and the major ultramafic dyke system in the southern part of the belt (Expo-Ungava) could be the principal fissure system from which the komatiite lavas were erupted. This is currently our preferred interpretation. If correct, it would indicate, after unfolding, that the main ore-forming channels such as at Katinniq were ~20–25 km downstream from their feeding fissure system, thus providing ~20–25 km of “processing length” for the intimate interaction and assimilation of the carbonaceous, sulphidic mudstone of the sedimentary substrate by the hot, eroding komatiitic lavas (Fig. 12). In addition to a local sulphide source (Nuvilik mudstone), this processing length may be critical to generating world-class orebodies.

Regionally, the interesting geology of the Cécilia Formation, and the relationships of the Parent, Spartan, and Watts groups remain insufficiently understood. Additional high-precision geochronology using more refined modern methods (e.g. chemical abrasion on single zircon grains), and detailed investigations of zircon populations (e.g. inheritance patterns, core and overgrowth relationships; detrital populations and provenance) on new and existing samples, together with detailed field studies, may help solve these problems. Some of this work is in progress, i.e. detrital zircon studies of units up through the stratigraphic column, and revisiting archived zircon populations. At the same time, the Quebec geological survey (MERN, Ministère de l’Énergie et des Ressources naturelles du Québec) is engaged in a remapping program, with geochronology support, of the Watts, Parent and Spartan groups to the north.

Farther afield, the stratigraphic and structural transitions into the Labrador Trough in the southeast (*see* Appendix), and into Hudson Bay and its various island groups to the southwest, remain to be resolved in detail. Our end goal is a full, modern integration and synthesis of all the Circum-Superior stratigraphy.

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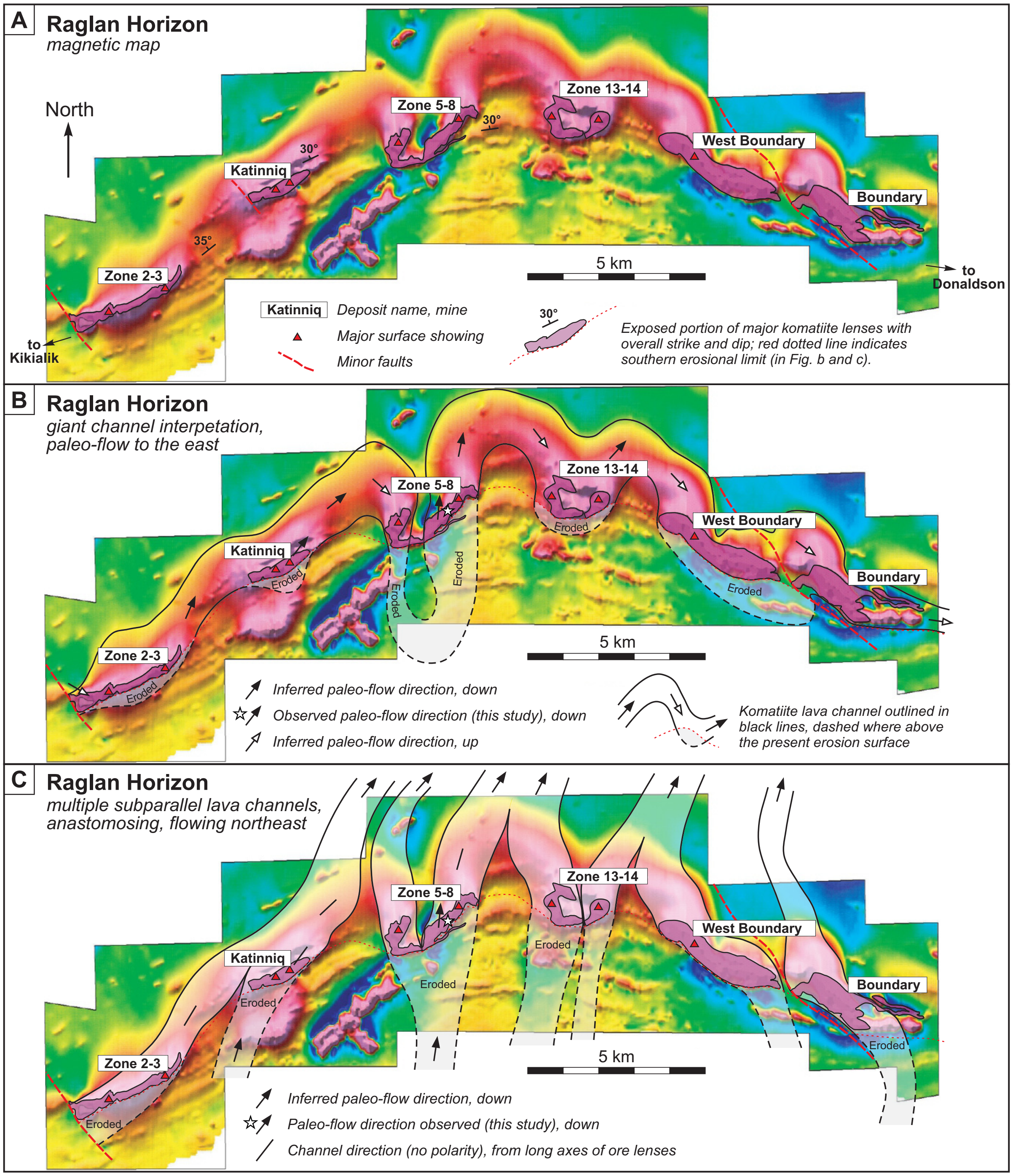

