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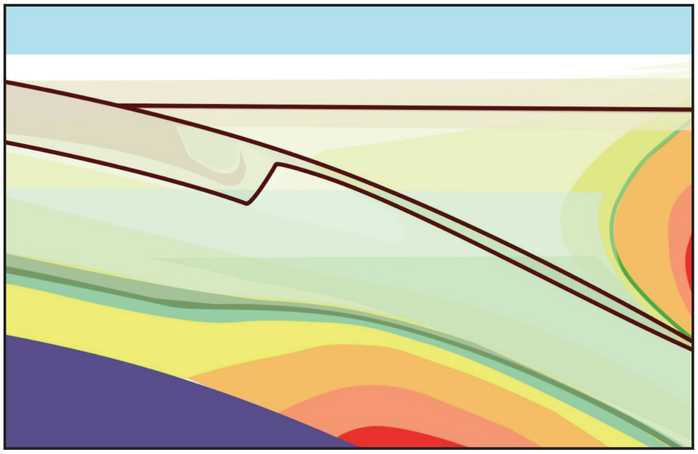
Cover Image: The classic view of James Hutton's unconformity at Siccar Point, Scotland. Gently dipping sandstone and breccia of the Devonian Stratheden Group (upper left) sit with profound discordance on subvertical turbiditic sandstone of the Silurian Gala Group. The tip of the hiking stick indicates the contact (photo: Andrew Kerr).

ANDREW HYNES SERIES: TECTONIC PROCESSES



Lithotectonic Framework of the Core Zone, Southeastern Churchill Province, Canada

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SUMMARY

The Core Zone, a broad region located between the Superior and North Atlantic cratons and predominantly underlain by Archean gneiss and granitoid rocks, remained until recently one of the less well known parts of the Canadian Shield. Previously thought to form part of the Archean Rae Craton, and later referred to as the Southeastern Churchill Province, it has been regarded as an ancient continental block trapped between the Paleoproterozoic Torngat and New Quebec orogens, with its relationships to the adjacent Superior and North Atlantic cratons remaining unresolved. The geochronological data presented herein suggest that the Archean evolution of the Core Zone was distinct from that in both the Superior and North Atlantic (Nain) cratons. Moreover, the Core Zone itself consists of at least three distinct lithotectonic entities with different evolutions, referred to herein as the George River, Mistinibi-Raude and Falcoz River blocks, that are separated by steeply-dipping, crustal-scale shear zones interpreted as paleosutures. Specifically, the George River Block consists of ca. 2.70 Ga supracrustal rocks and associated ca. 2.70–2.57 Ga intrusions. The Mistinibi-Raude Block consists of remnants of a ca. 2.37 Ga volcanic arc intruded by a ca. 2.32 Ga arc plutonic suite (Pallatin) and penecontemporaneous alkali plutons (Pelland and Nekuashu suites). It also hosts a coarse clastic cover sequence (the Hutte Sauvage Group) which contains detrital zircons provided from locally-derived, ca. 2.57–2.50 Ga, 2.37–2.32 Ga, and 2.10–2.08 Ga sources, with the youngest concordant grain dated at 1987 ± 7 Ma. The Falcoz River Block consists of ca. 2.89–2.80 Ga orthogneiss intruded by ca. 2.74–2.70 granite, tonalite, and granodiorite. At the western margin of the Core Zone, the George River Block and Kuujjuaq Domain may have been proximal by ca. 1.84 Ga as both appear to have been sutured by the 1.84–1.82 Ga De Pas Batholith, whereas at its eastern margin, the determination of metamorphic ages of ca. 1.85 to 1.80 Ga in the Falcoz River Block suggests protracted interaction with the adjacent Lac Lomier Complex during their amalgamation and suturing, but with a younger, 'New Quebec' overprint as well. The three crustal blocks forming the Core Zone add to a growing list of 'exotic' Archean to earliest Paleoproterozoic microcontinents and crustal slices that extend around the Superior Craton from the Grenville Front through Hudson Strait, across Hudson Bay and into Manitoba and Saskatchewan, in what was the Manikewan Ocean realm, which closed between ca. 1.83–1.80 Ga during the formation of supercontinent Nuna.

RÉSUMÉ

La Zone noyau, une vaste région située entre les cratons du Supérieur et de l'Atlantique Nord et reposant principalement

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sur des gneiss archéens et des roches granitiques, est demeurée jusqu'à récemment l'une des parties les moins bien connues du Bouclier canadien. Considérée auparavant comme faisant partie du craton archéen de Rae, puis comme la portion sud-est de la Province de Churchill, on l'a perçue comme un ancien bloc continental piégé entre les orogènes paléoprotérozoïques des Torngat et du Nouveau-Québec, ses relations avec les cratons supérieurs adjacents et de l'Atlantique Nord demeurant nébuleuses. Les données géochronologiques présentées ici permettent de penser que l'évolution archéenne de la Zone noyau a été différente de celle des cratons du Supérieur et de l'Atlantique Nord (Nain). De plus, la Zone noyau elle-même se compose d'au moins trois entités lithotectoniques distinctes avec des évolutions différentes, appelées ici les blocs de la rivière George, de Mistinibi-Raude et de la rivière Falcoz, lesquels sont séparées par des zones de cisaillement crustales à forte inclinaison, conçues comme des paléosutures. Plus précisément, le bloc de la rivière George est constitué de roches supracrustales d'env. 2,70 Ga, et d'intrusions connexes d'env. 2,70–2,57 Ga. Le bloc Mistinibi-Raude est constitué de vestiges d'un arc volcanique d'env. 2,37 Ga, recoupé par une suite plutonique d'arc d'env. 2,32 Ga (Pallatin) et de plutons alcalins péné-contemporains (suites Pelland et Nekuashu). Il contient également une séquence de couverture clastique grossière (le groupe Hutte Sauvage) renfermant des zircons détritiques de sources locales, âgés d'env. 2,57–2,50 Ga, 2,37–2,32 Ga et 2,10–2,08 Ga, le grain concordant le plus jeune étant âgé de 1987 ± 7 Ma. Le bloc de la rivière Falcoz est formé d'un orthogneiss âgé d'env. 2,89–2,80 Ga, recoupé par des intrusions de granite, tonalite et granodiorite âgées d'env. 2,74–2,70 Ga. À la marge ouest de la Zone noyau, le bloc de la rivière George et du domaine de Kuujjuaq peuvent avoir été proximaux il y a 1,84 Ga env., car les deux semblent avoir été suturés par le batholithe De Pas il y a environ 1,84–1,82 Ga, alors qu'à sa marge est, la détermination des datations métamorphiques de 1,85 à 1,80 Ga dans le bloc de la rivière Falcoz suggère une interaction prolongée avec le complexe adjacent du lac Lomier durant leur amalgamation et leur suture, mais affecté aussi d'une surimpression « Nouveau Québec » plus jeune. Les trois blocs crustaux formant la Zone noyau s'ajoutent à une liste croissante de micro-continents et d'écailles crustales « exotiques » archéennes à paléoprotérozoïques très précoces qui s'étalent autour du craton Supérieur depuis le front de Grenville jusqu'au Manitoba, à travers le détroit d'Hudson, la baie d'Hudson jusque dans le Manitoba et la Saskatchewan, là où s'étendait l'océan Manikewan, lequel s'est refermé il y a environ 1,83–1,80 Ga, pendant la formation du supercontinent Nuna.

Traduit par le Traducteur

INTRODUCTION

Much of the crustal growth of the interior of Laurentia (North American Precambrian continent) occurred by tectonic and magmatic accretion during the Paleoproterozoic, between ca. 2.0 and 1.8 Ga (Fig. 1). The resulting landmass consists of a collage of large, stable Archean cratons (Slave, Superior and North Atlantic), bound together by mobile belts (mostly components of the Churchill Province) that are composed of a mosaic of variably reactivated Archean crustal blocks (also referred to as 'cratons' or 'provinces') and microcontinents as well as juvenile Proterozoic crust, magmatic arcs, and intracratonic sedimentary basins (Hoffman 1988, 1990; Lewry and Collerson 1990; Rainbird 2004; St-Onge et al. 2006; Whitmeyer and Karlstrom 2007; Corrigan et al. 2009). The Churchill Province has been historically separated into a western part (Western Churchill Province) west of Hudson Bay, a central part situated north of Hudson Strait, and a southeastern arm (Southeastern Churchill Province), lying between the Superior and North Atlantic cratons south of Ungava Bay (Hoffman 1990). Earlier syntheses suggested that most of the Churchill Province was underlain by two distinct Archean crustal blocks termed the Rae and Hearne 'provinces' (e.g. Hoffman 1988), whereas subsequent models based on a large geochronological database and an interpretation of regional aeromagnetic lineaments permitted the identification of a collage of other distinct Archean to earliest-Paleoproterozoic crustal blocks confined within the mobile belts, including the Sask 'craton,' Sugluk 'block,' Meta-Incognita 'micro-continent' and Core Zone (Chiarenzelli et al. 1998; James and Dunning 2000; Hajnal et al. 2005; St-Onge et al. 2006; Corrigan et al. 2009). The Churchill Province is interpreted as the more or less contiguous area of the collage described above that was thermally and structurally affected by terminal collision with the Superior Craton during the interval 1.83 to 1.80 Ga (Lewry and Collerson 1990; Corrigan et al. 2009).

This paper presents a new synthesis of the Core Zone (Fig. 2), one of the Archean blocks or microcontinents forming the Churchill Province collage, and provides some speculations on its relationship with the bounding New Quebec and Torngat orogens. The results highlighted herein stem from recent 1:100,000-scale bedrock mapping in the Core Zone, led by the Ministère de l'énergie et des ressources naturelles du Québec (Hammouche et al. 2011; Simard et al. 2013; Lafrance et al. 2014), as well as thematic mapping by the Geological Survey of Canada under the auspices of the Geo-mapping for Energy and Minerals (GEM) program (Corrigan et al. 2015, 2016; Sanborn-Barrie et al. 2015; Sanborn-Barrie 2016). We present a synthesis of previous work and new bedrock geology observations, as well as U–Pb zircon ages that provide constraints on the crustal evolution of the Core Zone and its role in the tectonic evolution of the Churchill Province. Earlier work by Wardle and van Kranendonk (1996), Girard (1990a, b, c), James and Dunning (2000) and Simard et al. (2013), among others, has recognized the existence of a major network of sub-parallel to anastomosing shear zones separating elongate to lens-shaped blocks along the north-south extent of the Core Zone. We provide arguments suggesting that the Core Zone comprises at least three distinct Archean to earliest-Paleoproterozoic crustal blocks that are separated by sutures. We speculate on the crustal evolution of these crustal blocks, the timing of their amalgamation, their relationship with the flanking Superior and North Atlantic cratons, as well as their possible correlatives elsewhere in the Churchill Province.

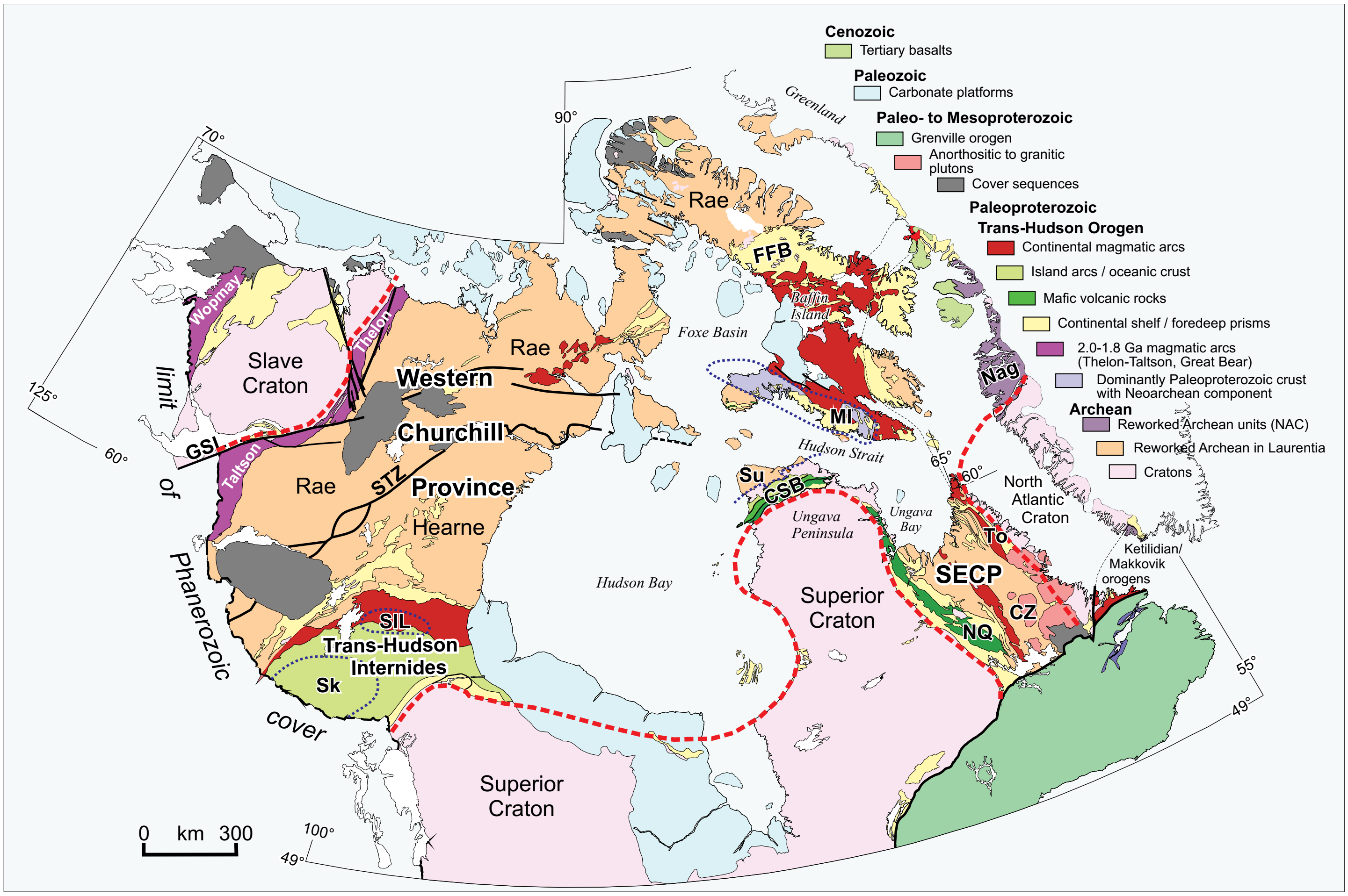

Figure 1. Simplified bedrock geology map of Laurentia. Abbreviations: CSB, Cape Smith Belt; CZ, Core Zone; FFB, Foxe Fold Belt; MI, Meta-Incognita microcontinent; Nag, Nagssugtoqidian Orogeny; NQ, New Quebec Orogen; SECP, Southeastern Churchill Province; SIL, Southern Indian Lake; Sk, Sask Craton (showing interpreted outline at MOHO); Su, Sugluk Block; To, Torngats Orogen. Map modified after Hoffman (1990).

REGIONAL SETTING

The Core Zone (Fig. 2) forms an ~ 500-km-long by ~ 200-km-wide crustal domain that is situated in the central part of the Southeastern Churchill Province. It has been interpreted as an elongate sliver of Archean continental crust (ribbon continent) that was accreted between the colliding Superior and North Atlantic cratons during the Paleoproterozoic (James et al. 1996; James and Dunning 2000; Wardle et al. 2002). It is flanked on its western side by the ca. 1.83–1.80 Ga New Quebec Orogen (Hoffman 1988; Perreault and Hynes 1990; Moorhead and Hynes 1990), and on its eastern side by the ca. 1.87–1.86 Ga Torngat Orogen (Wardle et al. 2002 and references therein). The extent to which it is affected by tectonism related to either of these orogens remains unclear, although the 'New Quebec' overprint appears to be more widespread. The earliest systematic mapping of the Core Zone was performed during 'Operation Torngat,' a helicopter-supported survey conducted by the Geological Survey of Canada that was completed in the late 1960s and resulted in the publication of a series of 1:250,000-scale bedrock maps (Taylor 1979). Lithological units on these maps consist mostly of Archean orthogneiss with minor paragneiss and plutonic rocks. Detailed mapping in the south-central part of the Core Zone by Girard (1990a, b) and van der Leeden (1994) highlighted the presence of supracrustal and plutonic rocks of low- to medium-metamorphic grade in the central part of the Core Zone (Mistinibi-Raude Block), with the supracrustal rocks hosting a plutonic unit that yielded a U–Pb zircon age of ca. 2.33 Ga (Girard 1990a). In addition, throughout the Core Zone, Girard (1990b) recognized the presence and significance of major, orogen-parallel ductile shear zones that separated distinct crustal blocks. Subsequently, James et al. (2003) and Hammouche et al. (2011) completed regional mapping and U–Pb geochronology on key protoliths in the southern part of the Core Zone north of Smallwood Reservoir. In the same area, Nunn et al. (1990) had previously recognized the presence of ca. 2.68–2.67 Ga tonalite and mafic volcanic rocks having minimal Proterozoic overprint, collectively suggesting variable degrees of tectonothermal overprint throughout the Core Zone, ranging from granulite to sub-greenschist facies. Bedrock geological mapping along the northern extents of the Core Zone was performed by Verpaelst et al. (2000) and Simard et al. (2013).

The Core Zone has historically been interpreted to encompass the entire span of Archean rocks exposed between Pale-

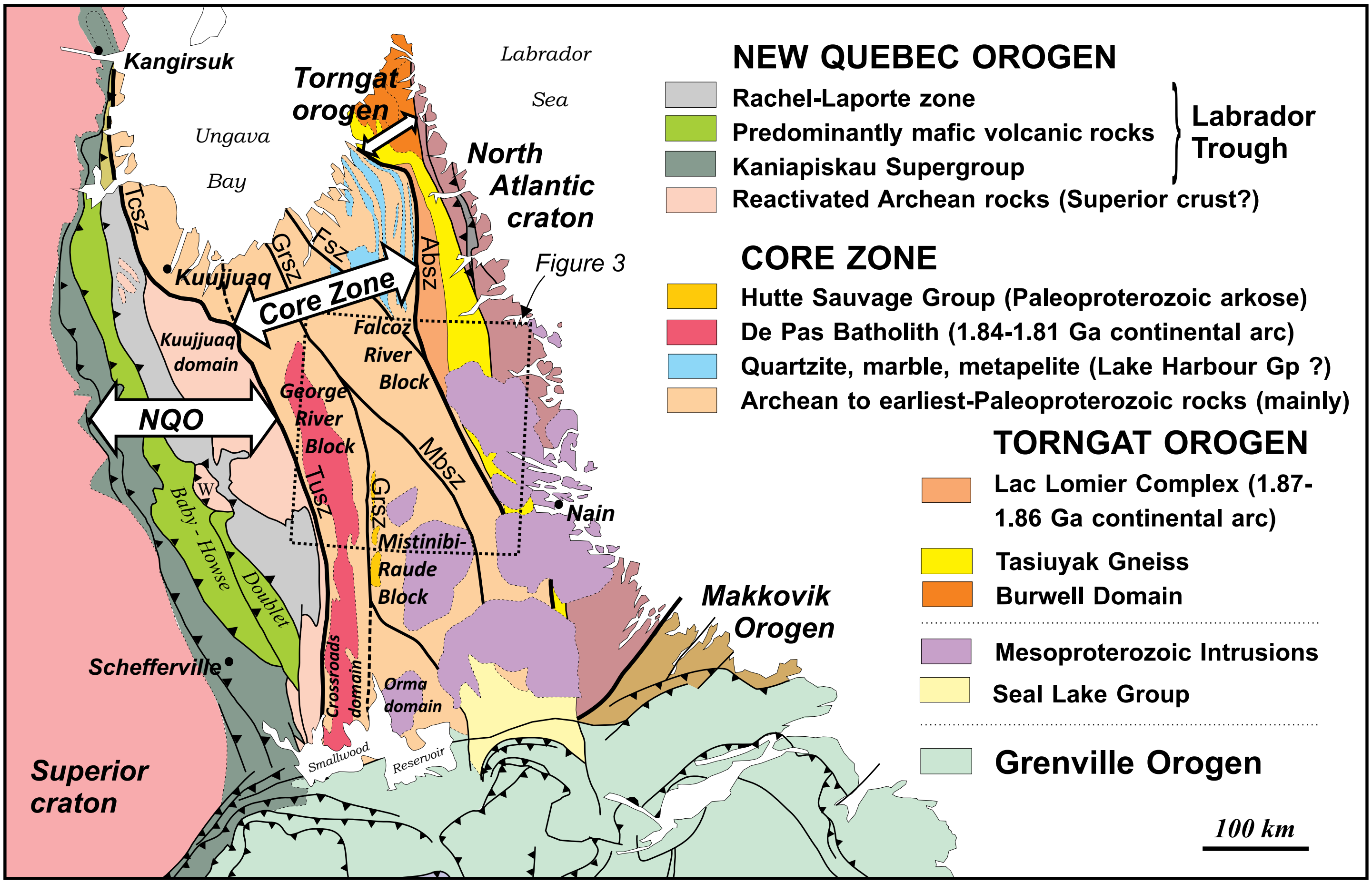

Figure 2. Simplified geological map of the Southeastern Churchill Province (SECP). Abbreviations as follows: Absz, Abloviak shear zone; Fsz, Falcoz shear zone; Grsz, George River shear zone; Mbsz, Moonbase shear zone; Tcsz, Lac Turcotte shear zone; Tusz, Lac Tudor shear zone; NQO, New Quebec Orogen; W, Wheeler dome. Location of Figure 3 shown in box. Modified after James and Dunning (2000).

oproterozoic rocks of the Labrador Trough to the west and the Lac Lomier domain to the east (Wardle and Van Kranendonk 1996). However, there are inherent uncertainties regarding this approach. Specifically, these concern the origin of Archean rocks exposed between the eastern edge of the Labrador Trough and the Lac Tudor shear zone (Fig. 2), and their potential affinity with the Superior Craton. That area, often referred to in the literature as "undivided Core Zone," has been interpreted by Poirier et al. (1990), Wardle et al. (2002) and Simard et al. (2013), based primarily on lithology and apparent continuity of aeromagnetic lineaments, as belonging to the Superior Craton. This interpretation is also supported by U–Pb ages recently obtained on various intrusions that suggest an affinity with the adjacent Superior Craton (Rayner et al. 2017). In addition, the Superior Craton can be traced around the northernmost lobe of the Labrador Trough north of Kangirsuq (Fig. 2), suggesting that it forms the direct basement beneath at least that part of the Trough. Moreover, basement domes and nappes with Superior crust affinities occur west of Kuujjuaq (Machado et al. 1989), and in a tectonic window in the central part of the Trough (Wheeler Dome). In this paper, we focus our attention on the geological framework of that part of the Core Zone situated between the Lac Tudor shear zone and the western edge of the Lac Lomier Complex, which we define herein as Core Zone *sensu stricto* (e.g. Wardle et al. 2002).

GEOLOGY OF THE CORE ZONE

For the most part, the Core Zone consists of variably transposed metaplutonic rocks, gneiss and migmatite that form North-South elongated crustal lenses, up to 500 km long and 100 km wide, separated by steeply dipping, ductile shear zones (Girard 1990b; Wardle and Van Kranendonk 1996). The metaplutonic rocks have yielded U–Pb ages ranging from 2.6 to 3.0 Ga (Nunn et al. 1990; Ryan et al. 1991; Isnard et al. 1998, 1999; James and Dunning 2000), with one of the crustal blocks (Mistinibi-Raude) hosting predominantly supracrustal and plutonic rocks with the latter yielding a significantly younger and from a global perspective, relatively unusual age of 2.33 Ga (Girard 1990a, c). Infolded remnants of a Paleoproterozoic cover sequence containing quartzite, marble, metapelite and rare ultramafic sills occur in the northeast part of the Core Zone and have been tentatively correlated with the Lake Harbour Group on Southern Baffin Island (Jackson and Taylor 1972; Scott and St-Onge 1998; Bourlon et al. 2002).

A ca. 1.84–1.82 Ga continental magmatic arc suite, the De Pas Batholith, occurs close to the western edge of the Core Zone and appears to be mostly confined to the George River Block (van der Leeden et al. 1990; Dunphy and Skulski 1996; James and Dunning 2000). Wardle et al. (2002) pointed out that negative ε_{Nd} values ranging from -7 to -3 obtained for the De Pas Batholith (Kerr et al. 1994; Dunphy and Skulski 1996) indicate significant contamination by Archean crust and suggested that parts of the batholith may be syn-collisional. The Core Zone is also host to a significant portion of the Mesoproterozoic Nain Plutonic Complex (Emslie and Hunt 1990). In the following sections we describe the various crustal blocks forming the Core Zone, which we define as the George River, Mistinibi-Raude and Falcoz River blocks. The George River Block correlates with the Crossroads and Orma domains identified farther south by James and Dunning (2000), and the Falcoz River Block amalgamates the Ford River, Henrietta, Anaktalik and Konrad Brook domains previously defined by Wardle et al. (2002) and references therein.

George River Block

The George River Block (Figs. 3 and 4), situated between the Lac Tudor and George River shear zones, is underlain by a distinct assemblage of metaplutonic and supracrustal rocks and is the main host to the ca. 1.84–1.82 Ga De Pas Batholith (Fig. 5A). Other than the batholith, its main lithology is the Archean (see below) Tunulik Belt (Lafrance et al. 2015), a supracrustal assemblage of mainly mafic to intermediate metavolcanic (Fig. 5B) and volcanogenic sedimentary rocks with rare felsic components. It also comprises a sub-volcanic plutonic root, composed of mixed, medium-grained, dioritic to granitic intrusions and quartz-feldspar porphyry (Fig. 5C), all intruded by megacrystic granite (Fig. 5D). The latter can be distinguished from the De Pas Batholith by its higher degree of recrystallization and migmatization. In contrast, the ca. 1.84–1.81 Ga De Pas Batholith is in general non-migmatitic, commonly preserving K-feldspar megacrysts in a weakly to moderately foliated matrix. Metamorphic assemblages are indicative of mid-amphibolite facies throughout the George River Block, and structural fabrics are generally oriented north-south, becoming more intense and progressively steeper towards the bounding shear zones. Some of the De Pas plutons contain orthopyroxene, but it is an igneous phase.

Falcoz River Block

Between the George River/Moonbase and Abloviak shear zones (Fig. 3) lies an area dominated by Archean rocks. This area has historically been divided into several domains based on dominant rock composition, metamorphic grade and/or presence of Paleoproterozoic-age cover sequences. These were named the Ford River, Henrietta Lake, Anaktalik and Konrad Brook domains by Wardle et al. (1990) and Wardle and Van Kranendonk (1996). Considering their similar age ranges and apparent continuity on aeromagnetic maps (see sections below) we group them all into the larger Falcoz River Block. The most common lithologies are meta-plutonic rocks, orthogneiss and migmatite (Fig. 5E) metamorphosed at upper-amphibolite facies. In its northern extents, the Falcoz River Block hosts distinct charnockite and enderbite plutons that retain most of their original igneous feldspars (only partially recrystallized) and are interpreted as Proterozoic-age intrusions, possibly related to the Cumberland Batholith on Baffin Island (Bourlon et al. 2002). Throughout this block, strain is variable, displaying fabrics becoming progressively more transposed near bounding shear zones. In its eastern part, the Falcoz River Block contains a greater abundance of late-Archean (see below) granite intrusions, as well as a widespread cover sequence that comprises quartzite, metapelite and marble, with mafic and ultramafic sills near their base. This supracrustal sequence has been tentatively correlated with the Lake Harbour Group on Southern Baffin Island (Jackson and Taylor 1972; Scott and St-Onge 1998). The metamorphic facies in the eastern part of the domain is uppermost-amphibolite to incipient granulite facies. The fact that biotite-out reactions have occurred in metapelites of potential Lake Harbour Group affinity, as well as evidence for orthopyroxene-in reactions in mafic rocks, suggests that > 800°C temperatures have been reached during the Paleoproterozoic, at least locally. However, the possibility that granulite facies conditions may have also occurred during the Archean cannot be ruled out. Fabrics in the eastern half of the Falcoz River Block are relatively flat to shallow-dipping, forming dome and basin structures that are slightly elongated along a north-south axis. These structures progressively steepen towards the Falcoz and Abloviak shear zones, as well as towards their contact with the Lac Lomier Complex.

Mistinibi-Raude Block

The Mistinibi-Raude Block (Fig. 3) is situated between the Moonbase and George River shear zones and is compositionally and metamorphically distinct from the George River and Falcoz River blocks. It consists of a supracrustal belt (Ntshuku Belt) composed mainly of mafic metavolcanic rocks (Fig. 5F), with minor meta-andesite and rhyolite, associated with staurolite-garnet-cordierite-bearing metapelite, psammite and calc-silicate gneiss (Fig. 6A). The supracrustal rocks are intruded by a distinct suite of calc-alkaline sub-volcanic metaplutonic rocks that includes feldspar- and hornblende-phyric diorite, granodiorite and monzogranite (Pallatin suite), for which a preliminary U–Pb zircon age of ca. 2.33 Ga has been reported (Girard 1990a). The existence of a second, slightly more alkaline plutonic suite is suggested by the presence of large composite intrusions that consist of gabbro, monzogabbro, diorite, monzodiorite, quartz syenite, and augite syenite. Silica-saturated rocks of that suite commonly contains blue, rutilated quartz, as well as rare orthopyroxene- and blue quartz-bearing pegmatite, suggestive of emplacement at very high temperatures under locally anhydrous conditions. That more alkaline suite coincides with two strong magnetic anomalies on regional airborne aeromagnetic surveys (Fig. 4) that have been referred to as the Nekuashu and Pelland plutons (Lafrance et al. 2015, 2016). The Mistinibi-Raude Block also hosts a fluvial clastic sedimentary sequence, the Hutte Sauvage Group (van der Leeden 1994), which comprises meta-conglomerate and

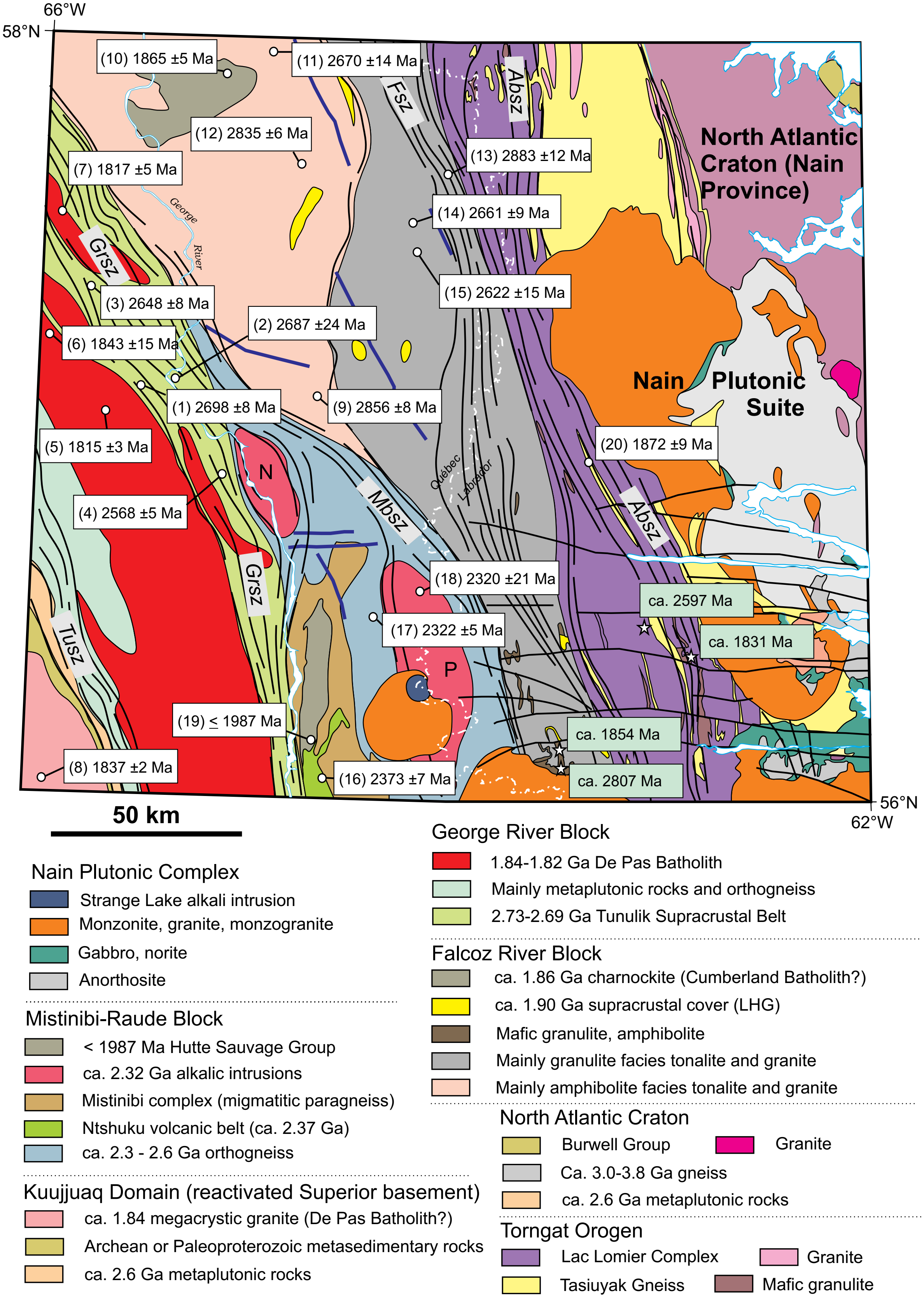

Figure 3. Bedrock geology map of the central part of the Core Zone and adjacent areas. Discontinuous black form lines show the location of high strain zones. U–Pb ages in white boxes are keyed to sample numbers in the text. Ages shown in the light blue boxes in the southeastern area are from Ryan et al. (1991). Absz, Abloviak shear zone; Fsz, Falcoz shear zone; Grsz, George River shear zone; Mbsz, Moonbase shear zone; Tusz, Lac Tudor shear zone.

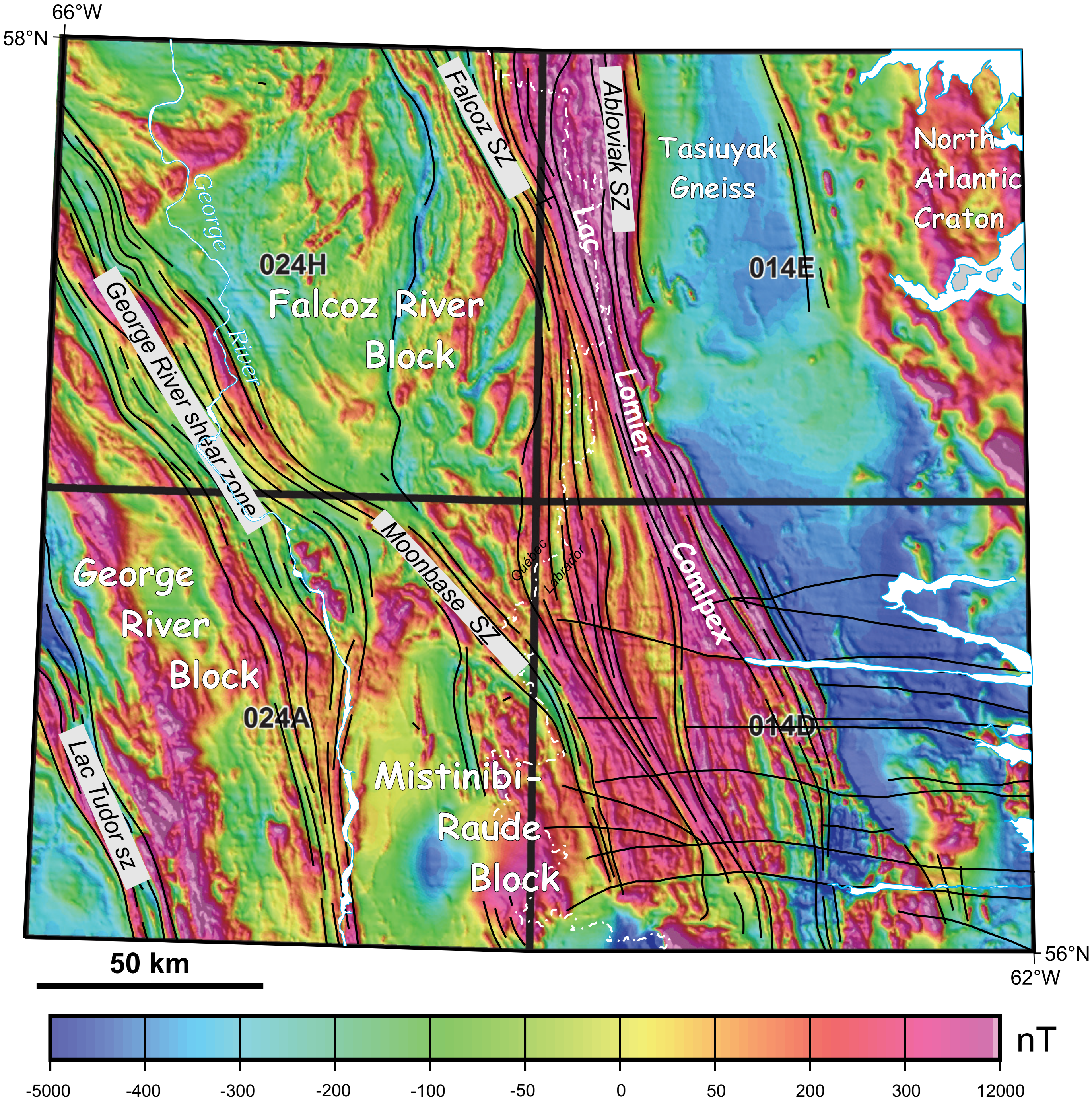

Figure 4. Coloured total-field aeromagnetic map of the central part of the Core Zone. Brittle E–W faults and ductile shear zones are highlighted with black form lines. Geological Survey of Canada database. 1:250,000-scale NTS map areas 014D, 014E, 024A and 024H are shown.

locally cross-bedded meta-arkose and quartzite (Fig. 6B). It was interpreted by Girard (1990a) as a post-1820 Ma sedimentary sequence based on the presence of clasts of K-feldspar megacrystic granite inferred to have been derived from the De Pas Batholith. Metamorphism within the Mistinibi-Raude Block ranges from lower to upper amphibolite facies.

