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ABSTRACT

The Geo-mapping for Energy and Minerals (GEM) Program provided an opportunity to update the state of bedrock geological mapping for nearly 92,000 km^2 of the northern mainland Northwest Territories, in a swath extending from the Colville Hills and Great Bear Plain, westward to the eastern and northern Mackenzie Mountains. Mapping focused initially on the region around the long-producing Norman Wells oil field, and subsequently extended north to the Colville Hills, a region of known oil and gas potential, and west into the Mackenzie Mountains, an area with numerous mineral showings. The result will be 24 new bedrock geology maps at 1:100 000 or 1:250 000 scales, published in GIS-enabled format as Canadian Geoscience Maps (CGMs). The mapping effort made extensive use of archival GSC data, notably those preserved following Operation Norman (1968-1970), as well as public-domain industry data. Maps incorporate numerous stratigraphic revisions that post-date the Operation Norman era, including innovations from the GEM program that affect a number of Tonian, Ediacaran, Cambrian, and Ordovician units. The present report is an overview of the mapping efforts, including summaries of stratigraphic revisions, as well as a preliminary treatment of the structural geology of the study area. Also included is a brief summary of subsurface studies. Following the conclusion of the GEM program, modern, GIS-enabled bedrock maps will be available for a swath of territory extending from the edge of the Selwyn Basin, near the Yukon border, to the Brock Inlier in the northeastern mainland Northwest Territories.

INTRODUCTION

This report summarizes bedrock mapping efforts and related stratigraphic studies that focused on the northwestern Northwest Territories between latitudes 65° and 68° N and longitudes 124° and 132° W (Figure 1) during the Geo-mapping for Energy and Minerals Program (GEM). Sedimentary rocks underlie the largest part of the mainland Northwest Territories north of 64°, and the region is rich in potential geological resources (Figure 2). In the Mackenzie River valley, the region around Norman Wells has been a site of active petroleum exploration and production for a century, and petroleum exploration since the 1970s has identified oil and gas resources in the Colville Hills and easternmost Mackenzie Mountains (see review in Hannigan et al., 2011). To the west, in the Mackenzie and Selwyn Mountains, there are more than 300 documented mineral deposits and prospects (Ootes et al., 2011; see also Ozyer, 2012). Nonetheless, in the early 2000s the state of published bedrock geology maps for the region was highly uneven. Although some areas were represented by professionally drafted, colour maps published as part of the "A" series of the Geological Survey of Canada (GSC), effectively all published maps for the region were based upon GSC reconnaissance operations carried out in the 1960s and early 1970s. Notably, GSC maps for the economically important region around Norman Wells were available only as hand-lettered manuscript maps, published as Open File reports, and GSC maps for the Colville Hills exploration region were black-and-white preliminary maps. Equally notable was the lack of a publicly available, quantitative, probabilistic oil and gas resource assessment for the region (indeed, for the entire mainland Northwest Territories).

In 2008, the federal government announced funding for the GEM Program. Following renewal in 2013, the program is set to end in 2020. The northern mainland Northwest Territories was a focus of GSC studies during both phases of GEM, with an emphasis on filling knowledge gaps. During the first phase (2008-2013), the Mackenzie Delta and Corridor Project (MADACOR) dealt with energy resources. The project was highly interdisciplinary, with research efforts grouped in three major activities. First, studies carried out in the Beaufort-Mackenzie Delta region (Dixon et al., 2008) brought to a close a long-standing GSC-industry research consortium for that region, with a focus on biostratigraphy, geochemistry, and quantitative basin analysis including thermal history (e.g., Issler et al., 2009; 2011, 2012); this work is not covered in the present report. Second, a quantitative, probabilistic oil and gas resource assessment was completed for the mainland Northwest Territories. This work was presented by Hannigan et al. (2011; see also Hannigan, 2012, 2013). Third, a major field component focused on preparing new bedrock geology maps for the four 1:250,000 scale map sheets around the Norman Wells oil field, including supporting stratigraphic work (Figure 3). Results of this work are summarized below.

During the second phase of GEM (2013-2020), the focus of bedrock mapping shifted (Figure 3), first to the Colville Hills (2015 field season; Fallas et al., 2015c) and then to the northern Mackenzie Mountains (2016, 2017, and 2018 field seasons; Fallas et al., 2016; MacNaughton et al., 2017, 2018). As in the first phase, supporting stratigraphic studies were conducted, commonly in tandem with the bedrock mapping. Many of these studies dealt with Neoproterozoic-to-Silurian stratigraphic evolution and, together with the bedrock mapping, constituted the "Shield-to-Selwyn geo-transect" (hereafter Shield-to-Selwyn) activity, which sought to update the structural geology and the pre-Devonian stratigraphic framework across the mainland Northwest Territories. These studies are summarized below. Shield-to-Selwyn also tied into GEM bedrock mapping and stratigraphic studies around Brock Inlier (Figure 3), to the northeast (Rainbird et al., 2015a, b; Greenman and Rainbird, 2018). During the second phase of GEM, Devonian studies were carried out as separate activities, albeit with field support from the "Shield-to-Selwyn" effort. Reports on these efforts will

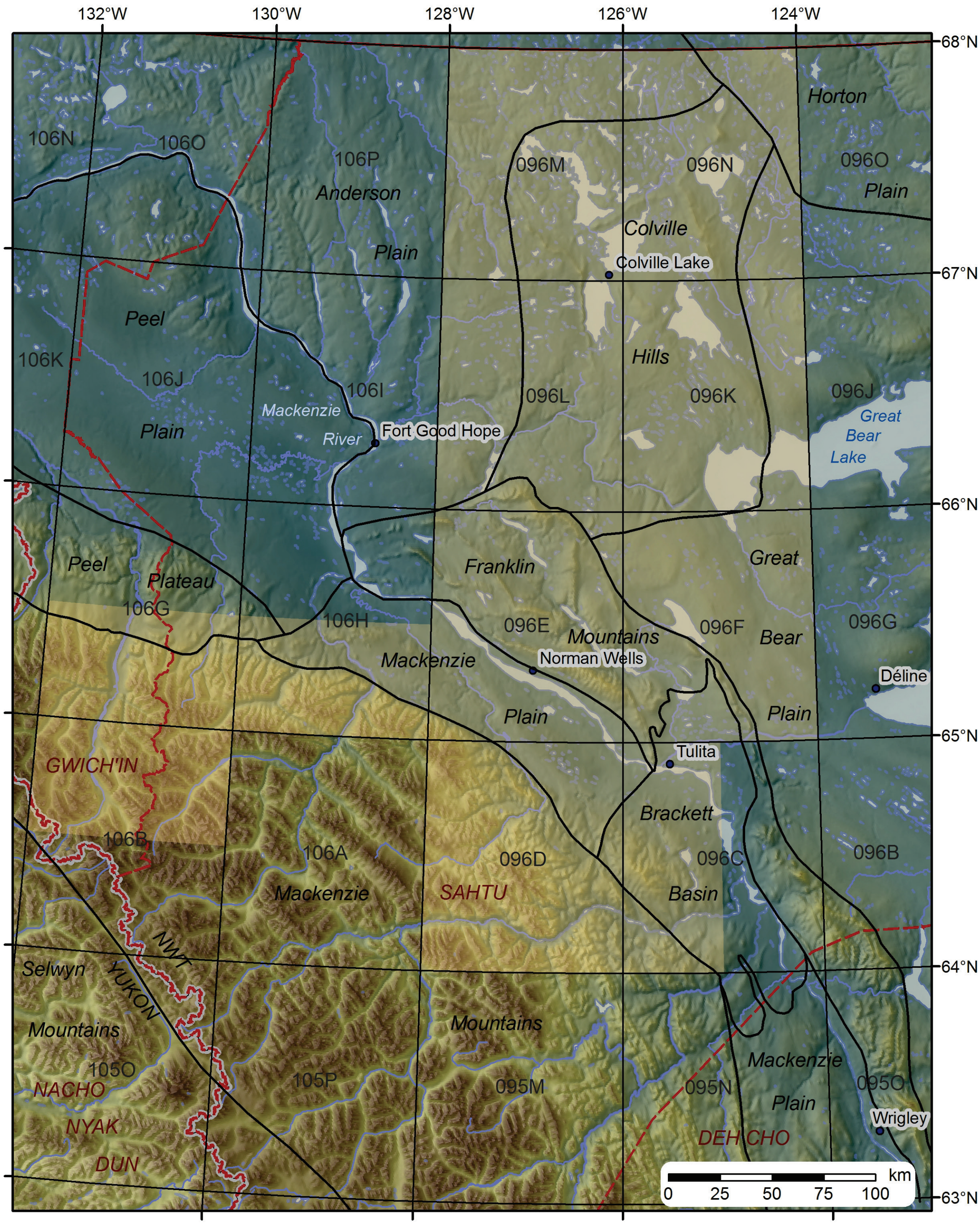

Figure 1. Digital elevation model map of GEM Mackenzie study area (yellow tint) showing physiographic boundaries (in black) and indigenous land-claim settlement area boundaries (in red). Communities are labelled.