Figure 14. Magnetic map (total intensity) of the central Raglan belt highlighting the alternative komatiite lava channel interpretations; channels outlined by black lines, with dashed lines where eroded (map image *after* Osmond and Watts, 1999; and *modified after* Fig. 28 in Lesher, 2007). Hot colours (red to purple) are magnetic highs. **a)** Magnetic map image showing the exposed portions of the main peridotitic komatiite bodies. Stratigraphy generally dips ~30° in a northerly direction. **b)** The giant, single, channel interpretation of Green and Dupras (1999), locally up to 2 km wide, with tight meanders. Inferred paleo-flow directions as indicated, based on general elongation of ore lenses (but without flow polarity). Our observation of flow direction (at star), including polarity (to the north, Zone 7; *see* Fig. 11) is also shown. The overall curvature of the surface trace of the Raglan Horizon is due to late cross-folding of the belt. Therefore, the Green and Dupras (1999) interpretation is that of a giant channel flowing from west to east, parallel to the surface trace of the horizon. **c)** Our alternative interpretation of multiple, subparallel, anastomosing channels flowing down a weak basinal slope to the north-northeast. This preferred interpretation is equally in agreement with flow indicators, allows linking to the ultramafic fissure system in the south, fits an inferred basinal slope, and is less fortuitous in the sense of a single channel being exactly parallel to the present erosion surface. Broadening and merging of the magnetic highs is simply an artefact of the peridotite channels dipping and plunging to depth, below a less magnetic hanging wall of basalts. If correct, it would mean that the “North Belt” ultramafic bodies, in the structurally repeated panel north of the Cross Lake Fault, is more likely to include, at least in part, the downstream continuation of some of the main Raglan channels.

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APPENDIX

Here we explore important questions of regional correlation of the Cape Smith Belt stratigraphy with that of the Labrador Trough to the southeast (*see* Fig. 1 for a regional map). The Labrador Trough is a ~900 km long belt along the eastern margin of the Superior craton with perhaps the best preserved and most extensive record of Paleoproterozoic craton-margin stratigraphy of the entire Circum-Superior Belt. The preserved stratigraphy thickens towards the east and is asymmetric. It has been divided into several lithotectonic zones, with generally more allochthonous units towards the east. Given its considerable length, the different lithotectonic zones, and the fact that it spans two jurisdictions (the provinces of Quebec and Labrador), the literature on the Labrador Trough is extensive (e.g. Baragar, 1967; Dimroth et al., 1970; Le Gallais and Lavoie, 1982; Wares and Goutier, 1990; Clark and Wares, 2006) and involves a bewildering variety of formation names, some of which are essentially duplicates from one mapping area to another, whereas others involve important questions of correlation from north to south or across lithotectonic zones. All of this we attempt to summarize in one lithostratigraphic column, a column that is necessarily imperfect but aims to highlight the essential elements (Fig. 15c). Quoted U-Pb zircon ages are from Chevé and Machado et al. (1988), Krogh (1988, unpub. data, mentioned in Machado et al., 1989), Parrish (1989), Rohon et al. (1993), Findlay et al., (1995), Machado et al. (1997), Buchan et al. (1998), Henrique-Pinto et al. (2017), and Bleeker and Kamo (2018).