Lac Lomier Complex

The Lac Lomier Complex bounds the Core Zone on its eastern side. It consists of metaplutonic rocks and orthogneiss of predominantly intermediate composition, but ranging overall from mafic to felsic in composition that is banded at the centimetre to metre scale. These rocks are metamorphosed at granulite facies, giving them a waxy green to light brown colour, and characteristically have orthopyroxene and hornblende as the main mafic phases (Fig. 6C).

The Lac Lomier Complex has been interpreted by Wardle et al. (1990) as a ca. 1.87 to 1.86 Ga continental arc emplaced

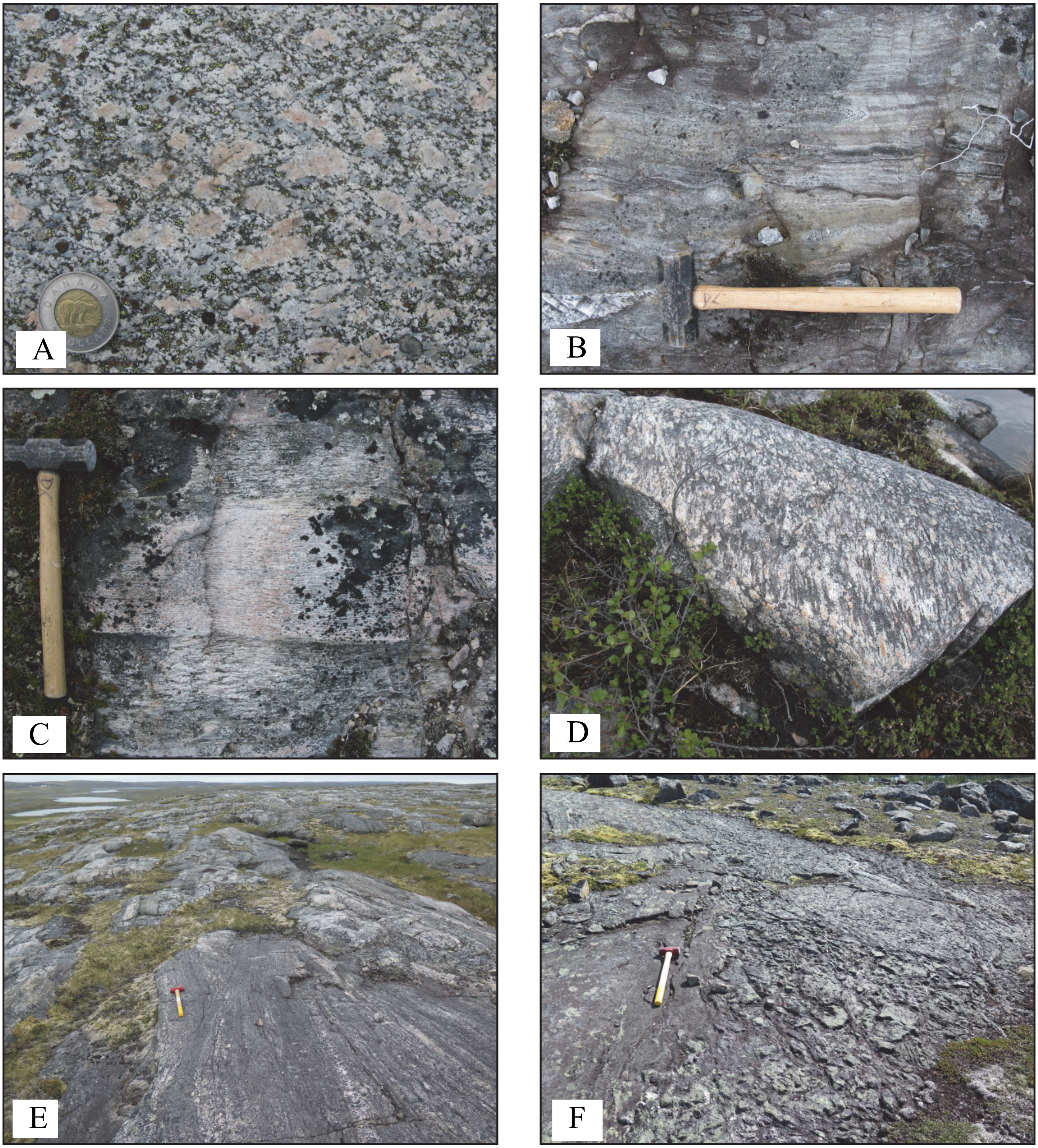

Figure 5. Field photographs from the Core Zone. A) K-feldspar megacrystic, hornblende-biotite granite from the De Pas Batholith. Coin for scale is 28 mm in diameter. B) Intermediate to felsic volcaniclastic rock outcrop from the Tunuliq Belt. Hammer for scale is 38 cm long. C) Sub-volcanic quartz-feldspar porphyry phase of the Tunuliq Belt (center of the photograph) intruding a coarser-grained granodioritic intrusion of likely similar age. Hammer for scale is 38 cm long. D) Metamorphosed and recrystallized K-feldspar megacrystic granite that intrudes metavolcanic rocks of the Tunuliq Belt (geochronology Sample 4). Base of photograph is 1.5 m across. E) Field photograph of a typical outcrop in the Falcoz River Block, showing variably transposed orthogneiss. Hammer for scale is 38 cm long. F) Outcrop photograph of flow breccia (right side of photo) in Ntshuku Belt basaltic rock. Hammer for scale is 38 cm long.

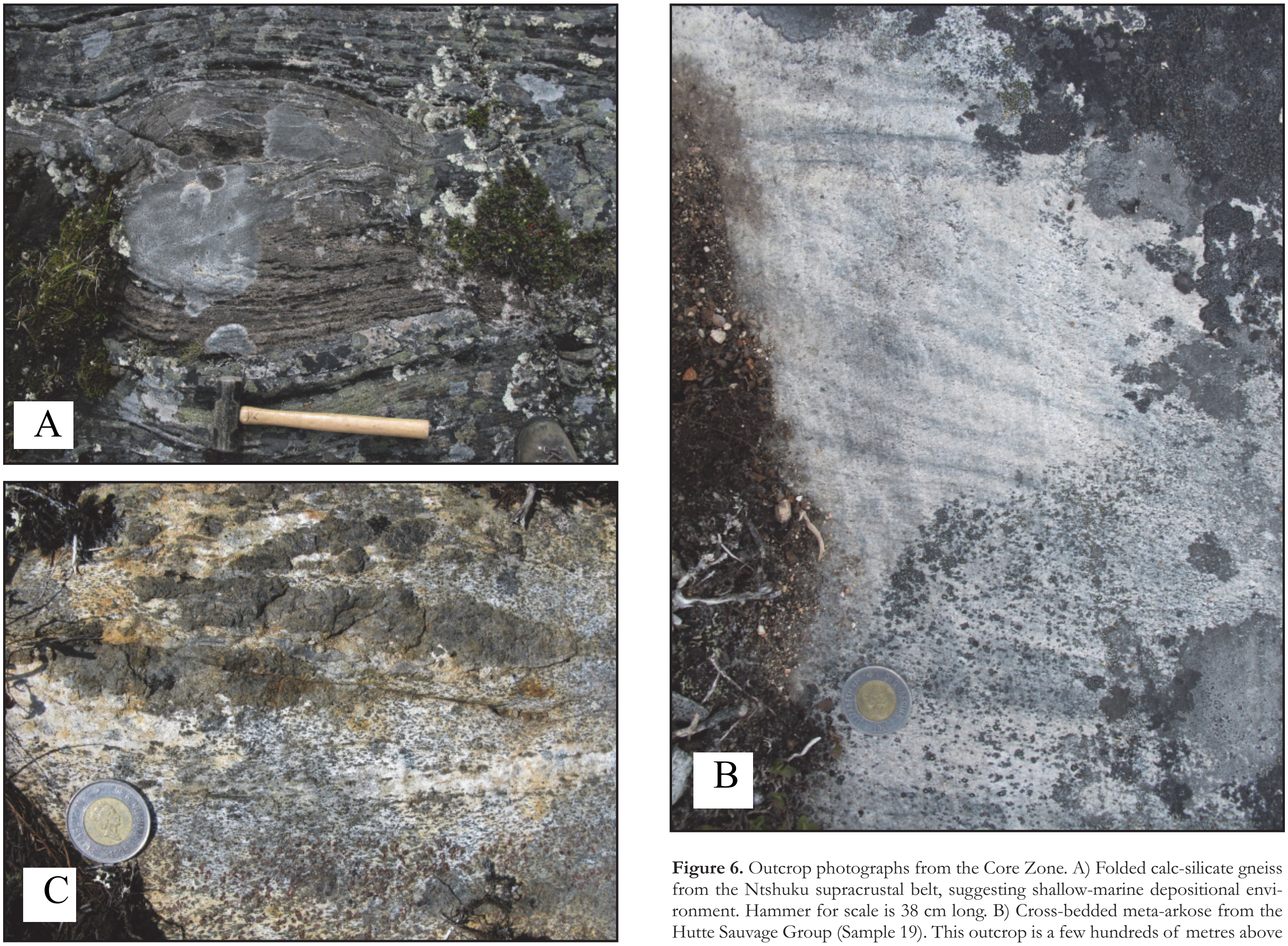

Figure 6. Outcrop photographs from the Core Zone. A) Folded calc-silicate gneiss from the Ntshuku supracrustal belt, suggesting shallow-marine depositional environment. Hammer for scale is 38 cm long. B) Cross-bedded meta-arkose from the Hutte Sauvage Group (Sample 19). This outcrop is a few hundreds of metres above a conglomerate horizon. Coin for scale is 28 mm in diameter. C) Very large orthopyroxene crystals (brown colour, top of photograph) in mafic to intermediate granulite of the Lac Lomier Complex. Coin for scale is 28 mm in diameter.

on the western margin of the North Atlantic Craton. The presence of map-scale screens of metapelitic rocks, likely derived from the Tasiuyak Gneiss, lends support to that interpretation. Overall, the Lac Lomier Complex is highly strained, with the very strong transposition of lithological layers forming a steeply-dipping gneiss with a pervasive, sub-horizontal mineral and stretching lineation. Kinematic indicators show a consistent dextral strike-slip sense of shear. Its contact with the Falcoz River Block is relatively sharp and appears to be structural.

ANALYTICAL PROCEDURES

Two different analytical techniques, performed in separate laboratories, were used to generate U–Pb ages. Eleven samples were analyzed using the sensitive high-resolution ion microprobe (SHRIMP) at the Geological Survey of Canada (GSC), and nine samples were analyzed by laser ablation, inductively coupled plasma mass spectrometry (LA-ICPMS) at the Department of Earth Sciences, University of New Brunswick. Four samples from the George River Block (samples 1, 3, 4 and 5), one from the Falcoz River Block (Sample 9), four from the Mistinibi-Raude Block (samples 16 to 19), and one from the Lac Lomier Complex (Sample 20) were analyzed using SHRIMP. The zircon separates were prepared using standard crushing, grinding, Wilfley$^{\text{TM}}$ table, and heavy liquid techniques, followed by magnetic susceptibility sorting using a Frantz$^{\text{TM}}$ isodynamic separator. SHRIMP analytical procedures followed those described by Stern (1997), utilizing standards and U–Pb calibration methods following Stern and Amelin (2003). Briefly, zircons were cast in 2.5 cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon (z6266, with a ^{206}Pb/^{238}U age of 559 Ma). The mid-sections of the zircon grains were exposed and polished using 9, 6, and 1 μm diamond compound, and the internal features of the grains (such as zoning, structures, alteration, etc.) were imaged in back-scattered electron mode (BSE) or in cathodoluminescence (CL) utilizing a Zeiss Evo 50 scanning electron microscope. Mount surfaces were evaporatively coated with 10 nm of high-purity Au. Analyses were conducted using a ^{16}O- primary beam, projected onto the zircon at 10 kV. The count rates at eleven masses, including background, were sequentially measured with a single electron multiplier. Off-line data processing was accomplished using SQUID2 (version SQUID 2.50.11.10.15, rev. 15 Oct. 2011) software written by Ludwig (2003). The 1σ external errors of ^{206}Pb/^{238}U ratios reported in supplementary data Table S-1 incorporate the error in calibrating the standard. The common Pb correction utilized Pb composition of the surface blank (Stern 1997). Yb and Hf concentration data were calculated using sensitivity factors derived from standard z6266 with values of 69 and 8200 ppm, respectively. Analyses of a secondary internal zircon standard (z1242, with an accepted age of 2679.7 ± 0.2 Ma (B. Davis, personnel communication)) were interspersed between the sample analyses to monitor Pb isotopic fractionation. Isoplot v. 4.15 (Ludwig 2003) was used to generate Concordia plots and the probability density diagram for detrital Sample 19, and to calculate weighted means. The error ellipses on the Concordia diagrams and the weighted mean errors are reported at 2σ.

U–Pb analyses for samples 2, 6, and 7 from the George River Block, and samples 10 to 15 from the Falcoz River Block were processed at the Department of Earth Sciences geochronology laboratory, University of New Brunswick. Zircon U–Pb dating was carried out using a Resonetics RESOlution M-50 series 193 nm excimer laser ablation system equipped with a Laurin Technic Pty S-155 ablation cell. Ablation was conducted in a mixed He (325 mL/min) and Ar (930 mL/min) carrier gas and mixed with N_2 (2 mL/min) downstream of the cell. Contamination at mass 204 from Hg in the carrier gases was < 150 cps. Data listed in supplementary Table S-2 were collected using either 17 or 24 µm diameter laser crater depending on the size of the grains, a repetition rate of 4.5 Hz, and laser fluence of ~ 4 J/cm^2. The data were standardized against FC1 zircon (1099 ± 2 Ma) which was distributed evenly throughout the sequence and analyzed at least 16 times per run. Each ablation was 35 seconds in duration and was preceded by 40 sec of background collection. Ablated aerosol was transferred to the ICP-MS using nylon tubing with an in-line 'squid' smoothing device connected immediately before the junction with the ICP-MS torch. Isotope intensities were measured using an Agilent 7700x quadrupole-ICP-MS operated in 'auto' detector mode: sensitivity and P/A factors were tuned by rastering across NIST610 glass before the start of each run. A second external rotary pump was used to enhance sensitivity. The ICP-MS method measured ^{90}Zr, ^{202}Hg, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U with a total quadrupole sweep time of 0.23 seconds. The background corrected ^{202}Hg ion beam measured during ablation was used to peak strip any small excess ^{204}Hg from the ^{204}Pb signal using the ^{202}Hg/^{204}Hg measured on the gas background. The magnitude of this correction was typically insignificant. The data were reduced offline using VizualAge (Petrus and Kamber 2012) and Iolite v2.5 (Paton et al. 2011) running as plugins in Wavemetrics Igor Pro 6.23. Concentration data were calculated relative to NIST610 (distributed throughout the sequence) and using the Iolite trace-elements "internal standardization" data reduction scheme. An estimated value of 44 wt% Zr in zircon was used as the internal standard composition. Common Pb was corrected using the background-corrected and Hg-interference corrected ^{204}Pb intensity, a common-Pb composition based on the Pb–Pb evolution curve of Stacey and Kramers (1975) and an estimate of the age of the zircon based on the uncorrected ^{206}Pb/^{238}U age. This correction method is suitable for grains with modest common-Pb content and minor Pb-loss. The %Pb* estimate reported in supplementary data Table S-2 was taken from the Andersen (2002) routine implemented in VizualAge. A summary of U–Pb ages is presented in Table 1.

RESULTS

Samples for dating were principally collected from the George River, Mistinibi-Raude and Falcoz River blocks of the Core Zone *sensu stricto*, with one each coming from the adjacent Kuujjuaq Block and Lac Lomier Complex to the west and east, respectively.

George River Block

Seven rock units were sampled from the George River Block, providing age constraints on the Tunulik volcanic belt, gneiss and migmatite associated with this belt, as well as late plutonism interpreted to be associated with the De Pas Batholith. Results are as follows:

Sample 1: Tunulik Meta-Rhyolite (14CXA-D90A1; SHRIMP)

The Tunulik meta-rhyolite is medium-grained, well-foliated and metamorphosed at mid- to upper amphibolite facies. It yielded numerous, clear, colourless, short prismatic zircon grains with internal oscillatory growth zoning and thick to thin unzoned rims likely of metamorphic origin (Fig. 7A). Thirty of the 32 U–Pb SHRIMP analyses fall into two main groupings with oscillatory zoned material yielding a weighted mean ^{207}Pb/^{206}Pb age of 2698 ± 8 Ma (n = 20/23; MSWD = 1.20, probability of fit (POF) = 0.25), interpreted as the timing of volcanism, and unzoned rims giving a weighted mean age of 2543 ± 20 Ma (MSWD = 0.28, POF = 0.92), interpreted as the time of metamorphic zircon crystallization or recrystallization. The two oldest analyses from this sample, with low U contents (17–19 ppm) and strongly discordant ages of 2855 and 2807 Ma, are interpreted to represent xenocrystic material.

Sample 2: Migmatitic Granodiorite (14CXA-D92A1; LA-ICPMS)

Sample 2 is from a complex outcrop that includes gneissic and migmatitic orthogneiss of predominantly felsic to intermediate composition. Field relationships suggest that it may comprise the oldest component of the George River Block and a granodiorite paleosome was sampled for dating. This sample contained small (10–150 µm long and approximately 50 µm wide) colourless to pale brown to dark brown zircons. Numerous grains are murky and turbid and moderately cracked. High-U cores surrounded by reddish-brown damage zones are locally visible in the transmitted light image. The cathode luminescence (CL) response is strongly quenched (high U content) and a combination of faint planar and locally oscillatory zoning is visible. The U–Pb data for this sample displays a combination

Table 1. Summary of U–Pb ages from the Core Zone, Southeastern Churchill Province, Canada.

								NAD 83		
Sample #	**Field number**	**Rock type**	**Belt/Suite**	**Crustal block**	**Age (Ma)***	**Method**	**Lab**	**Easting**	**Northing**	**Zone**
1	14CXA-D90A1	Meta-rhyolite	Tunulik	George River	2698 ± 8 p 2543 ± 20 m	SHRIMP	Ottawa	346644	6330719	20
2	14CXA-D92A1	Migmatitic granodiorite		George River	2687 ± 24 p 1731 ± 24 m	LA-ICP-MS	UNB	358780	6330859	20
3	14CXA-D75A1	Quartz-feldspar Porphyry	Tunulik	Greoge River	2648 ± 8 p 1831 ± 12 m	SHRIMP	Ottawa	333598	6357440	20
4	14CXA-D46A1	Megacrystic granite		George River	2568 ± 5 p	SHRIMP	Ottawa	372193	6302686	20
5	14CXA-D42A1	Ultrapotassic intrusion	De Pas Batholith	George River	1815 ± 3 p	SHRIMP	Ottawa	338374	6321438	20
6	SB-4053-A13	Megacrystic granodiorite	De Pas Batholith	George River	1843 ± 15 p? 1773 ± 7 m	LA-ICP-MS	UNB	321570	6354669	20
7	LP-2108-A13	Massive granite, med. gr.	De Pas Batholith	George River	1817 ± 5 p	LA-ICP-MS	UNB	344254	6375188	20
8	14CXA-D6A1	Megacrystic granite	De Pas Batholith?	Kuujjuaq Domain	1837 ± 2 p	SHRIMP	Ottawa	318992	6213758	20
9	14CXA-D97B1	Tonalite gneiss		Falcoz River	2856 ± 8 p 1845 ± 3 m	SHRIMP	Ottawa	399834	6325559	20
10	DB-1057-A13	Tonalite	Simitalik	Falcoz River	1865 ± 5 p	LA-ICP-MS	UNB	374480	6416931	20
11	LP-2049-A13	Granodiorite	Simitalik	Falcoz River	2841 ± 13 i? 2670 ± 14 p 1844 ± 15 m	LA-ICP-MS	UNB	386899	6423346	20
12	CB-5063-A13	Foliated granodiorite	Simitalik	Falcoz River	2835 ± 6 p	LA-ICP-MS	UNB	387578	6395018	20
13	IL-3157-A13	Enderbitic gneiss	Sukaliuk	Falcoz River	2883 ± 12 p 1768 ± 52 m	LA-ICP-MS	UNB	439232	6392190	20
14	BC-6179-A13	Massive enderbite	Innuluttalik	Falcoz River	2832 ± 21 i? 2661 ± 9 p 1808 ± 86 m	LA-ICP-MS	UNB	427923	6377552	20
15	SB-4161-A13	Tonalitic gneiss	Sukaliuk	Falcoz River	2622 ± 15 p 1718 ± 98 m	LA-ICP-MS	UNB	429457	6368209	20
16	14CXA-D94A1	Plagioclase-hornblende porphyry	Ntshuku	Mistinibi-Raude	2373 ± 7 p 2317 ± 8 m	SHRIMP	Ottawa	401577	6213626	20
17	14CXA-D72A1	K-feldspar megacrystic monzogranite	Pelland	Mistinibi-Raude	2322 ± 5 p 2093 ± 17 m	SHRIMP	Ottawa	416187	6260623	20
18	14CXA-D68B1	Granophyric gabbro	Pelland	Mistinibi-Raude	2320 ± 21 p 2053 ± 13 m	SHRIMP	Ottawa	429482	6267957	20
19	14CXA-D18A1	Meta-arkose	Hutte Sauvage	Mistinibi-Raude	< 1987 ± 7 d	SHRIMP	Ottawa	398026	6224724	20
20	14CXA-D30C2	Monzogranite dyke	Lac Lomier	Torngat Orogen	1872 ± 9 p	SHRIMP	Ottawa	479855	6305985	20

*Letters in the 'Age (Ma)' column are: i = inheritance age; m = metamorphic age; p = protolith age.

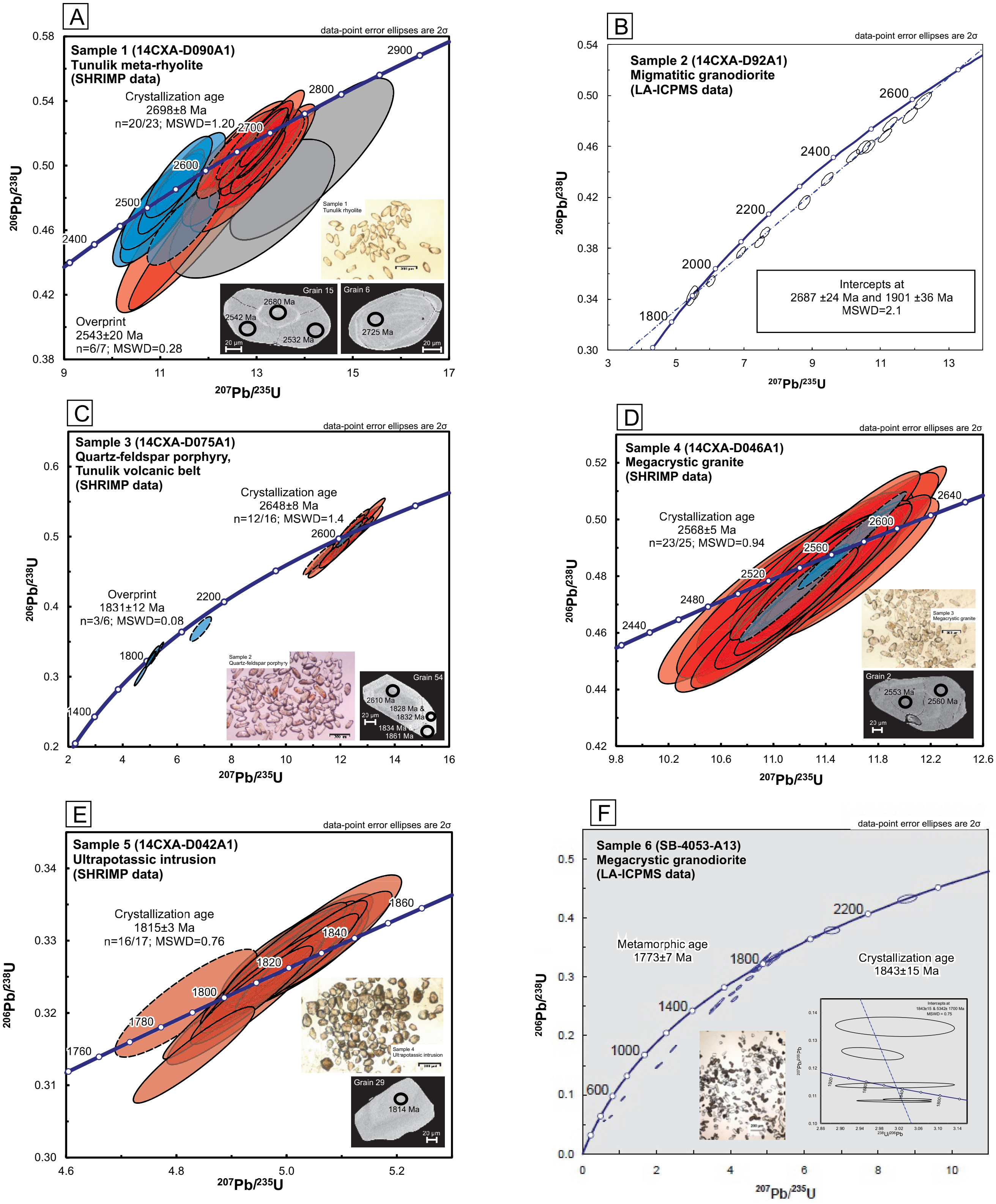

Figure 7. Concordia diagrams (2σ errors), transmitted light images of zircon, and/or BSE SEM images of representative zircon crystals for rock units from the George River Block. A) SHRIMP data for Tunulik meta-rhyolite Sample 1; B) LA-ICP-MS data for Sample 2, a granodiorite paleosome; C) SHRIMP data for quartz-feldspar porphyry Sample 3; D) SHRIMP data for megacrystic granite Sample 4; E) SHRIMP data for ultrapotassic intrusion Sample 5; F) LA-ICP-MS data for Sample 6, a megacrystic granodiorite from the De Pas Batholith. In SHRIMP Concordia diagrams, red ellipses correspond to analyses from magmatic zircon, blue ellipses to recrystallized or newly grown zircon, and grey ellipses to xenocrystic zircon or inherited components within zircon. Dashed ellipses not included in weighted mean age calculations. In BSE SEM images, circles indicate approximate locations of analyses with corresponding ^{207}Pb/^{206}Pb ages.

of recent and ancient Pb-loss as well as the effects of small and variable common-Pb incorporation (Fig 7B). To avoid effects of common-Pb incorporation, the data were filtered to consider only analyses that encountered > 98% Pb* (as estimated using the Andersen (2002) routine in VizualAge) as well as ^{206}Pbcps/^{204}Pbcps > 1000. This yielded a subset of data that defines a discordia with an upper intercept of ~ 2700 Ma and a lower intercept of ~ 1800 Ma. The Isoplot 'residuals' technique was used to refine this discordia to a statistically meaningful (MSWD = 2.1) regression line with an upper intercept of 2687 ± 24 Ma and a lower intercept 1901 ± 36 Ma.

Sample 3: Sub-volcanic Quartz-Feldspar Porphyry (14CXA-D75A1; SHRIMP)

Supracrustal rocks of the Tunulik Belt are intruded by sheets and dykes of mostly felsic quartz-feldspar porphyry that were interpreted in the field as sub-volcanic intrusions (Fig. 5C). They are mostly recrystallized except for the up to 5–10 mm-sized phenocrysts which locally preserve unrecrystallized cores. Sample 3 was taken near the George River shear zone, where different rocks of the Tunulik Belt are transposed into sub-parallelism and have been metamorphosed at mid- to upper-amphibolite facies during deformation. Zircon crystals form euhedral, short to elongate prisms with well-developed internal oscillatory zoning. Several grains have bright, thin to thick rims (see Fig. 7C). The twelve oldest SHRIMP U–Pb analyses of oscillatory zoned zircon yield a weighted mean age of 2648 ± 8 Ma (n = 12/16; MSWD = 1.4, POF = 0.16) interpreted as the crystallization age of the porphyry. Analyses of the bright rims yield a range of concordant to discordant ages between 2613 and 1828 Ma. The three youngest analyses from this population give a weighted mean age of 1831 ± 12 Ma (MSWD = 0.083, POF = 0.92) interpreted as the time of deformation and amphibolite facies metamorphism along the George River shear zone. The other three rim analyses with ages > 1861 Ma were excluded from the weighted mean as they may reflect incomplete resetting of the U–Pb system during metamorphic recrystallization.

Sample 4: Recrystallized Megacrystic Granite (14CXA-D46A1; SHRIMP)

Sample 4 is from a megacrystic granite that intrudes the Tunulik Belt and associated metaplutonic and gneissic rocks. It compositionally resembles the K-feldspar megacrystic rocks of the De Pas Batholith but, in contrast to the latter, contains totally recrystallized K-feldspar megacrysts (Fig. 5D) and appears to have been affected by a more complex metamorphic and deformation history. Zircons from this rock occur as euhedral to subhedral, short to elongate prisms that exhibit mostly diffuse oscillatory zoning. A subset of grains has bright rims. All U–Pb SHRIMP analyses, from both oscillatory zoned interior regions and bright rims, define a relatively tight grouping (Fig.7D) indicating that the observed internal structure reflects compositional zonation. Excluding the two high-U, precise rim analyses, the remaining 23 analyses yield a weighted mean age of 2568 ± 5 Ma (MSWD = 0.94; POF = 0.54), interpreted as the crystallization age of the megacrystic granite. This age is slightly older than, but within error of, the age of metamorphic rims from the Tunulik meta-rhyolite (Sample 1), indicating a potential link between emplacement of the Archean megacrystic granite and regional metamorphism in the George River Block.

Sample 5: Ultrapotassic Intrusion, De Pas Batholith (14CXA-D042A1; SHRIMP)

This very weakly deformed, biotite and K-feldspar rich, locally riebeckite- and epidote-bearing plutonic rock is spatially associated with the De Pas Batholith but its temporal relationship with it remains obscure. Zircon from this rock occurs as glassy, colourless to light brown, subrounded, anhedral to subhedral fragments. A number of grains exhibit faint broad zoning. U–Pb SHRIMP analyses on 16 of 17 zircon fragments yielded a weighted mean age of 1815 ± 3 Ma (MSWD = 0.76, POF = 0.72), interpreted as the age of crystallization (Fig. 7E). This age is distinctly younger than the mostly 1840–1830 Ma age range reported for the De Pas Batholith (e.g. Wardle et al. 2002; this paper), and could indicate the presence of a later, more metasomatized phase of the intrusion.

Sample 6: Megacrystic Granodiorite, De Pas Batholith (SB-4053-A13; LA-ICPMS)

This sample is from a moderately foliated K-feldspar megacrystic granodiorite from the northern part of the De Pas Batholith (Fig. 3). It contains murky-brown to pale brown zircons that form prisms with slightly rounded edges. Analyses show abundant Pb-loss in the majority of grains (Fig. 7F), but the five spots shown in the inset on the figure define an inverse isochron lower-intercept age of ~ 1843 ± 15 Ma, interpreted as age of emplacement. A younger array of normally-discordant spots defines an upper intercept age of 1773 ± 7 Ma, interpreted as the age of metamorphism. This crystallization age, together with the previous sample (Sample 5) corroborates with the known age range of the De Pas Batholith, which is generally accepted as ca. 1.84–1.82 Ga (Wardle et al. 2002).

Sample 7: Massive Granite, De Pas Batholith (LP-2108-A13; LA-ICPMS)

Sample 7 is a homogeneous, medium-grained, weakly foliated granite that represents a late phase of the De Pas Batholith. The zircons are long prismatic grains with rounded edges and are murky to light brown. LA-ICP-MS analyses have yielded a set of near-concordant points lying along an array between 1900 and 1750 Ma (Fig. 8A), with a cluster of five overlapping concordant points at 1817 ± 5 Ma, interpreted as the age of the intrusion. Another subset of points shows an inheritance at about 2.6 Ga. Data points trailing to older ages may represent inadvertent incorporation of older inherited components, whereas data points trailing down towards younger ages could represent either ancient Pb-loss or placement of spots astride narrow younger overgrowths.

Sample 8: K-feldspar Megacrystic Granite (14CXA-D6A1; SHRIMP)

Sample 8 is from a K-feldspar-megacrystic granite that has

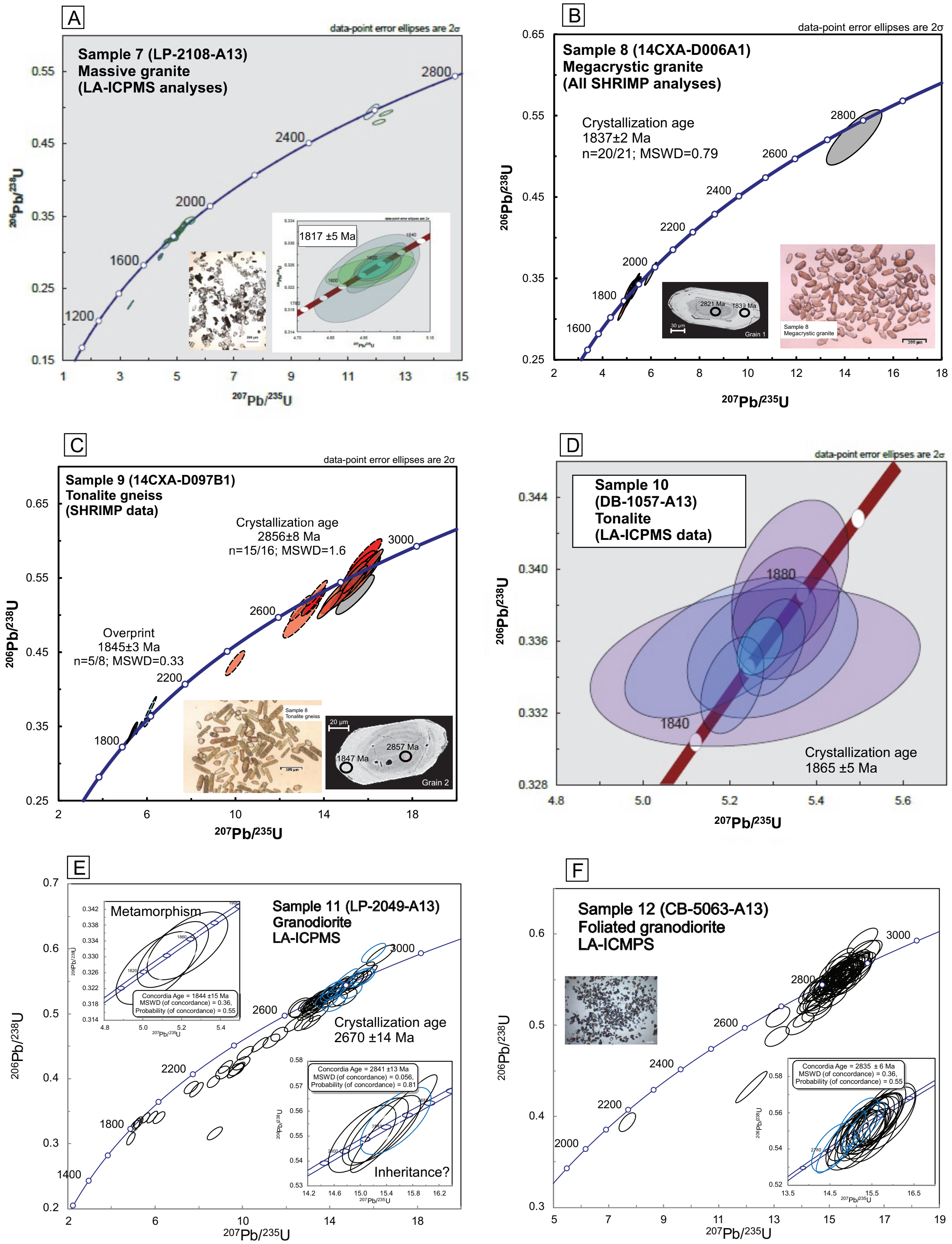

Figure 8. Concordia diagrams (2σ errors), transmitted light images of zircon, and/or BSE SEM images of representative zircon crystals for rock units from the George River and Falcoz River blocks, as well as Kuujjuaq Domain. A) LA-ICP-MS data for Sample 7, a late, massive granite phase of the De Pas Batholith, George River Block; B) SHRIMP data for K-feldspar megacrystic granite Sample 8, Kuujjuaq Domain; C) SHRIMP data for Sample 9, a tonalite gneiss from the Falcoz River Block; D) LA-ICP-MS data from Sample 10, a tonalite from the Simitalik Suite in the Falcoz River Block; E) LA-ICP-MS data from Sample 11, a foliated granodiorite from the Falcoz River Block; F) LA-ICP-MS data from Sample 12, a foliated granodiorite from the Falcoz River Block. In SHRIMP Concordia diagrams, red ellipses correspond to analyses from magmatic zircon, blue ellipses to recrystallized or newly grown zircon, and grey ellipses to xenocrystic zircon or inherited components within zircon. Dashed ellipses not included in weighted mean age calculations. In BSE SEM images, circles indicate approximate location of analyses with corresponding ^{207}Pb/^{206}Pb ages.

intruded strongly deformed Archean gneiss of the Kuujjuak Domain, located a few kilometres west of the Lac Tudor shear zone, and therefore lies outside of the George River Block. From a compositional and textural perspective, it is indistinguishable from rocks of the De Pas Batholith. This unit was sampled to test if it could potentially belong to the De Pas Batholith, or from a different, possibly Archean suite emplaced in the Kuujjuaq Domain, hence on the reactivated and tectonically uplifted margin of the Superior Craton. It contains abundant, colourless to brown prismatic zircon. The majority of the grains are fractured and contain inclusions. Twenty SHRIMP analyses from fine-scale, oscillatory-zoned zircon (Fig. 8B) with a wide range of uranium concentrations (184–1961 ppm) yield a weighted mean ^{207}Pb/^{206}Pb age of 1837 ± 2 Ma (MSWD = 0.79, POF = 0.71), interpreted as the crystallization age of the granite. The youngest analysis (11305-053.2) was excluded from the weighted mean calculation as it overlapped the edge of the grain. The five oldest analyses from faintly zoned, relatively low-U cores with ages between 2821 and 1847 Ma are interpreted to be inherited from surrounding plutonic rocks. This new age demonstrates that satellite intrusions related to the De Pas Batholith do in fact occur on either side of the Lac Tudor Shear Zone, and implications are discussed further down in the text.