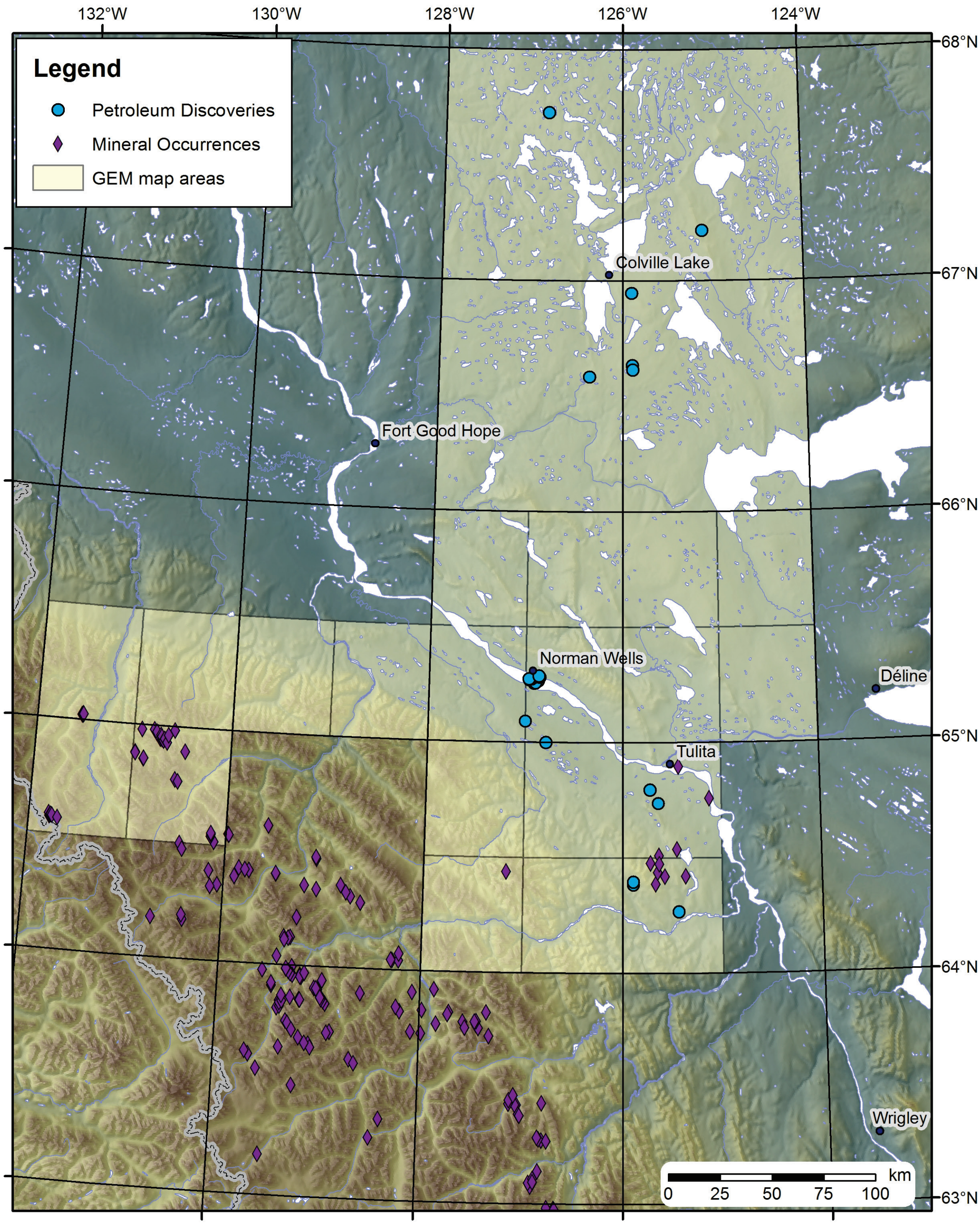

Figure 2. *Mineral and petroleum resources in study area and adjacent regions. Petroleum production is limited to the oil field at Norman Wells, and none of the mineral occurrences shown are currently under production.*

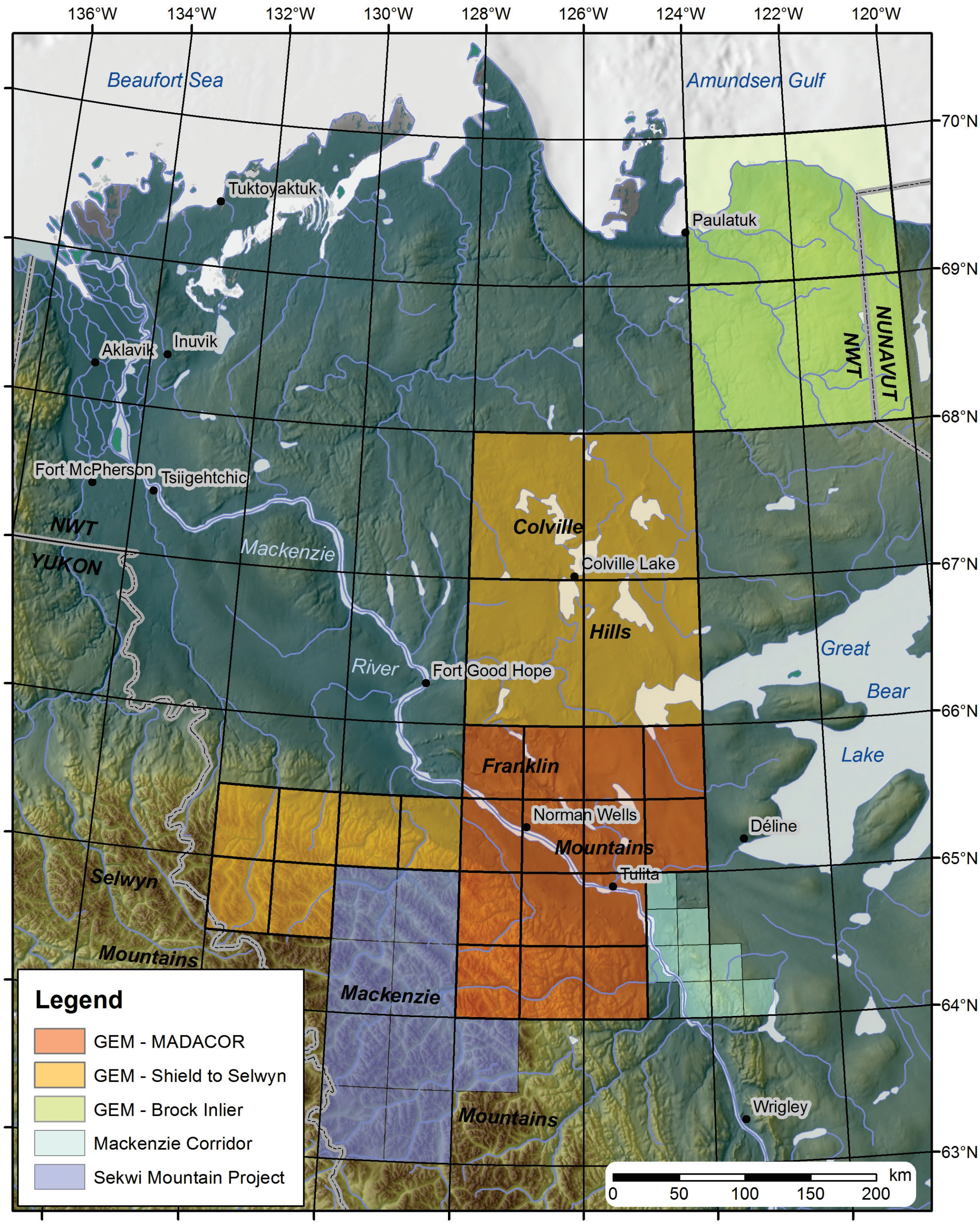

Figure 3. *GSC mapping activity in the sedimentary basins of mainland Northwest Territories (excluding the Richardson Mountains) since 2000. Mapping in the GEM - MADACOR area was conducted from 2009 to 2012; mapping in the GEM - Shield to Selwyn and GEM - Brock Inlier areas was conducted from 2015 to 2018. Mackenzie Corridor mapping was conducted in 2003 and 2004. Sekwi Mountain Project mapping (in conjunction with the Northwest Territories Geological Survey) was conducted from 2006 to 2008.*

be published separately, dealing with sedimentology and stratigraphy (P.B. Kabanov, work in progress) and conodont biostratigraphy (S.A. Gouwy, work in progress).

Both phases of GEM in the Mackenzie region involved collaborative studies using detrital zircon geochronology to elucidate sediment provenance of Proterozoic to Cretaceous strata (Lemieux et al., 2011; Hadlari et al., 2012, 2014, 2015; Rainbird et al., 2017). Also during both phases of GEM, aspects of the work were done in partnership with the Northwest Territories Geological Survey (NTGS; previously Northwest Territories Geoscience Office). This collaboration included reciprocal advice, in-kind support for studies of hydrocarbon systems (e.g., Pyle and Gal, 2011, 2012a, b; Pyle et al., 2011), and joint participation in fieldwork (e.g., Gal et al., 2010; MacNaughton et al., 2017). These aspects of the projects are mentioned for completeness but are not discussed in detail in the present report.

The balance of the report is in six parts. First, a summary of previous bedrock mapping efforts in the region is presented. Second, the approach adopted for bedrock mapping in the region during the two phases of the GEM Program is summarized. The third section discusses various revisions to the region's stratigraphy in the past four decades, with a particular focus on GEM Program studies and their recognition during bedrock mapping. The fourth part of the paper briefly summarizes subsurface stratigraphic studies in Mackenzie Plain and Great Bear Plain. The fifth section of the paper summarizes the structural geology of the study area, including key revisions arising from GEM bedrock mapping. Finally, the sixth section provides a summary of research highlights. Because key aspects of these studies are ongoing as of the time of writing (mid-2019), this report is a summary of work to date, rather than a detailed synthesis of scientific observations.

This report aims to be a source for those seeking recent information on the geology and earth resources of the study region. Such parties also can consult several other publications prepared during GEM. For an overview of Cambrian to Devonian geology east of the Mackenzie Mountains, see Fallas et al. (in press, a). For a similar overview of Cretaceous and younger strata, see Fallas et al. (in press, b). Both of these include summaries of stratigraphy, structure, tectonics, and petroleum geology. For a detailed treatment of petroleum potential in the mainland Northwest Territories, see Hannigan et al. (2011). Morrow (2012; see also 2018) reviews the Devonian of the same region. For the Mackenzie Mountains, the most thorough pre-GEM geological overview is the volume by Martel et al. (2011); also see Ozyer (2012) on the mineral potential of that area.

BACKGROUND TO GEM PROGRAM MAPPING EFFORTS

Early geographical and geological investigations in the project area have been summarized by Hume (1954) and by Aitken et al. (1973). The successful drilling of the Norman Wells oil field in 1920 was the stimulus for an early phase of GSC field studies in the Mackenzie River valley, which established key elements of the region's lower Paleozoic stratigraphy (e.g., Williams, 1922, 1923). The Second World War, during which the Norman Wells oil field assumed strategic importance, corresponded with a further period of intense geological study as part of the Canol Project. The results of the Canol Project contributed importantly to the broad strokes of the Mackenzie region's upper Paleozoic and younger stratigraphic framework (Hume and Link, 1945; Hume, 1954), but left numerous unanswered questions regarding relationships between Proterozoic and lower Paleozoic formations (Aitken et al., 1973).