In Figure 15a, we show the lithostratigraphic synthesis of the Cape Smith Belt, as presented earlier (Fig. 3b of this report). Again, key ages are shown, and those outlined in red are from the present study. As described earlier in this report, key features of the Cape Smith stratigraphy are the two major mafic volcanic sequences of the ca. 1998 Ma Povungnituk basalts and the much younger 1883–1870 Ma Chukotat komatiites and basalts, as well at the basal sedimentary Lamarche Subgroup. Unless there are undocumented structural-stratigraphic complexities, these basal sedimentary rocks must be older than 2038 Ma, the age of the intrusive Korak gabbro sills. This >2038 Ma age must also apply to the iron formations near the base of the sequence, which generally become more prominent in the eastern part of the Cape Smith Belt (St-Onge and Lucas, 1993; M. St-Onge, pers. comm., 2020).

Figure 15b shows the lithostratigraphy of the Roberts Syncline area, based on a traverse across the entire syncline in 2013 and the mapping of Hardy (1976). Although the entire section is moderately to strongly deformed and overlies a basal décollement, as in the Cape Smith Belt, it probably reflects, to a first degree, a primary stratigraphic succession. Top indicators from graded beds, pillows, and differentiated sills are all into the core of the syncline. The area generally has been considered as the northernmost parts of the Labrador Trough, but is only a mere 125 km to the southeast of the easternmost Cape Smith Belt where similar units are exposed. In the main part of the Roberts Syncline, the basal section is essentially similar to that of the Lamarche Subgroup of the Cape Smith Belt and, coming from Cape Smith (Fig. 15a,b), there is no compelling reason to not correlate the various units (*see also* Taylor, 1982). The iron formation near the base is thicker than in the Cape Smith Belt but this agrees with the general trend observed farther north, where the iron formation becomes thicker towards the east. The erosional remnant in the core of the Roberts Syncline, which is obviously truncated at its top, is occupied by a ~3–5 km thick sequence of massive and pillowed basalt flows that are intruded by mafic and ultramafic sills. Gabbro at the top of one of these sills has been dated at 1882 ± 4 Ma (Wodicka et al., 2002), as shown in Figure 15b. Importantly, several distinct quartzitic intercalations occur in this basaltic sequence and help to correlate it with the Povungnituk basalts. Detrital zircon grains from these quartzites are all derived from Archean basement (D. Davis, pers. comm., 2016: preliminary laser ablation data from samples collected in 2013). No such intercalations of sialic basement-derived, mature quartzite are known from the Chukotat sequence.

Figure 15c attempts to summarize the extensive and rather complex lithostratigraphy of the Labrador Trough proper, which can be divided into several major depositional cycles and subcycles (Dimroth et al., 1970; Le Gallais and Lavoie, 1982; Clark and Wares, 2006) that progress from shelf-like facies, including stromatolitic carbonates, to basinal facies dominated by greywackes and shale, with associated mafic volcanic rocks. Two major cycles are recognized, separated, at least locally, by a low-angle unconformity. A third cycle of synorogenic siliciclastic rocks occurs at the top. In large parts of the trough, the units of "Cycle 2" overstep units of "Cycle 1" to the west and onlap onto basement of the Superior craton, as schematically shown in Figure 15c.