Falcoz River Block

Sample 9: Tonalite Gneiss (14CXA-D97B1; SHRIMP)

Sample 9 is from a tonalite gneiss that forms a large part of the Falcoz River Block. It is medium to light grey in colour and typically migmatitic. Zircon grains, extracted from a non-migmatitic portion of the unit, occur mostly as brown to colourless, oscillatory zoned prisms to faintly zoned or unzoned equant grains. Many grains are highly turbid and show extensive alteration in SEM BSE images. U–Pb SHRIMP analysis of oscillatory zoned interior regions show a distinct grouping of analyses at 2856 ± 8 Ma (n = 15/16; MSWD = 1.6, POF = 0.084), interpreted as the crystallization age of the tonalitic protolith (Fig. 8C). The single oldest analysis at 2920 Ma is interpreted to be inherited. It is unclear whether the cluster at ca. 2.73 Ga, which included faintly zoned to unzoned equant crystals, reflects new growth of zircon or Pb loss from ca. 2.856 Ga zircon. Analyses from bright, recrystallized domains (rims or interiors of grains) with distinctly high uranium concentrations (1363–2468 ppm) and low Th/U ratios (< 0.09) yield a weighted mean age of 1845 ± 3 Ma (MSWD = 0.33, POF = 0.86), interpreted as the age of peak metamorphism that led to regional anatexis. Three high-U analyses with older ^{207}Pb/^{206}Pb ages (1989–1918 Ma) were excluded from this mean age calculation since they show incomplete resetting as a result of this recrystallization event.

Sample 10: Tonalite (DB-1057-A13; LA-ICPMS)

Sample 10 is from a massive to weakly foliated, biotite-hornblende tonalite from the Simitalik Suite in the Falcoz River Block. Plagioclase crystals are mostly light grey to purplish in colour and not recrystallized. It contains abundant pale-brown elongate zircon crystals with rounded terminations and obvious core-overgrowth relationships, as well as abundant apatite. The U–Pb data displays a combination of Pb-loss as well as the effects of high common-Pb content. A variety of inherited ages were encountered ranging from 2720 Ma to 2100 Ma. There is a more coherent cluster of near-concordant data with ^{207}Pb/^{206}Pb ages of ca. 1860 Ma (Fig. 8D). Within this cluster a set of 6 concordant analyses define a Concordia age of 1865 ± 5 Ma, which is taken as the best estimate of the zircon crystallization age. This age is similar to those reported from the Cumberland Batholith on Southern Baffin Island (Scott and St-Onge 1998), suggesting a possible link. Alternatively, it could indicate an earlier age of formation for the De Pas Batholith, but its petrology and texture is sufficiently different from other De Pas Batholith units to cast doubts on an unambiguous association.

Sample 11: Granodiorite (LP-2049-A13; LA-ICPMS)

Sample 11 is from a massive, homogeneous granodiorite of the Simitalik Suite that has intruded tonalitic to granitic orthogneisses and migmatites in the Falcoz River Block. It contains abundant colourless to brown zircon prisms ranging from 20–250 μm in length and 10–100 μm in width. Single crystals and broken fragments display terminations ranging from sharp pyramidal to subrounded shapes. Concentric oscillatory zoning is locally visible in larger brown grains. Optical CL imaging revealed pale yellow to grey oscillatory-zoned cores surrounded by blue-grey luminescent domains also containing combinations of faint oscillatory and rare convoluted or sector zoning. Zircon data for Archean components from a continuous array between 2841 ± 13 Ma and 2670 ± 14 Ma that is best interpreted as a mixing line between older inherited components and magmatic zircon overgrowths. Thus, 2670 ± 14 Ma (Fig. 8E) is interpreted as the age of emplacement. A younger cluster of concordant data points at 1844 ± 15 Ma is interpreted as the age of metamorphic overprint.

Sample 12: Foliated granodiorite (CB-5063-A13; LA-ICPMS)

Sample 12 is from a magnetite-bearing, foliated granodioritic layer in a generally felsic to intermediate orthogneiss that is part of the Simitalik Suite in the Falcoz River Block. It contains abundant colourless to dark brown equant to elongate zircon prisms with predominantly rounded to subrounded terminations. Crystals range in length from 10–150 μm and 10–100 μm in width. CL zoning in shades of blue, grey, and pale yellow is mostly planar with local patchy zoning with a subset of crystals exhibiting oscillatory zoned blue-grey cores with featureless overgrowths. Most analyses define a single cluster on a Concordia diagram (Fig. 8F), yielding a calculated age of 2835 ± 6 Ma, interpreted as the age of emplacement.

Sample 13: Enderbitic Gneiss (IL-3157-A13; LA-ICPMS)

Sample 13 is from an enderbitic gneiss from the eastern part of the Falcoz River Block. It contains abundant colourless to pale brown zircon ranging from 50–200 μm in length and 50–70 μm wide. Optical CL imaging revealed a combination of simple concentric oscillatory zoning with colours ranging from blue to grey to pale yellow. A few grains display oscillatory-zoned cores that are truncated by thin (10–20 µm) discontinuous overgrowths typically with pale yellow CL. Domains of more nebulous transgressive recrystallization that partially obscure oscillatory-zoned cores are also locally visible. The 24 µm laser craters were located wherever possible on subdomains where primary oscillatory zoning features were preserved, although some analyses were placed completely within overgrowth domains that yielded younger concordant ages. The U–Pb data for this sample (LA-ICPMS) display a combination of recent and ancient Pb loss as well as the effects of small and variable common-Pb incorporation (Fig. 9A). In order to avoid effects of common-Pb incorporation, the data were filtered to consider only analyses that encountered > 98% Pb* (as estimated using the Andersen (2002) routine in VizualAge) as well as ^{206}Pbcps/^{204}Pbcps > 1000. This yielded a subset of data that defines a statistically robust (MSWD = 1.7) discordia with an upper intercept of 2883 ± 12 Ma and a lower intercept of 1768 ± 52 Ma. The existence of a single concordant 2040 ± 13 Ma overgrowth (^{207}Pb/^{235}U age) hints at possible older reworking of this sample.

Sample 14: Massive Enderbite (BC-6179-A13: LA-ICPMS)

Sample 14 from massive enderbite contains sparse colourless to pale-brown stubby to elongate zircon prisms with rounded terminations. The grains are typically 40–60 µm wide and 100–200 µm long. A large number of the grains are fractured and a few contain small cores observable in transmitted light. Optical CL imaging revealed a diversity of CL intensities and internal zoning features with primarily dark-blue (higher U), pale-blue, grey, and pale-yellow colours. Zoning is primarily planar with rare concentric oscillatory zoning. Patchy transgressive zoning that truncates planar and oscillatory zones is also locally present.

The U–Pb data for this sample display evidence for ancient Pb-loss and possibly physical mixing between two older end-members. The evidence for mixing comes from a continuous array of near-concordant data points between ~2832 ± 21 Ma and 2661 ± 9 Ma and that for Pb-loss from the series of discordant analyses trending towards a lower intercept of 1808 ± 86 Ma (see Fig. 9B). These patterns are best interpreted as caused by mixed sampling, with the laser crater straddling ca. 2830 Ma domains representing inherited cores, and ca. 2660 Ma domains representing zones of crystallization.

Sample 15: Tonalitic Gneiss (SB-4161-A13; LA-ICPMS)

Sample 15 from tonalitic gneiss contains abundant elongate (~60 µm × ~200 µm), colourless to pale brown zircons with subrounded terminations. The majority of grains produced minimal CL response in shades of dark blue. A few colourless grains produced CL that revealed a combination of simple planar zoning and concentric oscillatory zoning. A few of the grains display small high-U cores marked by more severe radiation damage (reddish-brown zones) in the neighbouring overgrowths.

The U–Pb data for these highly radiogenic zircon grains form a discordant array between ~2650 Ma and ~1800 Ma (Fig. 9C). Data points with > 99% Pb* define a line (as a result of either physical mixing or ancient Pb-loss) with an upper intercept of 2622 ± 15 Ma (Fig. 9D), interpreted as the age of emplacement, and a lower intercept of 1718 ± 98 Ma interpreted as the approximate timing of metamorphism.

Mistinibi-Raude Block

Apart from the ca. 2.33 Ga age reported from Girard (1990a), there are no other U–Pb geochronological data reported in the literature for this block. Furthermore, the data for the above-mentioned age are not published, with only the interpreted age reported. In order to test that age, as well as provide information on the age and evolution of the Mistinibi-Raude Block in general, four rocks were sampled for U–Pb dating including: i) a plagioclase-hornblende porphyry sub-volcanic rock of intermediate composition that intrudes the Ntshuku supracrustal rocks (Sample 16), ii) a K-feldspar megacrystic monzogranite from a suite that intrudes the Ntshuku supracrustal rocks (Sample 17), iii) a granophyre from the Pelland alkaline intrusion (Sample 18), and iv) meta-arkose from the Hutte Sauvage Group (Sample 19).

Sample 16: Plagioclase-Hornblende Porphyry Intrusion, Ntshuku Suite (14CXA-D94A1; SHRIMP)

Sample 16 is from a 2-m-thick, hornblende-bearing, feldspar porphyry sill intruding mafic volcanic and meta-sedimentary rocks of the Ntshuku volcanic belt. It is interpreted as a subvolcanic intrusion, hence its age should provide a minimum (and also approximate) age for the evolution of the volcanic belt. Zircons from this rock consist mostly of clear, colourless, mildly fractured stubby to elongate prisms with diffuse igneous zoning and subordinate, clear, subrounded, faintly zoned to unzoned grains. Many zircon grains have thin to thick overgrowths, most of which are devoid of zoning. Fifteen U–Pb SHRIMP analyses from oscillatory-zoned prisms (Fig. 9E, inset, grain 118) give a weighted mean age of 2373 ± 7 Ma (MSWD = 2.1; POF = 0.011), interpreted as the crystallization age of the porphyry. The two youngest analyses from oscillatory-zoned prisms (11306-56.1 and -61.1) are interpreted to have experienced Pb-loss and were excluded from the weighted mean calculation. Faintly zoned rims and subrounded grains yield distinctly younger ages with a weighted mean age of 2317 ± 8 Ma (n = 9; MSWD = 0.74; POF = 0.66), which is interpreted as the time of metamorphic recrystallization. The oldest analysis from this zircon rim population (11306-26.2), not included in the mean age calculation, may reflect incomplete recrystallization as a result of the younger overprint event. There are no hints of inheritance or zircon cores, suggesting that the Ntshuku supracrustal belt may be juvenile. Interestingly, there are no hints of New Quebec or Torngat Orogen (i.e. ca. 1.87–1.80 Ga) metamorphic rims either, despite the rock having a moderately strong foliation parallel to the regional N–S fabrics.

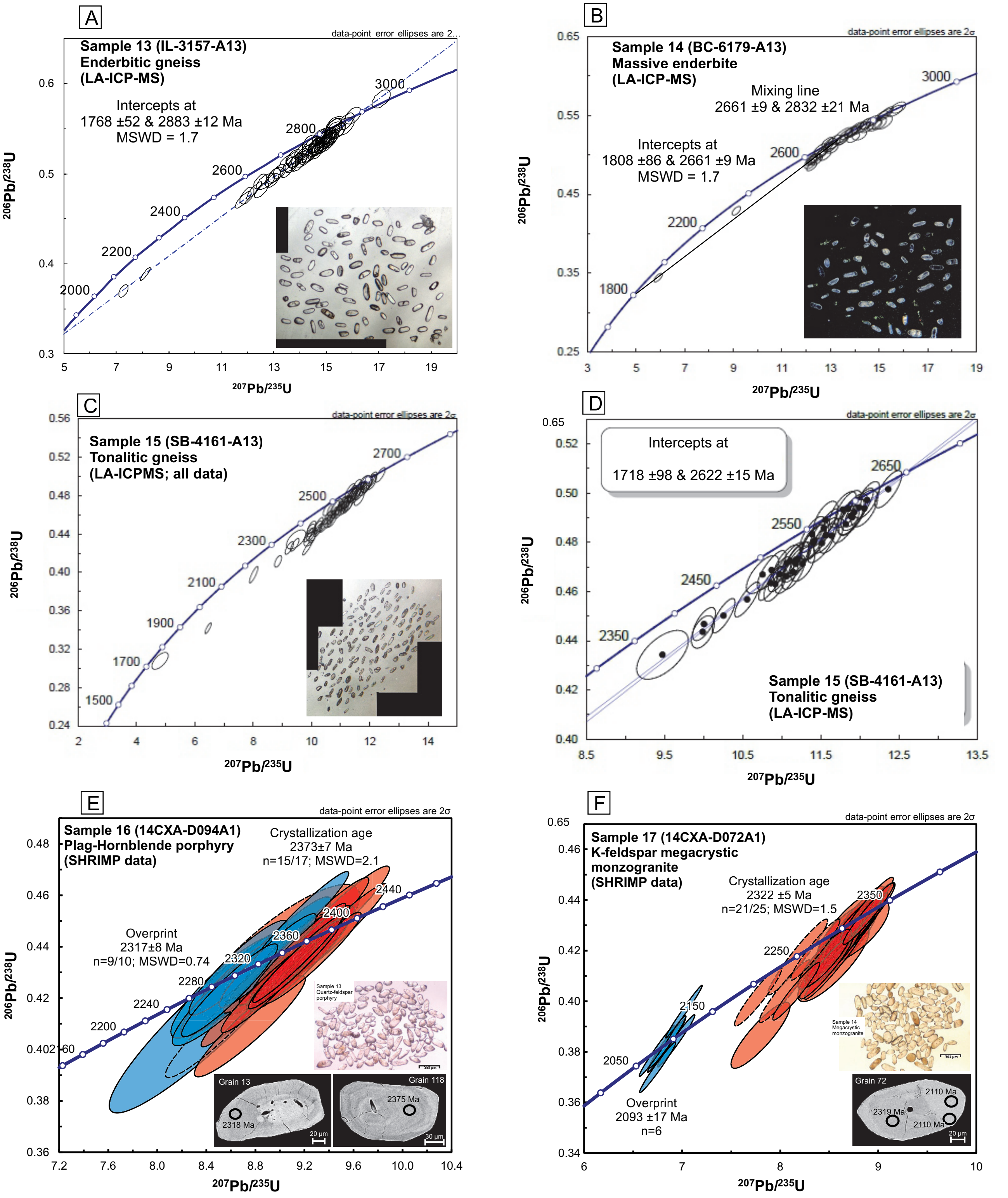

Figure 9. Concordia diagrams (2σ errors), transmitted light images of zircon, and/or BSE SEM images of representative zircon crystals for rock units from the Falcoz River and Mistinibi-Raude blocks. A) LA-ICP-MS data for Sample 13, an enderbitic gneiss from the Falcoz River Block; B) LA-ICP-MS data for Sample 14, a massive enderbite from the Falcoz River Block. Cathodo-luminescence image of zircons in inset; C) LA-ICP-MS data for granite Sample 15, a tonalitic gneiss from the Falcoz River Block; D) more detailed view of the upper data grouping on the Concordia plot for Sample 15; E) SHRIMP data for Sample 16, a sub-volcanic plagioclase-hornblende porphyry intrusion in the Ntshuku volcanic belt of the Mistinibi-Raude Block; F) SHRIMP data for Sample 17, a K-feldspar megacrystic monzogranite intruding orthogneiss in the Mistinibi-Raude Block. In the SHRIMP Concordia diagram, red ellipses correspond to analyses from magmatic zircon and blue ellipses to recrystallized or newly grown zircon. Dashed ellipses not included in weighted mean age calculations. In the BSE SEM image, circles indicate approximate location of analyses with corresponding $^{207}Pb/^{206}Pb$ ages.

Sample 17: K-feldspar Megacrystic Monzogranite, Pelland Pluton (14CXA-D72A1: SHRIMP)

Sample 17 is from one of a series of K-feldspar megacrystic granitoid bodies that have intruded the Ntshuku supracrustal belt, but are for the most part foliated and recrystallized. The monzogranite contains clear, light brown, faintly zoned, stubby to elongate zircon prisms. Medium-brown rims and subequant grains, characterized by a bright BSE response, are also present. The zoned prisms yield a grouping of concordant to near-concordant data points between 2339 and 2231 Ma. The 21 oldest analyses from this population define a weighted mean age of 2322 ± 5 Ma (n = 21/25; MSWD = 1.5, POF = 0.063), interpreted as the age of crystallization (Fig. 9F). Analyses from bright unzoned rims have high U concentrations (857–1855 ppm) and their individual dates are very precise. Thus, a robust Tukey's biweight mean calculation was used to minimize the effects of any outliers. The resulting age, 2093 ± 17 Ma, is interpreted as the age of a metamorphic overprint. It is noteworthy that the age of emplacement of this plutonic suite is within error of the metamorphic age obtained for the Ntshuku Belt (see Sample 16), suggesting that plutonism was accompanied by regional deformation and metamorphism within the Mistinibi-Raude Block.

Sample 18: Granophyric Gabbro from the Pelland Pluton (14CXA-D68B1; SHRIMP)

The Pelland pluton is a composite body consisting of metagabbro, monzodiorite, monzonite, and syenite, and is distinguished by the presence of blue rutilated quartz, rapakivi feldspar, and orthopyroxene-bearing pegmatite, all suggestive of high-temperature, and at least partially anhydrous, conditions during emplacement. The sample dated is from a marginal, granophyric phase of a gabbro containing rare K-feldspar megacrysts and blue quartz. Zircon grains from this sample form stubby to elongated prisms, many with rounded edges and terminations. Core–rim relationships are visible in a number of grains in transmitted light. The distribution of ages from unzoned and oscillatory-zoned zircon between ~2050 and 2370 Ma does not permit an unambiguous age interpretation (Fig. 10A). Nonetheless, the four youngest analyses from homogeneous rims and grains yield a weighted mean ^{207}Pb/^{206}Pb age of 2053 ± 13 Ma (MSWD = 1.16, POF = 0.32), interpreted as the age of metamorphism of the gabbro. Oscillatory-zoned zircons plot along Concordia from the metamorphic age to 2.37 Ga. The nine oldest analyses exhibit excess scatter with a weighted mean age of 2339 ± 22 Ma and MSWD of 6.5. The Tukey biweight mean age for these analyses, 2320 ± 21 Ma, overlaps with the weighted mean age and is taken as a more robust estimate of the age of the rock. However, given evidence for extensive Pb-loss in this zircon population as a result of the younger metamorphic event, this age should be regarded as a minimum estimate of the crystallization of the granophyric gabbro. The oldest analyses are from faintly zoned cores or grains that are interpreted as inherited. Their ^{207}Pb/^{206}Pb ages, which range from ~ 2350 to 2500 Ma, are interpreted as representing the approximate or minimum age of crust assimilated into the granophyric, marginal phase of the gabbro, again suggesting that the Mistinibi-Raude Block is principally juvenile as is the case with samples 16 and 17 above.

Sample 19: Meta-Arkose, Hutte Sauvage Group (14CXA-D18A1; SHRIMP)

The Hutte Sauvage Group unconformably overlies the Ntshuku and Mistinibi belts. It consists of matrix-supported pebble to cobble conglomerate at the base, grading upwards to meta-arkosic sandstone. The sample dated is from the upper part of the section, within a meta-arkosic layer containing trough crossbeds outlined by heavy mineral layers. Zircon from the meta-arkose consist of colourless to pale brown prisms or subequant crystals. Many grains preserve facets and terminations, but a small number show evidence for mechanical abrasion. Sixty five SHRIMP analyses were carried out on 61separate zircon grains, yielding dates between 2570 and 1978 Ma (Figs. 10B and 10C). All results are within ± 5% discordance and therefore considered to approximate the true crystallization ages of the zircon grains. The detrital provenance profile is characterized by three dominant modes at ca. 2510 Ma, ca. 2320 Ma, and ca. 2080 Ma. Replicate analyses on the youngest detrital zircon (grain 10) yield a weighted mean age of 1987 ± 7 Ma (n = 5/5; MSWD = 1.01, POF = 0.40), interpreted as the maximum age of deposition. Based on the three dominant modes, it is noteworthy that all detrital zircon grains appear to have been derived solely from the Mistinibi-Raude Block and have not sourced adjacent Archean domains. This dataset also provides constraints that do not support incorporation of detritus from the De Pas Batholith into the Hutte Sauvage Group, an interpretation made earlier based on the presence of K-feldspar megacrystic granite cobbles (Girard 1990a).

Lac Lomier Complex

The Lac Lomier Complex consists mainly of banded, granulite-facies orthogneiss ranging from mafic to felsic but of predominantly intermediate (enderbitic) composition. The complex locally hosts elongate map-scale ribbons or screens of metapelitic rock interpreted as fragments of the Tasiuyak accretionary wedge incorporated into the Lac Lomier continental magmatic arc during its emplacement (Wardle et al. 2002). U–Pb zircon data from the Lac Lomier Complex has been proven difficult to interpret, since its lower crustal emplacement under granulite-facies metamorphism have brought into question whether the dated zircon are igneous or metamorphic. An age of ca. 1.86 Ga has been generally attributed to emplacement (Wardle and van Kranendonk 1996). We have collected a sample to try to clarify that issue by analysing cores and rims with the SHRIMP method.

Sample 20: Monzogranite (14CXA-D30C2; SHRIMP)

The dated Sample 20 is from a highly strained, monzogranite dyke emplaced in ultra-high P-T metapelite assumed to belong to the Tasiuyak gneiss. The dyke is transposed into sub-parallelism with the metapelite, but has clearly intruded it. Zircon from this sample occurs mostly as clear, colourless to pale brown rounded crystals or anhedral fragments. Prismatic

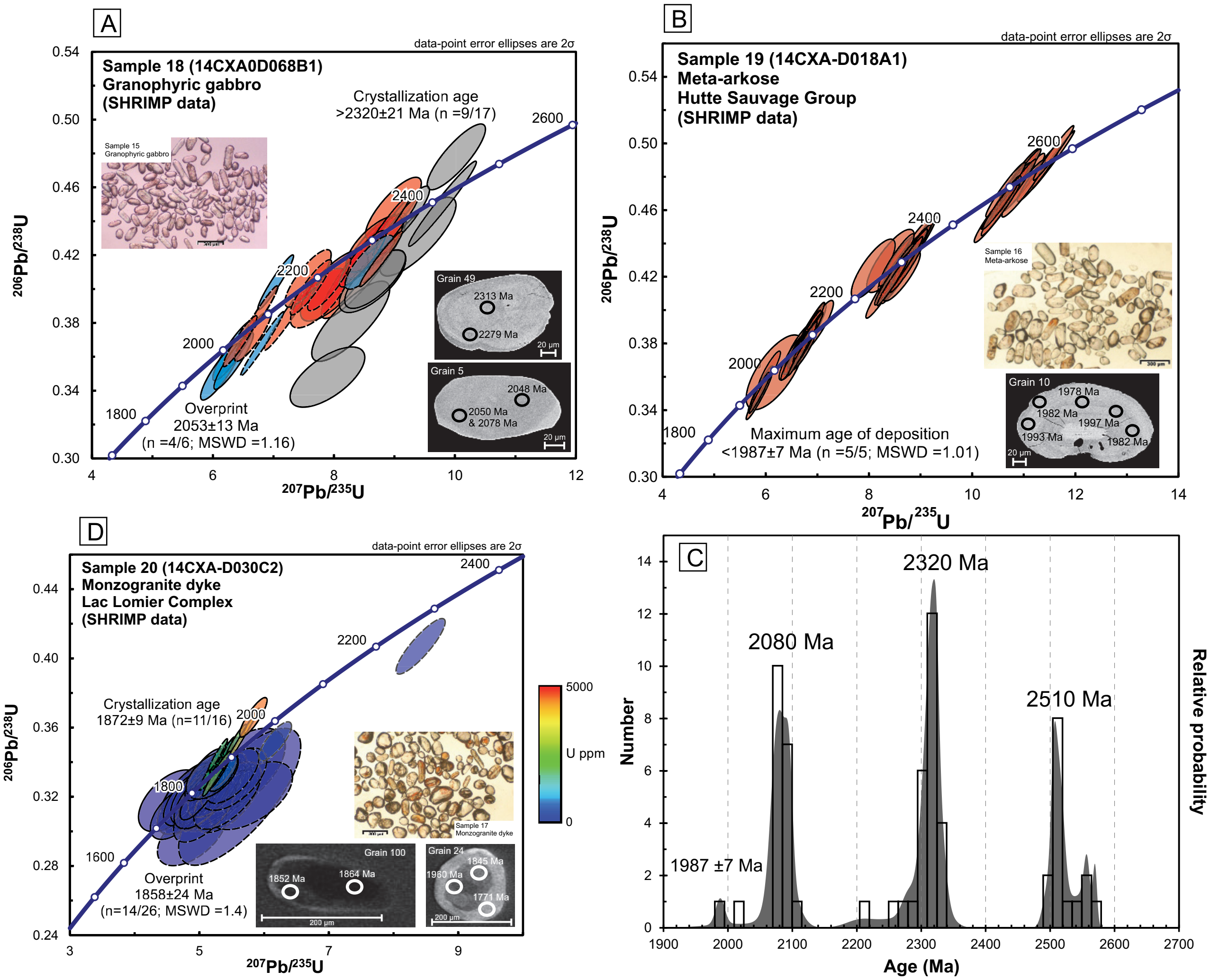

Figure 10. Concordia diagrams (2σ errors), transmitted light images of zircon, and BSE SEM images of representative zircon crystals for rock units from the Mistinibi-Raude Block (A, B) and Lac Lomier Complex (D). A) SHRIMP data for granophyric gabbro Sample 18; B) SHRIMP data of detrital zircons from a meta-arkose from the Hutte Sauvage Group (Sample 19); C) combined probability density plot and histogram for Sample 19 (bin width is 15 Ma); D) SHRIMP data for monzogranite Sample 20 from the Lac Lomier Complex. Ellipses in the concordia diagram are colour-scaled according to uranium concentrations. Dashed ellipses were not included in weighted mean age calculations. The blue ellipses with grey dashed lines represent analyses from core material from grain 69. In the CL images, circles indicate approximate location of analyses with corresponding ^{207}Pb/^{206}Pb ages.

grains are also present, but are strongly resorbed with no preserved facets, crystal edges or terminations. Rounded crystals and anhedral fragments predominantly display medium to high CL response with sector or irregular zoning, whereas most prisms are characterized by very low CL response (dark) with rare broad zoning. Bright CL rims surrounding darker cores are present in all morphological types. The SHRIMP data define two compositionally distinct groupings (Fig. 10D), which broadly correlate with grain morphology. The 11 oldest analyses from dominantly prismatic grains with high U concentrations (526–4742 ppm) and generally low but variable Th/U ratios (0.01–0.70) yield a Tukey's biweight mean age of 1872 ± 9 Ma (n = 11/16). The very low Th/U ratios from this population are consistent with metamorphic growth; however, the prismatic shape of the grains is more consistent with magmatic growth. Thus, based on this morphological evidence, we interpret the 1872 ± 9 Ma as the age of crystallization of the monzogranite dyke. Analyses derived from rounded crystals, anhedral fragments, and rims with a medium to high CL response are characterized by distinctly lower U concentrations (26–293 ppm), higher Th/U ratios (1.02–2.70), and highly variable ^{207}Pb/^{206}Pb ages ranging from 2110 to 1691 Ma. Fourteen of the fifteen youngest analyses from this population give a weighted mean age of 1858 ± 24 Ma (1 of 15 rejected; MSWD = 1.4, POF = 0.16). The rejected analysis is the youngest in the group at 1691 ± 68 Ma. Based on morphology, zoning characteristics, and chemistry, this age is assigned as the time of metamorphism. The older analyses from this grouping (1922–2110 Ma) are highly discordant (> 6%) and may include an inherited component. Two low-U analyses from the core of prismatic grain 69 with non-reproducible ^{207}Pb/^{206}Pb ages of 2345 and 2058 Ma also likely reflect inheritance. The host metapelite could be the source of the 1922–2345 Ma zircon, but these dates should be taken as minimum ages of inheritance given the strong discordancy of the data.

DISCUSSION

The data presented here as well as reported in the literature, together with field observations and recent mapping, suggest that the Core Zone consists of at least three distinct crustal blocks separated by ductile, sub-vertical shear zones that could potentially represent ancient sutures. We define them here as the George River Block, the Mistinibi-Raude Block, and the Falcoz River Block. Also, we exclude the Kuujjuaq Domain and Lac Lomier Complex from the Core Zone *sensu stricto*. The Kuujjuaq Domain has been interpreted as the uplifted and tectonically reactivated margin of the Superior Craton (Wardle et al. 2002; Rayner et al. 2017). The Lac Lomier Complex is the root of a 1.87–1.86 Ga continental magmatic arc emplaced along the western accretionary margin of the Nain Craton and it is in structural relationship with the Core Zone. While acknowledging the previous domain nomenclature, we introduce some new nomenclature in an attempt to bring uniformity and consistency throughout the region. In addressing this issue, we have generally considered priority and opted for the first published use of names for a particular crustal block or domain, or by grouping previous sub-domains if warranted by the U–Pb zircon data presented herein.

The George River Block consists of remnants of a Neoarchean terrane that comprises juvenile ca. 2.73 to 2.70 Ga supracrustal rocks (Tunulik Belt) and their plutonic root, with the latter including mainly felsic and intermediate composition intrusions that have yielded ages as young as 2568 ± 5 Ma. It is bounded to the west by the Lac Tudor shear zone, and to the east by the George River shear zone. The George River Block is the primary host of the ca. 1.84–1.82 Ga De Pas Batholith, although it is clear that K-feldspar megacrystic intrusions of similar age and composition also occur within the Kuujjuaq Domain to the west (i.e. Sample 8). There has been some debate as to whether the De Pas Batholith represents a continental magmatic arc, as suggested by Dunphy and Skulski (1996), or a syn-collisional magmatic suite (i.e. Wardle et al. 2002). We consider the common presence of hornblende and titanite as well as the absence of any significant volume of contemporaneous S-type magmas to be more suggestive of an arc derivation. The Lac Tudor shear zone has traditionally been interpreted as the ancient suture, where presumably east-dipping subduction of oceanic lithosphere would have generated the De Pas batholith (e.g. Wardle et al. 2002). However, our identification of rocks of similar composition and age to the De Pas suite in the Kuujjuaq Domain, west of the Lac Tudor shear zone, challenges that interpretation. Our current understanding of the distribution of De Pas age plutons would require either a single, west-directed subduction along the eastern margin of the George River Block (suture situated along the George River shear zone), or a divergent double subduction (e.g. Soesoo et al. 1997) situated along the Lac Tudor shear zone. We note that the divergent double subduction model is attractive inasmuch as it potentially involves slab floundering, which could account for the large volume of mantle-derived melt, a large portion of it having been emplaced at high temperatures under anhydrous conditions.

Farther south, the George River Block continues into the Crossroads and Orma domains (Fig. 1) identified by James et al. (2003). The Orma Domain hosts supracrustal rocks (Zeni Complex) that can be traced northwards on aeromagnetic maps and appear to merge with the Tunulik Belt. It also hosts metaplutonic rocks ranging in age from 2628 to 2581 Ma, similar in range to the 2648–2568 Ma intrusive rocks in the George River Block as determined herein. We therefore include the Crossroads and Orma domains in the George River Block, which thus extends from the Grenville Front north to Ungava Bay (Fig. 2).

The Mistinibi-Raude Block, which is separated from the George River Block by the George River shear zone and from the Falcoz River Block by the Moonbase shear zone, comprises crust formed at ca. 2.37–2.32 Ga and thus represents a unique component of the Core Zone. Moreover, from a global crustal growth perspective (e.g. Condie et al. 2009) it also forms a relatively rare fragment of arc-derived volcanic and plutonic rocks of earliest-Paleoproterozoic age, a period not well represented in the geological record. The oldest recognized component of the block, the predominantly mafic volcanic Ntshuku Belt, has not been directly dated as we have not been successful at finding zircon-bearing volcanic protoliths. However, a plagioclase-hornblende porphyry sill of intermediate composition that we interpret as a sub-volcanic intrusion, provides a minimum age for volcanism of 2373 ± 7 Ma. The supracrustal rocks of the Ntshuku Belt are intruded by a suite of mafic to felsic plutonic rocks of arc affinity, previously dated at ca. 2.33 Ga (Pallatin suite; age cited in Girard 1990a). We provide two new ages for plutonic units that confirm the existence of a substantial volume of plutonic rocks of that age-range. These are the Pelland pluton, for which a poorly defined age of ca. 2320 ± 21 Ma provides an approximate emplacement age (Sample 18), and a K-feldspar megacrystic monzogranite dated at 2322 ± 5 Ma (Sample 17). The Pelland pluton is composed of quartz-poor, mafic to alkaline intrusions that crystallized at very high temperatures, as suggested by the presence of rutilated quartz, hypersolvus feldspars and locally, orthopyroxene. A similar but yet undated suite (Nekuashu pluton) occurs about 25 km to the northwest of the Pelland intrusion. Zircons from the ca. 2.37 Ga subvolcanic intrusion (Sample 16) show evidence for metamorphism at ca. 2.32 Ga that can be broadly correlated to emplacement of the Pallatin and Pelland intrusions. The latter two, in turn, show evidence for metamorphic zircon growth at ca. 2.09–2.05 Ga, a feature that appears to be unique to the Mistinibi-Raude Block. The Hutte Sauvage meta-arkose, which appears to have sourced zircon uniquely from the Mistinibi-Raude Block, does not contain zircon derived from the ≥ 2.73 Ga Ntshuku volcanic rocks, but contains abundant zircon from the ca. 2.32 Ga intrusions. Interestingly, it contains an older population of detrital zircon as well, with a peak age of ca. 2.50 Ga and for which no local equivalents have yet been found in outcrop, either in the Mistinibi-Raude or adjacent blocks. We assume that zircon of that age represent older crust onto which the Ntshuku supercrustal rocks were erupted and deposited, and provide an upper age limit for the Mistinibi-Raude Block. Based on geochemical studies, Girard (1990b, c) suggested an immature arc setting for the Ntshuku volcanic rocks and related intrusions.

The large expanse of crust situated east and northeast of the George River and Mistinibi-Raude blocks, previously subdivided into four domains, is herein amalgamated into the Falcoz River Block. Along its western flank, the Falcoz River Block is separated from the George River and Mistinibi-Raude blocks by the George River and Moonbase shear zones. Along its eastern flank it is separated from the 1.87–1.86 Ga Lac Lomier Complex by the Abloviak and Falcoz shear zones (Fig. 2), two features that appear to anastomose with one another, and also enclose lenses of less strained crust. In the northern reaches of the map area, the Falcoz shear zone eventually splays from the Abloviak shear zone and can be traced some distance northwestwards towards Ungava Bay, where it loses definition. A feature common to the four former domains now amalgamated into the Falcoz River Block is the widespread presence of tonalitic to granitic gneiss and migmatite (tonalite-trondjemite-granite association), the oldest of which have yielded U–Pb crystallization ages of ca. 2856 ± 8 Ma and 2883 ± 12 Ma (samples 9 and 13, respectively). However, other dated protoliths are distinctively younger, yielding U–Pb zircon ages of 2835 ±6 Ma, 2670 ±14 Ma, 2661 ±9 Ma and 2622 ±15 Ma (samples 12, 11, 14 and 15, respectively), suggesting successively younger pulses of felsic to intermediate magmatism. The 2796 ± 29 Ma age is within error of a 2807 + 45/-27 Ma age obtained by Ryan et al. (1991) for a tonalitic gneiss from the southeastern part of the Falcoz River Block. Moreover, Ryan et al. (1991) also dated granitoid rocks ranging in age from ca. 2657 ± 18 to 2574 ± 8 Ma from the same area, suggesting an increase in the proportion of Neoarchean igneous rocks towards the southeast. Along its western flank, the Falcoz River Block is separated from the George River and Mistinibi-Raude blocks by the George River shear zone and Moonbase shear zone, respectively (Fig. 3). From a metamorphic perspective, the Falcoz River Block comprises granulite-facies assemblages along its eastern half, adjacent to the Lac Lomier Complex, and mainly upper-amphibolite facies assemblages in its northwestern part (see Fig. 2). It also preserves more Paleoproterozoic supracrustal cover rocks in its northern extents. There is definitely a Proterozoic-age granulite facies event, as is implied from metamorphic assemblages present in the cover rocks. However, it is also possible that Archean-age metamorphism also reached granulite facies, at least locally.