At the beginning of GEM, most of the published bedrock geology maps for Mackenzie Plain, the northern interior plains, the Franklin Mountains, and the Mackenzie Mountains (Figure 4A) were based on helicoptersupported, reconnaissance-scale mapping programs undertaken by the Geological Survey of Canada in the 1960s and early 1970s. Much of this area had been mapped between 1968-1970 during Operation Norman, which extended from a southern limit at 64° N, northward to the shore of the Arctic Ocean, and from a western limit at 132° W, eastward to the contact between Paleozoic strata and underlying Precambrian rocks of the Canadian Shield (Cook and Aitken, 1971; Aitken et al., 1973). It encompassed parts of the Interior Plains, Franklin Mountains, Mackenzie Plain (including the oil field at Norman Wells), and the northern and eastern Mackenzie Mountains. Parts of the Mackenzie Mountains to the west and south were mapped mainly during the 1960s as part of three other GSC projects: Operation Selwyn (Blusson, 1967, 1968, 1971; Gabrielse, 1968); Operation Stewart (Blusson and Tempelman-Kluit, 1970; Blusson, 1974); and Operation Nahanni (Gabrielse et al., 1973a). Operation Nahanni was of particular importance, inasmuch as it established much of the lithostratigraphy currently applied in the Mackenzie Mountains (Gabrielse et al., 1973a, b). Operation Norman also refined Proterozoic and lower Paleozoic lithostratigraphy in the Mackenzie Mountains and points to the east (e.g., Aitken et al., 1973; Norford and Macqueen, 1975), and laid the groundwork for the study by Yorath and Cook (1981) that established much of the Mesozoic stratigraphy for the region. The years following Operation Norman saw more limited bedrock mapping efforts by GSC in the Mackenzie and Selwyn Mountains (e.g., Gordey and Anderson, 1993; Cecile, 2000).

These mapping programs, taken together, produced a set of non-digital, reconnaissance-scale, printed geology maps for the eastern Cordillera and Interior Plains of the Mackenzie region of the Northwest Territories north of 63°N. Maps were published as uncoloured Preliminary Maps and Open Files (the latter generally being hand-drafted and hand-lettered), or coloured GSC A-series maps (Figure 4A). Covering the largest part of the area were maps produced by Operation Norman.

In the post-Operation Norman era, most GSC work in the Mackenzie Mountains dealt with stratigraphic problems. Notable progress included studies on the Proterozoic (e.g., Aitken, 1981, 1989, 1991; Aitken et al., 1978; Eisbacher, 1978, 1981; Jefferson and Parrish, 1989; Narbonne and Aitken, 1990, 1995), Cambrian (e.g., Fritz, 1972, 1976, 1978, 1979, 1982; Fritz et al., 1983), and the platformal Devonian succession (Morrow, 1991). To the west, Cecile (1982) clarified the lower Paleozoic lithostratigraphy of the more distal Selwyn Basin succession. In Mackenzie Plain and adjacent areas, surface and subsurface studies refined parts of the Paleozoic stratigraphy (e.g., Tassonyi, 1969; Pugh, 1983; Hamblin, 1990; Meijer Drees, 1993; Dixon and Stasiuk, 1998). Relevant chapters in the Decade of North American Geology volume on the Canadian Cordillera (Gabrielse and Yorath, 1991) provide an important summary of the state of knowledge for the region as of the late 1980s – early 1990s.

In 2005, NTGS began a major bedrock mapping initiative in the Mackenzie Mountains, in partnership with GSC. The Sekwi Mountain Project (Martel et al., 2011) conducted field seasons in 2005, 2006, 2007, and 2008, updating the bedrock geology of NTS 105P, 106A, and the northwest part of 95M. Resulting maps (Figure 3, Figure 4B) were published in 2012, with an accompanying GIS data release (Gordey et al., 2012). These marked the first effort in the Mackenzie Mountains to produce digital bedrock maps with GIS data that are more easily integrated with other research. At roughly the same time, Cook et al. (2010) produced GIS-enabled maps that updated Operation Norman maps for the McConnell Range (Franklin Mountains) in the eastern half of NTS 96C (Figure 4B); this effort was part of GSC's "Mackenzie Corridor Project" (Secure Canadian Energy Supply Program). On the same timeframe, NTGS undertook a major study of stratigraphy and petroleum potential in the Peel Plateau and Plain region (Pyle and Jones, 2009).

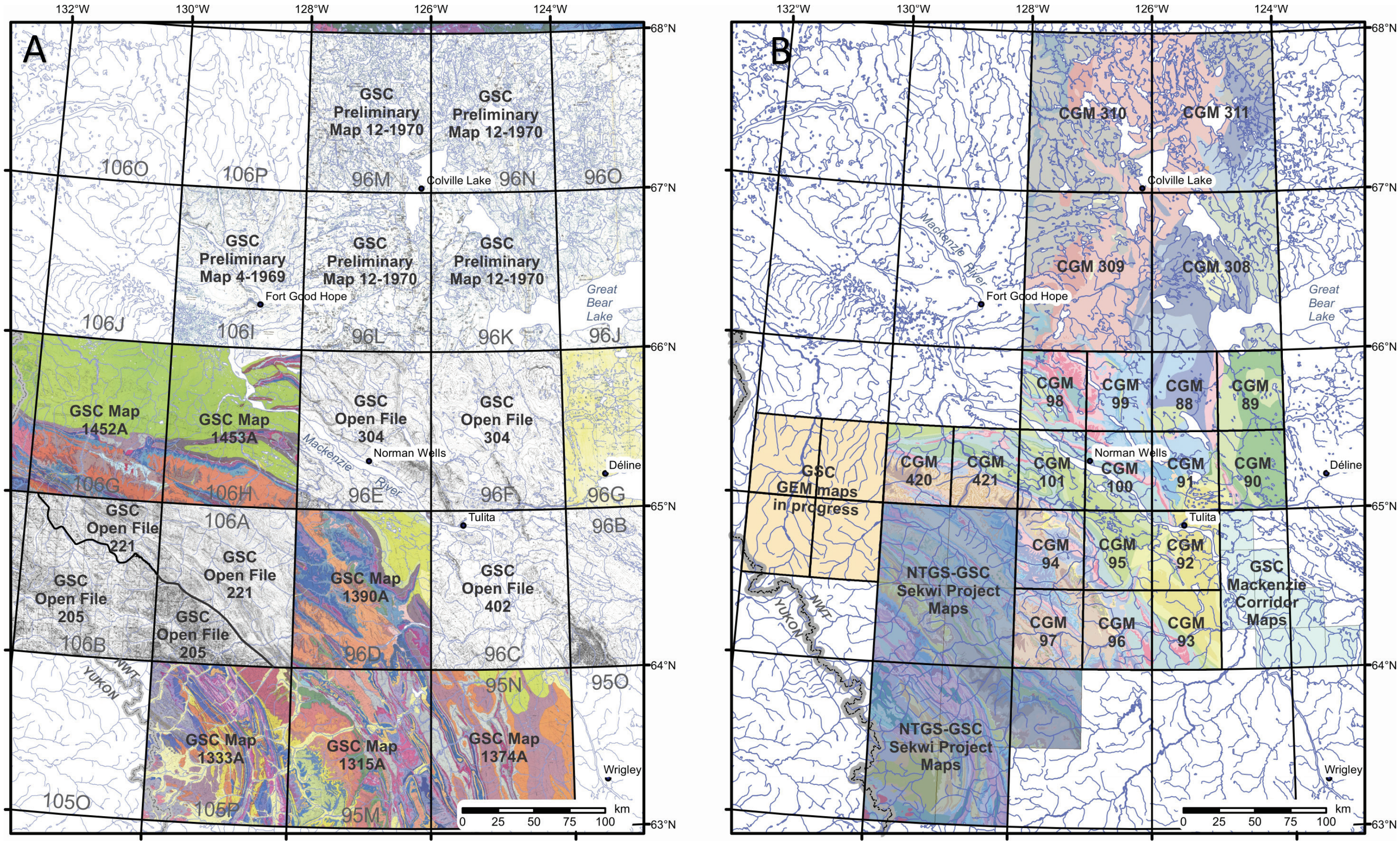

Figure 4. *Comparison of state of bedrock mapping in Mackenzie region, before and after 2008. A. Hardcopy maps available in the Mackenzie region prior to 2008. National Topographic System (NTS) map numbers shown in dark grey. Preliminary Map 4-1969: Cook and Aitken (1969); Preliminary Map 12-1970: Aitken and Cook (1970); Open File 205: Blusson (1974); Open File 221: Aitken and Cook (1974b); Open File 304: Aitken and Cook (1976); Open File 402: Cook and Aitken (1977); Map 1315A: Gabrielse et al. (1973c); Map 1333A: Blusson (1972); Map 1374A: Douglas (1974); Map 1390A: Aitken et al. (1974); Map 1452A: Aitken and Cook (1979a); Map 1453A: Aitken and Cook (1979b). B. GIS-enabled maps published since 2008; Sekwi Project (2005-2008) maps shown in dark blue (Gordey et al., 2012), and Mackenzie Corridor Project (2005-2008) maps shown in light blue (Cook et al., 2010). GEM program maps CGM 88: Fallas (2013a); CGM 89: Fallas and MacLean (2013a); CGM 90: Fallas (2013b); CGM 91: Fallas et al., (2013a); CGM 92: Fallas et al. (2013b); CGM 93: Fallas and MacLean (2013b); CGM 94: Fallas and MacNaughton (2014a); CGM 95: Fallas et al. (2013c); CGM 96: Fallas and MacNaughton (2014b); CGM 97: Fallas and MacNaughton (2014c); CGM 98: Fallas (2013c); CGM 99: Fallas (2013d); CGM 100: Fallas and MacNaughton (2013); CGM 101: Fallas et al., (2013d); CGM 308: Fallas (2017a); CGM 309: Fallas (2017b); CGM 310: Fallas (2017c); CGM 311: Fallas (2017d).*

Following the Sekwi Mountain Project, the GEM program targeted adjacent maps (NTS map areas 96C, 96D, 96E, and 96F) for updated mapping, stratigraphic work, and GIS-enabled map production (Figure 3; Figure 4B); these areas straddle the petroleum exploration region of the central Mackenzie Valley. As part of the MADACOR Project, reconnaissance fieldwork in 2009 was followed by month-long field seasons in 2010 and 2011, and by a short wrap-up season in 2012. Fieldwork was conducted in the eastern Mackenzie Mountains, Mackenzie Plain, Franklin Mountains, and adjacent Great Bear Plain (Fallas et al., 2012). During the second phase of GEM, the Shield-to-Selwyn Activity expanded this work (Figure 3; Figure 4B), with an annual report on activities following each field season. During the summer of 2015, one month was spent in the Colville Hills (NTS map areas 96K, 96L, 96M, 96N; Fallas et al., 2015c). Three weeks were spent mapping in the northern Mackenzie Mountains during the summer of 2016 (southern halves of NTS map areas 106G, and 106H; Fallas et al., 2016), and logistical support was provided for studies on Devonian stratigraphy (Kabanov et al., 2016). In 2017, one month was spent around the headwaters of the Arctic Red and Orthogonal rivers (northern half of NTS map area 106B; MacNaughton et al., 2017), with logistical support also being provided for work on Devonian biostratigraphy (Gouwy et al., 2017b). This area saw a second one-month field season during July, 2018, following by a week of reconnaissance in NTS 95M and 105P (MacNaughton et al., 2018).