With the three lithostratigraphic columns side by side, the first-order problem of correlation is immediately clear: the major Sokoman iron formation of the central and southern Labrador Trough, the age of which is reasonably well constrained to ca. 1880 Ma (Chevé and Machado, 1988; Findlay et al., 1995) and thus coeval with the climax of Chukotat magmatism, cannot be the same iron formation unit as near the base of the Roberts Syncline, even though essentially all previous authors have made this correlation. One solution would

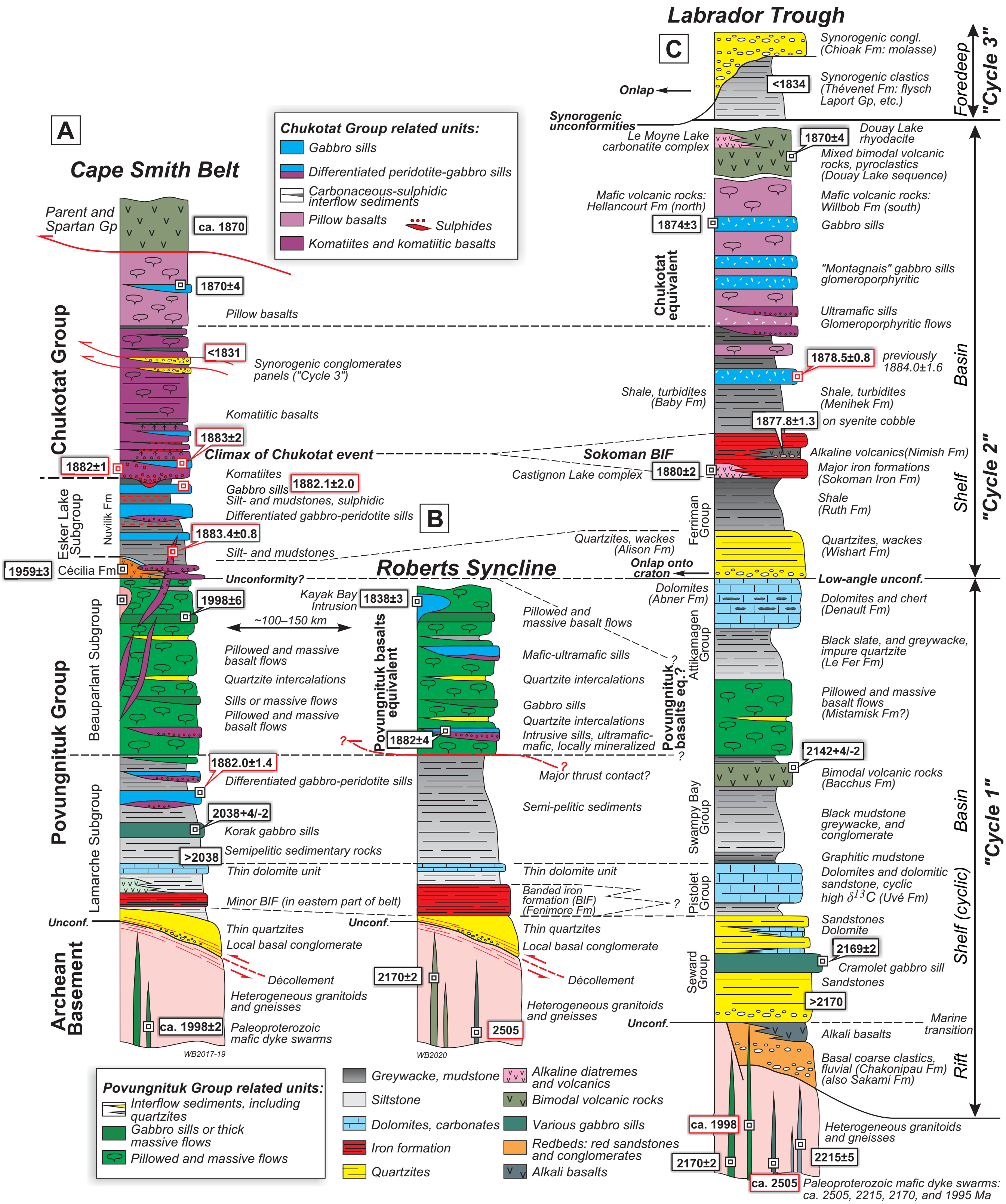

Figure 15. Composite lithostratigraphic columns for **(a)** the Cape Smith Belt; **(b)** the Roberts Syncline area ~100–150 km to the southeast; and **(c)** the Labrador Trough. Dashed lines indicate tentative correlations. The age of the major iron formation of the Labrador Trough, the Sokoman Iron Formation, in "Cycle 2" is constrained to ca. 1882–1877 Ma and overlaps in age with the climax of the Chukotat magmatic event. Iron formations near the base of the Cape Smith stratigraphy represent an older cycle of chemical sedimentation.