The Tasiuyak gneiss has historically been interpreted as a thick accretionary complex formed during the Torngat Orogeny and is intruded by the 1.87–1.86 Ga Lac Lomier continental arc (Wardle et al. 1990; Wardle and van Kranendonk 1996). At the location of Sample 20, a large enclave of granulite-facies metapelite, interpreted as a raft of Tasiuyak gneiss within the Lac Lomier Complex, is intruded by a 2-m-thick monzogranite dyke, dated herein at 1872 ± 9 Ma. The monzogranite dyke is presumably an offshoot of the main Lac Lomier Complex and both it and its host metapelite were strongly transposed within the Abloviak shear zone and, hence, the 1858 ± 24 Ma metamorphic age obtained from this sample (Fig. 10D) provides an estimate for the timing of shearing. However, in detail, the actual metamorphic history appears to be relatively more complex as suggested by the spread of metamorphic age data (i.e. see grain 24, Fig. 10D inset, with spots as young as ca. 1.77 Ga), suggesting that the Abloviak shear zone may have been a long-lived feature. Other small map units of Paleoproterozoic cover sequences composed of high-grade metapelite that occur throughout the mid- to northern Falcoz River Block are more likely related to the Lake Harbour Group than to the Tasiuyak gneiss (Scott et al. 2002, but see discussion below). East of the Tasiuyak gneiss lies the Nain Province, an ancient crustal block that forms part of the North Atlantic Craton. It is composed of two main blocks, the ca. 3.0–3.2 Ga Hopedale Block to the south, and the 3.0–3.8 Ga Saglek Block to the north (James et al. 2002). Both these blocks are significantly older than the Falcoz River Block, suggesting that there is no obvious relation between it and the Nain Province.

"Exotic" Core Zone and Speculations on its Northern Extension

In light of the previous discussions it is clear that: i) the Core Zone is composed of three distinct Archean to early Paleoproterozoic crustal fragments (shear-zone bounded blocks) with contrasting geologic histories, implying that they developed separately prior to their tectonic juxtaposition in the Core Zone in the Paleoproterozoic, and ii) that all three blocks comprising the Core Zone are apparently exotic with respect to the adjacent Superior and North Atlantic cratons. These relationships cast doubts on (but do not preclude) the former interpretation that the Archean rocks in the Core Zone formed a ribbon continent (James and Dunning 2000). They also provide context for a discussion about the possible correlatives of either George River, Mistinibi-Raude or Falcoz River blocks farther north in the Trans-Hudson Orogen, and more speculatively about their linkages to other cratons that comprised parts of the Nuna supercontinent between ca. 1.90 and 1.80 Ga (Stauffer 1984; Hoffman 1990; Corrigan et al. 2009; Pehrsson et al. 2015). A proposed correlation of the Falcoz River Block with parts of the Meta-Incognita microcontinent (Fig. 1), exposed on the peninsula of the same name on southern Baffin Island (see Jackson and Taylor 1972; Scott and St-Onge 1998; St-Onge et al. 2000; Bourlon et al. 2002) is primarily based on the similarity between Paleoproterozoic quartzite-pelite-marble (QPM) associations at both localities. However, the correlation is not entirely unambiguous. In the Falzoz River Block, QPM rocks unconformably sit on ca. 2.9–2.7 Ga Archean basement gneisses and are intruded by minor Paleoproterozoic plutonic rocks of ca. 1.86 Ga age, for which a correlation with the Cumberland Batholith remains to be proven. Both the lack of *bona fide* Archean basement to the Paleoproterozoic QPM lithologies in the Meta-Incognita microcontinent and their occurrence there in detached slices in a thrust stack, suggest the proposed correlation should be considered tentative at best. On the other hand, although not exposed at surface, evidence of Archean crust-forming events of ca. 2.68 Ga and 2.63–2.60 Ga with a minor contribution from Mesoarchean crust (ca. 3.00 and 2.85 Ga) is found in detrital and xenocrystic zircons in QPM and metaplutonic rocks from the Meta-Incognita microcontinent (Wodicka et al. 2010), making a correlation with the Falcoz River Block permissible. In light of the robust confirmation of distinctive, ca. 2.38 and 2.32 Ga plutonic units in the Mistinibi-Raude Block in this study and their rarity in the geological record of the Canadian Shield, perhaps the most compelling evidence that the Core Zone rocks may link with the Meta-Incognita microcontinent is the presence there of detrital and xenocrystic zircon of ca. 2.34–2.31 Ga age, also reported in Wodicka et al. (2010), as well as a 2310 ± 3 Ma cobble from a deformed and metamorphosed conglomerate reported by Partin et al. (2014). These ages fall within the range determined from the Mistinibi-Raude Block and suggest a possible correlation. Although it could be argued that these Baffin Island zircon ages could represent detrital grains with a Core Zone provenance and not a local basement source, the presence of cobble suggests a proximal source.

Correlation of the George River Block northwards into the Trans-Hudson Orogen is a bit more problematic as there are no known crustal slices of that specific and relatively ‘tight’ Neoarchean age range (2.70–2.57 Ga) identified in the immediate area north and west of Ungava Bay. Along Hudson Strait, the Superior Craton, or at least its reactivated margin (Kovik antiform), is flanked by the Sugluk Block (Fig. 1) which hosts predominantly 3.2–2.8 Ga Archean crust with Paleoproterozoic intrusions (see Corrigan et al. 2009 and references therein). If any correlation would be proposed for the Sugluk Block, it would more likely involve the Falcoz River Block, which comprises ca. 2.9–2.8 Ga crust that overlaps in age with the latter. However, correlations at this point would be speculative at best due to limited geochronological data available from the Sugluk Block.

Following the same line of investigation farther afield to the southwest across Hudson Bay, reveals other possible correlations. Within the former tract of the ancient Manikewan Ocean that was closed during the Trans-Hudson Orogeny (Stauffer 1984), ca. 2.4–2.5 Ga plutonism has been identified in the Sask Craton (see Bickford et al. 2005 and references therein), located in the Trans-Hudson orogeny internides in what is now central Manitoba and Saskatchewan (Fig. 1). Moreover, ca. 2.3–2.5 Ga detrital zircons have been identified in metagreywacke and as xenocrysts in plutonic rocks within the Trans-Hudson Orogen internides between the Sask and Hearne cratons (Southern Indian Lake area; see Rayner and Corrigan (2004) and Partin et al. (2014)), suggesting the presence of crust of the same age as the Mistinibi-Raude Block in that portion of the orogeny (‘SIL’ in Figure 1). Hence, there is evidence for the presence of earliest-Paleoproetrozoic crust of ca. 2.5–2.3 Ga age now isolated in distinct crustal slices within a closed paleo-ocean realm west, north and east (present day coordinates) of the Superior Craton. Whether these represent vestiges of a tectonically dismembered, single continental mass remains to be determined. To the northeast towards Greenland, on the other hand, there is no hint of ca. 2.5–2.3 Ga protoliths in the Nagssugtoqidian Orogen (Fig. 1), which is the site of ocean closure and ca. 1.86–1.82 Ga continent-continent collision north of the North Atlantic Craton (van Gool et al. 2002).

Paleoproterozoic Tectonic Evolution and Metamorphism

In this paper we have presented evidence for the presence of at least three lithologically distinct crustal blocks forming the Core Zone. The ductile shear zones that bound these blocks are steep and locally form an anastomosing array that accommodated bulk dextral transpressional shear via mainly sub-horizontal, transcurrent motion. Wardle and van Kranendonk (1996) and Wardle et al. (2002) speculated that this bulk regional deformation was a result of oblique convergence between the North Atlantic and Superior cratons during the Paleoproterozoic. The distinct chronological and lithological character of the three Core Zone blocks with respect to the bounding Superior and North Atlantic cratons suggests that: i) they formed at different times in completely different environments and are exotic to both the North Atlantic and Superior cratons, and ii) the Lac Tudor, George River, Moonbase and Abloviak shear zones represent paleo-sutures. From a tectonothermal perspective, the George River and Falcoz River blocks bear similar metamorphic age ranges, between ca. 1831 and 1773 Ma for the former and 1845 and 1768 Ma for the latter (excluding metamorphic ages for samples 14 and 15, which show very large analytical errors), suggesting that they were structurally and metamorphically reactivated during the Paleoproterozoic, particularly during the New Quebec Orogen phase. However, the interior of the Mistinibi-Raude Block, as well as the southeastern extents of the George River Block (Orma Domain of James and Dunning (2000)) appear to have mainly escaped ca. 1.85–1.76 Ga Paleoproterozoic metamorphism. This might be the result of south-directed crustal extrusion and resulting north-to-south extension, a hypothesis that will be discussed in a subsequent publication.

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*For access to the Corrigan et al. (2018) supplementary data, Table S-1 SHRIMP U–Pb data and Table S-2 LA-ICP-MS U–Pb data, please visit the GAC's open source GC Data Repository link Andrew Hynes Series: Tectonic Processes at: https://www.gac.ca/wp/?page_id=306.

NEW SERIES

Classic Rock Tours – An Introduction

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Like most who opted for geoscience as a vocation rather than a mere job, I am often asked exactly *why* I chose this particular career path, and continue to be involved in my retirement. There are also times when I ask myself the very same question, but it usually boils down to this – being a geologist provides opportunities to visit inspiring, unique and often remote locations through field work and other field trips. In Scotland a couple of years ago, on a conference trip that led to the following article, I read Stephen Baxter's excellent book *Revolutions in the Earth*. I thoroughly recommend it – as a biography of James Hutton it gives some insight into his personality – and it illustrates the love-hate relationship that geologists have with field work. In a letter written to a friend, Hutton complained *"Lord pity the arse that's clagged to a head that will hunt stones"*. I could amplify this with a detailed footnote explaining the meaning of the archaic dialect verb *to clag*, but I don't need to because all geologists will understand Hutton's sentiment. We don't really have a choice in this – our interest in exploring the natural world is just part of who we are. Such a conclusion may not be fully scientific, but there's no denying its truth.

Even in a technological age where some geoscience careers are built around black boxes and vast computer models, geology remains at its core an *observational* science, and the theories that we build are ultimately subject to the ground truth of field observations. It was the lure of field work, the outdoors and travel that brought me into geology, and I know that the same is true for many of my colleagues. Modern geoscience may be sophisticated, multidisclipinary and quantitative, but it always links back to careful field observations and their thoughtful interpretation. Even if technology gives us details and constraints, the essential plotline of the story of Earth comes from reading the rocks.

Geoscientists are generally keen and adaptable travellers, who like to get off the beaten tourist paths, sometimes at their own peril. One of the great things about being a student of the Earth is that it surrounds us, and there will always be something interesting to find out, wherever we roam. We enjoy a special relationship with the Earth because we understand its dynamic nature and can visualize it in four dimensions. Travelling geologists are always glancing surreptitiously at roadside outcrops as they flash by, or asking exactly why that range of hills is where it is and shaped just so. This can at times be a source of great frustration to our families or our travelling companions, but it is a natural expression of our curiosity about all things that connect to earthly processes. The one thing that I fear most in aging is to lose such curiosity, as happened to my father.

Our idea for a new series in *Geoscience Canada* that can provide helpful travel information and thoughtful geological context for influential or exceptional field areas is an attempt to both exploit and celebrate our innate curiosity. We envisage a series of articles that will provide readers not only with historical and scientific context for areas of remarkable geology, but also the essential practical information for self-directed excursions. In many cases, there is more than enough technical geoscientific data available for these places, but it is scattered within specialist publications, most of which require other knowledge to fully comprehend. To bring such sources together and communicate them more widely is by itself a service to our science. Areas of great scientific interest are commonly also featured in field trip guides, often from conferences, but these documents can be difficult to locate and access. Even if such sources can be tracked down, they will often emphasize the specialized technical aspects of sites over their wider context, and may lack the practical considerations of where they are and exactly how one might get there. Our vision for articles in *Classic Rock Tours* is to bring this information together in one place, such that geological context, site descriptions and practical advice are integrated with good maps, clear graphics, and interesting photographs. We do not see this series primarily as a venue for original research, but rather for synthesis and presentation of material from varied sources. It is true that a determined and time-consuming search of literature can eventually provide much of the information that a keen travelling geologist needs, but we seek here to place it all conveniently in one easily accessible source.

We envisage papers in this series to sit at an intermediate technical level, so that they will inform and interest a wide cross-section of the *Geoscience Canada* readership. We also envisage a diverse target audience, not restricted to professional geoscientists engaged in conference or vacation travel. Many areas around the world provide type examples and/or influential sites that have influenced wider geological thought, so these articles can have considerable educational value, even if

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students are unable to visit in person. However, we hope that carefully constructed articles of this type will also provide a valuable resource for planning student excursions and ultimately contribute to the retention of vital field skills by a new generation. We anticipate an emphasis on destinations within Canada and parts of the United States, as these are easiest to visit and many are documented through familiar materials developed for conferences. The annual GAC–MAC conferences held across Canada provide a rich legacy of field trip guides, many of which are important scientific documents in their own right, as they contain data and observations not published elsewhere. Despite this importance, many of these guides are now difficult to consult or even to locate, which is a great loss to our community. Drawing upon this rich heritage for articles in *Classic Rock Tours* may in the end provide a way for these efforts to gain a wider audience and greater longevity.

I have learned as an editor that it is unwise to set too many preconditions, and that even if what we get diverges widely from what we expect, this can sometimes benefit all. For this reason, we are reluctant to impose too many advance specifications for articles, but a few general thoughts follow. First, it is very important that such articles feature places for which there is a reasonable prospect of independent travel. There are many fantastic sites in extremely remote places, and I have been lucky enough to see some, but these are probably not ideal subjects. If it requires a helicopter charter, an all-terrain vehicle, or a mule rental, it is probably not a candidate for a *Classic Rock Tour*. We anticipate a natural focus on North American examples, for logistical reasons, but are keen also to see some International flavour within these same constraints of easy and safe access. For example, the British Isles feature many superb field excursions in areas that have influenced the very course of geology, which are generally easy to complete and experience and in some cases protected for their importance. No doubt the same is true for many other parts of the world, and perhaps our efforts can encourage such protection efforts. In short, we welcome contributions from all parts of the world that might reasonably represent destinations for travelling geologists.

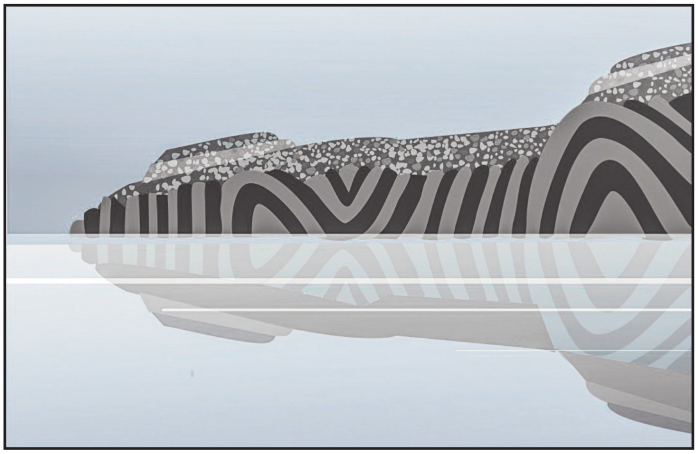
I have participated in many field trips over the years and some proved more rewarding than others. I am sure that I am not the only one who has been driven for miles over abominable roads to visit a small scruffy outcrop of nondescript sandstone or (worse) badly altered metavolcanic rock only to be regaled with a detailed discussion of its detrital zircon population, trace element patterns, isotopic signature, or some other feature that has absolutely no visual expression. Such things may indeed be important, but we are very much interested in the *visual* – the observational facts and the linked interpretations.

In addition to clear writing, we want such articles to contain well-constructed maps and graphics, ideally adapted and simplified for their purposes, and to also feature abundant photographic material. One of the great advantages of being an online journal is that the constraints for colour illustrations and for the overall length of articles are greatly diminished. There is no reason why a *Classic Rock Tours* article could not explore a multi-day excursion. Finally, we must emphasize that such articles will need to contain clear information for finding, accessing and understanding sites, and that aspects of safety and respect for the property owners and other users must be considered and included. Even if *Geoscience Canada* does not assume any legal responsibility for the safety of those who use our published information, we need to ensure that guidelines are accurate and that potential users are fully aware of any specific hazards, concerns or restrictions.

With these general thoughts in mind, we invite our readers to consider possible future contributions to this series, and to contact the editor about their ideas. The first article in this series follows, completed with the assistance of guest editor Brendan Murphy, and we are very happy to have finally made a start on this idea. As is often the case, it proved necessary to start the ball rolling, but this proved to be one of the most enjoyable writing tasks of recent times. The choice for a starting point was in retrospect obvious, because James Hutton's unconformity at Siccar Point in eastern Scotland was the destination for the most famous field trip in the history of geology. It is a deserving place of pilgrimage for geologists and all others who love the mysteries of the Earth, but it is certainly not the only one. We invite you to share your knowledge of these special places, to help readers of *Geoscience Canada* expand their horizons in future travels, and also to help a new generation of geologists understand the critical importance of field observations in our science. There is no shortage of wonderful places to consider; to fill out the blank space in the pages of this introduction, one obvious possibility is provided via a less-than-subtle visual hint. This introduction is too long already, and I need to get back to scheming to find a way to get to the IAGOD conference in northern Argentina this August – I hear that there is some amazing geology down there.

The Grand Canyon of the Colorado River is justly famous as a place of pilgrimage for geologists. It is one of many candidates for articles in this series, should anyone in Arizona be reading this introduction. Photo from the North Rim of the Canyon in 2006, by Andrew Kerr.

SERIES



Classic Rock Tours 1. Hutton's Unconformity at Siccar Point, Scotland: A Guide for Visiting the Shrine on the Abyss of Time

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SUMMARY

The angular unconformity at Siccar Point in Scotland is one of the most famous localities in the history of geology. At this spot, steeply dipping, folded turbiditic sandstone of early Silurian age is clearly overlain by subhorizontal red conglomerate, breccia and sandstone of late Devonian age. Siccar Point was not the first unconformity ever to be described or illustrated, but it is unquestionably one of the most spectacular and informative that geologists are likely to see. In June of 1788, a famous excursion by James Hutton, John Playfair and Sir James Hall first discovered this striking evidence for the cyclic nature of geological processes and the probable antiquity of the Earth. Contrary to myth, it was likely not the inspiration for Hutton's famous phrase *no vestige of a beginning, no prospect of an end*, but Playfair's metaphor of *looking so far into the abyss of time* is forever associated with this place. Siccar Point influenced many other geologists, including the young Charles Lyell, who would eventually bring the ideas of James Hutton together with those of William Smith, to build the uniformitarian paradigm that founded modern geology. Lyell's writings would in turn influence the young Charles Darwin in his search for the reality and causes of evolution. Siccar Point is easy to visit from the historic and vibrant city of Edinburgh, and such a pilgrimage is easily combined with other sights of geological or cultural interest. Visiting the shrine involves a short coastal hike in one of the most beautiful parts of Scotland. This article combines practical advice for would-be pilgrims to Siccar Point with some historical context about its pivotal role in the development of geological ideas in the enlightenment of the late 18th and early 19th centuries.

RÉSUMÉ

La discordance angulaire de Siccar Point en Écosse est l'une des localités les plus célèbres de l'histoire de la géologie. À cet endroit, un grès turbiditique plissé à fort pendage du début du Silurien est recouvert de conglomérats rouges subhorizontaux, de brèches et d'un grès de la fin du Dévonien. Siccar Point n'est pas la première discordance qui ait été décrite ou illustrée, mais c'est sans conteste l'une des plus spectaculaires et révélatrices que les géologues puissent voir. En juin 1788, avec leur célèbre excursion, James Hutton, John Playfair et Sir James Hall ont découvert cette preuve frappante de la nature cyclique des processus géologiques et de l`ancienneté probable de la Terre. Contrairement à ce qu'on croit, ce n'est probablement pas la fameuse phrase de Hutton « aucun vestige d'un début, aucune perspective de fin », mais la métaphore de Playfair « voir si loin dans l'abîme du temps » qui est à jamais associée à ce lieu. Siccar Point a influencé de nombreux autres géologues, y compris le jeune Charles Lyell, qui a fini par réunir les idées de James Hutton et celles de William Smith qui ont défini le paradigme uniformitariste, devenu le fondement de la géologie moderne. Les écrits de Lyell influenceront à leur tour le jeune Charles Darwin dans sa recherche de la réalité et des causes de l'évolution. Il est facile de se rendre à Siccar Point depuis cette ville chargée d'histoire et dynamique qu'est Édimbourg, et un tel pèlerinage se combine facilement avec d'autres sites d'intérêt géologique ou culturel. La visite de ce « sanctuaire » implique une courte randonnée côtière dans l'une des plus belles régions d'Écosse. Le présent article combine des conseils pratiques pour les visiteurs potentiels à Siccar Point et présente un historique de son rôle central dans le développe-

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ment des idées géologiques à la fin du XVIIIe siècle et au début du XIXe siècle.

Traduit par le Traducteur

PROLOGUE

In introductory geology classes, I often use images of the Grand Canyon as symbols for the immensity of geological time. Impressive as it is, the canyon is really not the original shrine to our knowledge of Earth's antiquity. The true *shrine on the abyss of time*, as I call it here, lies instead on the temperate coast of eastern Scotland. It was first encountered on one of the most famous field trips in the history of geology – a boat excursion by James Hutton, John Playfair and Sir James Hall in June of 1788. Siccar Point is a place of pilgrimage for geologists and all others who love the mysteries of the Earth, and it seems an appropriate place to begin this new thematic series in *Geoscience Canada*.

James Hutton's archetypal unconformity is easy to visit and enjoy. The scenic hike along the coastal path can be as short as a 3 km round trip, although it can be made longer if you wish. Siccar Point itself reveals one of the clearest and most instructive unconformities that I have ever seen, and its influence in confirming and connecting the ideas that Hutton (1788) expressed in his *Theory of the Earth* is easy to comprehend. On this rocky headland, the first salvo in the great debate about the age of the Earth was fired, creating cracks in a religious dogma that accorded geologists only 6000 years to explain the history of an entire planet. Those fractures would propagate over a century or more, until Arthur Holmes published a famous book that marked the start of modern geochronology (Holmes 1913). Siccar Point is much more than a field locality, so this article includes not only the rocks and how to see them, but also explores the context of those times and the ways in which this singular place influenced subsequent geological thinking.

This article contains no original research. It is built instead from the published scientific record, several books on James Hutton and his contemporaries, and other public-domain sources. The observations, photographs and practical suggestions come from my own visits in March 2016, and the references given at the end should be the primary source for any citations. I commence with some simplified regional and local geology, followed by information for safely and respectfully visiting the site, and some descriptions of rocks and relationships. I then take an historical turn, by recounting some early descriptions and thoughts from 1788, and discussing how Siccar Point might have influenced later geologists. Hutton's insights were undeniably prescient, but their presentation was often disorganized and muddled, and it took the work of others to mould them into a paradigm for physical geology. Knowledge of this wider historical context certainly is not essential to take a beautiful walk to a famous place, but I firmly believe that it can enrich the experience.

LOCATION AND REGIONAL GEOLOGICAL CONTEXT

Siccar Point is located in eastern Scotland, between the city of Edinburgh and the English border, within the historical county of Berwick, now included within the 'Scottish Borders Unitary Region.' It is close to the A1, a main trunk road leading to Berwick-upon-Tweed. If you are willing to walk a few extra kilometres, you can get there using public transport. The site is a coastal headland and some low-relief outcrops that form part of a wave-washed platform on the North Sea coast, situated below steep but negotiable slopes. Other coastal outcrops that form part of a well-known Devonian and Carboniferous section can also be visited in this general area, to make a full-day hiking excursion.

This region is part of the Caledonian orogenic belt, which makes up most of the pre-Carboniferous bedrock of Scotland, England and Wales, aside from older Precambrian areas in northwest Scotland (Fig. 1). Most readers will know that the Caledonian and Appalachian orogenic belts were contiguous prior to the Mesozoic and record the closure of the early Paleozoic Iapetus Ocean and its related basins. The overall geological progression from north to south in Britain is similar to the northwest to southeast progression seen in the Canadian Appalachians, although there remains debate about the exact location of key features. For example, the 'Iapetus Suture' (the limit of Laurentian and peri-Laurentian crust in the orogen) is placed in a more southerly ('outboard') location in Britain than in most interpretations for Newfoundland and elsewhere in Canada (e.g. van Staal et al. 1998). In southwestern England and in south Wales (Fig. 1), Paleozoic rocks are variably affected by Carboniferous deformation (termed Variscan or Hercynian), which is less prevalent in Canada. Some distal effects of Variscan deformation are also recognized north of the Variscan Front (Fig. 1). Central and southeastern England consist of late Paleozoic to Cenozoic sedimentary rocks that form a largely undisturbed southeast-younging and southeast-dipping sequence. On the south coast of England, some of these younger sedimentary rocks are affected by distal deformation caused by the formation of the modern Alpine orogenic belt. It was in southeastern England that the principles of stratigraphy were first elucidated by William Smith, who shares with James Hutton the title of 'the father of geology.' Smith is best known for having constructed the first true regional geological map (e.g. Winchester 2001; Sharpe 2015), whereas Hutton first voiced the idea that geological history might be explained by modern day processes operating over immense periods of time, amongst many other ideas. Hutton's ideas would eventually lead to the well-established doctrine of uniformitarianism (e.g. Lyell 1874) which persists today, albeit with some modifications.

Siccar Point is located within a few kilometres of a major structure known as the Southern Upland Fault (Floyd 1994; Figs. 1, 2), which separates a region dominated by lower Paleozoic rocks (the Southern Uplands) from a region dominated by Devonian and Carboniferous rocks (the Midland Valley of Scotland). The Midland Valley represents a rifted basin that also contains volcanic rocks, and it developed following the closure of the Iapetus Ocean (e.g. McKirdy et al. 2007). Devonian and Carboniferous sedimentary rocks also occur within the Southern Uplands, where they form thinner sequences that sit unconformably upon older deformed and

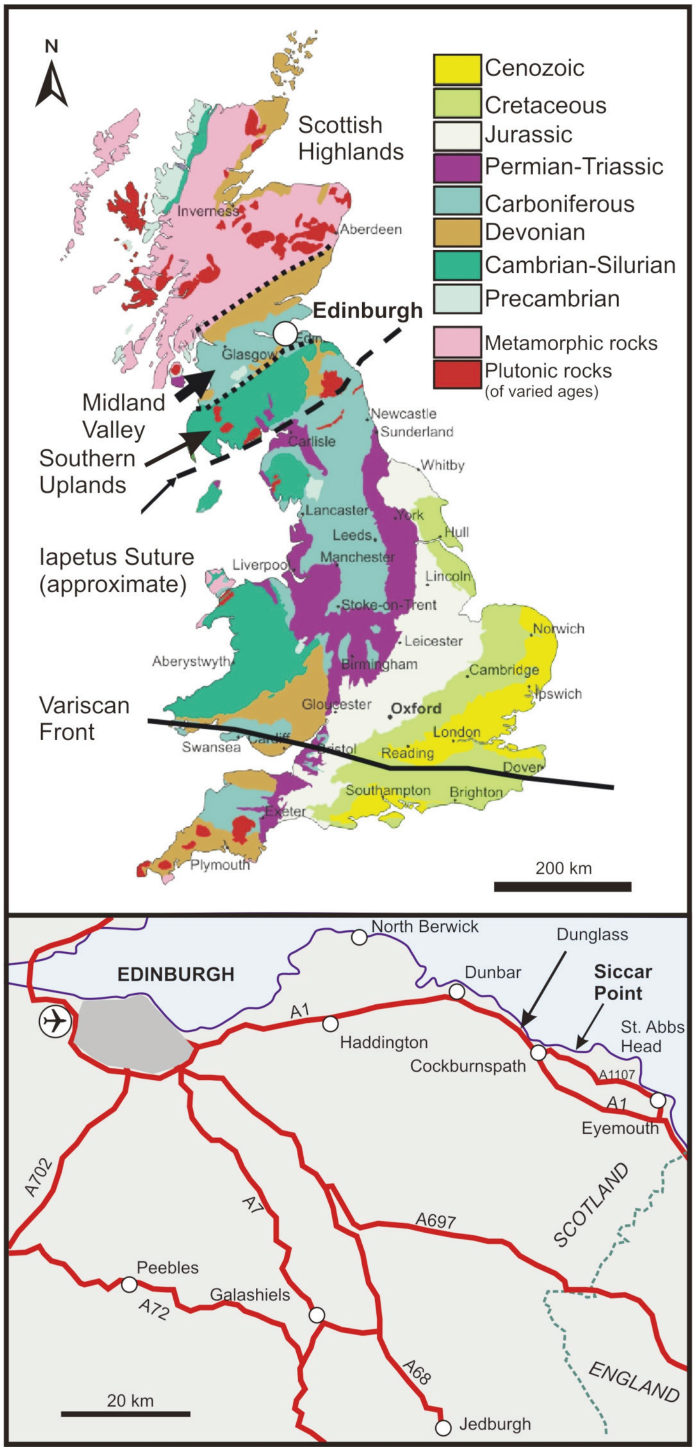


Figure 1. A. Simplified geology of England, Wales and Scotland, showing the location of the area near Edinburgh covered in this paper and some important geological features. B. The location of Siccar Point in relation to local towns and major roads in the area. The geological map in (A) is modified from one published online by the British Geological Survey.

metamorphosed sedimentary rocks. Siccar Point is the classic expression of this regional unconformity, but it was not the only such site examined by Hutton in the late 18th century. The Southern Uplands Terrane is considered in Britain to be of peri-Laurentian affinities, and to represent an accretionary wedge formed as the last vestiges of the Iapetus Ocean were subducted (e.g. McKirdy et al. 2007; Stone 2012; Stone et al. 2012). Rocks occupying the same relative position in eastern Canada are considered to be of peri-Gondwanan affinity (e.g. van Staal et al. 1998), but of similar tectonic setting. The paleogeographic setting of the Southern Uplands Terrane was recently reassessed by McConnell et al. (2016), using detrital zircon to establish sediment provenance. This debate, although interesting, is not relevant to the story of Siccar Point, other than to illustrate that discussion of the geology continues and probably always will.

The regional and local geology are summarized in a recent article by Archer et al. (2017) and also in more general publications from Scottish Heritage and the British Geological Survey (notably MacAdam and Stone 1997; source of Figure 2). A more detailed summary is provided by Barclay et al. (2005) as part of an extensive review of “Geological Conservation Review Sites,” some of which are designated or suggested as Sites of Special Scientific Interest (SSSI) in the United Kingdom. The area lies within the Eyemouth Sheet (1:50,000) of the British Geological Survey, first published in 1982, with an accompanying Memoir (Grieg 1988). In the area east of the town of Dunbar, there is a westward progression from Silurian sedimentary rocks, through Upper Devonian and Carboniferous sedimentary rocks, towards the Southern Upland Fault (Fig. 2). The local geology of the area around Siccar Point is depicted in Figure 3, modified after Grieg (1988) and Barclay et al. (2005). The oldest rocks are the turbiditic sandstone, siltstone and mudstone of the Silurian Gala Group, which are overlain by Devonian terrestrial sandstone of the Stratheden Group, which then passes up into the more varied Carboniferous rocks of the Inverclyde and Strathclyde groups (Fig. 3). The sedimentary rocks of the Gala Group are assigned to the Llandovery stage based on fossil graptolites (Stone et al. 2012). The Devonian rocks belong to the sequence traditionally known as the ‘Old Red Sandstone’ in Britain, as distinct from the ‘New Red Sandstone,’ which is of Permian to Triassic age. These red-bed sequences represent post-orogenic ‘molasse’ cover rocks linked to the Caledonian and Variscan orogenies, respectively. Fossil fish remains from the lower Stratheden Group indicate a late Devonian (Fammenian) age (Barclay et al. 2005).

None of these familiar stratigraphic terms existed at the time of James Hutton’s explorations, and there was no geological time scale as such. Indeed, most of the concepts that we now take for granted were not developed until well into the 19th century. In the time of James Hutton, the questions about geology were of a much more fundamental nature, i.e. how and when were rocks formed, and what did they mean?

PRACTICALITIES AND LOCAL GEOLOGY SIGHTS

There are published descriptions of the local geology and the Siccar Point site, most recently by Archer et al. (2017) and in some previous excursion guides by Craig (1960, 1986), which are less easily accessible. There is also a summary suitable for self-guided excursions in an excellent book on the geology of Scotland (McKirdy et al. 2007). Several books about James

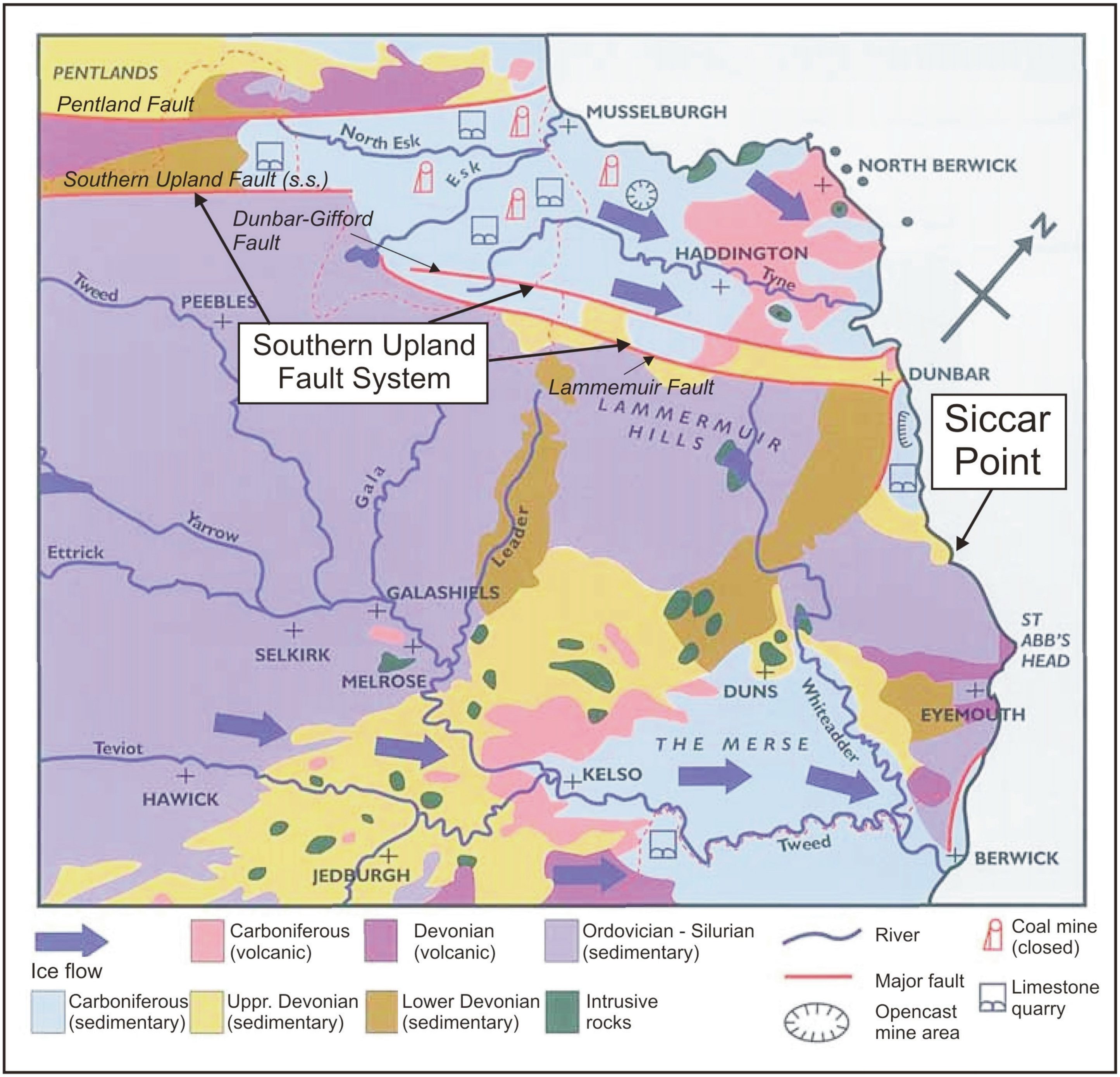


Figure 2. Simplified geology of the area east of Edinburgh and including the area around Siccar Point. From MacAdam and Stone (1997) with some slight modifications and additions. Base geological map from report used with permission of the British Geological Survey and Scottish Natural Heritage.

Hutton also provide discussions of the initial visits by Hutton and his colleagues (e.g. Baxter 2003; Repcheck 2003). Montgomery (2003) provided an illuminating discussion of Siccar Point in the context of teaching the history of geology, emphasizing it as an example of the scientific method. In this section, I integrate some of these sources with my own observations to simplify matters for the travelling geologist. Readers should note that references to landmarks, although current as of early 2016, may become obsolete, and also that odometer readings for vehicles in the UK are given in miles, rather than kilometres.