As of this writing (mid-2019), GIS-enabled bedrock geology maps have been published for the Mackenzie Plain and adjacent mountain belts and for the Colville Hills; maps for the northern Mackenzie Mountains are in press or in preparation (Figure 4B). The aim at the conclusion of GEM is to have modern, GIS-enabled bedrock maps from the edge of Selwyn Basin, near the Yukon border, to the Brock Inlier in the northeast. A continuous swath of updated digital maps facilitates revising stratigraphic nomenclature, stratigraphic relationships, and structural relationships, as well as improving our ability to assess the context of energy and mineral resources within the sedimentary basin (Figure 2).

MAPPING APPROACH

To improve efficiency in covering the 91,363 km^2 of the MADACOR Project and Shield-to-Selwyn Activity, the projects made extensive use of historical datasets. Geological observations from Operation Norman (985 mapping stations; 147 measured sections), subsequent published stratigraphic measured section data (416), and archived observations from the petroleum and mineral industries (1677 stations) have been digitized where possible and integrated with observations made during the GEM program (2751 mapping stations, 84 measured sections) to inform new map interpretations (Figure 5). Fallas et al. (2015a) described the techniques used for this data capture effort, with particular reference to Operation Norman mapping data and archival stratigraphic sections. For examples of public-domain industry data being used during the program, see Finley et al. (2017) and MacNaughton and Fallas (in press). For a major release of unpublished GSC archival data from measured stratigraphic sections, see Aitken et al. (2011). Also see Fallas et al. (2015b) for a bibliography of published measured stratigraphic sections in the project region and adjacent map areas, including some sections from the first part of the GEM Program. Once assembled in a geodatabase, the historical data could be cross-referenced and analysed for gaps, inconsistencies, anomalies, or problem areas where additional field observations would be helpful (Fallas et al., 2015a). These steps helped prioritize locations for field visits.

As with a majority of projects in the GEM program, GIS techniques extended to digital data collection in the field, allowing for locations that are more accurate, faster integration with historical data, and the ability to check observations against georeferenced satellite imagery or geophysical datasets while in the field. Gravity

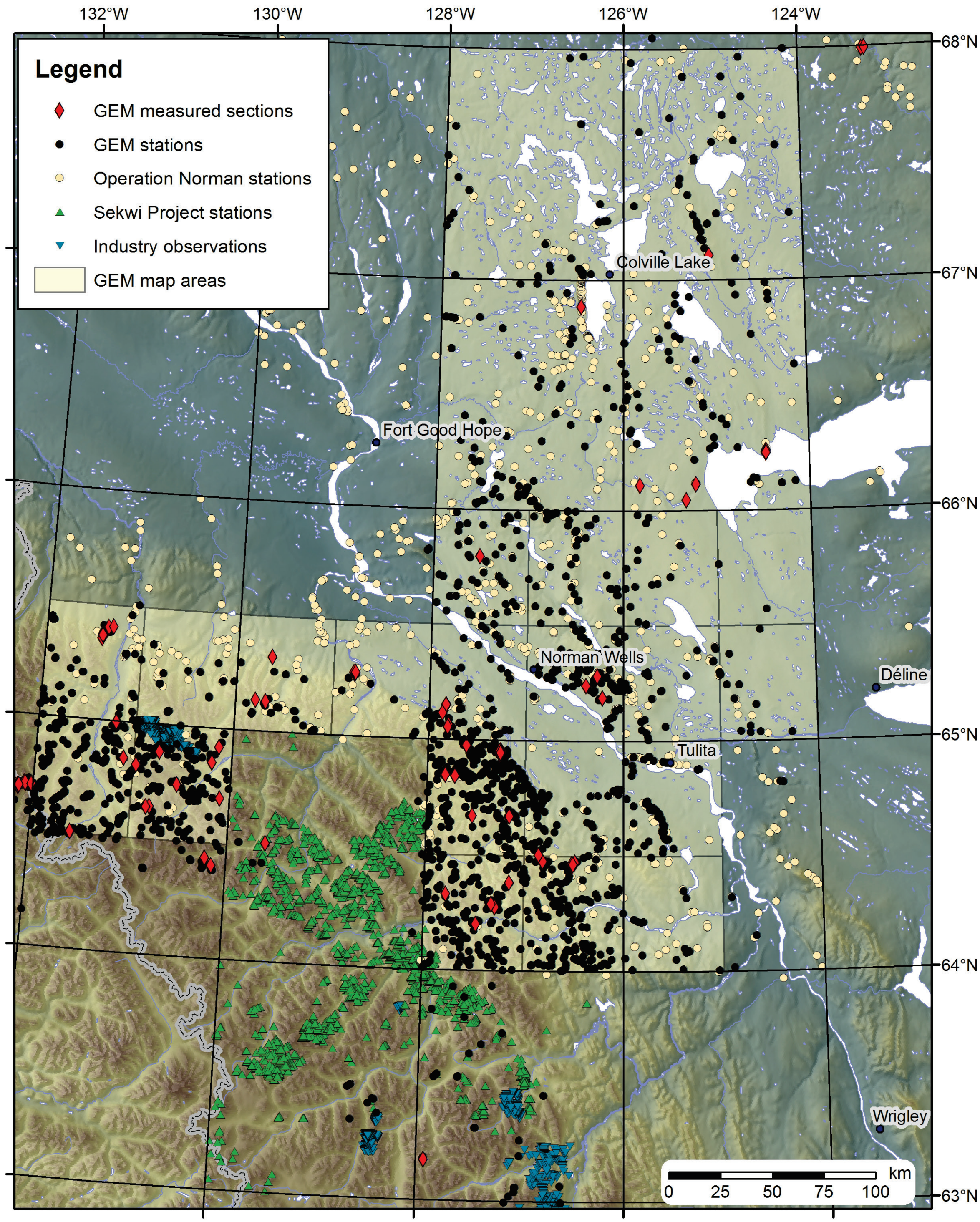

Figure 5. *Distribution of bedrock geology observations from GEM program and other sources. Operation Norman observations were digitized during the GEM program from original field notes (1968-1970); Sekwi Project observations were released as GIS data by Gordey et al. (2012); industry observations were digitized during the GEM program from archived reports.*

and aeromagnetic anomaly data acquired in the Mackenzie region during the GEM program (Dumont, 2009; Kiss, 2018) were incorporated as they became available. With the availability in the field of new observations from each contributing scientist, map interpretation and analysis could take place concurrently and inform ongoing fieldwork. New map interpretations that consider all available evidence were facilitated by combining all these data in GIS software.

STRATIGRAPHIC REVISIONS

Maps generated during MADACOR and the Shield-to-Selwyn activity reflect numerous post-Operation Norman revisions to stratigraphic nomenclature, and in some areas have added stratigraphic detail in comparison to the pre-GEM maps. Changes to Operation Norman-era nomenclature affect Neoproterozoic to Cretaceous strata, with implications throughout the study area, and are summarized in two figures. Figure 6 covers Neoproterozoic units across the study area, as well as Ediacaran to Lower Cambrian units in the central and western Mackenzie Mountains. Figure 7 deals with Cambrian to Paleocene-Eocene stratigraphy across the study region. The following paragraphs summarize changes in stratigraphic nomenclature, as well as key stratigraphic work carried out in the project areas as part of GEM. For reference, Figure 8 illustrates changes in stratigraphy from region to region across the study, including their relationship to major tectonic elements.

The oldest map units in the study area belong to the Neoproterozoic (Tonian) Mackenzie Mountains Supergroup, which was named by Young et al. (1979) and widely used by other authors (see Long et al., 2008, for a review), but was not formalized until the GEM Program (Long and Turner, 2012; Turner and Long, 2012). Formalization was supported by the publication of a large number of archival measured stratigraphic sections from the Mackenzie Mountains Supergroup during the first phase of GEM (Aitken et al., 2011). The Tonian age of the Supergroup is bracketed by detrital zircon found in the Katherine Group at 1005 Ma (Leslie, 2009) and the crosscutting Gunbarrel intrusions at 779 Ma (Harlan et al. (2003). Detrital muscovite dating of Tsezotene Formation, Katherine Group, and Little Dal Group, undertaken as part of a student project supported by GEM, recorded youngest grains between 818 Ma and 1005 Ma (Powell and Schneider, 2013), in agreement with previous work.

At the deepest level of exposure of the Mackenzie Mountains Supergroup, a dolostone unit, formerly identified as Map-unit H1 (Aitken et al., 1973), is now known as the Tabasco Formation (Turner and Long, 2012). The overlying shale-dominated Tsezotene Formation is unchanged from its original definition (Gabrielse et al., 1973a, b), though Long and Turner (2012) informally subdivided the unit into a lower ‘grey’ member, and an upper ‘red’ member. These members are identifiable within the Mackenzie Mountains where the Tsezotene Formation is well exposed. In southwest Carcajou Canyon map area (NTS 96D), a locally mappable carbonate interval forms a resistant cliff in the upper third of the formation (Fallas and MacNaughton, 2014c).