be to make the entire Roberts Syncline stratigraphy part of Cycle 2, with the basalt sequence in the core of the syncline being equivalent to the Chukotat and Hellancourt sequences, but we do not favour this view. It ignores the important observation of mature quartzite intercalations in the Roberts Syncline volcanic sequence and forces the question of why the major, ~3–5 km- thick Povungnituk basalt sequence is suddenly missing over a lateral distance of just over 100 km from the Cape Smith Belt. Furthermore, the basal sedimentary section of the Roberts Syncline is not a perfect match to the Menihek shales and turbidites that overlie the Sokoman Formation further south. A thin dolomitic carbonate unit near the base of the Roberts Syncline is identical to a thin carbonate unit in the lower Povungnituk Group. We thus favour the correlations as shown in Figure 15, acknowledging that a there are a number of questions that remain to be resolved:

1. Is there a Povungnituk basalt equivalent in the northern and central Labrador Trough, as part of Cycle 1? Only one widely quoted U-Pb zircon age (unpub.; T. Krogh, pers. comm., mentioned in Machado et al., 1989), on a rhyolite, occurs in the relevant part of the Labrador Trough column and the associated volcanic rocks appear to be older, i.e. 2142 Ma, and too old to be part of the Povungnituk sequence. Many volcanic packages remain undated, however, and the different lithotectonic zones complicate overall correlations.
2. Could the major sequence boundary between Cycle 1 and Cycle 2 stratigraphy perhaps be ca. 1960 Ma and correlate with the hiatus at either the base or the top of the Cécilia Formation in the Cape Smith Belt?

In the Labrador Trough, we have redated, using CA-ID-TIMS on single zircon grains, the glomeroporphyritic "Montagnais" gabbro sill that intruded the Menihek Formation greywackes. The previously reported age for this sill, based on discordant but collinear zircon fractions, was 1884.0 ± 1.6 Ma (Findlay et al., 1995). Even though the quoted upper intercept age was relatively precise, from the nature of these data we predicted that it was an over-estimate and too old. Our new, refined and concordant zircon age of 1878.5 ± 0.8 Ma erases the apparent age reversal in the previous data—an 1884 Ma intrusive sill above ca. 1880–1878 Ma iron formation and volcanic rocks. No part of the Sokoman iron formation is therefore older than 1884 Ma.

Towards the top of Cycle 2, the primitive Hellancourt basalts, generally correlated with the Willbob Formation further south, are a relatively straightforward continuation of the upper Chukotat sequence (e.g. Skulski et al., 1993).

The major Sokoman iron formation, and broadly correlative Superior-type iron formations elsewhere along the Circum-Superior Belt (e.g. Gunflint and Biwabik formations in Ontario and Minnesota), are coeval with the climax of the 1883–1880 Ma Chukotat event, indicating the likely global scale of perturbations in the ocean-atmosphere system. Iron formations near the base of the Cape Smith Belt, and the Roberts Syncline, and into the northern Labrador Trough (Fenimore Formation), must represent an older cycle of chemical sedimentation and possibly overlap in time with major perturbations such as the Lomagundi event. Melezhik et al. (1997) demonstrated that carbonates in the middle of Cycle 1 (Pistolet Group; subgroup in previous publications) are characterized by heavy $\delta^{13}C$ signatures above 10‰.

As is evident from this preliminary correlation exercise, numerous questions remain and the scope for exciting new work is enormous. High-precision zircon dating of key stratigraphic units, intrusive sills, and carefully selected detrital zircon samples is probably the most efficient way forward to test many of the questions and predictions raised here.