Safety, Security and Conservation

Siccar Point is accessed via a coastal hiking trail that is well-defined and maintained for the most part, but its condition may vary seasonally, and it may be muddy and uneven in places. In some areas, it is situated close to the edges of steep slopes or vertical cliff faces. Sturdy footwear is important,

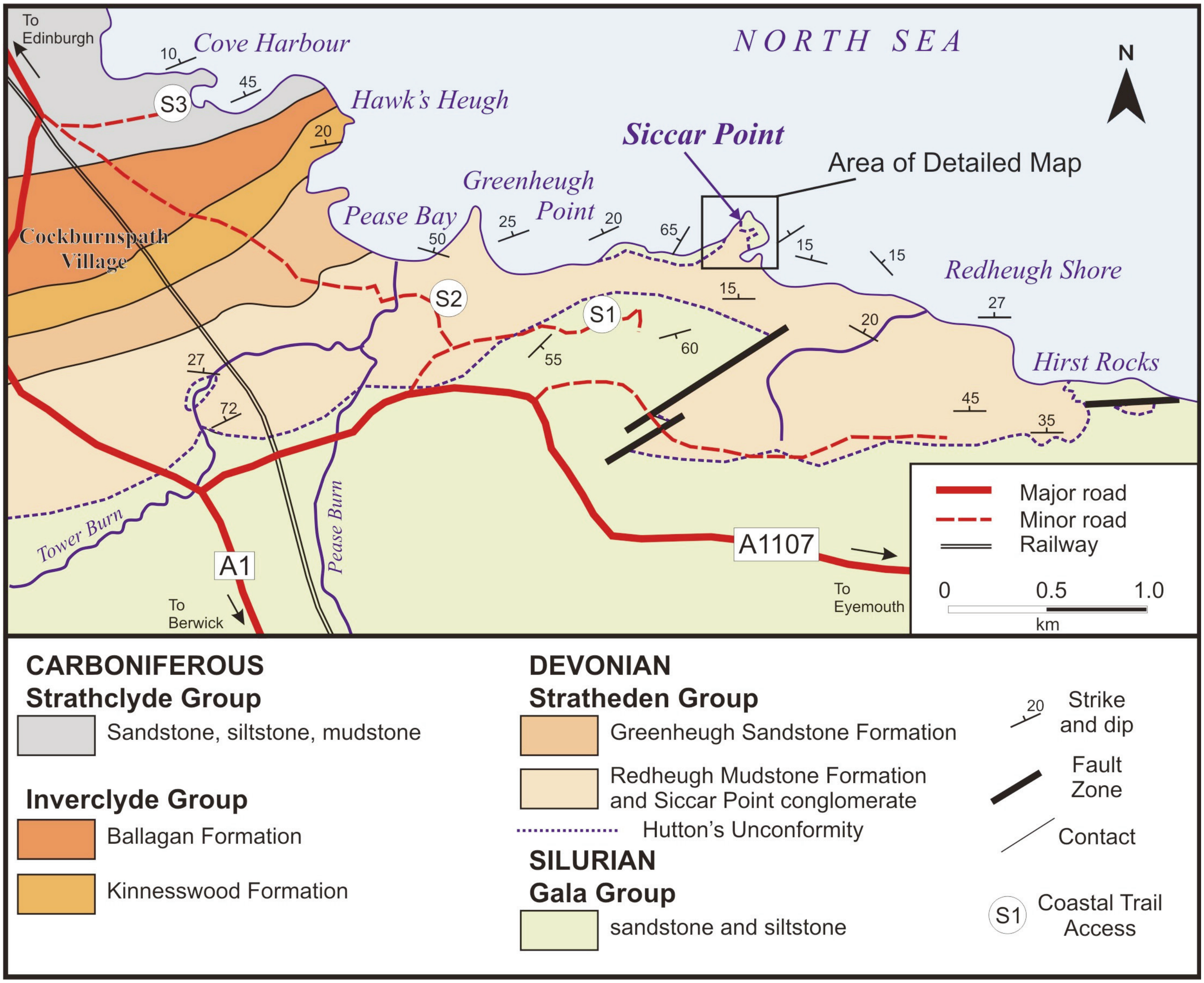


Figure 3. Simplified geological map of the area around Pease Bay and Siccar Point showing the access roads and entry points to hiking trails. From the British Geological Survey map (Grieg 1988); compare Barclay et al. 2005. Note that there is extensive outcrop in the intertidal zone along this coast, which is omitted for the sake of clarity.

preferably with good support for the ankles, and care should be exercised at all times. The weather in eastern Scotland is just as unpredictable as it is in Newfoundland or Nova Scotia, so walkers should be prepared for wind and rain as well as sunshine and everything else in between. The descent from the path to the coastal outcrops at Siccar Point is the steepest and most challenging part of the excursion. However, this path is well-trodden and follows a comforting fence. The unconformity site consists of coastal outcrops, which are uneven, and from which there may be vertical drops to the cold waters of the North Sea. Part of the area is a wave-cut platform across which larger waves may travel if sea conditions are rough. Visitors should monitor wave activity carefully before descending, and determine which areas might be dangerous, and should stay well away from the water or any areas that appear wet. Note that any excursion or activity described here is conducted *entirely* at your discretion, and that neither the author nor the Geological Association of Canada accepts any responsibility for injury or loss that might occur. Geoscientists visiting this area should follow all the safety protocols that they would normally employ in their professional work.

Siccar Point is designated as a Site of Special Scientific Interest (SSSI) and it is protected; the collecting of samples and removal of material is prohibited, as is any hammering or defacement of outcrop surfaces. There is no need to even bring a hammer. There are codes of conduct that apply to outdoor activities (the Scottish Outdoor Access Code), and these can be consulted at www.outdooraccess-scotland.com. Scottish Natural Heritage even publishes a specific 'geological code,' which can be found on their website at www.nature.scot. Visitors are urged to consult these guidelines.

Getting to the Siccar Point Area

The easiest and most flexible way to visit the area is with your own vehicle, but it is also possible via public transport. Driving in metropolitan Edinburgh is not for everyone, as the streets are narrow and congested, and parking is expensive and elusive. It is currently possible to arrange a guided tour to the site through *Geowalks* (www.geowalks.co.uk), which represents an easy solution, including transportation. If you have a rental vehicle and are staying in central Edinburgh, it may actually be cheaper to leave the car at long-term parking at the airport and use the excellent tram service for city centre access. If travelling from Edinburgh by road, the A1 is the route out of the urban area to the village of Cockburnspath, where there is a roundabout with a left turn signposted for Pease Bay, just before the road crosses the path of the railway. The looming bulk of the Torness Nuclear Power Station (on the left) provides a useful marker around 5 km before the roundabout. If this turn is missed, take the later left turn on the A1107, signposted for Eyemouth. The Siccar Point area can then be accessed via the minor road on the left, a few hundred metres past the bridge over Pease Burn. These roads are all shown on the local geology map (Fig. 3).

Public access is via the bus service linking Edinburgh and Berwick-upon-Tweed (England) which is provided by Borders Buses (www.bordersbuses.co.uk). Currently, the service is numbered 253, and it runs approximately once an hour; note that the last return bus (as of February 2018) to Edinburgh from Cockburnspath departs at 16.49 (weekdays) and just after 17.00 on weekends. Be sure to check the latest schedules, and to leave Edinburgh early to ensure enough time for hiking. From Cockburnspath village, walk along the road to Pease Bay, as shown in Figure 3. Note that the road lacks a pedestrian walkway, and that drivers may come around corners at high speeds. Care should be exercised and you should face the traffic at all times.

There are several choices for an excursion to Siccar Point, depending on how far you wish to walk. The shortest option is to drive through the Pease Bay Caravan Park (Plate 1), through the ford on Pease Brook, and then take the side road on the left that leads into the Drysdale's farm property. The company has thoughtfully provided a small parking area for geologically minded visitors (Point S1 on Fig. 3). Alternatively, park at the junction of the Drysdale's farm road, and walk a short distance back towards the Caravan Park, to connect to a hiking trail clearly signposted for Siccar Point (Plate 2; Point S2 on Fig. 3). This will lead eventually to the same parking area at Point S1, but provides a scenic diversion. The longest and most adventurous route is to take the short access road on the left from the Pease Bay Road, about 200 m after the roundabout on the A1. This leads to Cove Harbour, from where the coastal path can be accessed at Point S3 and then followed all the way through Pease Bay to Siccar Point. However, remember that you will have to retrace your steps to return, or walk back on the roads, and that parking is limited around Cove Harbour. The full hike provides a walk down-section from Carboniferous into Devonian rocks and terminating at Hutton's unconformity. The higher part of the stratigraphic section is also well-known for superb exposures of fluvial and aeolian sedimentary rocks, and also important fossil fish localities (Barclay et al. 2005). Note that these sites are also SSSI, with the same protection criteria as Siccar Point itself. Although I have not completed the walk from Cove Harbour to Pease Bay, there is a useful description provided in an informal report by the Glasgow Geological Society that describes a 2016 field excursion (Hollis 2016).

Plate 1. View of the large caravan park at Pease Bay. You will pass through this en route to Siccar Point.

Plate 2. View of Pease Bay from the road leading towards Siccar Point, where it intersects the Berwickshire coastal path.

The Coastal Hike to Siccar Point

From Pease Bay, the path leads along the coast, but not on the clifftops, and then rejoins the farm access road that leads to Point S1. A signboard here provides some background information on the Siccar Point locality. The trail from here leads northward toward the coast, and first passes the ruins of St. Helen's Chapel. Like many older buildings here, and most of the stone walls that bound fields, this is constructed from local

Plate 3. The ruins of St. Helen's Chapel, which the trail passes. Note the mixture of red and grey-green stone blocks used in construction.

stone blocks (Plate 3). In this case, there is a striking colour contrast between most of the stones (grey or pale green sandstone of Silurian age) and a smaller number of orange-red blocks (Devonian sandstone). It is noted on the signboard that the mixture of sandstone types used in construction alerted James Hutton to the possibility that the contact between the 'primary' and 'secondary' sedimentary series that he had already defined might lie in this general area. This is not mentioned in other sources, but it certainly makes sense as a useful observation. Indeed, the dry-stone walls near Siccar Point itself contain almost equal proportions of the two sandstone types (Plate 4).

Beyond the chapel, the trail meets a stone wall that runs parallel with the cliff edge and follows this wall eastward towards Siccar Point. The wall can be climbed in places, although care must be taken to avoid the barbed wire. The coastal side of the wall allows sufficient space for safe walking, and provides better coastal views, but it places walkers close to the cliff in some places. There is really no need to climb the wall, as there is a gate providing access closer to the point. Views of the coastline here reveal the outcrop pattern of gently dipping Devonian sandstone, protecting sand and gravel beaches (Plate 5), and then provide views towards Siccar Point (Plate 6). The latter provides an illustration of the three-dimensional topography of the unconformity surface. The steeply dipping grey beds in the lower section of the slope are the older Silurian rocks, and the largely unexposed upper section conceals subhorizontal red sandstone. However, the offshore rocks in the far distance, close to Siccar Point, also represent the basal surface of the Devonian section, which is essentially at sea level, because it sits within an incised paleochannel (see below).

Plate 4. Dry-stone wall not far from Siccar Point on the hiking trail. Note the almost equal proportions of red (Devonian) and grey-green (Silurian) stones.

Plate 5. Coastal view en route to Siccar Point. The low outcrops in the water are gently dipping Devonian sandstone.

Above Siccar Point, the trail is marked by a second sign board, which provides some additional information on unconformities and their significance. The point is clearly visible below, and the colour contrast between the grey Silurian strata and the red Devonian strata is obvious even from above.

Descending to the Siccar Point Outcrops

The view of Siccar Point from the clifftop (Plate 7) suggests that this is a steep descent, and it is, but it is easier than it

Plate 6. Approaching Siccar Point on the coastal path. The steeply dipping grey beds in the middle are Silurian greywacke, but the upper part of the slope (unexposed) consists of subhorizontal Devonian sandstone. The rocks in the distance are part of the Siccar Point outcrop, where the unconformity is essentially at sea level.

Plate 7. View of the Siccar Point outcrops from the clifftop, showing the route down to the locality following the fence line. Devonian sandstone visible in right of photo, underlain by subvertical Silurian greywacke. The reddish outcrops on the left are Devonian sandstone and breccia sitting on the Silurian rocks in an incised paleochannel, which extends northward below sea level.

appears. This is because a sturdy fence leads almost all the way down and provides secure hand-holds and guidance. Previous visitors have also created a series of eroded steps parallel to the fence, which also helps, but be wary of slippery red mud if there has been recent rain. The steepest part of the descent is close to the bottom, and this should be avoided. About two-thirds of the way down there is a double fence post; from here, turn to the left and descend diagonally across a gentler grassy slope, and then double back towards the outcrops. The ascent follows the same course, and is actually somewhat easier than the descent, if more tiring. This section of the hike is definitely unsuitable for children or for anyone who is uncomfortable with heights, but it will not intimidate most field geologists. However, good footwear and caution are essential, and a hiking stick is a valuable accessory.

As seen from above, the southeast side of Siccar Point contains a slot-like channel backed by vertical cliffs (Plate 7), and the descent provides a spectacular view back towards the unconformity surface, which is high in the cliff face (Plate 8). This view also shows the way in which the contact cuts down sharply into the older rocks, which here strike almost parallel to the cliff face. This is because the area of Siccar Point itself is an incised channel beneath a regional unconformity surface that is more planar, but still topographically complex (Craig 1986; Barclay et al. 2005; Archer et al. 2017).

Geological Relationships and Sights at Siccar Point

In my time as a field geologist, I have not seen an unconformity as accessible and informative as Siccar Point. James Hutton and his colleagues were indeed lucky to have found such a clear and instructive example in June 1788.

The geology of Siccar Point is described by Archer et al. (2017) and in previous accounts by Craig (1986), Grieg (1988), Barclay et al. (2005) and McKirdy et al. (2007). The local geology is illustrated in Figure 4, modified after Grieg (1988). The outcrop is in three parts; to the west, well-bedded grey sandstone and siltstone dip towards the south at 45° or more. These same rocks in the southeast dip more steeply to the north, suggesting tight folding; according to Grieg (1988) bedding is locally overturned in this area, although access to these outcrops is not easy. In the central part of the outcrop, and on some offshore reefs, red sandstone and basal breccia dip gently to the north. The younger rocks are draped over steeply dipping Silurian rocks, and resistant sandy beds locally protrude through the unconformity surface to emerge as tiny inliers on the outcrop surfaces. Similarly, patches of the basal breccia facies sit in low-lying sections of the outcrops, forming complementary outliers. The angular discordance between Silurian greywacke and Devonian sandstone is clearly seen and there is

Plate 8. View of the unconformity in the cliffs, about halfway down the fence line. The Silurian greywacke beds are steeply dipping in the plane of the photo. Note how the elevation of the unconformity surface descends at the right side of the photo, illustrating the paleotopography on the surface.

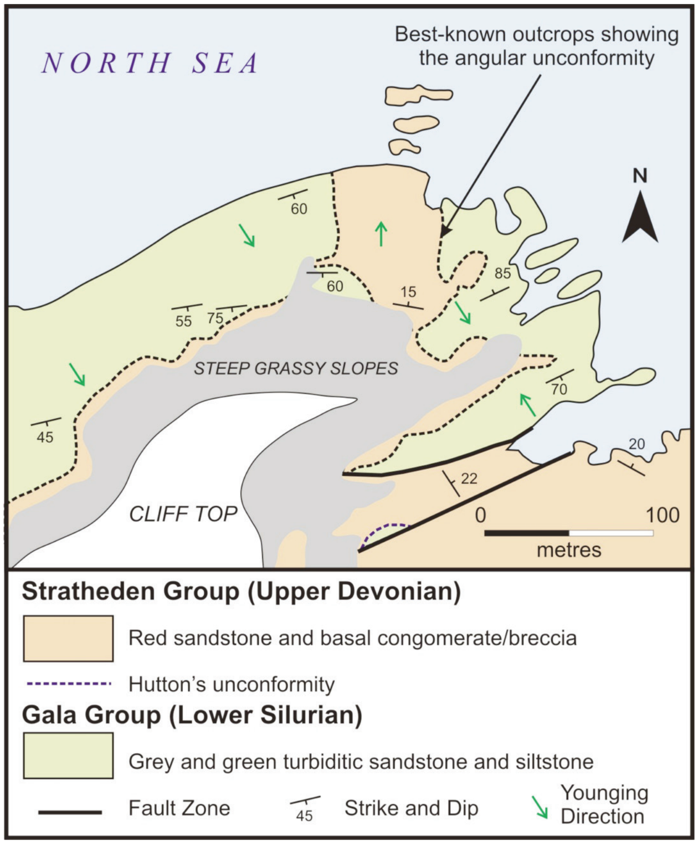


Figure 4. Geological sketch of the Siccar Point locality (Hutton's unconformity). Simplified slightly from Grieg (1988) and Barclay et al. (2005).

Plate 9. This is the classic view of the unconformity seen in many other sources. The unconformity surface is just above the hiking stick. Note how the surface is draped over the resistant Silurian sandstone unit at the left of the photo.

Plate 10. A closer view of the unconformity surface shown in Plate 9, showing the angular discordance, which here is almost 90°. The basal conglomerate and breccia unit sits between the older rocks and the red sandstone, but is only a few centimetres thick. Note a possible tight fold closure in the older rocks to the right; this was not confirmed in my field notes, so it could be an optical illusion caused by inclined fracture surfaces.

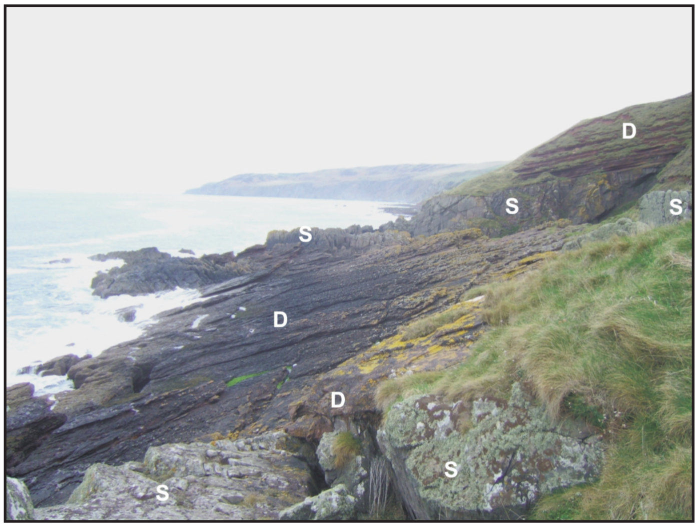


Plate 11. A view of the entire unconformity surface, showing the channel containing conglomerate and breccia (tilted to left, flow direction to right), resistant Silurian outcrops (centre and upper right) and gently dipping sandstone sitting directly on the Silurian greywacke (top right) outside the incised channel feature (S-Silurian, D-Devonian).

essentially no sign of disturbance by later faulting. The most famous section of the outcrop is indicated in Figure 4, and Plates 9 to 15 highlight some of the relationships.

All descriptive accounts of Siccar Point emphasize the marked paleotopography of the unconformity surface, which is seen on scales from centimetres to tens of metres (Craig 1986; Grieg 1988; Barclay et al. 2005; Archer et al. 2017). Regional studies of the Devonian sedimentary rocks imply that they were deposited in erosional valleys that overlapped in time and space, and the Siccar Point exposures are interpreted as an incised gully formed in an arid climate, which experienced periodically intense water flow. The most detailed account of sedimentological features is provided by Barclay et al. (2005), drawn from earlier and more detailed studies of the Devonian rocks. The central part of the outcrop contains most of the breccia, and the clast population is dominated by angular plate-like chunks of older greywacke, along with pieces of quartz (likely from veins). The imbrication of clasts, and information

Plate 12. A view across the bottom of the paleochannel that contains much of the Siccar Point unconformity surface. The breccia and conglomerate in the foreground dip gently to the right (north) but the paleocurrent direction is to the left (south). This gives the slightly disorienting sense of an uphill water flow. The massive grey rocks in the middle are resistant Silurian greywacke, which would have formed islands in the Devonian channel or gully. The breccia passes upwards into red sandstone that eventually filled the channel (see centre of photo) but has now largely been eroded. This part of the outcrop is especially evocative.

Plate 13. Part of the unconformity surface and basal breccia unit shown in oblique plan view; steeply dipping greywacke at left, with red sandstone matrix to breccia infilling the less resistant areas.

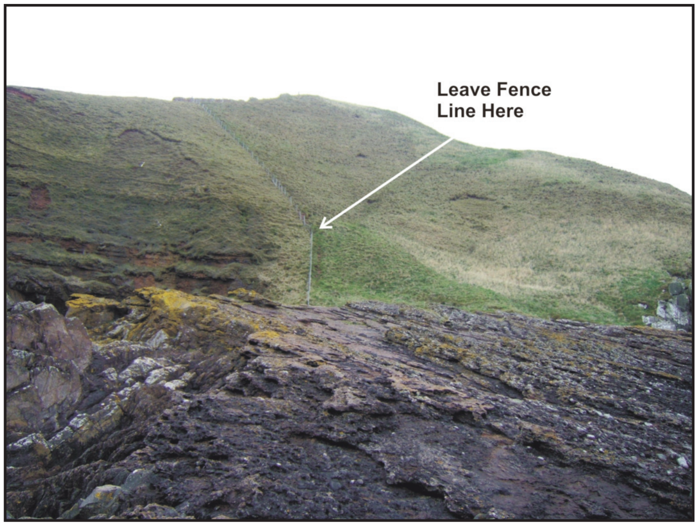


Plate 14. A view looking up from Siccar Point towards the access route along the fence line. This also shows the unconformity surface and north-dipping breccia and conglomerate in the channel floor at right. The white-weathering steeply dipping beds at left are the older Silurian greywacke. In the left distance is the red sandstone that sits above the basal unit, but which is largely eroded from the coastal outcrops. Note the inflection point in the fence line, marked by a double fence-post. The route down to the point diverges from the fence line at this point, as shown to cross the gentler grassed slope to the right.

Plate 15. A close-up view of the conglomerate and breccia unit that marks the unconformity surface almost everywhere at Siccar Point. Note the poorly sorted matrix (the 'arenaceous cement' of John Playfair), and the wide range of clast sizes and shapes. A clast of probable white vein quartz is at top left.

from cross-bedding foresets in younger sandstone, imply that the paleocurrent in the channel flowed towards the south or southeast (Grieg 1988). Standing within this area, at the bottom of a Devonian gully, it is easy to imagine the cobble and boulder-choked watercourse, with rocky resistant outcrops of older greywacke beds standing up as islands within it (Plates 11 and 12). Cross-bedded sandstone overlies breccia and conglomerate, showing the change in depositional environment. Due to the regional northward tilting of the unconformity surface the paleocurrent appears now to be flowing uphill, which is somewhat disorienting, but the sense of stepping back in time and walking in an ancient riverbed is palpable, and it will strike visitors who have little geoscience knowledge.

The amount of missing time represented at the Siccar Point unconformity surface is not measured directly because the sedimentary rocks are not amenable to radiometric dating. The older rocks are of Silurian age, in the Llandovery Stage (~ 444 Ma to 428 Ma) based on regional correlations and graptolite data. Loose blocks of Devonian sandstone from Siccar Point contain fossil fish remains indicating an upper Devonian (Famennian) age of ca. 370 Ma (Barclay et al. 2005 and references within). Thus, the unconformity does not by itself closely constrain the timing of the deformation and low-grade metamorphism of the Silurian rocks. In addition to its value in teaching the essential principles of geology and science (Montgomery 2003), Siccar Point is also relevant as an end-member of a spectrum of unconformable and paraconformable surfaces involved in traps for petroleum resources (Archer et al. 2017). For more details on the local geology and related matters, see Archer et al. (2017), its contained references and the other sources cited above. After visiting the site and spending some hours exploring it (including a leisurely lunch) I can only express my agreement with the views of McKirdy et al. (2007):

> *"If you go nowhere else to see the geological gems of Scotland, go to Siccar Point"*

Taking a Virtual Tour

A virtual tour of this locality is available online. The British Geological Survey has produced an excellent video using drone photography, appropriate music and a well-conceived commentary intended for non-geologists. Find the video at: https://www.youtube.com/watch?v=JCEDCcHcpYE, or by searching keywords. The production is an excellent model for what we could do in Canada for important geological sites, but it is no substitute for visiting Siccar Point in person.

SICCAR POINT AND GEOLOGICAL THOUGHT

For most classic geological localities, there are elements of history to consider, but Siccar Point is unique, as it played a key role in changing ideas about the age of the Earth and influenced subsequent thinking. A visit to this place is thus also a chance to contemplate and appreciate the origins of modern geology. For more complete accounts of the lives and accomplishments of James Hutton and his acquaintances, see several biographies (Bailey 1967; Dean 1992; Repcheck 2003; Baxter 2003). The latter reference has my strongest recommendation for easy and informative reading and also for giving some glimpses into the human side of Hutton. I attempt here only to highlight some key points within the wider context of 18th century geological thought. It is also interesting to revisit original descriptions and famous words that the site inspired, although these certainly appear in other accounts, and the most famous phrase of all even made its way into rock music. I cannot resist mentioning the irony of Hutton's words being used in a song by an American punk rock band named *Bad Religion*. I suspect that one of the band members must at the very least have taken an introductory geology course, but have found no documentary evidence.

The Age of the Earth: Genesis Versus Science

We have all grown up with the knowledge that the Earth is around 4.6 billion years old, as demonstrated from U–Pb isotopic studies of meteorites, but the road to this insight was not straight or smooth. In 1788, when Hutton and his friends boarded a boat at Dunglass, the age of the Earth was accepted by almost all at around 6000 years, based on biblical interpretation by James Ussher, Bishop of Armagh (1581–1656), who in turn derived it from previous scholars. Similarly, the idea of divine creation was questioned by very few, and even then only at their peril. James Hutton was one of the first to propose that the Earth's origin was far more distant in time. In 1785, three years before visiting Siccar Point, his ideas were first expressed in a paper read to the Royal Society of Edinburgh (Hutton 1785). Although this was only an outline of his concepts, it remains one of the clearest, leading to suggestions that much of it was actually written with assistance from more lucid friends, either John Playfair (Bailey 1967) or William Robertson (Dean 1992). Hutton's (1785) 'abstract' contained the memorable phrase:

> "*...with respect to human observation, this world has neither a beginning nor an end...*"

These words are nowhere near as famous as the sentence that closed the later 1788 edition of "*Theory of the Earth*," but they are perhaps more accurate, as they are qualified. Unfortunately, Hutton's critics did not appreciate these terms of reference and castigated him for suggesting that the Earth was eternal. To the pious, this was atheism and heresy, because only one entity could truly be eternal. Hutton was actually not an atheist, but a *deist* – he believed in creation, but not as depicted in Genesis, and he saw no divine role in the routine workings of the world, on any time scale. His ideas began the 'Age of the Earth Debate,' during which views directly based on theology, or developed to be consistent with theology (e.g. 'catastrophism') would be superseded by the concept of uniformitarianism, which demanded that the Earth be very ancient. The 1788 visit to Siccar Point was undoubtedly an important influence on such ideas, but it was not the *source* of such a concept, because it came later than its first presentation. Siccar Point was also not the first unconformity that Hutton had visited during his explorations, although it is undoubtedly the clearest (e.g. Montgomery 2003).

Three Men in a Boat

In 1788 James Hutton and two colleagues embarked on a boat excursion from Dunglass, located to the west of Cockburnspath (Fig. 1). This is probably the most famous field trip in the history of geology, so it is fitting to introduce the characters and reflect upon their words and other depictions of the time. Three visual illustrations, chosen to represent their probable appearance ca. 1788, appear in Figure 5. There is little choice of subject material when it comes to Hutton, for the portrait by Henry Raeburn, completed around 1775, seems to be the only image that we now possess.

The name of *James Hutton* (1726–1797) is familiar to every geology student, but few know more than this and his status as one of the 'fathers of geology.' Hutton was a wealthy man, interested initially in chemistry, who later went on to qualify as a medical doctor. He never actually practised medicine, but instead took to farming, introducing 'modern' agricultural methods at his Berwickshire farm. For full biographical accounts, see Baxter (2003) and Repcheck (2003). Hutton's ideas about earthly processes reputedly came from his obser-

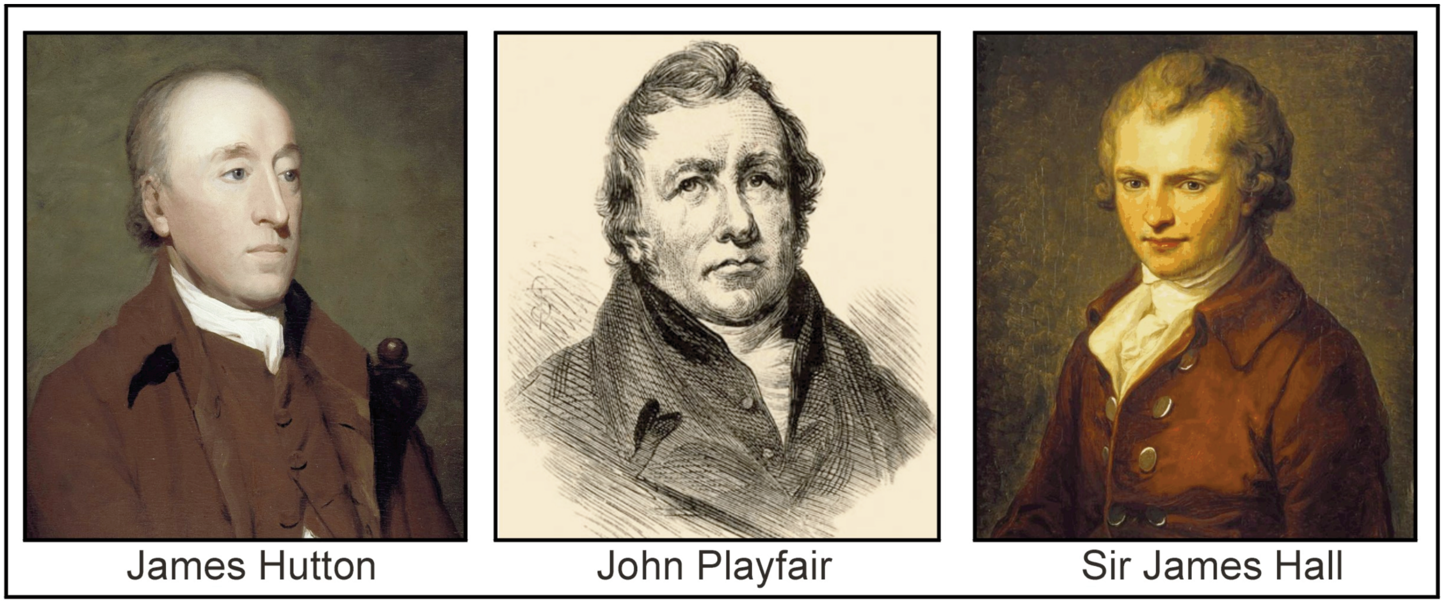


Figure 5. The protagonists of the Siccar Point story, namely James Hutton, John Playfair, and Sir James Hall. The images are chosen from limited selections in order to correspond roughly with their likely appearance in 1788, when they embarked on the famous field trip from Dunglass, west of Pease Bay. Portrait of Hutton by Henry Raeburn (1756–1823), around 1775, now located in the Scottish National Portrait Gallery. Engraving of John Playfair, obtained from ClipArt ETC (Florida Centre for Instructional Technology) and featured in the Amadeus Grabau's "*Textbook of Geology*," published in 1920. Details of the date and artist proved difficult to establish. Portrait of the young James Hall by Angelica Kauffman around 1785, now located in the Scottish National Portrait Gallery.

vations as a farmer. He saw that soil was slowly but steadily removed by erosion and transported by rivers to the sea. He reasoned that there must be an opposing process, by which material deposited in the seas was somehow returned to the land, to begin the cycle again. This represents the 'rock cycle' taught in every school today, and he suspected that long expanses of time were essential. He had other prescient ideas, notably that granite and other igneous rocks were once molten, rather than crystallized from some early 'universal ocean.' He argued that vast internal heat was responsible for raising rocks from the ocean basins to form mountains that would then be eroded. He is even credited with the first thoughts that the Earth might be likened to a vast machine that maintains a habitat for life, a concept that would later expand into the 'Gaia Hypothesis' of the 1970s, minus the element of design (e.g. Lovelock 1988). Gaia is still with us, but is unfortunately now covered by the far less imaginative term 'Earth System Science.' Baxter (2003) speculated that some of Hutton's ideas about thermal energy and the workings of machinery came from his close friendship with James Watt (1736–1819), the inventor of the steam engine. I myself wonder if Hutton's Gaia-like ramblings had some connection to the economic theories of another friend, Adam Smith (1720–1790), with their checks, feedback loops and balances. Hutton, Watt, Smith and other well-known intellectuals were all part of what is now known as the 'Scottish Enlightenment,' when Edinburgh gained the unlikely nickname of "The Athens of the North". In 1788, Hutton was 62, and not as strong and fit as he once had been. He had abandoned active farming and returned to live in Edinburgh and was a prominent (if eccentric) member of the city's intelligentsia. Later that year, the first edition of "*Theory of the Earth"* would be published, and much if not all of its text was already completed. A two-volume expanded edition was published in 1795, but his health was by then frail and additional volumes remained uncompleted when he died in 1797.

The name of *John Playfair* (1748–1819) is less familiar than that of Hutton, but he was in large part responsible for the impact of Hutton's ideas. He began his career as a church minister and was then known as a mathematician who wrote a landmark textbook on geometry. He also dabbled in physics, which led him into the natural sciences. Playfair was a keen observer, a logical thinker and a lucid writer; this latter quality differentiated him from Hutton, whose writing was at times impossibly convoluted, long-winded and multidirectional. "*Theory of the Earth*" was dubbed one of the "*least read most important books in the history of science*" (Bill Bryson 2003), although it likely has some competitors for that honour. John Playfair commented on its turgid and confusing prose and, as he was a close friend and admirer of Hutton, we can only assume that he erred on the side of generosity in stating:

> *"The great size of the book, and the obscurity that may justly be objected to many parts of it, have probably prevented it from being received as it deserves".*

Following Hutton's death, Playfair became his loyal advocate, and in 1802 he published "*Illustrations of the Huttonian Theory of the Earth,*" which outlined Hutton's ideas in an ordered and clear treatment. This book is not exactly short, and is perhaps misnamed because it lacks any true illustrations, but the wider recognition and discussion of Hutton's concepts in the 19th century came from Playfair's efforts. Interestingly, Playfair's exposure to geology was largely through John Walker

(1731–1803), a professor of Natural History at the University of Edinburgh. Walker was a noted follower of 'neptunism,' the idea that all rocks, including what we now see as igneous and metamorphic types, were crystallized from primordial ocean waters, and he would later become one of Hutton's fiercest critics, along with the Irish scientist Richard Kirwan. Some accounts (e.g. Repcheck 2003) suggest that both Playfair and Sir James Hall (see below) were initially skeptical of Hutton's 'plutonist' ideas, which were directly opposed to what they had been taught by Walker.

The third man on the June 1788 excursion was *Sir James Hall of Dunglass* (1761–1832), a young aristocrat who had recently inherited this local estate and title; he would later become president of the Royal Society of Edinburgh. Then only 27 years old, his scientific interests lay largely in chemistry, but he was also influenced by John Walker's view of natural history. James Hall went on to have a very important career in geology, as the pioneer of experimental petrology, and his work was instrumental in refuting neptunism. He placed mixtures of minerals or powdered rocks in sealed rifle barrels and subjected them to high temperatures and pressures in blast furnaces. Among his achievements was proving that limestone could be converted to marble without losing carbon dioxide and that basalt could be melted and recreated as a coarser grained rock if cooled slowly. Wyllie (1999) discussed his many contributions to our knowledge. Like Playfair, Hall became a lifelong defender of Hutton's view of the Earth and he continued to live at the estate in Dunglass. It is likely that he took many other early 19th century geologists to Siccar Point, and I like to think of him as the 'keeper of the shrine' through much of his life, although there is no written support for this fanciful view.

A Day Not Soon to be Forgotten

The field trip in June 1788 took place in fair weather, which allowed them to 'sail' close to the shore. It seems unlikely that they would have been driven along solely by the wind and one account suggests that they were accompanied by 'several sturdy farmhands,' who provided at least some motive power. They progressed past the red cliffs and fine sands of Pease Bay, then unblemished by hundreds of box-like caravans. Biographical works (Repcheck 2003; Baxter 2003) both commence with 'fictionalized' reconstructions of this trip, which is in itself an indication of its importance. Many undergraduate geology texts mention it, and some include embellishments, such as Hutton watching the waves move sediment and actually deposit it. Others portray the landing at Siccar Point as a moment of epiphany in which Earth's antiquity suddenly struck Hutton, much as the displacement of water reputedly struck Archimedes in his bathtub in ancient Syracuse. Montgomery (2003) provided an interesting summary of varied reconstructive accounts and comments on their inconsistency with the historical record. Siccar Point is also sometimes depicted as the first recognition of an unconformity, although there are accounts in earlier French literature concerning the Alps, and Hutton had actually made references to these (Montgomery 2003). Furthermore, Hutton himself had previously visited two other unconformity locations in Scotland since presenting his theory in 1785, but neither was as striking as the one he would encounter on that day. His own description (here taken from McKirdy et al. 2007) seems in many respects rather mundane:

> *"Having taken the boat at Dunglass Burn, we set out to explore the coast. At Siccar Point, we found a beautiful picture of this junction washed bare by the sea. The sandstone strata are partially washed away, and partially remaining on the ends of the vertical schistus; in many places, points of the schistus are seen standing up through among the sandstone, the greater part of which is worn away. Behind this, we have a natural section of the sandstone strata, containing fragments of the schistus. Most of the fragments of the schistus have their angles sharp; consequently they have not travelled far, or been worn away by attrition."*

John Playfair's description of the field relationships is clearer and is actually a good model to show students. It is certainly better than most of the ramblings found in my own notebooks.

> *"It is here a micaceous schistus, in beds nearly vertical, highly indurated, and stretching from SE to NW. This schistus has a thin covering of red horizontal sandstone laid over it, and this sandstone, at a distance of a few yards farther back, rises into a very high perpendicular cliff. Here, therefore, the immediate contact of the two rocks is not only visible, but is curiously dissected and laid open by the action of the waves. The rugged tops of the schistus are seen penetrating into the horizontal beds of sandstone, and the lowest of these last form a breccia containing fragments of schistus, some round and some angular, united by an arenaceous cement"* (Playfair 1802).