Above the Tsezotene Formation, the sandstone-dominated Katherine Group forms the core of many of the large anticlines found in the northeastern Mackenzie Mountains. On Operation Norman maps this group was subdivided into a lower part consisting of sandstone with minor shale-dominated intervals, and an upper part of shale and dolostone overlain by another sandstone interval. Subsequent stratigraphic work by Aitken et al. (1978) documented that the Katherine Group could be subdivided into seven units based on alternating sandstone-dominated and shale-dominated intervals. During the GEM program, Long and Turner (2012) formalized these seven units into formations, which are recognized in the GEM map areas. Significant frost shattering of the sandstone units tends to create very rubbly slopes where underlain by Katherine Group

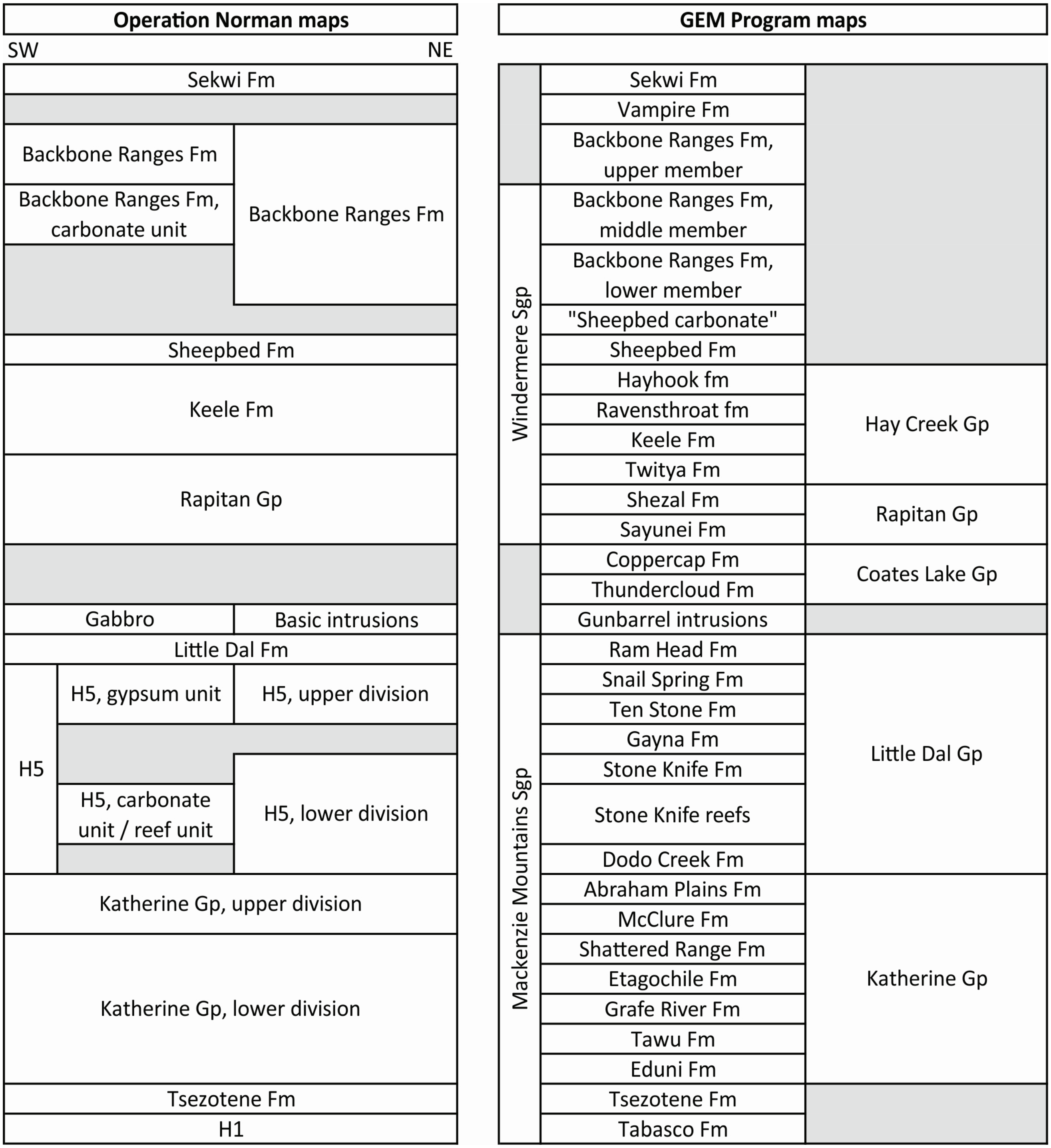

Figure 6. *Comparison of map unit terminology used on Operation Norman (Aitken and Cook, 1970; 1974b; 1976; 1979a, 1979b; Aitken et al., 1974; Cook and Aitken, 1977) and Operation Stewart (Blusson, 1974) maps with the revised terminology used for the GEM program. Diagram covers Neoproterozoic units and Ediacaran to Lower Cambrian units encountered in Mackenzie Mountains. Units postdating Gunbarrel intrusions are only found west of Mackenzie Arch.*

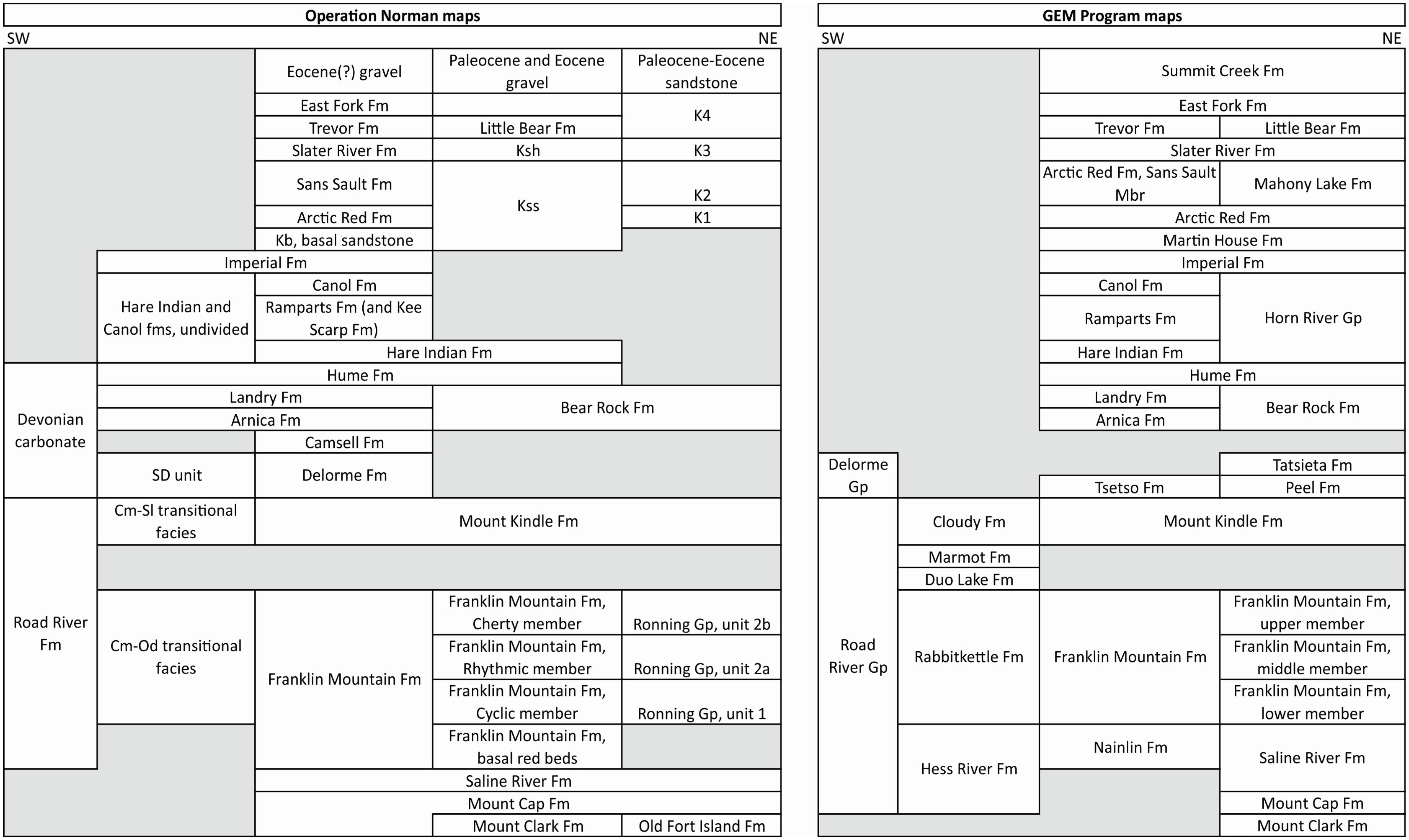

Figure 7. *Comparison of map unit terminology used on Operation Norman (Aitken and Cook, 1970; 1974b; 1976; 1979a, 1979b; Aitken et al., 1974; Cook and Aitken, 1977) and Operation Stewart (Blusson, 1974) maps with the revised terminology used for the GEM program. Diagram covers Lower Cambrian found from eastward edge of Mackenzie Mountains and extending to the east, and Middle Cambrian and younger units across the study region.*