Note that the term 'schistus' was then applied to almost any deformed or weakly metamorphosed sedimentary rocks, and that the Silurian rocks beneath the unconformity are not schist in our modern sense of the word. The profound message of Siccar Point, where relationships show that one group of sedimentary rocks first must have been deposited, then twisted and uplifted and then eroded, before being submerged and buried by a second series of very different sedimentary rocks, and then together uplifted and tilted for a second time to be eroded anew, is most eloquently delivered by John Playfair (1802). His words are repeated in many textbooks:

> *"On those of us who saw these phenomena for the first time, the impression made will not soon be forgotten. The palpable evidence presented to us, of one of the most extraordinary and important facts in the natural history of the Earth, gave a reality and substance to those theoretical speculations, which, however probable, had never till now been directly authenticated by the testimony of the senses. We often said to ourselves, what clearer evidence could we have had of the different formation of these rocks, and of the long interval that separated their formation, had we actually seen them emerging from the bosom of the deep?"*

Playfair's description continues in a similar vein, with an imagined trip to a time when the older rocks were still accumulating on the sea floor, and then to *"epocha still more distant in time"*, before with a short sentence that has become justly famous:

> *"The mind seemed to grow giddy by looking so far into the abyss of time"*

These words are what most geologists associate with Playfair, but his contribution to geological thinking was far greater than one memorable phrase. He was a keen observer and a gifted communicator, who promoted the ideas of Hutton and also modernized them. He continued to gather firm evidence, not just for the depth of his abyss of time, but for the nature of plutonism, folding, metamorphism and all manner of things that would come to define the dynamic Earth. He initiated an effort to locate and describe other unconformities, understanding their great importance in reconstructing geological history. But his words on Siccar Point are probably not the most famous uttered by early geologists. That honour goes to Hutton himself who closed the 1788 edition of "*Theory of the Earth*" with a phrase that has echoed through the centuries:

> *"The result, therefore, of our present enquiry, is that we find no vestige of a beginning, no prospect of an end"*

There is an implication in some texts that Hutton's famous words were inspired by or even came to him at Siccar Point, but this is probably not so, because the text of the book was complete by then, and it makes no mention of the excursion (Montgomery 2003). Hutton already had in his mind the concept of an unconformity, having recognized the differences between what we now know to be Silurian and Devonian strata. He had visited two other examples and read other descriptions that fitted his hypothesis. Siccar Point provided a dramatic example of the cyclicity of geological processes, and the immense time periods involved, but it was the *test* of a concept, not the inspiration for it. Rather than a moment of epiphany on a rocky shoreline, the Siccar Point excursion was a successful application of the scientific method. Montgomery (2003) advocates that it should be taught as such, and I now do this.

Unconformities – Observations, Hypotheses and Proofs

The Siccar Point location is one of three unconformities in Scotland that bear Hutton's name. The first location that he visited, in 1786, is near the village of Lochranza, at the northwest end of the Island of Arran, in the Firth of Clyde, southwest of Glasgow (Fig. 1). Hutton was fond of Arran, which contains striking geological and scenic diversity for so small an island – it has long been referred to as 'Scotland in Miniature.' The location preserves the contact between metamorphic schists of the Dalradian Supergroup, likely of late Neoproterozoic age, and Carboniferous strata. Far more time is missing at this site, as much as 300 million years, and descriptions (Barclay et al. 2005) suggest that it is not as clear or as dissected as Siccar Point. In 1787, Hutton visited and described a location in the town of Jedburgh (Fig. 1) where vertical Silurian greywacke is juxtaposed with horizontal red Devonian sandstone. This is a small and inconspicuous outcrop located on private property and not easily viewed; it is designated as a SSSI, and the landowner reportedly struggles to clear creeping vegetation on an annual basis (Baxter 2003). I have not visited it, but the outcrop is the subject of a famous engraving by John Clerk of Eldin, a close friend of Hutton's who later would provide illustrations for the never-completed later editions of "*Theory of the Earth.*" Eldin's surviving illustrations of geological localities are now considered highly valuable, and his work in documenting 18th century Scotland is justly famous (Craig 1978; Bertram 2012). The engraving, completed in 1787, clearly depicts the conglomerate and breccia horizon developed at the unconformity surface (Fig. 6a). This is probably the first visual representation of an unconformity, but an equally famous sketch of Siccar Point created by the young James Hall in 1788 (Fig. 6b) is likely more accurate in terms of scale and geological relationships. Photos of the actual outcrop in Jedburgh (*in* Montgomery 2003) suggest that it is far smaller than Clerk's lovely artistic depiction. It is unfortunate that Clerk's talents were never applied to Siccar Point itself. A website offering reproductions of his drawings for sale lists the locality, but the drawings in question actually appear to be those of James Hall (see above).

The Later Influence of Siccar Point

There is no visitor's book at Siccar Point, but perhaps there should be one, because it must have seen many famous visitors. Arthur Holmes, the father of modern geochronology, would have been among them, for he spent many years at the University of Edinburgh. In his iconic textbook "*Principles of Physical Geology*," Siccar Point is extensively described and illustrated (Holmes 1944). I have long wondered if there was ever any connection between James Hutton and the younger William Smith. There seems to be no record of a meeting and given their age difference, this seems unlikely. However, in the year of Hutton's death (1797), Smith himself described an angular unconformity in underground mine workings in Somerset. Smith may also have been the first to use the modern term, as he commented on "the unconformableness of some of the other strata" (as noted in Woodward 1911). In this case, the coal-bearing (Carboniferous) rocks sat *below* the unconformity, rather than above. Instead of a sub-Devonian unconformity, as at Siccar Point, Smith had defined a younger unconformity, because Somerset lies south of the limit of Variscan deformation (Fig. 1). Thus, within a decade, Hutton and Smith had each recognized an important gap in the stratigraphic record, recording the two main orogenic cycles that built most of the British Isles. But if Hutton and Smith never met, did the older man influence the younger through his written work? Again, there seems to be no record of this in material about Smith (e.g. Winchester 2001), so perhaps he was unaware of the "*Theory of the Earth.*" Smith himself claimed that his work was "*unincumbered with theories*" (sic) and Woodward (1911) suggested that his knowledge of scientific works was 'meagre.' There were many theories of the Earth in those early days and

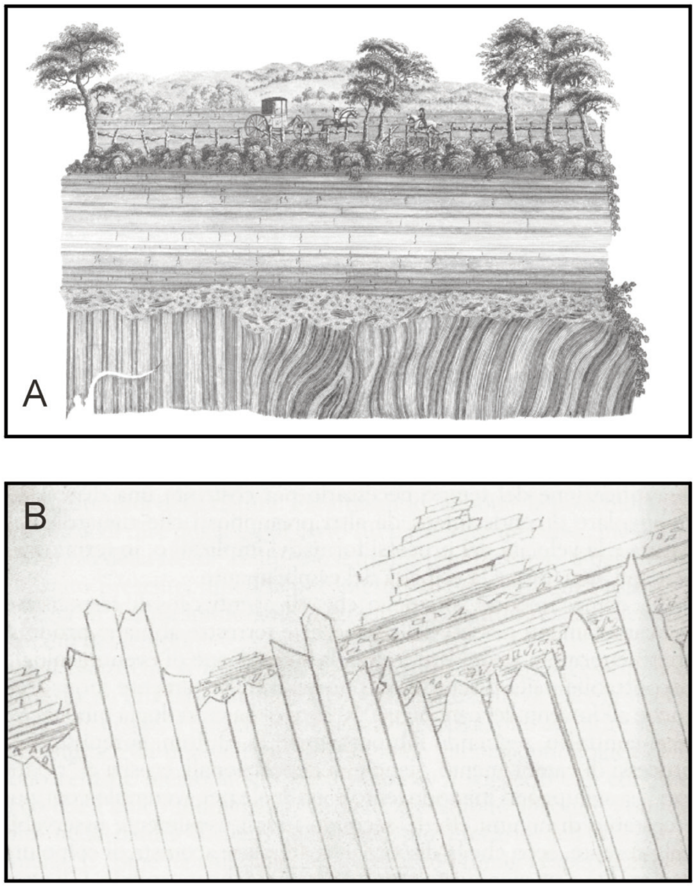
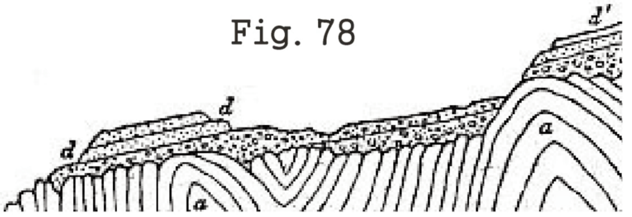


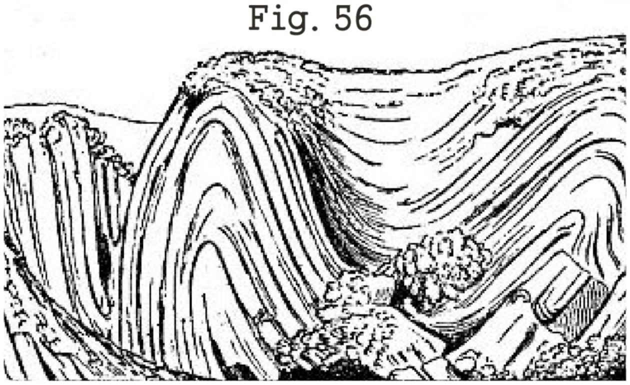
Figure 6. A. The famous engraving by John Clerk of Eldin, depicting the unconformity at Jedburgh visited by Hutton in 1787, before the Siccar Point visit. This image is found in many books and papers. Note the conglomeratic unit shown just above the unconformity and also the depictions of folds and intrusive dykes in the older rocks. The illustration has considerable artistic license, as the actual outcrop is very small and inconspicuous. B. Part of an equally famous field sketch of the relationships at Siccar Point drawn by the young James Hall following their visit. This has also been widely reproduced, most recently by Archer et al. (2017).

Hutton's work remained contentious, even after Playfair had wrung clarity from its obscurity, so perhaps Smith drew his conclusions independently. A connection between Playfair and Smith seems more of a possibility, but again there seems to be no record of any meeting or influence. Smith's 1815 map extends to Berwickshire, but does not discriminate strata in the Siccar Point area. I cannot resist some speculation about how the evolution of geological science might have differed had these men had the opportunity to share their ideas and collaborate. However, as is clear from the biography of Winchester (2001), the stratification of society in those times was just as marked as that of the rocks, much to Smith's disadvantage, and could have impeded such connections.

In 1824, Siccar Point had a young visitor who would later go on to merge the ideas of Hutton and Smith. Charles Lyell (1797–1875) was born in the year of Hutton's death and certainly knew of Smith's map; by this time Playfair's efforts to disseminate the ideas of Hutton had at least partially succeeded. Lyell grew up in England, but was born in Scotland and had many connections there. The new offices of the British Geological Survey in Edinburgh are today known as the Lyell Centre. He came as a guest of Sir James Hall of Dunglass, who was by that time elderly and distinguished. Lyell mentions his visits to see coastal geology in rather matter-of-fact terms in correspondence with family members, but the visit to Siccar Point surely had a profound impact upon him and his concept of uniformitarianism. Lyell's own discussion of unconformities makes reference to Siccar Point, and it is illustrated along with nearby localities (Fig. 7; Lyell 1874). Lyell combined the threads woven by Hutton and Smith into a single tapestry that would in turn influence a young man named Charles Darwin who became the natural scientist aboard H.M.S. Beagle. It is not clear if Darwin ever visited Siccar Point, although he did spend several years in Edinburgh, but its testimony of near-endless time was critical for his ideas. Curiously, James Hutton was a friend of Erasmus Darwin, Charles' grandfather, and some believe that the "*Theory of the Earth*" contains vague concepts that resemble later ideas about evolution. Was there perhaps another branch in the tangled tree of thought that connected these defining ideas?



Unconformable junction of old red sandstone and Silurian schist at the Siccar Point, near St. Abbs Head, Berwickshire.



Curved strata of slate near St. Abbs Head, Berwickshire (Sir J. Hall)

Figure 7. Two illustrations taken from the author's copy of Charles Lyell's "*Student's Elements of Geology*," first published in 1874. One is of Siccar Point and the other depicts folded Silurian rocks at nearby St. Abb's Head, as illustrated by Sir James Hall. Both illustrations also appeared in Lyell's famous textbook "*Principles of Geology*." Note that the original text in the images was replaced digitally to improve clarity.

EPILOGUE

Unconformities are a key concept in historical geology, defining multiple cycles of geological evolution and reinforcing the great antiquity of our planet. Siccar Point may not be where such ideas truly *began*, but it is surely where they first came to be clearly understood. It is indeed a shrine on the abyss of time, worthy of our pilgrimage, but also deserving of our protection. Many might think that the Age of the Earth debate is long concluded in an age of ion probes and mass spectrometers, but that would be naïve. If you search ‘Siccar Point’ on the internet, you will quickly find accounts that seek to discredit its testimony. For example, at www.creation.com, you will find a page dedicated to the Siccar Point trail, claiming that all features described here can easily be explained by the violence of the biblical flood. ‘Young-Earth Creationists’ take particular aim at John Playfair, perhaps because of his church background. It is tempting to dismiss such ideas with amusement or disdain, but there have been several attempts to insert such thinking into educational curricula (Montgomery 2003) and they visibly compete with more ‘factual’ sources such as Wikipedia. It is therefore important not only to preserve remarkable locations such as Siccar Point, but to use them at every opportunity to promote scientific reason.

James Hutton has a reputation for difficult and confusing language, but he seemed to compose memorable phrases to close his works. The final statement of his original 1785 written summary, as recounted by Monro and Crosbie (1999) reads as follows:

> *“...there is opened to our view a subject interesting to man who thinks; a subject on which to reason with relation to the system of nature; and one which may afford the human mind both information and entertainment”*

I think that says it all.

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ARTICLE

Albert Peter Low in Labrador– A Tale of Iron and Irony

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SUMMARY

In 1893–1894, Albert Peter Low of the Geological Survey of Canada, along with D.I.V. Eaton and four indigenous assistants explored the Labrador Peninsula, then perceived as one of the last great unexplored wilderness areas of North America. The expedition left Lake St. John (now Lac St. Jean) on June 17, 1893, canoeing across the northeastern edge of the North American continent, arriving at Fort Chimo (now Kuujjuaq) on August 27, 1893. They departed Fort Chimo by steamer for Rigolet on the Labrador coast and the Hudson Bay Company post at North West River in the fall of 1893. On March 6, 1894 the party started up the Grand (now Churchill) River continuing through large central lakes into the Ashuanipi river system in western Labrador, then out via the Attikonak River to the Romaine River and finally the Saint Jean river system to arrive at Mingan on the north shore of the St. Lawrence River on August 23, 1894. Low described their fifteen-month journey as having covered over 8700 km including 1600 km on foot, over 4700 km in canoe, 800 km by dog team and 1600 km by steamer. The report from the expedition provides a compendium on the natural history of the region as well as the first geological maps. In terms of economic and scientific results, the greatest was documentation of the vast iron ore deposits of western Labrador; a world-class mining district that has been producing for sixty-three years since 1954. Low's account also provides details on the essence of such an epic journey, which stands as a classic in the annals of Canadian geological surveying.

RÉSUMÉ

En 1893–1894, Albert Peter Low de la Commission géologique du Canada, accompagné du D.I.V. Eaton et quatre assistants autochtones ont exploré la péninsule du Labrador, alors perçue comme l'une des dernières grandes étendues sauvages inexplorées d'Amérique du Nord. L'équipe a quitté le *Lake St. John* (aujourd'hui le lac Saint-Jean) le 17 juin 1893, a traversé la bordure nord-est du continent nord-américain en canoë, et est arrivé à Fort Chimo (aujourd'hui Kuujjuaq) le 27 août 1893. À l'automne de 1893, ils ont quitté Fort Chimo à bord d'un vapeur pour Rigolet, sur la côte du Labrador, et le poste de la Compagnie de la Baie d'Hudson sur la rivière North West. Le 6 mars 1894, les membres de l'équipe ont remonté la rivière Grand (aujourd'hui Churchill), puis à travers les grands lacs centraux jusqu'au bassin de la rivière Ashuanipi, dans l'ouest du Labrador, puis, par la rivière Attikonak jusqu' à la rivière Romaine et, enfin, le réseau de la rivière Saint-Jean jusqu'à Mingan, sur la rive nord du fleuve Saint-Laurent, le 23 août 1894. L'excursion décrite par Low a duré quinze mois et parcouru plus de 8700 km dont 1600 km à pied, plus de 4700 km en canoë, 800 km en attelage de chiens et 1600 km en bateau à vapeur. Le rapport de l'expédition constitue un recueil sur l'histoire naturelle de la région ainsi que des premières cartes géologiques. En ce qui concerne les répercussions économiques et scientifiques, la plus importante en a été la documentation des vastes gisements de minerai de fer de l'ouest du Labrador, un district minier de classe mondiale, en production pendant soixante-trois ans depuis 1954. Le récit de Low fournit également des détails sur le caractère épique d'une telle expédition, laquelle est un classique dans les annales de la Commission géologique du Canada.

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Geoscience Canada, v. 45, https://doi.org/10.12789/geocanj.2018.45.130 pages 43–58

GC Data Repository: D.H.C. Wilton: A.P. Low's (1896) map quadrants

INTRODUCTION

Albert Peter Low (1861–1942; Fig. 1 inset) was a geologist with the Geological Survey of Canada (GSC) from 1882 to 1907 (with a two-year break). In 1893 and 1894 he made a pioneering trek through Labrador (Fig. 1) travelling the major rivers of central and western Labrador and documenting the geology exposed therein. The title, *Albert Peter Low in Labrador – A Tale of Iron and Irony*, is somewhat of a triple-entendre as Low's Labrador journey was truly of epic proportions, one of many that he undertook for the GSC throughout eastern and central Canada, but also because he documented the vast iron-ore horizons of western Labrador, which became the Labrador City, Wabush and Schefferville mines. The Geological Survey of Canada refers to Low as Canada's 'Iron Man' based on his exploits and expeditions. The irony refers to the ultimate fates of both he and his senior assistant, D.I.V. Eaton.

This paper is concerned in detail with Low's expedition through Labrador and an earlier version was published in *Very Rough Country: Proceedings of the Labrador Explorations Symposium* (MacDonald 2010), a book produced by the Labrador Institute of Memorial University. The original paper (Wilton 2010) has been modified for the more geological audience of *Geoscience Canada*. The 2005 symposium was held as part of the centennial celebrations of Mina Hubbard's journey from North West River, Labrador, to Ungava Bay (Hubbard 1908).

Mina's journey was the final act in an adventure story that gripped North America in the first years of the 20th century. In 1903, Mina's husband, Leonidas Hubbard, along with his friend Dillon Wallace, and George Elson, a mixed-race Cree from Ontario, attempted to canoe from Northwest River across Labrador to the headwaters of the George River and thence downriver to Ungava Bay (Wallace 1905). They left the Hudson Bay Post at North West River on July 15 and canoed to the head of Grand Lake where they took the wrong river, the Susan, into the interior; they should have taken the Nascaupee (now Naskaupi River). After two months of hardscrabble canoeing and portaging, the party was running out of supplies and summer, so decided to return to Northwest River. Hubbard succumbed to starvation around October 18 at their final camp after Elson and Wallace had left for help. Elson made it back to North West River and Wallace was rescued on October 30. The party overwintered in North West River before returning to New York in May 1904.

Mina, upset by Wallace's (1905) account of the ill-fated expedition, decided to complete her husband's journey with the aid of George Elson. Wallace also determined to complete the journey and likewise put together an expedition. Incredibly, both expeditions left North West River on the same day, June 27, 1905, albeit from opposite sides of the river. Mina was first out at the George River (now Kangiqsualujjuaq) trading post on August 29. She wrote *A Woman's way through unknown Labrador,* which has subsequently become part of the modern feminist canon (e.g. Grace 2000; Pratt 2002; Buchanan et al. 2005). As will be described below, Albert Low's 1893–94 maps played an important role in the whole Hubbard story.

GEOLOGICAL SURVEYS

Geology became firmly established in Europe as a scientific endeavor in the latter part of the 18th century mainly because of the growing need for coal; the lifeblood of the Industrial Revolution. As well described by Winchester (2001), early geologists, such as William 'Strata' Smith, recognized that the distribution of coal-measures could be mapped across the countryside and the three-dimensional form of distinct layers so defined.

National governments established geological surveys to define the endowment of natural resources present within state boundaries. These initial 'surveys' became scientific institutions charged with studying the Earth in their respective territories. The venerable British Geological Survey began as the Ordnance Survey in 1832. With some prescience, and an eye on the developing coal industry in Cape Breton, the fledgling representative Government of Newfoundland initiated the Geological Survey of Newfoundland with J.B. Jukes in 1839 (Cuff and Wilton 1993). The enterprise only lasted until 1841 when the same assembly revoked Jukes' funding due the perceived lack of results (i.e. no discovery of significant coal resources); the survey was perhaps the earliest, but not the last, victim of government budget cuts. The Geological Survey of Newfoundland (GSN) was subsequently resurrected in 1864 under the leadership of Alexander Murray.

In 1842, the Legislative Assembly of the Province of Canada created the Geological Survey of Canada (GSC) with Sir William Logan as its first Director. With the creation of the Dominion of Canada and its exponential growth into the second-largest country in the world, the GSC geologists had to spread out and cover vast expanses of northern North America. As described by Alcock (1944, p. 195), the mid- to late 18th century GSC consisted of a small band of "*geologists who belonged to that great period of Canadian exploration when, following Confederation, it became the task to explore and map the vast spaces that had been added to Canada's frontier. In many respects* [this] *was the most interesting and romantic part of the survey's history.*" Since these surveying geologists ventured into 'unknown' regions of the Canadian landscape, they also operated as natural scientists and were expected to collect data not only on the rocks, but also the topography, flora and fauna and, most controversially, in present contexts, information on indigenous peoples. These latter observations must be viewed through the social lenses of the time.

Even though the GSN had been operating as a viable entity since 1864, the first GSN survey in Labrador was not undertaken until 1939 (Kranck 1939), and even then Kranck's work was not carried out as an official GSN project, but rather he was part of the 1937 Finland–Labrador Expedition (Tanner 1944). Prior to Kranck's work, geological surveying of Labrador had been left to the GSC. The first such expedition was by Robert Bell in 1884, when he completed a reconnaissance geological survey of the Labrador coast on a trip into Hudson Bay (Bell 1884) on board a Newfoundland sealing vessel, the 'Neptune.' Bell travelled through the area again in 1885 on the vessel 'Alert' (Bell 1885). He stopped briefly at Nain and Nachvak Fiord. As noted by Brookes (2016), Bell's main obser-

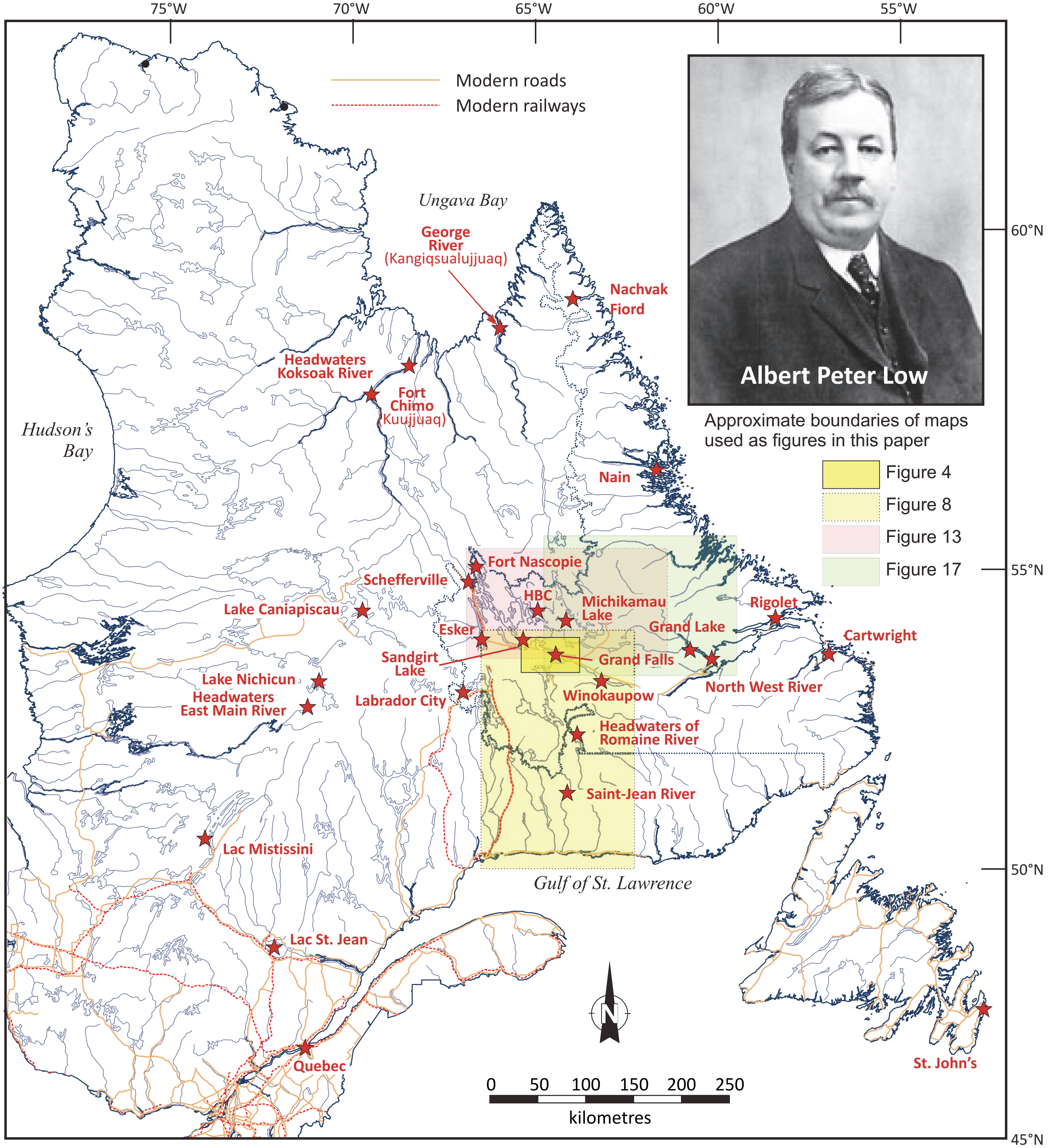

Figure 1. Map of the Labrador Peninsula with locations of important sites from Low's 1893–94 journey; note HBC refers to the approximate (underwater) location of the Michikamau Hudson Bay Company post and that Low referred to the community of North West River as Northwest River. Inset of A.P. Low from the Natural Resources Canada photo archives.

vations were that, although "*glacial grooves*" were observed at sea-level, the tops of the Torngat Mountains appeared to him to be unglaciated with evidence of "*long-continued atmospheric decay*" (Bell 1885, p. 7–8).

THE GEOLOGICAL SURVEY OF CANADA 1893–94 LABRADOR FIELD PARTY

The GSC party that set out in 1893 consisted of A.P. Low, his senior assistant, D.I.V. Eaton and "*four young Indians*" (Low 1894b, p. 136). The names of these other crew members are not mentioned. They hired local guides and assistants along the route as needed, likewise all unnamed.

A.P. Low

In their extensive research, Finkelstein and Stone (2004) note that it is very difficult to derive a sense of A.P. Low, the man. His contemporaries have left little record about his personality and in his own writings there is little introspection. In one of his few narratives on his exploration through Labrador (Low 1894b), he describes himself and the expedition in the third person; albeit fairly self-promotional. For instance, in describing the GSC in the 1890's, he described:

> "…*these explorations, often very difficult and dangerous, have attached to the staff of the Survey, several of the most intrepid and successful young explorers on the continent*" (Low 1894b, p. 135). He further states that "*Mr. Albert Low, of the same Department, has just returned from an exploration extending over nearly two years, in the largest unknown tract of the Dominion, the interior of the Labrador Peninsula, or North-East Territory, comprising some 289,000 square miles, an area equal to twice that of Great Britain and Ireland.*" He concluded that "*Mr. Low has crossed this area from south to north, and from east to west, and his detailed report when published will contain the first trustworthy account of the great region which promises to be of considerable importance on account of the immense mineral deposits which he has discovered there*" (p. 135–6).

The bare facts about Albert Peter Low are that he was born in Montreal on May 24, 1861, and was educated at McGill University, earning a degree in Applied Sciences (1st Class Honours) in 1882 (Alcock 1944). He "*obtained his geological training under Sir William Dawson*" (Low 1894b, p. 136). He was hired by the GSC on July 1, 1882, having spent the previous summer mapping with the survey in the Gaspé Peninsula (Alcock 1944). He began independent mapping in 1883. He worked with the GSC for the next 17 years, before taking a two-year break (1901–02) to work with the mineral industry in an iron ore exploration program (Alcock 1944). He returned to the GSC in 1903 and commanded the 1903–04 Canadian government expedition to the Arctic aboard the Newfoundland sealing vessel, the 'Neptune.' He became Director of the GSC in 1906 at age 45 and in 1907 became Deputy Minister of the newly created Mines Department into which the GSC was moved (Stewart 1986).

D.I.V. Eaton

Low's equally hard-working assistant on the 1893–94 Labrador expedition was Daniel Isaac Vernon Eaton (born 19 September, 1869 in Nova Scotia). Eaton was the surveyor and cartographer for the expedition producing the geological and geographical maps. He worked with the Newfoundland Railway in 1889–1990 as an informally-trained surveyor (Wright 1998) before joining the GSC in 1890. He stayed with the GSC until 1896 when he left to join the Royal Canadian Regiment (Zaslow 1975).

THE MISTASSINI INCIDENT

An insight into Low's character may be gleaned from the 1884 'Mistassini Incident' (Gittins 1985; Stewart 1986). Low had been with the GSC for two years and had been conducting independent mapping for only one season when he was tasked to join a joint Canada–Quebec survey of the Lac Mistassini region (Fig. 1) as second-in-command to J. Bignell, of the Quebec Geographic Society. According to Stewart (1986), Bignell was a veteran 67-year old surveyor.

Right from the start of their 'collaboration,' Low was displeased with delays. He described leaving Ottawa on June 9, 1884, arriving in Quebec City June 12th, then "*waiting*" until July 19th before leaving for Rimouski, arriving there on July 25th, and then being delayed again, due to helpers not being hired, such that field work did not begin till August 8th (Low 1885). Thereafter, he described continually awaiting Bignell throughout the canoe trip to their winter camp at the Hudson Bay Company post on Lake Mistassini.

The last 10 days of his trip were particularly arduous for Low's group, involving "*short rations and temperatures of - 40°F*" (Low 1885). By the end of January, 1885, Low "*had several disagreements with Mr. Bignell regarding the operations of the party,*" so he left for Ottawa to clarify who was to be in charge. He departed the post on February 2nd with two other men (the latter carrying mail) and arrived at Lake St. John (Lac St. Jean) on February 21st. They walked on snowshoes, but the trip was anything but boring and mundane as "*two heavy snowstorms occurred while we were on the way, making the walking so difficult that our tent and sheet iron stove had to be abandoned, and we were obliged to sleep in the snow for more than a week.*" The distance in a straight line from Lake St. John to midway on the southeast shore of Lake Mistassini is over 256 km. Low then left Lake St. John on February 23rd by horse and sleigh to Quebec City and then on to Ottawa, arriving March 2nd.

With new instructions putting him in charge of the combined party, Low left Ottawa on March 23rd, arriving at Lake St. John on April 5th. In the company of seven others, he left Lake St. John on the 9th of April. The trip back was no picnic either, as described by Low (1885).

> "*It was found necessary to travel mostly in the early morning, before the heat of the sun melted the crust of the snow. We therefore commenced our day's tramp about 3 a.m. and stopped about noon... we passed overland to Lake Chibougamoo* [sic]*, arriving there on the 20th of April. Up to this time the weather, being cold and clear, was very favorable for traveling, but we were now overtaken by a period of mild weather, which made the snow so soft and heavy as to render tramping with loads almost impossible. In addition we were short of provisions, and the 24th, I decided to*

> *send four men ahead without loads, with instructions to reach the Hudson Bay post on Mistassini and send back provisions from there. These men traveled over sixty miles in forty hours without food and thus reached the post. From here two Indians were sent back with provisions to relieve us, and arrived at out camp on the east side of Lake Chibougamoo* [sic], *April 28th. Continuing our journey we reached the post the next day."*

Gittins (1985) notes that Low was paid $2.05/day in 1884, which was raised to $2.20/day in 1885. Bignell, on the other hand, received $5/day. Based on US Bureau of Labor Statistics data (Canadian data only goes back to 1917), Mr. Low was paid the equivalent of $58.85/day and Mr. Bignell, $117.65/day; the latter being just above the minimum wage in all Canadian provinces as of 2017.

THE 1893–94 EXPEDITION THROUGH THE LABRADOR PENINSULA

Year 1893

The original plan for Low's exploration in 1893–94 (Low 1894b) was that his party would travel to the headwaters of the East Main River then cross over to the headwaters of the Koksoak River and follow it downstream into Ungava Bay, overwinter there and then proceed to explore the Hamilton (now Churchill) River (Fig. 1). Although not explicitly stated, it would seem that the plan was for the party to ascend the George River from Ungava Bay, thence through Michikamau to the Hamilton River and out.

Low and his senior assistant, D.I.V. Eaton, left Ottawa on June 3rd, 1893 travelling through Montreal, to Quebec City and thence to Lake St. John. They shipped supplies from Montreal to Fort Chimo (now Kuujjuaq) as they planned to winter there prior to going inland the next summer. In June, 1893, at Lake St. John (Low 1894a, p. 63A) found that:

> "…*it was impossible to obtain provisions or any supplies of any kind from the Hudson's Bay posts, and as all the able-bodied men are at this season away to Hudson Bay, engaged in bringing the next season's supplies to the posts, a quantity of provisions sufficient for the whole season had to be taken from Lake St. John, and four men engaged for the entire trip. To transport the provisions, six canoes were found necessary*"

They departed Lake St. John on June 17th with "*four young Indians*" who were to stay with them for the whole trip and "*eight others to assist in transporting the provisions as far as Lake Mistassini*" (Low 1894b, p. 136). Low (1895, p. 515) described the vessels used to get to Lake Mistassini as

> "…*two Peterborough canoes, 19 feet long, built of cedar, and each capable of easily floating a load of 1000 lbs together with a crew of three men, along with these was a smaller cedar canoe and three others of birch bark.*"

The party arrived at the Lake Mistassini Hudson Bay post on July 2nd and left for the Hudson Bay post at Nichicun (Fig. 1) on July 5th. Low states that "*only three canoes were used, and an old Indian was engaged as a guide, who subsequently proved quite useless in that capacity, as he had entirely forgotten the route to Nichicun, which place he had not visited since his boyhood*" (Low 1894b, p. 136). The party finally arrived at the Nichicun post on August 4th. At this post, Low was fortunate to find a guide who would take the party to Lake Caniapiscow (now Caniapiscau or Kaniapiskau), on the Koksoak River.

Departing Nichicun on August 7th and descending the Koksoak River, the party reached Ungava on August 27th and Low simply stated that "*thus the trip across Labrador from south to north was completed in seventy days*" ((Low 1894b, p. 137). Low offered a somewhat more personal view of this leg of the expedition in a letter to the GSC Director from Rigolet in October 1893 that was subsequently published as his 1893 report:

> "*From it you will see that we reached Ungava 27th August, after a summer of very hard work, in fact, the hardest that I have ever experienced, but as everyone was in good health, it was not unpleasant*" (Low 1893, p. 4A). In his more detailed, and seemingly self-promotional report from 1894, Low (1894a) stated that: "*By working hard, early and late, wet days and Sundays, Fort Chimo was reached at least twenty-five days sooner than it would have been under ordinary conditions of canoe travel*" (Low 1894a, p. 68A). He estimated the canoe trip at over 1200 miles [1920 km].

A catastrophe afflicting the local indigenous peoples awaited Low on his arrival at Fort Chimo (now Kuujjuaq) and this would significantly alter his plans for exploration in 1894. In his first description of the tragedy, Low (1893, p. 5A) states:

> *"On arriving at Fort Chimo, I found the natives there in a most deplorable state, owing to the absence of deer last winter, and to the failure of the Hudson Bay Company's agent to supply their needs, as a consequence between 200 and 300 died last winter, and the small remainder are in a state of abject poverty. Such being the case, I considered it inadvisable to send provisions inland, as they would probably be stolen. The stock of pork at the post was also not sufficient to supply the wants of my party, and as the work can as advantageously be carried on from Hamilton Inlet, I resolved to proceed there on the Hudson Bay Company's steamer."*

In his 1894 report on the starvation at Fort Chimo, Low (1894a, p. 68A–69A) tempers his description and removed any suggestion of wrongdoing by the Hudson Bay Company, describing that when his party had arrived at Fort Chimo, they:

> "…*soon learned that a great famine had prevailed during the past winter among the Indians trading at this post, whereby nearly two-thirds of them, or upwards of one hundred and sixty persons died of starvation. This calamity was due to the failure of the reindeer to follow their accustomed routes of migration during the preceding autumn, when they did not cross the Koksoak River in great bands as usual. In consequence the Indians who depend on*

> *the reindeer for both food and clothing were soon reduced to starvation, and unable to obtain other supplies, died off by families during the winter. About twenty-five Eskimo also perished from the same cause. The surviving Indians having been in a state of constant starvation throughout the past year, and consequently being unable to trap furs and so pay their debts, were at the time of our visit in an abject state of poverty."*

He also noted that the Hudson Bay personnel held a clothes drive for aboriginal children. Low later simply stated that "*the conditions at Ungava were not such that work the following year could be carried on advantageously*" (Low 1894b, p. 137). In his final report on the expedition, Low (1896) does not directly discuss the calamity and how it affected his survey plans; he just noted that "*At Fort Chimo the famine of 1892–93 reduced the number of Indians in that district from 350 to less than 200 persons.*" More charitably, he stated that "*Dishonesty and theft are unknown to the interior Indians; provisions and outfit can be left anywhere inland with perfect safety for any length of time. Only in the case of absolute starvation will provisions be taken, and then only a small part, for which payment will be left by the persons taking them*" (Low 1896, p. 47L). Hence, he was perhaps mitigating his earlier suggestion that he could not safely leave supplies inland during the fall-winter of 1893–94.

In his 1894 report to the Director, Low (1894a, p. 69A) hints at the realization that his proposed plan to cover the Labrador Peninsula might be better conducted from the Labrador coast as:

> *"The supply of pork at the Hudson's Bay post was too small to provide sufficient for the party if they remained at Fort Chimo... it was deemed advisable not to winter at Fort Chimo, as originally intended; especially when it was learned that the work in hand could be carried on more advantageously from the head of Hamilton Inlet."*

So, it was actually while at the Fort Chimo post that Low was informed that the best way through the interior of Labrador was via North West River (subsequently, the starting points for the Hubbard and Wallace expeditions).