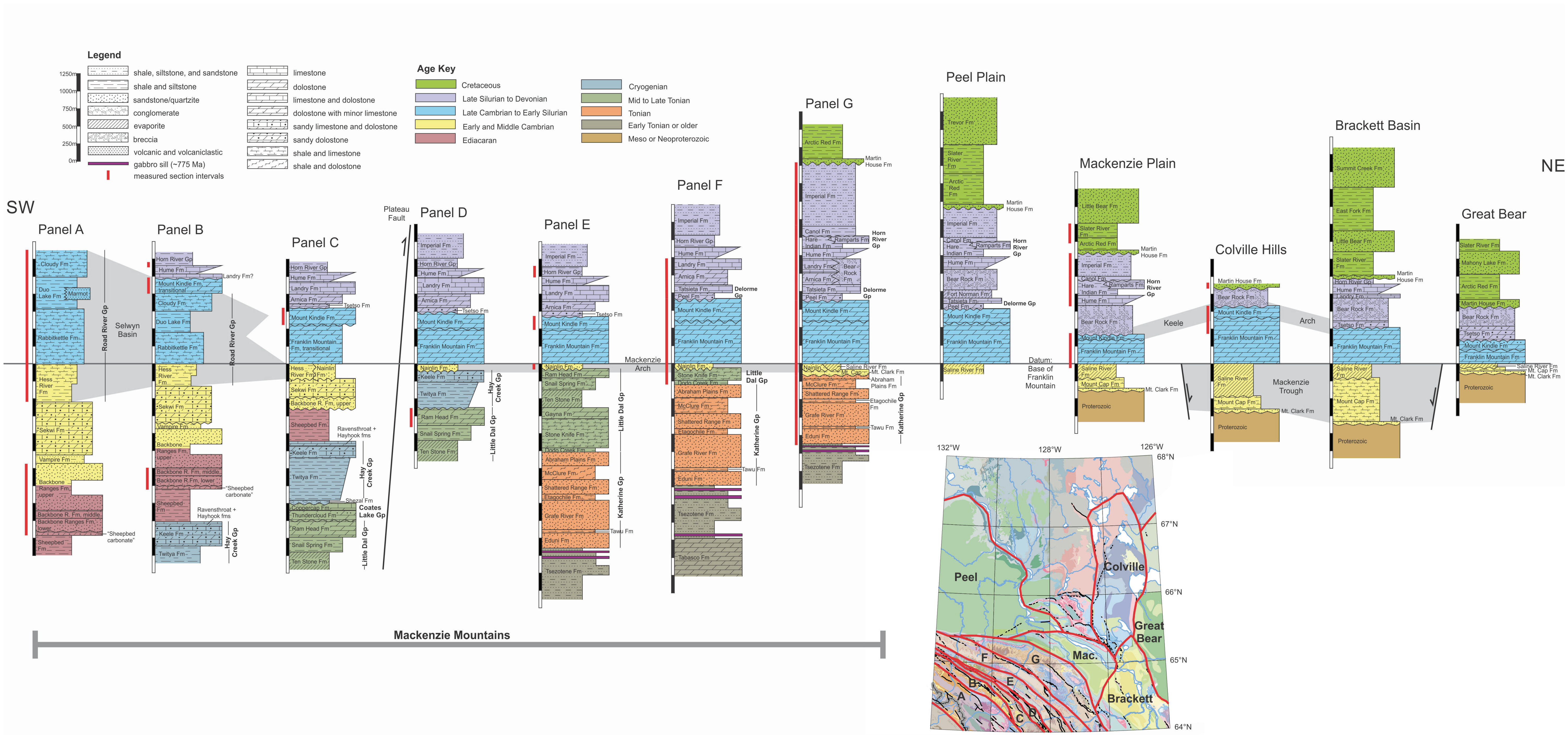

Figure 8. *Chart of regional variations in stratigraphy across the Mackenzie region illustrated by a series of graphic logs, organized by structural domain (indicated on inset map). Panels A through G represent structural panels within the Mackenzie Mountains; remaining columns are identified by physiographic region. Stratigraphic intervals measured in detail during GEM are shown with vertical red bar beside the appropriate column; other stratigraphic thicknesses determined from historical measured sections and field relationships. Lower Paleozoic shale-dominated Selwyn Basin in the southwest part of the study area passes northeastward into carbonate-dominated Mackenzie Platform. Thinning of Cambrian strata across the Mackenzie Arch is visible in panels D through G. Thicker Cambrian succession of the Mackenzie Trough is documented by reflection-seismic data and petroleum exploration wells across the Colville Hills and Brackett Basin (MacLean, 2011b). Keele Arch is illustrated by thinned or absent Mount Kindle Formation in the Mackenzie Plain, Colville Hills and Brackett Basin columns.*

strata, which covers some of the recessive shale-dominated formations. Despite this, efforts made during the GEM program to map out these seven formations (Fallas and MacNaughton, 2014a, b, and c; Fallas, 2019) have helped delineate previously undocumented faults (see below).

The uppermost succession of the Mackenzie Mountains Supergroup is dominated by carbonate, shale and evaporite, formerly assigned to Map-unit H5 or the Little Dal Formation on Operation Norman maps. The relationships between units within this interval are complicated by faulting and erosion beneath the sub-Cambrian unconformity, and the full succession of units was only clarified after Operation Norman (Aitken et al., 1978; Aitken, 1981). This succession is now known as the Little Dal Group and formal formation-level terminology was introduced during the GEM program by Turner and Long (2012), replacing the previous informal subdivisions of Aitken (1981). Maps produced during the GEM program use the new formation names. From GEM mapping activities it is apparent that the former Map-unit H5 was equivalent to Dodo Creek Formation, recessive shale intervals of the Stone Knife Formation, the Ten Stone Formation, and the Snail Spring Formation (Figure 6), whereas the former Little Dal Formation was locally applied to carbonate intervals of the Stone Knife Formation, the Gayna Formation, and the Ram Head Formation.

Mafic igneous rocks, identified as ‘basic intrusions’ on Operation Norman maps, intrude strata of the Mackenzie Mountains Supergroup within the GEM program map areas of the Mackenzie Mountains. These rocks occur as discontinuous sills at various levels within the Tsezotene Formation and as dykes cutting through strata from the Tabasco Formation to the upper Little Dal Group. Geochemical and geochronological studies (Harlan et al., 2003; Sandeman et al., 2014; K. Fallas and S. Kamo, unpublished data) indicate a single suite of intrusions ranging in age from 770 Ma to 782 Ma, assignable to the Gunbarrel mafic magmatic event (Harlan et al., 2003).

Units of the Coates Lake Group, a Neoproterozoic (Tonian) succession that unconformably overlies the Mackenzie Mountains Supergroup, are exposed on either side of the Plateau Fault in a narrow belt known as the Redstone Copper Belt (Jefferson and Ruelle, 1986). These units had not been identified in the study area prior to the GEM program. During the 2017 and 2018 field seasons, two units of the Coates Lake Group, the heterolithic (dolostone, shale, sandstone, conglomerate) Thundercloud and limestone-dominated Coppercap formations, were traced across parts of the Bonnet Plume Lake and Ramparts River map areas (NTS 106B and 106G), extending the known range of these units by approximately 85 km (Figure 9). Some workers have assigned Coates Lake Group to the overlying Windermere Supergroup (e.g., Aitken, 1991; Narbonne and Aitken, 1995), but we have opted to follow Jefferson and Parrish (1989) by excluding it from either of the adjacent supergroups.

At the base of the Neoproterozoic (Cryogenian to Ediacaran) Windermere Supergroup, the Rapitan Group (Cryogenian) originally was subdivided into lower, middle, and upper units (e.g., Gabrielse et al., 1973a, b), a practice followed on various historical maps. Eisbacher (1978) erected the formal names Sayunei Formation (deep-water marine shale and sandstone, commonly maroon, with minor diamictite), Shezal Formation (diamictite), and Twitya Formation (deep-water marine shale and sandstone, locally coarsening upward to sandstone and conglomerate) for the three subdivisions (ascending order). Later workers excluded the Twitya Formation from the Rapitan Group and instead treated it as the basal unit of the overlying Hay Creek Group (Yeo, 1978; Young et al., 1979; Turner et al., 2011). Twitya Formation is recognized in the westernmost GEM

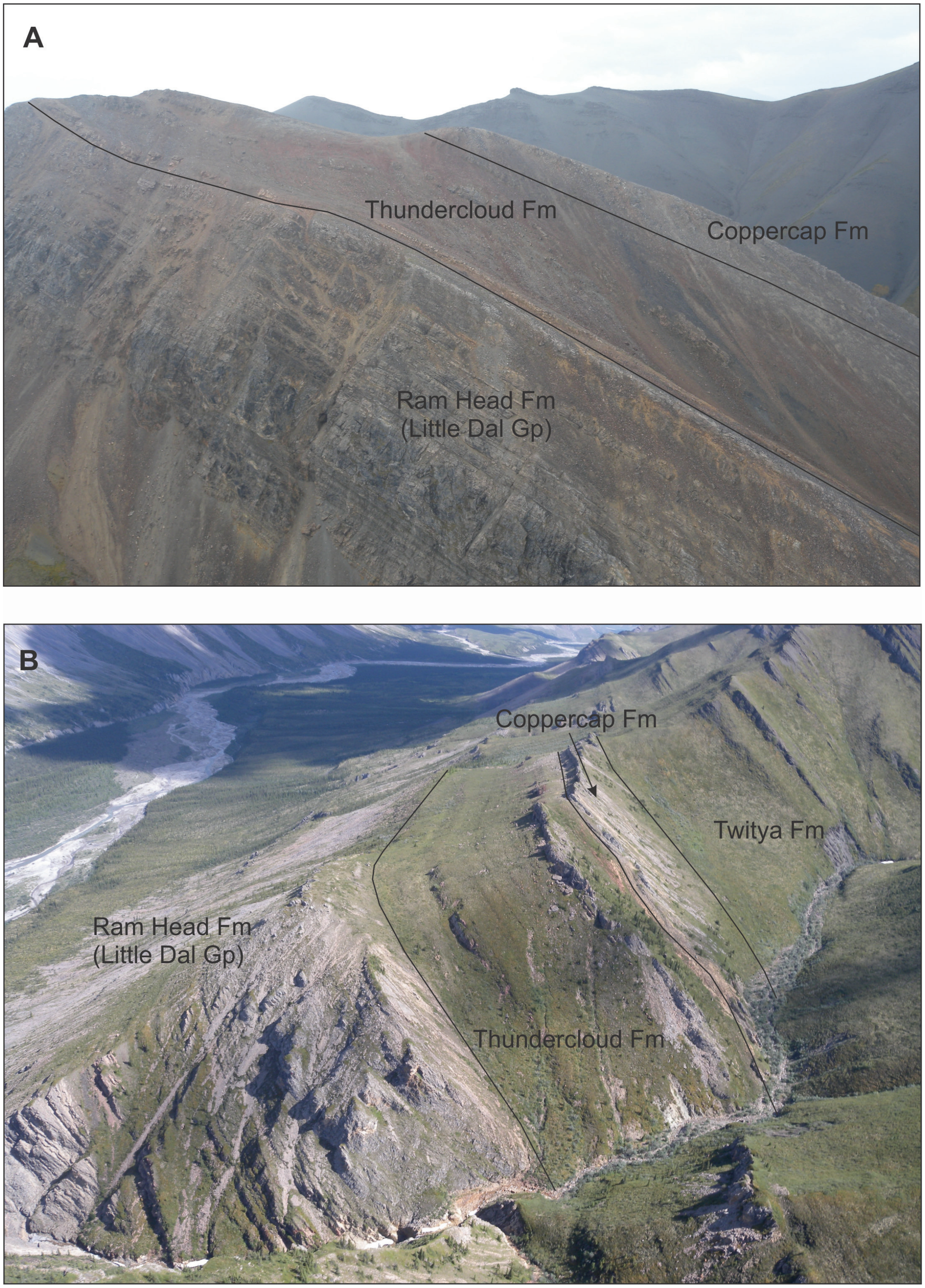

Figure 9. *Exposures of Coates Lake Group (Thundercloud and Coppercap formations) exposed in the hanging wall of the Plateau Fault in NTS 106B, newly recognized during GEM Program. A. Exposures at 64.797881, -130.350652 (NAD83); view is looking to south. Thundercloud Formation is approximately 150 m thick. B. Exposures at 64.952091, -131.075250 (NAD83); view is looking to southeast. Thundercloud Formation is approximately 160 m. This figure originally appeared in MacNaughton et al. (2018).*

map areas, Bonnet Plume Lake (NTS 106B) and Ramparts River (NTS 106G), and Sayunei and Shezal formation strata may be present locally in the Bonnet Plume Lake area.

Also included in the Hay Creek Group is the Keele Formation (Gabrielse et al., 1973a,b), which may be dominated by carbonate or sandstone, depending on location, and commonly displays repetitive vertical facies successions (Eisbacher, 1978; Day et al., 2004). Keele Formation appears on historical maps for Bonnet Plume Lake (NTS 106B) and Ramparts River (NTS 106G) map areas. On these maps, the Keele Formation included a capping set of distinctively pale-weathering carbonate units, which were originally treated as an informal member of the Keele Formation (Gabrielse et al., 1973a, b). Later workers referred to them as the informal 'Tepee dolostone' (Eisbacher, 1981; Aitken, 1991), and they subsequently were divided into the informal Ravensthroat and Hayhook formations (James et al., 2001). Although thin (10's of metres), the Ravensthroat and Hayhook formations were recognized and mapped as a combined unit in the southwestern part of the GEM program study area. Local diamictite deposits at the top of the Keele Formation indicate that facies of the glacially influenced Ice Brook Formation (Aitken, 1991) may also be present.