Low's revised plan had the party depart Fort Chimo on September 10th on the Hudson Bay Company steamer 'Eric' arriving in Rigolet on October 1st. The party stopped at the Hudson Bay Company posts of George River (now Kangiqsualujjuaq), Nachvak and Davis Inlet enroute. From Rigolet, Low (1893, p. 5A) told the GSC Director that he now proposed:

> *"…to immediately send my men and the canoes up the Hamilton River, with instructions to take them as far as the Grand Falls portages if ice will permit. They will remain there until they can return to North-west River on foot, and will then be employed drawing in provisions on the ice, so that by open water in the spring, next season's outfit will be well inland, thus leaving the summer free for exploration in the interior."*

The party's provisions were shipped by steamer from Rigolet to the Hudson Bay post at North West River and the men followed in canoes. Low used this post as his winter base taking trips to Cartwright, Sandwich Bay, and Rigolet (Low 1895). Meanwhile four men were sent from North West River 192 km up the Hamilton River on October 23rd; they stayed there till the ice formed fully on the river and they returned on December 29th. In a slightly different version, Low (1894b, p. 137) stated:

> *"The four Indians were sent up the Hamilton River, with instructions to go as far as possible before the river became covered with ice; they succeeded in reaching a point about one hundred miles above the river's mouth. Here they remained till Christmas, when they descended on the ice to the Post."*

Year 1894

In January 1894, Low hired eight men from Rigolet and four men from North West River to aid his crew of Eaton and 'four Indians' in carrying supplies up the Hamilton River. According to Low (1894a, p. 137):

> *"On the 19th of January, Mr. Eaton started up the river with a party of seventeen men, each hauling two hundred pounds of provisions on a sleigh. He succeeded in ascending seventy miles, when owing to a lack of snow on the rough ice in the heavy* [Gull Island] *rapids, he was obliged to cache the loads and return. A final start was made on the 6th of March, when the party* [now including Low] *assisted by eight men proceeded inland with more provisions and outfit sufficient for six months travel."*
> *"…Arriving at the cache in five days* [note that he is stating that they travelled five days from North West River with full sled loads in the middle of winter, all the way to Gull Island]*, they continued on seventy miles farther, until they were stopped by open water, extending ten miles below Lake Winokaupow. A second cache was made here and the whole party returned downstream to the first cache for a second load. When this load and the canoes had been hauled to the foot of the open water, the loads were put into canoes and they were tracked and poled up the lake – a novel and disagreeable mode of travel, with the thermometer standing a few degrees below zero"* (Low 1894b, p. 137–8). The temperature reference is, of course, in Fahrenheit, so this was no small excursion.

In his report to the Geographical Journal, Low (1895) described the ordeal of getting past Lake Winokaupow in more graphic detail:

> *"Slow progress was made along the narrow sloping margin of ice near the water's edge for 10 miles, until further travel with sleds became impossible. The loads were stored at another cache here, and the party returned to the lower one, for the remainder of the provisions left there. On the way up, the canoes were taken out of winter quarters about 10 miles below the upper cache, and drawn on sleds to that point. The provisions, outfit, and sled were loaded into the canoes, and they were then poled and tracked up the remaining 10 miles to the lake. This proved a… dangerous undertaking, as the temperature of the air was 5° to 10°* [F] *below zero, and the river was full of ice. The men, working in the canoes, were able to grip the ice-covered poles only with their bare hands, and all were more or less frost-bitten."* (p. 532).

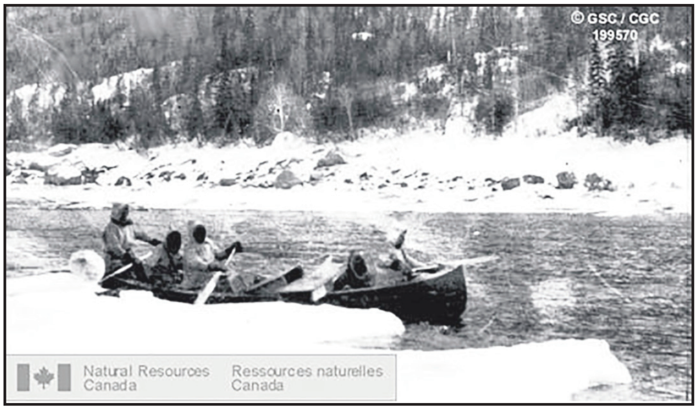

Figure 2. a (left) and b (right): Low party moving supplies up Lake Winokaupow, winter 1894. (note the sled dog (black) in Figure 2b). Natural Resources Canada, A.P. Low.

Figure 2 shows photographs of Low's party on Lake Winokaupow and Figure 3 is a view of the lake in 2009. Low (1896, p. 135–136L) described the lake as being:

> *"…remarkably deep; an isolated sounding taken fifteen miles up the lake, and about midway across, gave 427 feet... A third sounding was made fifty feet from the shore on the south side, opposite the first mentioned, and gave a depth of 80 feet. No other soundings were made, owing to the difficulty experienced in cutting through the ice, which at the time we passed was four feet nine inches thick, and two hours were required to make a hole through it with the implements at hand.*
> *…From Lake Winokaupow the extra men were sent home on the 1st of April and the party continued on alone, each person hauling four loads weighing from 250 to 400 lbs. On this account the ground had to be covered seven times and progress was consequently slow, so the Grand Falls were not reached until the 2nd of May… On the 19th of May hauling was abandoned, owing to the rotten state of the ice, and the next ten days were passed awaiting open water. At the end of the time the river opened and the party started up it in their canoes, but experienced considerable difficulty and danger from the thick ice coming down from the lakes above. Double loads were made until June 18th when part of the provisions were cached at Sandy Lake, where several canoe routes meet."*

This account of the most arduous, and certainly dangerous leg of the expedition, as given in the Canadian Record of Science (Low 1894b), is of necessity brief, but also curiously incorrect; the lake he refers to as Sandy Lake is actually Sandgirt Lake (now Lake Kanikauwinikau).

Low (1896) provided a much more detailed report on the journey from Lake Winokaupow to Sandgirt Lake. From the mouth of the Elizabeth River on the western end of Lake Winokaupow, it was a canoe journey of 72 km to Bowdoin Canyon. This canyon extended below the Grand (now Churchill) Falls for a distance of over 12.8 km by river, but for only 6.4 km in a straight line. Of course the party could not ascend the falls and instead followed a string of lakes and rivers starting with Portage River. Figures 4 and 5 show details of this area on Low's (1896) map and sketches. The route from Lake Winokaupow thus involved a canoe trip up the Hamilton River for about 54 km to the mouth of Portage River and "*the portage-route of the Grand Falls, leaves the valley on the north side four miles above the mouth of the Portage River*" (Low 1896, p. 138L). The latter is also described in detail:

Figure 3. View to west along Lake Winokaupow in August 2009.

> *"The portage-route past the fall and rapids, leaves the main valley on the north side at the foot of the rapids fifteen miles below the mouth of the canon. The road rises 700 feet in a quarter of a mile as it ascends the steep wall of the valley by a narrow cut beside a small stream. It then passes over undulating wooded country, rising slowly for two miles, to a small lake that lies north-west of the lower end of the portage"* (Low 1896, p. 143L). The ground conditions were quite bad; "*….great difficulty was experienced in the ascent of the steep hill with provisions, sleds, canoes, and outfit, as at the time it was covered with ice and slush, rendering it, in places, almost impassable*" (Low 1895, p. 527).

To finally reach Sandgirt Lake from this point involved canoeing over 93 km with portages in excess of 10 km. Thus, the total distance covered to Sandgirt Lake from Lake Winokaupow was greater than 154 km by canoe with over 15 km of portages, part of which rose 210 m over 400 m, carry-

Figure 4. Detail of Portage River portage route over Grand (Churchill) Falls. From Low's (1896) geology map. Natural Resources Canada.

ing 100–182 kg of supplies, repeatedly from April 1 to June 18th, with only 10 days' break waiting for ice to clear!

Low and Eaton were amongst the first half-dozen or so Europeans to see the Grand Falls and Low produced the first photographic image of the falls (Fig. 6a, b). He described the raw naturalistic essence of the falls: "*the noise of the fall has a stunning effect, and, although deadened because of its inclosed* [sic] *situation, can be heard for more than ten miles away, as a deep, booming sound. The cloud of mist is also visible from any eminence within a range of twenty miles*" (Low 1896, p. 141L). "*These Falls are probably the highest and grandest in America. The river here rivals the Ottawa in volume*" (Low 1894b, p. 138). He also evocatively spoke of the falls in terms of aboriginal tradition in that:

> *"The Indians believe that the space between the falling water and the rocky wall is occupied by the spirits of two maidens who were accidentally carried over the falls, and who now pass their time in dressing and preparing deer skins. On this account, or more probably because of the feelings of awe inspired by the grandeur of the surroundings and the enormous power displayed in this rush of waters, those who hunt in the vicinity cannot be induced to visit the falls or the cañon below."* (Low 1895, p. 141L).

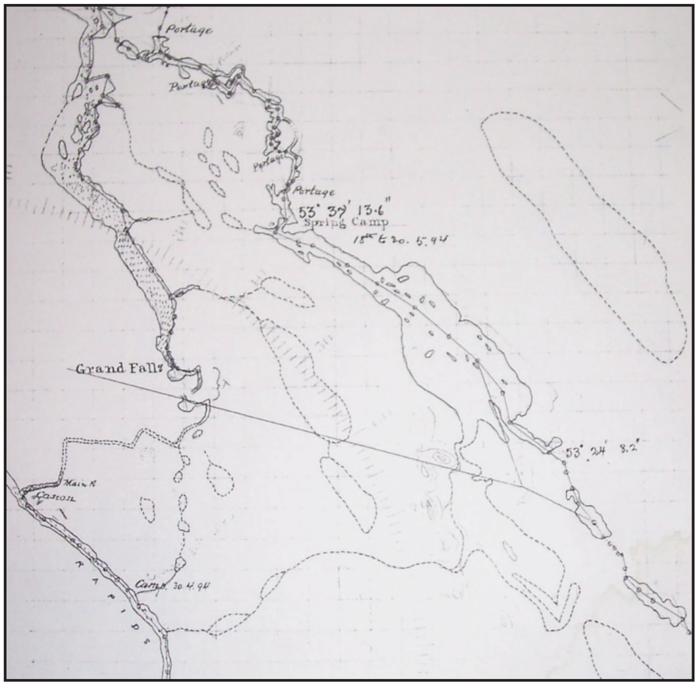

Figure 5. D.I.V. Eaton's sketch map of the Grand Falls portage (Low 1896). From Library and Archives Canada; courtesy of James Stone.

Anybody who now views the present strangled nature (Fig. 7) of the falls can easily surmise that the magic and the maidens have fled since the capture and relocation of their waters. The water that flowed over the falls was diverted to create the 6,527 km^2 Smallwood Reservoir, which actually submerges part of Low's route through to western Labrador. The Churchill Falls Generating Station produces 5428 MW of electricity which flows through the HydroQuébec transmission system all the way to New England.

Continuing on towards the west, Low (1895, p. 147–148L) found that:

> *"Sandgirt Lake is an important gathering place for the Indians of the interior, on account of the number of routes that centre here. The Hamilton River divides into two branches, the larger or*

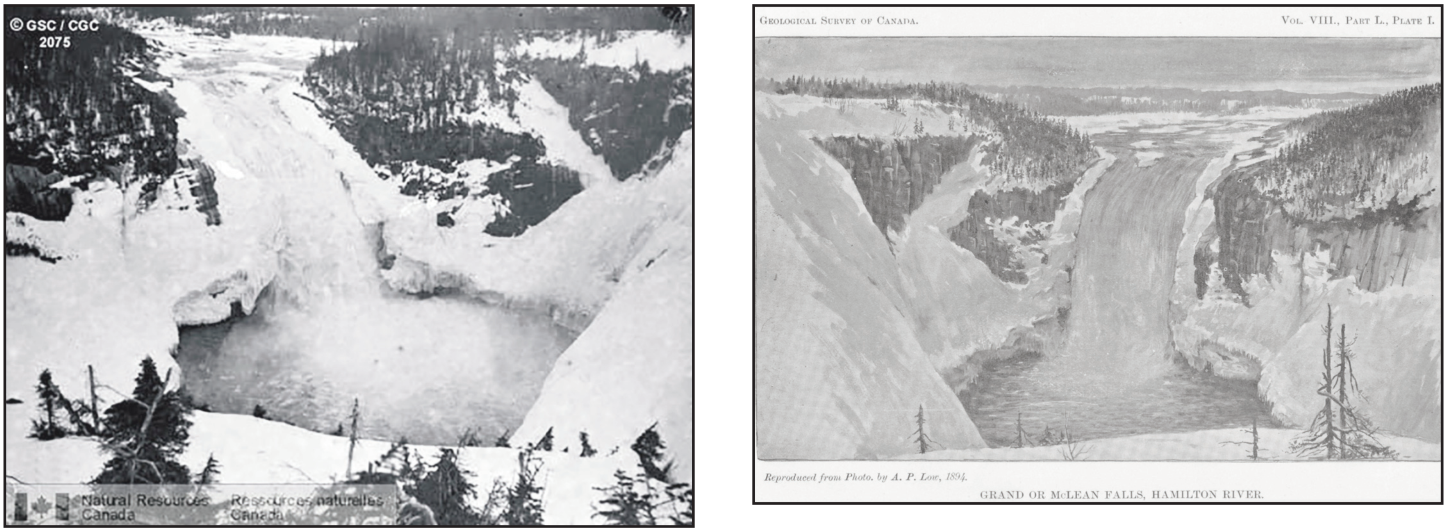

Figure 6. a: Low's photograph of Grand (now Churchill) Falls as on file with Natural Resources Canada (based on Figure 6b, the correct view, it appears that this digital image has been reversed). b: Plate I from Low (1896) of Grand (Churchill) Falls from his original photograph (Figure 6a). Natural Resources Canada.

Figure 7. The current (July 2011) appearance of the Grand (Churchill) Falls; the water has been diverted to fill the Smallwood Reservoir.

> *Ashuanipi Branch flowing in the north-west and the Attikonak Branch from the south. The main route from the Hamilton River to Lake Michikamau also ends here. The Indians who trade on the lower St. Lawrence and hunt anywhere in this vicinity, always congregate here in the spring, and descend to the coast in company, either by the Romaine or Moisie River."*

Thus, Sandgirt Lake was the hub of transportation through Labrador connecting the north shore of the St. Lawrence River, western and central Labrador, Ungava Bay and the Atlantic Coast.

As described by Low (1894b), the final legs of the expedition seem almost trivial when compared to the earlier ones. This is somewhat surprising in that the discovery and documentation of the vast iron resources of western Labrador constitutes probably the most significant result of his work. In his *Geographical Journal* report, Low (1895, p. 531) stated, when describing their trip through the Ashuanipi branch that:

> *"…before leaving this part of the river, attention must be drawn to the immense amount of rich iron ore seen about the shores of the lakes, which can only be estimated by millions of tons."* He was even more effusive when writing in the Canadian Record of Science (Low 1894b, p. 139) where he describes his vision of the iron deposits: *"…an immense area of Cambrian rocks, previously unknown, and found to consist of conglomerates, sandstones, limestones and shales, generally all highly charged with iron, and which often occurs as thick beds of hematite interstratified with the limestone and sandstone in such quantities as to rival or surpass the iron fields of the Lake Superior region of the United States."*

The Iron Ore Company of Canada, which opened up these western Labrador deposits in 1954, was formed by the Hollinger North Shore Exploration, the M.A. Hanna Company (Cleveland) and other steel companies (Geren 1990; Neal 2000). The steel companies needed to replace output from the Lake Superior district, which was depleted after the war. The western Labrador iron deposits actually superseded those around Lake Superior, much as Low had predicted 60 years before when the Labrador deposits were in unmapped wilderness.

Leaving the iron deposits behind, the party travelled for twenty-five days from Sandy (sic) Lake (Low in the Canadian Record of Science paper referred to Sandgirt Lake as Sandy Lake) northwest then south and back through the Ashuanipi branch; they travelled along the Ashuanipi River to south of present-day Esker, now a passing place on the iron ore railway through western Labrador. They then canoed 120 km through Michikamau Lake from Sandgirt Lake; along the north shore of Michikamau, "*a large area of precious Labradorite was found extending over ten miles*" (p. 139) was observed.

From Sandy (sic) Lake the party began its homeward journey on August 1st:

> *"The route followed was by the south-east branch* [of Sandgirt Lake] *to its head in Attikonak Lake there crossing the height of land, the Romaine River was descended nearly two hundred miles, and was left about sixty miles from the coast by a difficult portage route, which passes westward through and over a high range of anorthosite mountains to the St. John River. This stream was descended to its mouth, and the Hudson Bay post at Mingan was soon after reached. The party then crossed on the pocket schooner to Gaspe* (sic) *and so reached home after an absence of sixteen months, during which time they only once received letters from the outside world*" (Low 1894b, p. 139).

In contrast, the modern exploration camp must be equipped with wireless internet such that a worker in any tent can instantly hook into the world-wide web.

Low (1896) provided much more graphic detail on the final hardships of the trip out to the St. Lawrence River. The party travelled down the Romaine River until a point where the portage to the St. John River was taken (Figs. 8, 9); he describes the Romaine River downstream from the portage point as follows:

> "[it] *flows south-east for four or five miles in a wide shallow channel that slowly contracts as the current increases, and finally breaks into heavy rapids where the river passes into a cut between steep high hills. Nothing is known of the river for over fifty miles below this point, except that it is quite impassable for canoes, probably on account of long rapids with perpendicular rocky walls, where portages are impossible."* (Low 1896, p. 170L). The actual portage to the St. John River was up a western tributary and according to Low (1896): *"nothing but the absolute impossibility of passing up and down this part of the river* [the Romaine], *would induce the Indians to make use of the present portage-route between the Romaine and St. John rivers, which is the longest and worst of those known anywhere in north-eastern Canada."* (p. 170L).

In summarizing this very tough portage, Low (1896) concludes that *"the total number of portages from the Romaine to the St. John is*

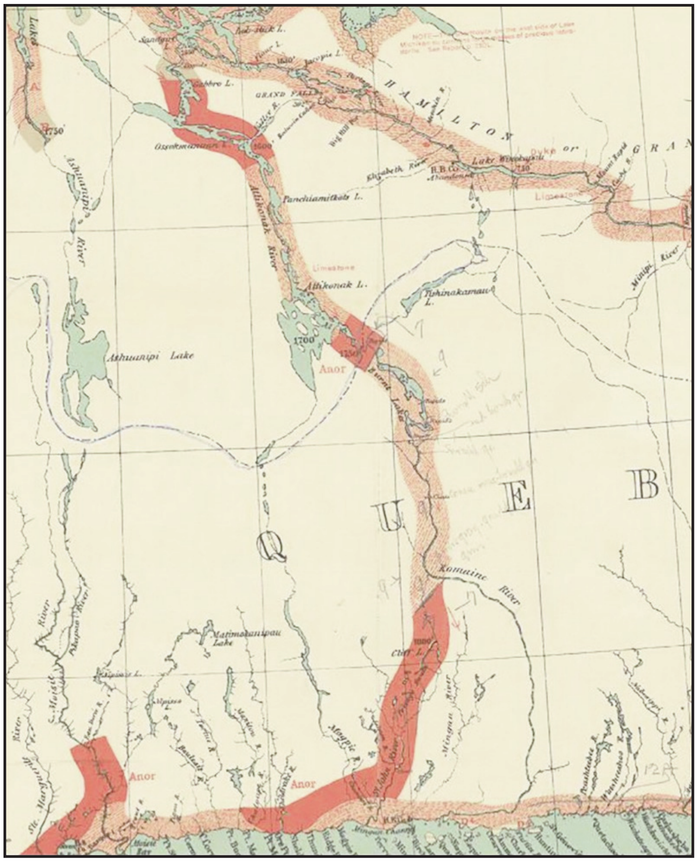

Figure 8. Detail of St. John [Saint-Jean] River portage from Low's (1896) geology map. Natural Resources Canada.

thirty-one, and their combined length aggregates nineteen miles and a half" (p.173L).

Along the portage route between the Romaine and St. John rivers, the party canoed down the 12.9 km long by 2.4 km wide Cliff Lake. He described the area: "*The scenery about this lake is very striking. Both sides are formed of vertical cliffs, often rising sheer from 500 to 600 feet above the water and terminating, in the higher points, in bare, rocky knolls, without a particle of soil*" (Low 1896). Low's photograph (Fig. 10) captures the weathered essence of the surrounding anorthosite.

These ordeals were not the end of the intense portaging, as 45 km downstream from the portage entrance, the St. John River "*descends a narrow gorge, with a heavy rapid ending in a fall of twenty feet*" (Low 1896, p. 173L). To get around it:

> "*the portage past the chute is nearly a mile long and passes along the almost perpendicular side of the valley some 300 feet above the stream. The ascent and descent at both sides is so steep that the Indians are forced to cut steps out of the soil in order to pass over with loads. In the middle it is close to the rocky wall, and the road has been made by placing logs along narrow parts, which almost overhang the boiling stream below.*"

Figure 9. The Romaine River near its headwaters (July 2011).

Figure 10. Low's photograph of 'Anorthosite Cliffs, Cliff Lake,' as on file with Natural Resources Canada photo archives.

Low (1896, p. 170L) described the distance covered in his expedition that started from Lake St. John: "*the total mileage of travel for 1893–94 was 5460 miles, made up as follows:- In canoe, 2960 miles; on vessel, 1000 miles; with dog-teams, 500 miles; and on foot, 1000 miles.*" He also reported (Low 1894a) that the cost of the 1893–94 expedition was $5,857.95; this would be on the order of $140,000 in present-day currency; much less than a standard one-month helicopter contract.

THE ESSENCE OF HIS REPORTAGE

General Natural History Knowledge

Low's reports (1893, 1894a, b, 1895 and 1896) were the first published descriptions of the travel routes through the Labrador Peninsula. His principal report (Low 1896) is a 387-page compendium of information on Labrador including not only descriptions of travel routes, but also photographs (some of the earliest), a brief anthology of history and bibliography of previous explorers, a wealth of natural history data including information on flora (especially trees) and fauna (from insects to mammals), anthropological and sociological information on the aboriginal and European inhabitants, climate data recorded during each day of their trip, and information ranging from fisheries in the region to the glacial history of the peninsula.

His 1896 report includes seven appendices listed as: Appendix I. *List of Mammalia of the Labrador Peninsula*; Appendix II. *List of Birds of the Interior of the Labrador Peninsula*; Appendix III. *List of the principal Food Fishes of the Labrador Peninsula*; Appendix IV. *List of Insects collected in the Interior of the Labrador Peninsula*; Appendix V. *Notes on the Structure of some Rocks from the Labrador Peninsula*; Appendix VI. *List of the Plants known to occur on the Coast and in the Interior of the Labrador Peninsula*; and Appendix VII. *Meteorological Observations in the Labrador Peninsula,* which includes temperature, pressure, wind velocity and cloud cover observations for each day until the last of their thermometers broke in June, 1894.

Low stated that they collected and "brought out" 120 species of plants from the Hamilton River (1894) leg of the expedition, along with specimens of birds, birds eggs, butterflies and insects. Nearly 200 "*specimens of typical rocks* [were] *brought home*" (Low 1894b, p. 139); 34 of these specimens were further examined in the laboratory and this work constitutes Appendix V.

Geology

Evaluation of Low's geological work must be tempered by the fact that it was completed long before isotope geochronology had developed to the point that the precise ages of rocks could be determined, and long before modern ideas on plate tectonics, mountain building, and metamorphism had been postulated. Low's work was also completed in a state of constant motion, and was truly reconnaissance, such that no detailed mapping could be completed.

Low's geological observations mainly involved detailed descriptions, down to the outcrop in places, of the track they followed; there is little 'big-picture' musing. Aside from the Innu place names, Low described somewhat whimsical locales mainly related to a canoe expedition such as Quartz Hill, Fault Hill, Shale Shute, Paint Mountain, Flour Lake, Sharp Rock Portage, Talking Falls, Disaster Rapids, Broken Paddle Brook, Broken Paddle River and Astray Lake; a place where the crew missed their route.

The main geological formations from oldest to youngest as defined by Low (1896) were the Laurentian ('crystalline Archean rocks'), the Huronian banded volcanic and sedimentary rocks, which were infolded with the Laurentian, and the Cambrian mixed detrital sedimentary, limestone, basic intrusive and volcanic rocks. Low described the Cambrian rocks unconformably overlying both the Laurentian and the Huronian. "*Basic irruptive*" rocks cut the Cambrian rocks and these in turn were cut by even younger granites. Much older eruptive rocks cut the Laurentian rocks. The legend for his series of four maps covering this enormous expanse of territory (Fig. 11) summarizes his thinking on geological relationships. The maps themselves cannot be represented adequately in this paper, but they are in the public domain. To examine these maps, interested readers are referred to the Geoscience Canada data repository, (http://www.gac.ca/wp/?page_id=306), where high-resolution files are placed for convenience.

The Laurentian, as mapped by Low, covered 90% of the Labrador Peninsula and comprised schists and gneisses. Low (1896) suggested that "*by far the greatest area of the peninsula is underlain by medium to coarse-textured, hornblende-granite-gneiss, corresponding to the Fundamental Gneiss of Logan.*" "*Mica-gneisses and mica-schists*" that Low suggested (1896, p. 199L) were "*representatives of the Grenville Series of Logan,*" were the second most abundant rock type on the peninsula. Low mapped anorthosite, which he also included in the Laurentian designation, south of Nain, (now termed the Nain Plutonic Suite) as well as around Grand Lake (now termed the Mealy Mountains Intrusive Suite), and Lake Michikamau (now termed the Michikamau Intrusion).

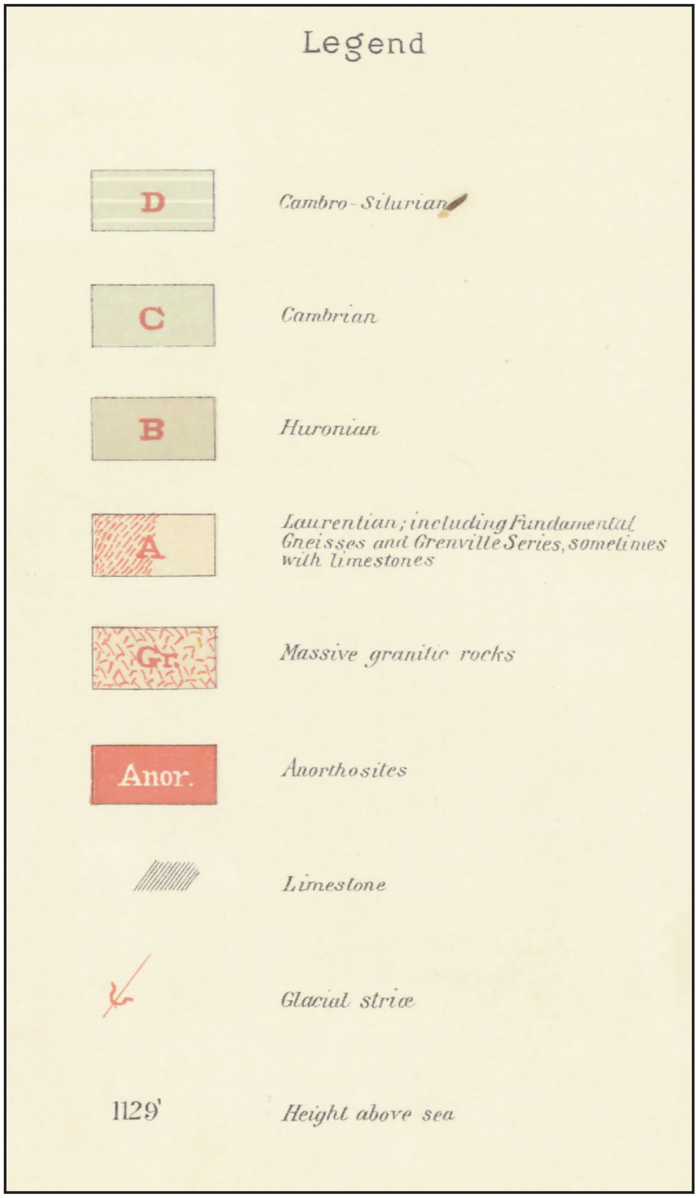

Figure 11. Geological legend from Low (1896). Natural Resources Canada.

The rocks of the Grenville Province, as this region is now called, have been proven to actually be much younger than the Archean at ca. 1.5–1.0 Ga. (e.g. Rivers 1997). The northwest boundary of the Grenville Province corresponds with Lake Mistassini, hence Low's 'Archean' rocks from Lake St. John

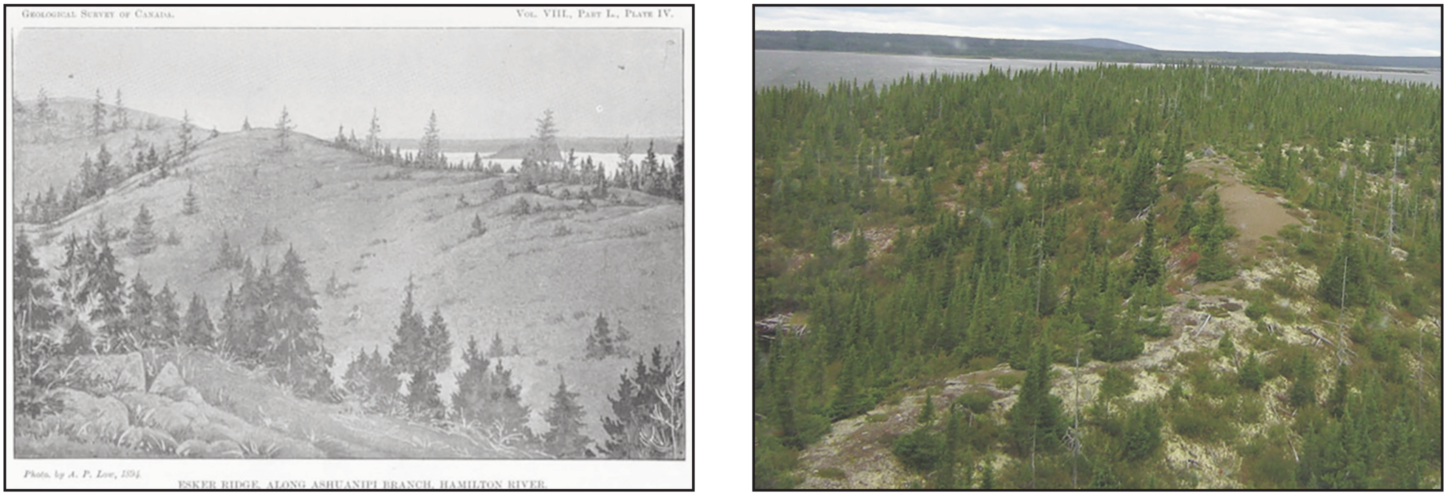

Figure 12. a: Plate IV from Low (1895), "Esker Ridge along Ashuanipi Branch, Hamilton River" (note human figure on caribou moss in centre). Natural Resources Canada. b: A similar esker near Ashuanipi River, with Smallwood Reservoir in background (July 2011).

(Lac St. Jean) to Mistassini are actually much younger rocks of the Grenville Province. From Lake Mistassini to the Koksaok River, Low was correct in describing the rocks as Archean, but otherwise no other rocks on his journey actually constitute areas now defined as Archean in age. To the west of Esker, (a station on the Quebec North Shore and Labrador rail line, serving iron ore mines in the region), Archean basement rocks are exposed, but Low's trip along the Ashuanipi branch did not get that far west.

Based on detailed mapping and geochronology, the anorthosites mapped by Low (1896) as Laurentian (i.e. Archean), are now recognized as some of the youngest igneous rocks in Labrador at 1.5 to 1.2 Ga. They intrude all the older rocks. His Laurentian limestones belong to the much younger Grenville Province.

Low (1896) mapped the Huronian in two principal areas. The first area was along the East Main River in Quebec. The second area was southwest of Lake Mistassini, also in Quebec. He did map some Huronian rocks in western Labrador near the Ashuanipi River, but outcrops were too few to map out its areal extent.

In terms of the Cambrian, Low was hampered by the lack of fossils, such that he could not directly correlate the Labrador 'Cambrian' with the Lower Cambrian rocks from the Labrador Straits area, exposed in both Labrador and Newfoundland. Low mapped the iron formations of western Labrador as Cambrian. The remarkably iron-rich rocks, which Low noted along the Koksoak River and in western Labrador, are part of what is presently called the Labrador Trough (e.g. Neal 2000), a ca. 2.0–1.88 Ga sedimentary sequence that was deposited on the shelf along the margin of the more ancient Archean continent. Thus, Low was incorrect in assigning an age to the iron formations, but correct in correlating the iron-bearing rocks from the Koksoak River south to the Ashuanipi.

The discovery and documentation of the iron-bearing rocks of the Labrador Trough is obviously a tremendously significant product of Low's geological work. The elemental compositions of some rocks that he collected as reported in 1896 are remarkably similar to those reported by Neal (2000) from modern geochemical analyses over 100 hundred years later. In addition to the iron, there has been mineral exploration conducted over the anorthosites that Low mapped at Lake Michikamau (Smallwood Reservoir) and Ossokmanuan Lake. These rocks are analogous to those that host the Voisey's Bay nickel–copper–cobalt deposits (e.g. Naldrett et al. 1996; Evans-Lamswood et al. 2000).

Low (1895) also noted Quaternary geomorphologic features such as striae, eskers, moraines and erratics (Fig. 12). In fact, he recorded a large number of striae directions from throughout the region. Low mapped striae at the Nachvak trading post, corroborating Bell's (1884, 1885) observations that although glacial striae were visible up to a height of 104 m, the tops of the Torngat Mountains appeared to be unglaciated. Low also formulated the supposition that there was a central glacial ice-cap that covered Labrador and that the ice accordingly flowed outwards in different directions from this centre. Along with describing the iron-bearing rocks of western Labrador, Alcock (1944) suggests that this idea on the continental ice sheets constitutes the most important results of Low's expedition.

Photographs

Low took numerous photographs of the Labrador interior. These plates constitute some of the earliest visions of the region. His 1896 report only contained four plates, including that of Grand (Churchill) Falls reproduced as Figure 6b. An intriguing feature of some of these images (as in Fig. 6b and Fig. 12a) is that they are not the actual photographs, but artistic renderings of the photographs in pen and ink. Presumably this reflects the difficulty of publishing true photographic images compared to line drawings. The vast majority of Low's photographs, however, remain unpublished in the Natural Resources Canada photographic archive (there are 376 photos attributed to A.P. Low in the files).

Descriptions of the Hudson Bay Company and Other Trading Posts

Low also provides important historical information. According to Low (1896, p. 41L):

> "*In 1857 there were seven trading posts in the interior of the peninsula* [these included posts at Lake Winokaupow, Michikamau, and Fort Nascaupee (now Fort Nascopie) in Labrador], *and at present there are but three, Waswanipi, Mistassini and Nichicun* [all in what is today Quebec]. *Fort Chimo … was not then opened. The policy of the Hudson's Bay Company was then to keep the Indians away from the coast and contact with opposition traders; this has now changed, and the great body of natives travel annually to and from their hunting grounds in the interior, to the various coast posts.*"

The Michikamau and Fort Nascaupee posts closed in 1873, and the Lake Winokaupow post closed in 1874. Low (1896, p. 153L–154L) suggests that Fort Nascaupee was quite successful but closed because the Nascaupee 'deserted' it in favour of Fort Chimo, which was established in 1866.

> "*Those* [the Nascaupee] *from the north going to Fort Chimo while the southern Indians traded at Mingan or Seven Islands on the Gulf of St. Lawrence, or at Northwest River – all of them preferring to undertake the long arduous journey to and from the coast, where they could obtain better prices for their furs, and purchase provisions and other necessities at a much cheaper rate than at the interior post, where the cost of transport and maintenance added several hundred per cent to the original cost of the goods.*"

Thus, the fate of the inland posts was related to the economics of transport costs; a theme that resonates in Labrador to the present. Low (1896) described the long-closed post at the head of Lake Winokaupow, located on his map of the region:

> "*there is a wide, sandy plain about twenty-five feet above the river, and on it the Hudson's Bay Company formerly had a post, which was abandoned in 1873, and subsequently destroyed by fire*" (p. 136L). "*Lake Winokaupow is well stocked with fish, the employees of the... company when stationed there, depended to large extent on fish for food. In the old journals of the post* [held at Rigolet], *the catches of the nets are recorded, and show that fish were taken abundantly, especially in the spring. The catch included carp, whitefish, lake and river trout in the order named. Potatoes and turnip were grown at the post, but not very successfully, as after planting in the spring, everybody left the place, and did not return, until September, leaving the crops to grow without cultivation.*" (p. 137L).

Another post was located along a stream that flowed southwest from Lake Michikamau into the Lobstick Lake route (see Fig. 13). Presumably, the site of this post at Michikamau is now underwater in the Smallwood Reservoir, which includes the former waters of Lake Michikamau.

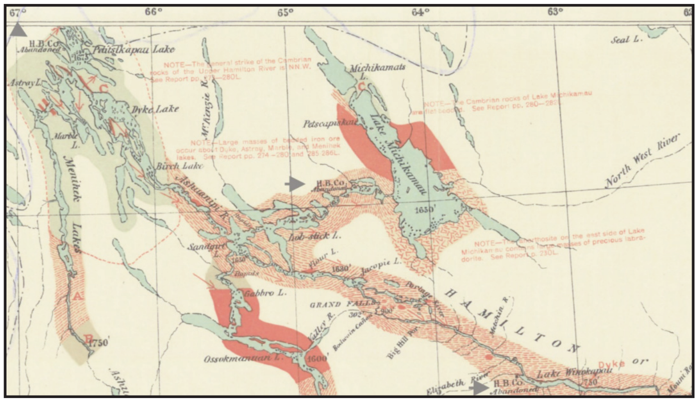

Figure 13. Location of Hudson's Bay posts: Lake Winokaupow to southeast, Lake Michikamau in the middle, and Fort Nascaupee (Nascopie) to the northwest (labeled as H.B.Co Abandoned); detail from Low's (1896) geology map. Natural Resources Canada.