Although the shale-dominated Sheepbed Formation (Ediacaran) is unchanged from its original usage (Gabrielse et al., 1973a, b), a carbonate unit locally present at the top of the unit has required additional consideration. The carbonate was first documented by Eisbacher (1981) and later referred to informally as the 'Sheepbed carbonate' by Aitken (1984). Exposures of the unit along the Plateau Fault subsequently were assigned to the Gametrail Formation (Aitken, 1989) and were mapped as such during the Sekwi Mount Project (Turner et al., 2011). Macdonald et al. (2013) falsified this assignment based on evidence from stable-isotope chemostratigrapy and reverted to the earlier, informal name. During mapping and stratigraphic work of the GEM program, the Sheepbed carbonate was documented in the Bonnet Plume Lake map area (NTS 106B), where it likely was incorrectly assigned to the overlying Backbone Ranges Formation on historical maps. Several sections were measured through the unit during GEM (e.g., Figure 10A), and it will be formalized under a new formation name in the near future.

Backbone Ranges Formation (Ediacaran to Cambrian) was defined based on exposures in NTS 95L and 95M (Gabrielse et al., 1973a, b) but is widely distributed in the Mackenzie Mountains. In its type area, Backbone Ranges Formation is subdivided into three mappable members: a lower member dominated by quartzite or sandstone, a middle carbonate member, and an upper quartzite member that regionally is a prominent cliff-forming interval. The Backbone Ranges Formation appears on historical maps for the northwest Mackenzie Mountains either as an undivided unit of quartzite or sandstone with minor carbonate, or as a succession with the carbonate shown as a separate unit. During GEM Program mapping, the typical three-fold subdivision was recognized in the Bonnet Plume Lake (NTS 106B) map area (Figure 10A), and map publications derived from this work will reflect these subdivisions.

In western Bonnet Plume Lake map area, near the Yukon-Northwest Territories border, the upper member of the Backbone Ranges Formation shows a consistent succession of sandstone-dominated versus shale-dominated units, suggesting the upper member can be subdivided further into mappable units (Figure 10B). MacNaughton et al. (2018, p. 11) described these units as follows. "A basal, semi-resistant succession (Unit A: approximately 225 m thick) is dominated by maroon and grey weathering sandstone and siltstone, and contains a distinctive medial marker of grey-weathering, platy, locally fetid limestone. The basal unit is overlain in turn by a mainly recessive succession (Unit B: approximately 170 m thick) dominated by brown

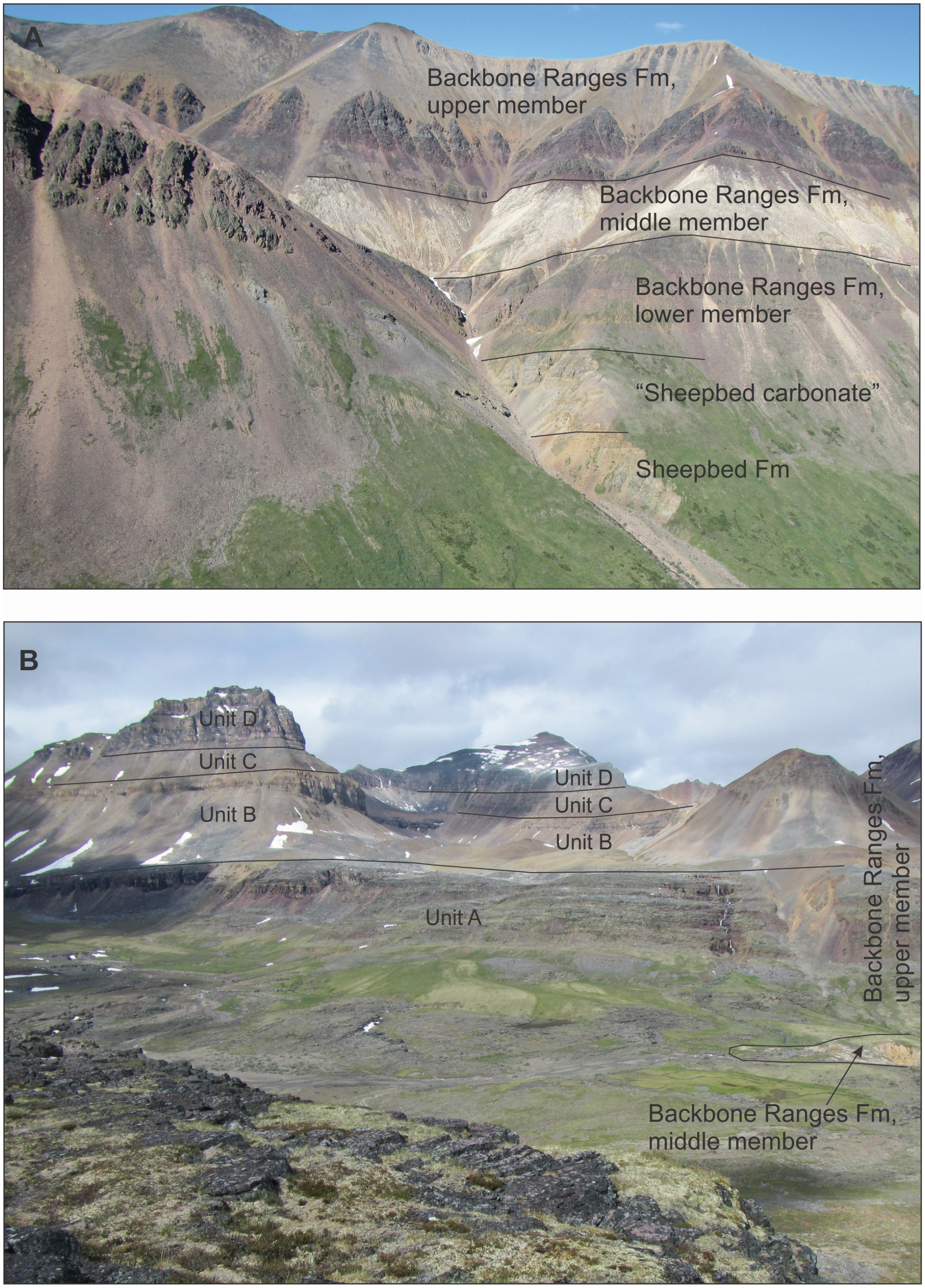

Figure 10. *Ediacaran-Cambrian stratigraphy, headwaters of Reptile Creek, immediately west of western edge of NTS 106B. A. Sheepbed Formation, including "Sheepbed carbonate", overlain by Backbone Ranges Formation showing typical tripartite arrangement of members. Lowest exposures of Sheepbed Formation are at 64.69656001, -132.07110168 (NAD83); view is to northeast. Middle member of Backbone Ranges Formation is approximately 100 m thick. B. Newly recognized internal divisions of upper member, Backbone Ranges Formation. Unit labels are keyed to descriptions in the text. Unit C is approximately 50 m thick. Photograph looking northwest from 64.685042, -132.132602 (NAD83). Figure modified from MacNaughton et al. (2018).*

siltstone with lesser sandstone and dolostone. This succession is capped by a grey- to orange or brown-weathering carbonate that is generally only a few metres thick in the project area, but that thickens into a potentially mappable unit to the south and west. Above this is a second recessive succession (Unit C: approximately 50 m thick), consisting of brown siltstone and sandstone and locally containing abundant trace fossils. The uppermost part of the succession is dominated by quartzite (Unit D: approximately 220 m thick) that mimics the cliff-forming character of the upper Backbone Ranges Formation as seen in other areas." These subdivisions of the upper member will be formalized as new units on the project maps. These units are of formation scale and mappable over a large area, emphasizing the long-standing need for review and revision of the Backbone Ranges Formation. The need for revision is further emphasized by biostratigraphic (MacNaughton and Fallas, 2018) and lithostratigraphic (MacNaughton and Fallas, in press) evidence that the sub-Cambrian unconformity lies within the upper member, rather than at its base as commonly has been argued (see review by MacNaughton, 2011).

Locally, a recessive shale and sandstone interval overlies the Backbone Ranges Formation. This does not appear on historical maps for Bonnet Plume Lake, but was documented by Fritz (1976, 1978, 1979) in several measured sections and is treated as a tongue of the early Cambrian Vampire Formation (Fritz, 1982). The Vampire Formation locally separates the Backbone Ranges Formation from the overlying Sekwi Formation. Sekwi Formation (Lower Cambrian) is a heterolithic, carbonate-dominated unit (Handfield, 1968; Fritz, 1976, 1978, 1979) that contains facies recording tidal-flat to deep-water marine deposition (Krause and Oldershaw, 1979; Dilliard, 2006; Dilliard et al., 2010). The treatment of the Sekwi Formation during GEM was essentially unchanged from historical mapping, although an isopach study prepared during the program emphasized the desirability of subdividing this very thick unit into members (Chan et al., in press; see also Turner et al., 2011).

Passing northeast from the Bonnet Plume Lake map area (NTS 106B), map units from the Little Dal Group to the Sekwi Formation are truncated beneath one or more unconformities at the base of, or within, the Cambrian succession (Figure 8). Lower Paleozoic strata (Cambrian to Devonian) are found throughout the entire study area.

Within the Mackenzie Mountains, in the extreme southwest portion of the study area, the shale-and-carbonate-dominated Road River Group (shown as undivided Road River Formation on historical maps) represents Lower Paleozoic (Cambrian to Silurian) strata. These strata constitute the relatively recessive basinal facies of Selwyn Basin. Cecile (1982) subdivided the Road River Group (ascending order) into Hess River (dark shale, argillaceous limestone, local sandstone), Rabbitkettle (thin-bedded silty limestone), Duo Lake (dark shale, commonly graptolitic, with silty limestone), Marmot (volcanic and volcaniclastic strata), and Cloudy (limestone with shale and chert) formations (Figure 7). Each of these units is recognizable and mappable in Bonnet Plume Lake map area (NTS 106B).