> "*the Hudson's Bay Company kept a small outpost called Michikamau during the time that Fort Nascaupee was occupied. Nothing can be learned about this outpost from the...* [Company] *journals at Rigolet or Northwest River, beyond the bare facts that a post was maintained there for a number of years, and was finally abandoned from the same reasons which caused Fort Nascaupee to be given up. This post was not visited, but from the accounts of the Indians, some of the buildings have been accidentally burnt, and those remaining are in about the same state of decay as Fort Nascaupee.*" (Low 1896, p. 159L-160L).

The westernmost Hudson's Bay Company post in the Labrador interior, Fort Nascaupee, was established ca. 1841 along a northern bay in Lake Petitsikapau (Low 1896), and is located on the map of Figure 13:

> "*The ruins of Fort Nascaupee stand in a small clearing, close to the shore of the lake.... The houses were built of small, squared logs, with board roofs. When visited, the dwelling-house was in a fair state of repair, with the window sashes and some of the glass still in place.... The roof was nearly unbroken, and leaked only in a few places* [they must have overnighted there]... *adjoining the main building on each side are two smaller buildings, evidently used for a kitchen and store; the roofs of both have fallen in. About fifty yards behind, the powder-house covered with earth was seen, with broken roof and partly filled up with earth. Adjoining this is a small burying place with a large wooden cross in its centre, but without any marks on the graves, which are probably those of Indians. In the attic a fragment of "The Albion", of March 7th, 1846, was found. Close to the house were several patches of rhubarb eighteen inches high, while a number of introduced plants still flourish in the old door-yard*" (p.154L).

This paper was presumably the "*The Albion, or British, colonial, and foreign weekly gazette*" published in New York. Clearings, depressions and scattered artifacts along with rhubarb remain the only indication of this fort (McCaffrey 1986). Low's photograph of the site is provided in Figure 14.

Figure 14. Photograph of Fort Nascaupee (Nascopie) Hudson's Bay post in 1894 from Low's journey. Natural Resources Canada photo archives.

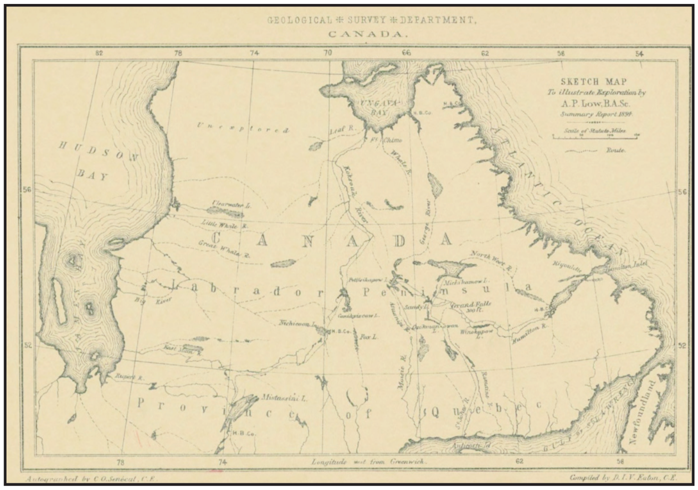

Figure 15. 'Sketch Map' of the Labrador Peninsula that accompanies Low's 1894a report. Natural Resources Canada.

Maps

The expedition produced a number of maps, both geological and geographical, and as such these constitute the first documentation of the Labrador interior and were used by most subsequent trekkers. The map from the Low (1894a) report was termed a 'Sketch Map' and it shows the Labrador Peninsula, the coastline, the interior along the expedition route and some other interior landmarks (Fig. 15). Note that the map shows the North West River flowing from Lake Michikamau to Grand Lake (this latter body of water is not named on the map), and also a small tributary flowing from the northeast into the North West River just above the mouth of Grand Lake. The later map (Fig. 16) attached to Low's (1895) *Geographical Journal* report is basically the final version of the geographical map. It outlines the route taken during the expedition and illustrates the correct orientation of Lake Michikamau, but also contains the North West River linking Grand Lake and Lake Michikamau.

The final maps from the expedition were published in 1896 and were done so in four separate sheets (located in the Geoscience Canada data repository); the southeastern map sheet also includes geological data on the area from Hamilton Inlet south to Partridge Point compiled from Packard (1891). These maps are beautifully drawn, and while described as geological maps, they also provided geographical, physiographical, and cultural information for the territory along their routes. Considerable care was taken to reproduce the aboriginal place names; for instance, the hill behind Makkovik, now called Monkey Hill, was originally named Altagaiyaivik according to Low's maps.

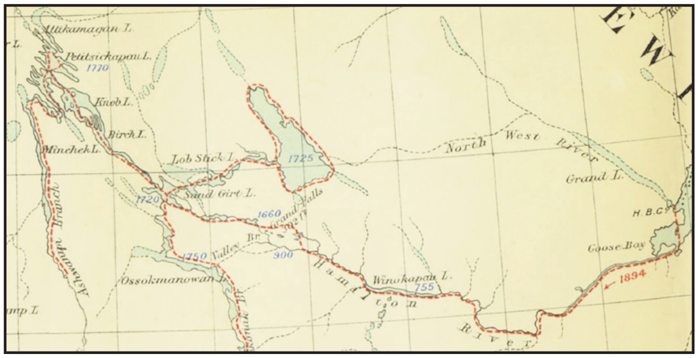

Figure 16. Close-up of map from Low's (1895) *Geographical Journal* paper report illustrating the canoe route up Hamilton (Churchill) River (note North West River flowing from Lake Michikamau). – this was reproduced from Geographical Journal 1895.

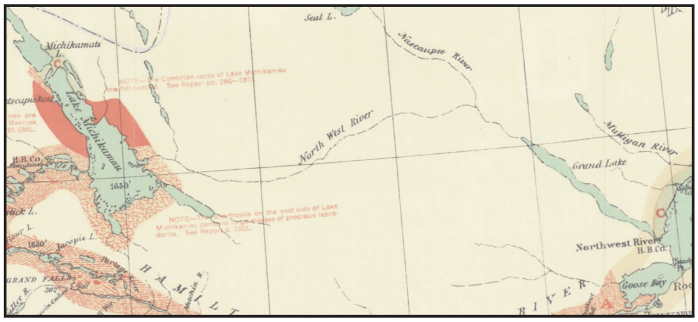

Figure 17. Detail of Lake Michikamau, North West River and Grand Lake from Low's (1896) geology map. Natural Resources Canada.

Low's maps played an important role in the ill-fated 1903 Leonidas Hubbard expedition. The 1895 *Geographical Journal* map shows the 'North West River' flowing into the head of Grand Lake splitting into two just above Grand Lake (Fig. 16). One river, continues north to an unnamed lake, whereas, the North West River branch was mapped as heading west into Lake Michikamau. On the final 1896 map, in the Grand Lake watershed, the river which splits off to the north of the North West River was correctly mapped as 'the Nascaupee,' and the lake from which it flows was termed Seal Lake. But the map again showed a North West River flowing from Lake Michikamau into Grand Lake (Fig. 17). In these maps (Low 1895, 1896), the geographical detail of the rivers leading towards Lake Michikamau, and hence to the route to George River is incorrect. However, he did represent the rivers with dashed lines suggesting that the information was approximate and unconfirmed.

As subsequently shown by Mina Hubbard's journey, the route to Lake Michikamau goes up the Nascaupee (now Naskaupi River) and through Seal Lake. There is no river running west to Lake Michikamau as the so-called 'North West River,' and in fact there is no North West River flowing into Grand Lake. The modern North West River is a short waterway flowing out of Grand Lake through the community of the same name. Wallace (1905) includes a map (p. 261) which is listed as "*From map accompanying Report by A.P. Low Geological Survey of Canada*" which incorporates elements of both Low's 1895 and 1896 maps and has a 'North West River' flowing from Lake Michikamau towards Grand Lake. If he was using this map, it is easy to understand why Hubbard stubbornly held to the notion that he had to journey *west* to Lake Michikamau, rather than north and then west as he should have done.

Wallace (1905, p. 6) did blame Low's map of Grand Lake as the cause of their tragedy, stating that "*the Geological Survey map is the best of Labrador extant, but its representation as to the Northwest River (made from hearsay) proved to be wholly incorrect, and the mistake it led us into cost us dear.*" However, it is also an example of how Hubbard should have used local knowledge.

IRONY

The lives of both A.P. Low and D.I.V. Eaton would encounter unexpected turns in the years that followed their monumental expeditions. In 1907, after leaving active field work and serving as Director of the GSC, Low was "*seized with a severe attack of meningitis from which he never wholly recovered*" (Alcock 1944, p. 197). Stewart (1986, p. 275) provides a more detailed description, stating that Low was:

> "*…stricken by what is thought to have been a cerebral hemorrhage and, soon after that, by spinal meningitis. He never fully recovered and eventually retired in 1913 under a cloud of controversy over his physical inability to carry out his work. Amazingly, the strength and endurance of his youth did not totally fail Low, for he lived out a long, apparently quiet, retirement in Ottawa, ultimately dying in virtual obscurity in 1942 at the age of 81.*"

Zaslow (1975) noted a contemporary report which suggested that Low had suffered an "*attack of the grip"* in January 1907 and that he been "*reported dying*" (p. 263). Other colleagues suggested that Low had suffered from a serious brain disease and that it was uncertain that he will recover his mental faculties. Zaslow succinctly sums up the ironic misfortune that constituted the final years of Low's life as: "*tragically, he lived on and on, the mind of a child inhabiting his once powerful frame.*"

D.I.V. Eaton served through the Boer War and rose up the ranks of the Canadian military to become Lieutenant-Colonel and commander of B Battery, Royal Canadian Horse Artillery (Wright 1998). He was a professional soldier who served through the period of peace from the Boer War to World War I. He served in France during World War I and on the eve of the Battle of Vimy Ridge, while visiting his troops preparing for the great engagement, he was mortally wounded by enemy fire on April 8, 1917 (Wright 1998); he succumbed to his injuries on April 11, 1917.

CONCLUSION

Albert Peter Low's exploration through Labrador provided a veritable cornucopia of data on what was, at the time, a last great unexplored wilderness of North America. The story of the expedition itself was perceived by the outside world as a journey of epic proportions and provided endless evenings of inspiration to dreamers such as Leonidas Hubbard. Alcock (1944) went so far as to state:

> "*…ranking as the greatest of these* [in comparison with other GSC expeditions through Canada] *were the achievements of Low in traversing and investigating the vast hitherto unexplored spaces of the Labrador Peninsula. In fact, the information about this region, both geographical and geological, is so largely the result of this explorer, that the names Low and Labrador are almost synonymous.*"

Reviewing the route, the distances travelled, the observations made, and the incredibly difficult work that the trip must have entailed, one can only come away with a sense of awe at what Low, Eaton and their crew achieved. The trip required constant counting. As described by Jolliffe (1987), GSC field crews had to count each step, and even every paddle stroke, to define distances. Meteorological measurements were made and recorded every day. Descriptions of the day's observations were dutifully written down each evening. Hundreds of specimens, ranging from birds' eggs to rocks, were packaged and carefully transported out, over every painstaking metre of portage, every kilometre of each river, and up and down steep cliffs. They actually brought out more than they took in, unlike many of today's geologists.

Compared to the other 'explorers' of Labrador, Low's group were professionals of the highest order. They knew what they were doing and equipped themselves accordingly for their travels. Low's crew travelled for sixteen months covering thousands of kilometres by the most basic of means, their own locomotion, and yet all returned in good health (however, Low did lose a man in 1895 to an accident on some rapids).

With all due respect owed Low for his trip, one cannot but also feel tremendous respect for the aboriginal inhabitants of Labrador who pioneered the routes and portages, and even built the cliff steps that Low's group used. These people did not make a single voyage; they made these perilous journeys annually to the coast, both out and back in, to trade their furs. Low was essentially following and reporting on their travel routes, not breaking the trails.

Figure 18 is a photograph of Low and Eaton, somewhere in central Labrador in the middle of their expedition, at the peak of their prowess as explorers, bestriding the Labrador wilderness. Unfortunately, both their subsequent fates were ironic and tragic. Low went from a man of incredible physical ability to a broken invalid some 13 years later, lingering on for a further 35 years. Twenty-three years later, Eaton, a professional soldier for in excess of 20 years, was mortally wounded, on its eve, in preparation for what is considered the greatest Canadian military triumph in which the 'creeping barrage' of artillery support was critical. Eaton was a commander of, and

Figure 18. A.P. Low and D.I.V. Eaton, central Labrador in 1894; as on file with Natural Resources Canada. Natural Resources Canada.

expert in, artillery techniques, and would most assuredly have been involved in the planning for the Battle of Vimy Ridge.

ACKNOWLEDGEMENTS

Martha MacDonald and the Labrador Institute are kindly thanked for permission to revise and republish the earlier Low paper from the *Very Rough Country* volume. It gave me a chance to become reacquainted with the most formidable Mr. Low. Andy Kerr is also kindly thanked for the opportunity to take Mr. Low out for another small paddle; Andy's gentle reminders, urgings on and editing, helped me finish. The modern-day map-making whiz, Mr. Rod Churchill of Altius Minerals Corp. produced Figure 1. Low's photos and maps were retrieved from the Natural Resources Canada repository and photo archives and this information is licensed under the Open Government Licence – Canada, https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=nrcanphoto/nrcanphoto_e.web.

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For access to the four geology maps that accompany A.P. Low's (1896) report, please visit
GAC's open source GC Data Repository link at:
https://www.gac.ca/wp/?page_id=306.

GAC-MAC: FIELD GUIDE SUMMARY

Vancouver 2018: RFG 2018 / CIM–GAC–MAC Joint Annual Meeting Field Trips

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RFG 2018 / GAC–MAC FIELD GUIDE SUMMARY

The GAC-MAC Annual Meeting this year will be associated with the inaugural Resources for Future Generations (RFG) 2018 Conference that will be held in Vancouver, British Columbia. The conference theme is focused on exploring resource and sustainability issues, such that we can develop and utilize these resources in better, sustainable and cleaner ways that minimize impact. Vancouver, a coastal city surrounded by ocean, mountains, glaciers and forests, and whose essence is deeply entwined with natural resources, is a perfect setting for the RFG 2018 conference.

The RFG 2018 meeting will offer a wide variety of pre- and post-conference field trips that are aligned with the main themes of RFG 2018, including renewable energy and resources, hydrology, natural hazards, urban geology and geoheritage, metallogeny, geochemistry, structure, petrology and tectonics. In total, there are 15 field trips to choose from that range in length from local one-day field trips, to multi-day field trips in the southern interior of British Columbia, the foothills of Alberta and Nevada.

Pre-Conference Field Trips

Pre-conference field trips include a one-day excursion titled *"Urban Geology and Geoheritage of Metro Vancouver, British Columbia."* Participants will examine Metro Vancouver's bedrock and surficial deposits that span the last 200 million years of Earth history, as well as consider the breadth of societal contributions afforded by Urban Geology. Emphasis will be on the glacial history and geology of the region. Geotechnical challenges of the region will be examined including water resources, flooding and mass wasting. Challenges in recent tunnel construction in thick glacial and glacial-marine sediments for expansion of the Skytrain Light Rail Transit system will also be explored. In addition, the growing interest in geoheritage and the educational values of geological sites will be addressed along with their potential for fostering a sense of place for an increasingly diverse urban population.

Columnar andesite, Stanley Park, Vancouver, British Columbia (Photo: Lionel Jackson).

Further afield, *"The Cretaceous–Cenozoic Coast-Cascade Orogen: The Chilliwack Valley-Harrison Lake Connection"* is a two-day field trip in a region that occupies an important position in a mid-Cretaceous to Cenozoic (100–45 Ma) orogen whose southern extent includes the Coast and Cascade Mountains of southwestern British Columbia (BC). Here, there is excellent preservation of allochthonous terranes sandwiched between terranes to the east accreted in the Jurassic, and Wrangellia terrane to the west underlying most of Vancouver Island. The region is characterized by mid-Cretaceous to early Cenozoic granitic intrusions, metamorphic rocks, folds, thrust and reverse faults, all overprinted by late Eocene through Neogene volcanic rocks and plutons of the Cascade Magmatic Arc.

View of snowcapped peaks of mid-Cretaceous Breakenridge orthogneiss (up to 10 Kbar) adjacent to the little deformed and metamorphosed rocks of the Harrison Lake Formation (tree covered rocks in foreground to the left), southwestern British Columbia (Photo: Dan Gibson).

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Across the Salish Sea, a two-day field trip titled *"Karst Hydrology of Central Vancouver Island"* will examine two forested karst areas including: the Horne Lake Caves Provincial Park and Quadra Island. The focus for the field trip will examine how these karst landscapes influence the hydrology of the region. At Horne Lake Caves participants will explore the 'karst trail' and have a guided trip into the subsurface. Karst features and geology outside of the park will also be examined. At Quadra Island they will visit a series of karst springs as well as the associated recharge area.

Karst spring, Quadra Island, British Columbia (Photo: Tim Stokes).

To the east within the southern interior of British Columbia, a six-day field trip titled *"Southern BC Porphyry Field Trip,"* put on by the Mineral Deposits Research Unit (MDRU) of the University of British Columbia, focuses on the diverse porphyry Cu–Au systems in the prolific Late Triassic Quesnel Terrane (Quesnellia). Participants will be exposed to various types of porphyry deposits, mineralization and alteration styles, mining methods, and background lectures near Kamloops and in the Copper Mountain district. Emphasis is placed on alkalic porphyry systems, characteristic of regional porphyry metallogeny.

Copper Mountain mine, southern interior of British Columbia (Photo: Robert Lee).

Post-Conference Field Trips

The one-day post-conference field trips include a bus trip titled *"Geology and Natural Hazards of the Sea-to-Sky Corridor"* that takes you from Vancouver to Squamish. Topics addressed during field trip stops include the geology of the southern Coast Mountains, the origin of Howe Sound, Pleistocene glaciation of British Columbia, and geologic hazards on the south coast. An underground tour of the Britannia Mine, once the largest mine in British Columbia, is included in the trip.

Howe Sound, a network of fjords northwest of Vancouver, British Columbia (Photo: John Clague).

Another local one-day field trip titled *"Resourcing Urban Water – the Seymour-Capilano Water System and Twin Tunnels Project"* will take in aspects of the geology of the mountainous north side of Vancouver harbour and will include visits to both the Capilano and Seymour watersheds to understand the Seymour-Capilano Twin Tunnels Projects and tour some of the associated facilities. The field trip will examine a major, modern urban water handling and treatment scheme that supplies domestic drinking water to 2.4 million local residents, at a rate of 1.8 billion litres per day.

A third one-day field trip titled *"Seabreeze Farm Renewable Natural Gas Plant Tour"* will examine a multi-generational family owned dairy operation in Delta, BC that produces Renewable Natural Gas (RNG) from the farm's dairy manure for injection into the FortisBC gas grid.

Seabreeze Farm Renewable Natural Gas plant, Delta, British Columbia (Photo: Greenlane Biogas).

A fourth one-day field trip titled *"Geochemistry Lab 101"* is offered in Metro Vancouver. The field trip will feature a morning technical seminar and an afternoon laboratory tour at one of two sponsoring Vancouver mineral laboratories (Bureau Veritas or SGS Canada Inc.). The trip is envisioned as a theoretical and practical learning experience for participants new to the industry or unfamiliar with geochemical analytical science.

The multi-day post-conference field trips range from 2.5 to 4 days in length. These include a 2.5-day field trip titled *"Highland Valley Porphyry Copper Deposits: District-Scale Footprints"* located near Merrit, British Columbia. This field trip will examine the magmatic evolution, mapped alteration, outcrop hyperspectral response, and the lithogeochemical and Carbon isotope footprints around the Highland Valley Porphyry Cu (HVC) deposits that are hosted in the Late Triassic Guichon Creek batholith within Quesnel terrane.

South of the 49th parallel, another 2.5-day field trip titled *"Navigating a porphyry Cu hydrothermal system: Alteration and geochemical dispersion mapping"* will examine the geology, hydrothermal alteration mineralogy, and geochemical dispersion around Yerington, Nevada, USA. Yerington is a classic locality where porphyry Cu deposits, high level Fe-oxide deposits, and a volcanic and plutonic complex have been tilted 80° on to their side so that a complete 3-D picture of a zoned magmatic-hydrothermal system is exposed.

Yerington, Nevada – View from lithocap to porphyry across 3 fault blocks (Photo: Richard Tosdal).

There will be 3 three-day post-conference field trips. One of which titled *"Geochemical Field Techniques"* will explore glacial landforms on macro- and micro-scales and the sampling of soils, tills, sediments and vegetation. Topics covered include Quaternary geology, biogeochemistry, exploration geochemistry and analytical chemistry. Sampling techniques designed for defining baseline and anomalous trends employed in environmental and exploration geochemistry on property, reconnaissance and global scales will be explored. Visits to two mineral deposits include a reclaimed massive sulphide deposit on the BC mainland and a porphyry Cu–Au prospect on Vancouver Island. *In situ* analysis of samples using field portable instruments (e.g. pXRF) combined with subsequent lab analyses of collected samples will give the participants a full appreciation of discovering geochemical anomalies and tracing these to mineralization.

Another three-day field trip within southeastern BC titled *"Upper Fir Carbonatite-Hosted Nb–Ta Deposit"* visits the Upper Fir carbonatite complex (330 Ma) hosting one of the largest and best studied Nb–Ta deposits within the Omineca belt of east-central British Columbia (Blue River area). Although the late Paleozoic carbonatites formed in an active tectonic setting, they are mineralogically and isotopically indistinguishable from worldwide carbonatites generated by deep-mantle plumes in intracratonic settings. Participants will examine late Paleozoic pillowed basalts along the way to Blue River and a range of metamorphic rocks and structures at Upper Fir. In a wider context, the trip will evaluate back-arc extension from eastward subduction beneath ancestral North America and its possible connections to mantle plume development that may have triggered formation of the Slide Mountain ocean.

Upper Fir carbonatite – apatite and ferrikatophorite in a Fe-dolomite matrix; southeastern British Columbia (Photo: Alexei Ruklov).

Farther east, another three-day field trip will be offered, titled *"The southern Canadian Rocky Mountains – Front Ranges and Foothills."* This field trip, within a picturesque part of southern Alberta, focuses on the geological evolution of the Foreland thrust and fold belt between the Foothills and Front Ranges from Banff to the US border.

There will be 2 four-day post-conference field trips offered. The first is titled *"The Tulameen Alaskan-type ultramafic-mafic intrusion: architecture, emplacement mechanisms and Cr–PGE vs Cu–PGE 'Reef-style' mineralization in a convergent margin setting."* This field trip near Tulameen, BC, will examine the lithological zoning and temporal evolution of the Tulameen Alaskan-type intrusive complex and contrasting styles of chromitite-PGE mineralization in the dunite core versus newly encountered Cu–PGE sulphide mineralization in the more differentiated ultramafic rocks. Highlights include examination of 'magmatic avalanche' deposits exposed in the Tulameen River bed, and a 700 m zone of Cu–PGE mineralization similar to Cu–PGE 'reef' occurrences documented from layered intrusions in extensional tectonic settings. This trip complements the Special Session: *"Advances in the study of platinum group elements and ultramafic rocks."*

Dunite-clinopyroxenite outcrop in the Tulameen River bed, near Tulameen, British Columbia (Photo: Nichole Moerhuis).

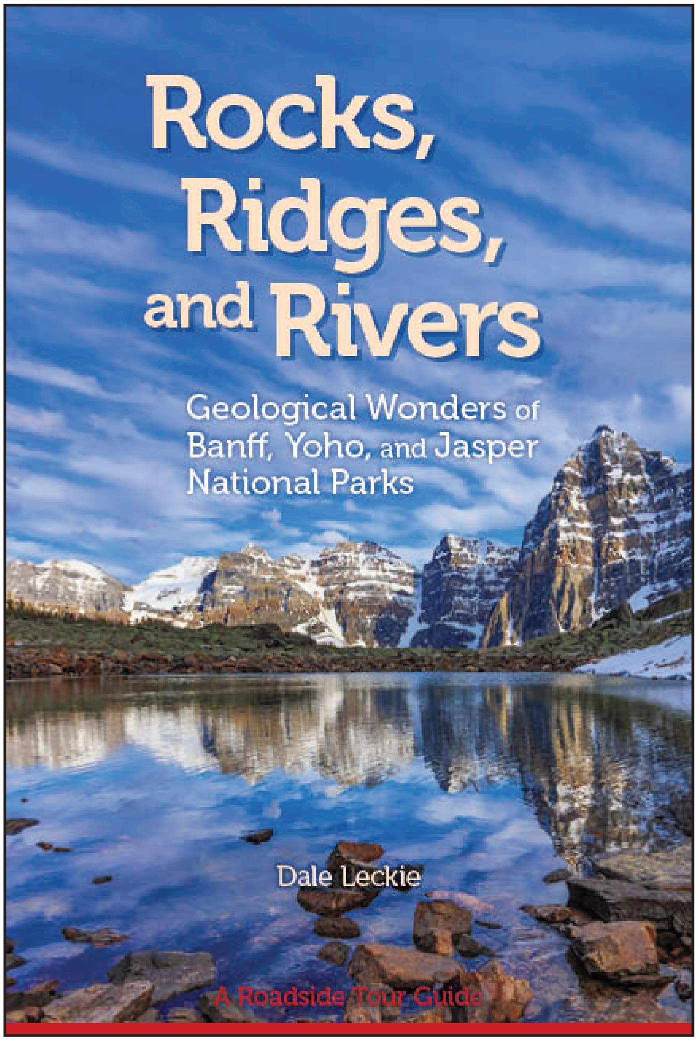
The other four-day field trip titled *"Torrents, Terrains and Tuyas–Waterfall and Volcanoes of South Central British Columbia"* will highlight BC's magnificent mountain scenery, provincial parks, volcanoes and especially its water falls. The trip is suitable for the specialist and non-specialist alike. The group will investigate a zone of transition between the Cariboo and Monashee mountain ranges where deep crustal faults have provided pathways for mafic magmas producing the Wells Gray–Clearwater volcanic field. Here, the interaction between volcanism and multiple glaciations over a three-million-year period have created rugged terrain and unique subglacial landforms called 'Tuyas.' River valleys cut the landscape. The vertical lava walls create spectacular water falls, including Canada's fourth highest – Helmcken Falls. In addition to the stunning vistas, there will be opportunity of hands-on examination of complex stratigraphy related to volcano-glacier interaction.

Helmcken Falls cutting through Wells Gray-Clearwater volcanic field; Wells Gray Provincial Park in south-central British Columbia (Photo: Catherine Hickson).

We hope this wide assortment of field trips will appeal to the broad geoscientific community and that you will visit Vancouver for RFG 2018. See you in June! Further information can be found at: www.rfg2018.org.

Photo by the late Harold (Hank) Williams

REVIEW



ROCKS, RIDGES, AND RIVERS: Geological Wonders of Banff, Yoho, and Jasper National Parks. A Roadside Tour Guide

Dale Leckie

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Dale Leckie is an ex-Geological Survey of Canada geologist, a former Chief Geologist for Wascana Energy (later Nexen) and now an adjunct professor at the University of Calgary. Dale has a long-standing interest in the majestic Rocky Mountains and their formation over several hundred million years, and he is known as an expert on the Cretaceous rocks of western Canada. In 2016, he was awarded the R.J.W. Douglas Medal by the Canadian Society of Petroleum Geologists for his contributions to sedimentology and regional geology. After authoring or coauthoring numerous technical publications over many years, he has now turned his hand to writing a general guidebook about his favourite field areas, which I have thoroughly enjoyed reading at intervals over the last three months. Many of us contemplate writing such books, but few of us can accomplish the task, which is easy to conceive but very difficult to fulfill. I know this only too well, because I have had a rather similar project on my own very crowded back burner for many years. As far as I know, this is Dale's first effort in the direction of Geoscience Outreach, but I certainly hope it will not be his last such excursion. In this compact yet highly informative book, he has managed to successfully balance the divergent needs of professionals, informed amateurs and those who lack a geoscience background, and has provided us with an excellent model for a regional guidebook at an intermediate level. I have certainly drawn much from it in the way of presentation ideas, and with luck it might assist me to actually get something done with that lingering back burner project.

The challenges in developing such a project are well known to many of us. As geoscientists, we need to convey stories that involve hundreds of millions of years, thousands of kilometres of motion, or more likely both of these and much more, to explain a world that appears superficially unchanging. The concepts of deep time and great distance, and the need to think in three dimensions and often in four, seem familiar to us, although I still question whether any of us *truly* comprehend the immensity of geological time. But for those who

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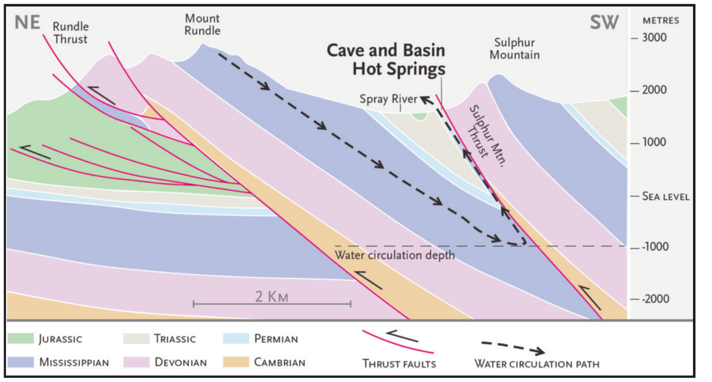
encounter such ideas for perhaps the first time, making links between such ideas and what is observed in nature is a leap that often defeats understanding. On top of this, like all sciences, geology has its own language, which is sometimes impenetrable to geologists themselves, let alone nonspecialists. To visualize geology in any given place will always require some stratigraphic nomenclature and the basics of the geological time scale. The language of geoscience is itself sometimes a moving target on a time scale measured in decades rather than by millennia.

To accommodate such diversity of readership, a good geoscience guidebook needs a glossary and some clear explanation of concepts. *Rocks, Ridges, and Rivers* adopts the approach of many such efforts by placing the glossary towards the end of the book, on the reasonable assumption that not all readers will need to consult it. As I read through the text and admired its illustrations, I purposely checked for definitions and explanations of familiar technical terms, and was happy to find that almost all were accessible in the glossary and well explained in simple language with cross-references. The subdivision of the glossary into an initial section for technical terms and then a second index to the principal stratigraphic units is also a good idea, which will certainly help the reader – even experienced geologists are likely to need the latter. There is a 'quick reference chart' for the stratigraphy that also illustrates lateral facies transitions and the idea of time-equivalence between some of the formations. The placement of this chart on the inside front cover, with a complementary summary of the geological time scale on the inside back cover, is ideal for easy reference. There is no doubt that understanding a book about geology can present challenges for a nonspecialist (and sometimes for other geologists!) but my judgement is that the approach used here serves well for a wide range of readers.



Schematic cross-section showing the area around the Banff Hot Springs and illustrating the processes involved in their generation (from Leckie 2017, p. 71; after Grasby et al. 2003 and Price 1970).

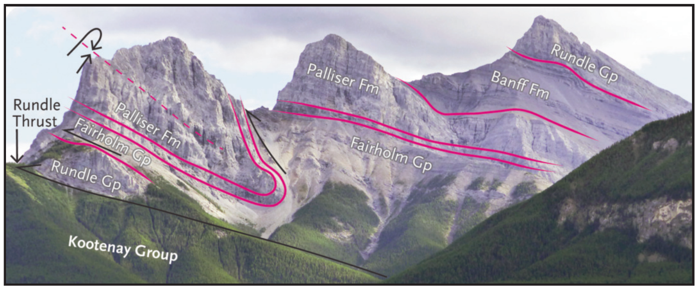
The organizational structure of the book clearly was given much thought by the author, and it also helps those without specialist knowledge. The first chapter gives some necessary logistical information and obligatory safety advice, and then moves to a concise but clearly written account of the regional geology and tectonics of the Canadian Rockies. I am no expert on Cordilleran geology and I found Dale's treatment to be comprehensive and informative, without any 'information overload.' I am sure that his review involves some skilful simplification of contrasting opinions, but this is exactly what is needed in this context, and the book's references are there for those who need more. This skilful first chapter places the individual excursions that follow within a wider context, and also previews them in many respects, but avoids burying the reader in a landslide of formation names. There is also an excellent 'trip planner' chart which gives vital information about the stops within each excursion, which trips are associated with essential or optional hiking excursions, and the distances and other constraints involved. Readers interested in gently stretching their legs with short strolls or acquiring blisters on longer treks will quickly know which of the subsequent sections best meets their needs. The chart is linked conveniently to a summary map of the excursions on preceding pages, with a consistent colour coding to easily locate the areas of greatest interest or proximity.

There are eight *Geological Experiences* in the main body of this guide, which cover a route from Calgary to the area around Jasper, including parts of the three main National Parks of the Canadian Rockies – Banff, Yoho, and Jasper. I have not added up the total distances involved along the Trans-Canada Highway and several other highways in Alberta and British Columbia, but to complete the entire route would certainly involve several days and several hundred kilometres. The route begins in the Banff area, goes westward past Lake Louise, and then over the continental divide to the area around Field in British Columbia, home of Yoho National Park and the famous Burgess Shale. From there, it proceeds northwest along the spine of the Rockies, following the Icefields Parkway to Jasper, and closes with sections covering the area of Jasper townsite, the Maligne River area, and part of Jasper National Park. These individual experiences include between four and eleven specific geological localities, which vary widely in their nature. Roadside outcrops are in a minority for obvious safety reasons, and many such stops are viewpoints, for equally obvious reasons – this is an area where large-scale geology can best be appreciated from a distance. The mountain vistas are helpfully illustrated with annotated photos and diagrams. Indeed, as discussed below, the wealth of illustrative material is a major strength of this book. The longest and most complex section of the book is the one concerned with the Icefields Parkway region. Some stops involve hikes, either to access the sites or viewpoints, or to illustrate features on a larger scale than individual outcrops can ever do. The hikes are also scenic excursions that will provide outdoor experiences that go well beyond geology. Readers with knowledge will probably expect that stratigraphy and structure – notably thrust tectonics – would form the technical core of any book about the Canadian Rockies, but this is not entirely the case. Many stops also incorporate information on geomorphology and glacial landforms, and some have a distinct historical aspect, as in the case of Banff Hot Springs. Some attention is also paid to examples of early mining, and to the wider relevance of geology to petroleum resources. I applaud the effort to convey the economic importance of geoscience, even if it isn't a primary goal for such a book.

Two aspects of the *Geological Experiences* merit special mention. The first is a sensible hierarchy of stop locations – each core excursion is a progression of sites along or very close to the highway corridors, for which access hikes are easy and brief. But alongside this core are optional side trips, labelled 'nearby and interesting,' which provide diversions for those who seek longer hikes, or have a specific interest in a given topic. This arrangement is ideal for planning a mixture of activities, especially in conjunction with the summary table and maps in the first part of the book. The second feature that I admired was the inclusion of specific sections containing more detailed scientific information on topics of particular interest. These are built into the more general descriptions of excursions, but they amplify concepts and information introduced in the first part of the book. I found the treatment of the legendary Burgess Shale fauna and their scientific importance to be very useful and informative. These are not really 'sidebars' in the conventional sense of the word, as they are not separated from the main text, but they play the same role in conveying details that will be important to those with a geoscience background. Other sections of this nature elaborate on topics ranging from the intense colours of mountain lakes to an explanation of hot springs in the Banff area.

Geoscience really is a visual topic, and good graphics and thoughtful graphic design are to me the essence of any book that emphasizes field geology. Conversely, poor graphics are the downfall of many a paper, as those of us in the editorial world know only too well. *Rocks, Ridges, and Rivers* truly excels in the area of graphical illustration, and I think it provides a good model for this aspect of guidebooks. The maps and illustrative sections are all coloured, and they are clear in construction and easily legible without excessive detail. Their format is consistent and their captions are informative. The temptation to simply reuse existing material designed for more specialized purposes without proper simplification was avoided. In fact, the book had a dedicated designer, Sergio Gaytán, who richly deserves the short biographical note at the close of the book. Authors of scientific papers – or at least some of them – could really benefit from looking at some of the figures and other material in this book as examples. To help encourage this, a few examples are included as part of this review, with the kind permission of Dale and his publishers.

The book contains many excellent photographs, most of which come from the author. Given that many stops are mountain vistas, these are not only eye-catching, but very important to convey interpretations and context. Another notable feature of the book is its use of creative artwork in the form of many paintings that showcase the work of Heather Pant. Her colourful and at times slightly other-worldly landscapes augment the traditional photos, and are to be admired in their own right. There are many shared possibilities between geologists and artists, as both produce interpretative works that may not be true in scale or realistic in depiction, but which emphasize important things and leave a lasting impression. For the appreciation of readers and to recognize her great talent, one of Heather's images is also included as part of this review.



The Three Sisters, part of the South Banff Range, Canadian Rockies, annotated to show a typical combination of stratigraphy and structure (from Leckie 2017, p. 51).

"*Three Sisters Resplendence*", acrylic on canvas, 15 by 30 inches. Painted by Heather Pant and reproduced with her kind permission (from Leckie 2017, p. 39). For more examples of the artist's work, visit *www.heatherpant.com*.

Overall, *Rocks, Ridges, and Rivers* is a first-class guidebook that is skilfully designed for a diverse audience, which showcases up-to-date scientific data in an attractive and readable manner. The illustrations alone provide much enjoyment and also clear and useful information that complements the well-written text. This is a first-class effort of which the author and publishers should be proud, and I sincerely hope that Dale and his collaborators might soon apply their skills to other areas of Canada.

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