On Mackenzie Arch (Figure 8), a long-lived, elongate, northwest-trending positive tectonic feature in the northeast Mackenzie Mountains (Aitken et al., 1973; MacNaughton et al., 2016), basal, red-weathering siliciclastic Cambrian strata were identified as 'Franklin Mountain Formation red beds' on Operation Norman maps. During GEM, this succession was separated from the overlying carbonates of the Franklin Mountain Formation and defined as the Nainlin Formation (Figure 11). This new unit has been mapped in the Carcajou Canyon (NTS 96D), Sans Sault Rapids (NTS 106H), and Ramparts River (NTS 106G) map areas (MacNaughton and Fallas, 2014; Fallas and MacNaughton, 2014a, b, c; Fallas et al., 2016; MacNaughton et al., 2017).

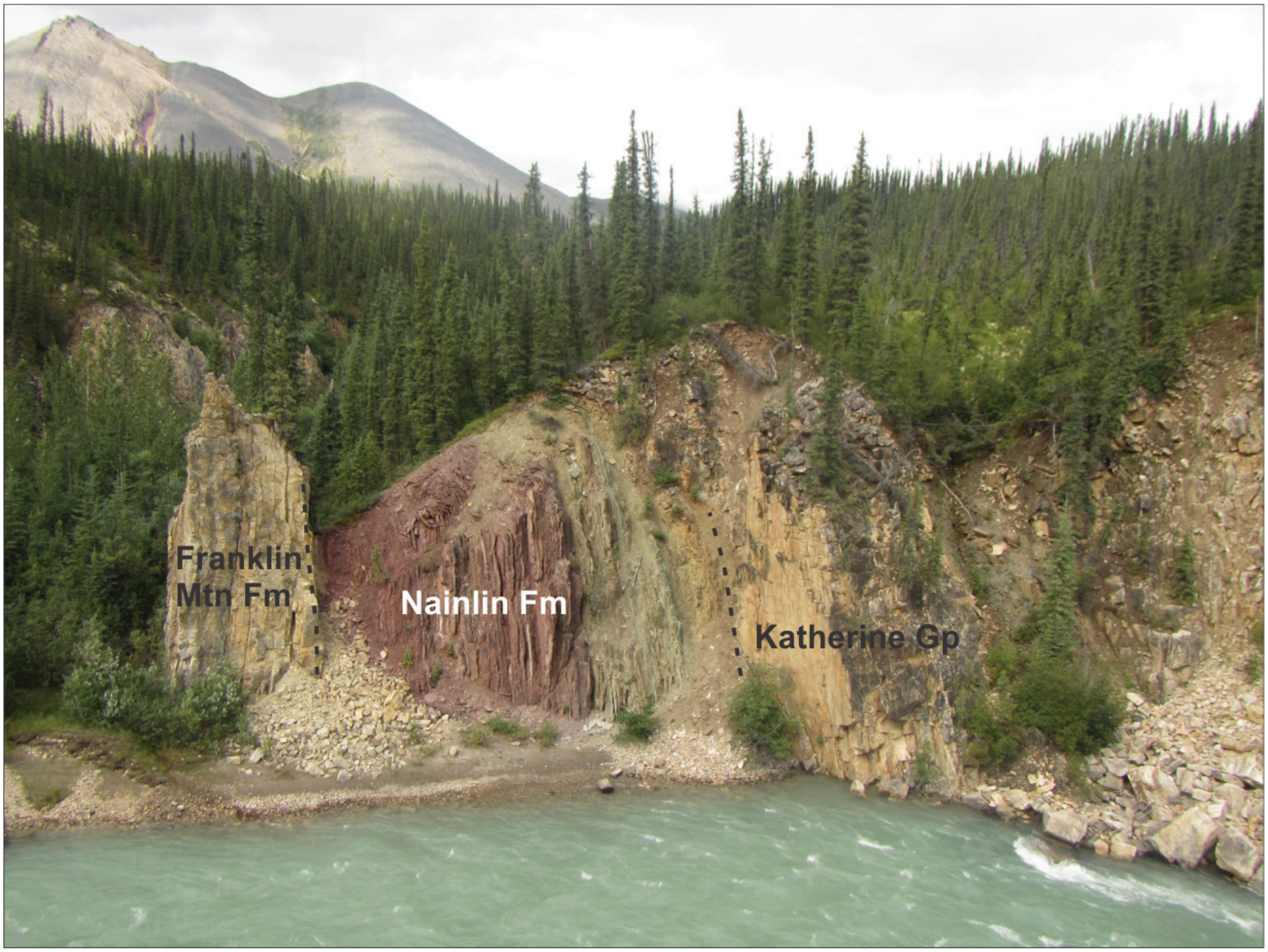

Figure 11. *Near-complete exposure of Nainlin Formation along Gayna River, southwestern NTS 106H. Nainlin Formation was defined during the first phase of GEM bedrock mapping in the Mackenzie Region, and its mapped extent subsequently extended further into the Mackenzie Mountains. Contact between Nainlin Formation and underlying Katherine Group strata is at 65.13545725° N, 129.79209492° W. Measured thickness of Nainlin Formation at this location is 22 m.*

Northeast of Mackenzie Arch, from the northeast margin of the Mackenzie Mountains to the edge of the Canadian Shield, the Lower and Middle Cambrian consists of three formations. In ascending order, these are the Mount Clark (dominantly quartz sandstone), Mount Cap (shale, carbonate, and lesser sandstone) and Saline River (shale, evaporites, and lesser carbonate) formations (Williams, 1922, 1923; Aitken et al., 1973; Dixon and Stasiuk, 1998). This nomenclature was used maps produced by Operation Norman, although the name Old Fort Island Formation (Cook and Aitken, 1971; Balkwill, 1971) was applied to Mount Clark equivalent strata along the edge of the Canadian Shield. Old Fort Island Formation subsequently was abandoned by Dixon and Staskiuk (1998). The presence of the Mount Clark Formation in the eastern Mackenzie Mountains was not recognized during Operation Norman, although a basal sandstone was considered to be present in the Mount Cap Formation (Aitken et al., 1973). Subsequent suggestions that Mount Clark Formation was present in the Mackenzie Mountains (Serié et al., 2013) were confirmed during GEM (Fallas and MacNaughton, 2012; MacNaughton et al., 2013; Hamel and MacNaughton, 2013). Trilobite biostratigraphy for the Mount Cap Formation, dating to Operation Norman and before (Kobayashi, 1936; Aitken et al., 1973), was augmented during GEM (MacNaughton et al., 2013; see also Serié et al., 2013) and currently is the subject of MSc research by N. Handkamer (work in progress) at the University of Saskatchewan.

During mapping for the GEM program, the Mount Clark, Mount Cap, and Saline River formations were recognized on the Carcajou Canyon (NTS 96D) and eastern Sans Sault Rapids (NTS 106H) map areas. Saline River Formation was also mapped within the Franklin Mountains of the Norman Wells (NTS 96E), Mahony Lake (NTS 96F), and western Fort Norman (NTS 96C) map areas. Along the eastern flank of Mackenzie Arch, proximal facies assigned to the Saline River Formation during Operation Norman (Aitken et al., 1973) have been reassigned to the Nainlin Formation (MacNaughton and Fallas, 2014).

Lying conformably upon the Nainlin or Saline River formations is the Franklin Mountain Formation (Williams, 1922, 1923), a dolostone unit of Late Cambrian to Ordovician age. On Operation Norman maps, this unit and the overlying Mount Kindle Formation (see below) were assigned to the Ronning Group. Additionally, during Operation Norman (Figure 7) the Franklin Mountain Formation variously was identified as Ronning Group (units 1, 2a, and 2b), Franklin Mountain Formation (Cyclic member, Rhythmic member, and Cherty member, in ascending order), or Franklin Mountain Formation (undivided). Note, however, that the Ronning Group was rendered obsolete in the project area by the work of Macqueen (1970; see also Norford and Macqueen, 1975). Stratigraphic work by Turner (2011) during GEM reassessed the subdivisions of the Franklin Mountain Formation and recommended the use of lower, middle, and upper members in place of Cyclic, Rhythmic, and Cherty members respectively. The lower, middle, and upper members of the Franklin Mountain Formation are recognizable in the Franklin Mountains, Colville Hills and northeastern Mackenzie Mountains, and these three subdivisions are used on maps generated for these areas during the GEM program. Regional studies by E.C. Turner of the Franklin Mountain Formation and its correlatives are ongoing (e.g., Chevrier and Turner, 2013; Fallas et al., 2015c; Rainbird et al., 2015b; MacNaughton et al., 2016; Turner et al., 2017).

Mount Kindle Formation (Williams, 1922, 1923) was applied during Operation Norman (Norford and Macqueen, 1975) to a distinctively fossiliferous, locally silicified dolostone unit. The unit is a feature-former with a distinctive dark grey weathering tone at a distance, and thus a useful marker during mapping. In the project area, it forms an unconformity-bounded Late Ordovician to Early Silurian sequence. Mount Kindle Formation passes southward into the Whittaker Formation (Gabrielse et al., 1973a) in the Mackenzie Mountains, and westward into the Duo Lake and Cloudy formations in Selwyn Basin (Cecile, 1982).

Stratigraphic sections were measured through the Mount Kindle Formation in the eastern Mackenzie Mountains and Franklin Mountains (Pope and Leslie, 2013), the Colville Hills (Fallas et al., 2015c), and along the northern edge of the Mackenzie Mountains (Fallas et al., 2016). Sections also were measured in the northwestern Mackenzie Mountains, where the Mount Kindle Formation passes into Selwyn Basin equivalent units (MacNaughton et al., 2017, 2018). These observations and associated samples are the subject of an MSc project being pursued by J. Martell (work in progress) at Texas A&M University under the supervision of M.C. Pope. Ongoing conodont biostratigraphy and stable isotope chemostratigraphy will be aids to regional correlation (e.g., Pope and Leslie, 2013).

On Operation Norman maps, the Mount Kindle Formation was shown as overlain by a discontinuous, unnamed Siluro-Devonian unit. In a few cases, this unit was identified as the Delorme Group (latest Silurian to Early Devonian). Stratigraphic work on the Delorme Group by Morrow (1991, 1999) distinguishes Peel (mainly dolostone, locally argillaceous) and Tatsieta (limestone, shale, local dolostone) formations on the north slope of the Mackenzie Mountains (see Pugh, 1983, for the definitions of these units) , and Tsetso Formation (dolostone, sandstone, shale; see Meijer Drees, 1993) within the Mackenzie Mountains and Franklin Mountains (Figure 7). Maps of the GEM program follow Morrow's geographic constraints on the application of terminology for these three units.

Early and Middle Devonian units used on Operation Norman maps included (in ascending order) the Arnica (dolostone; Douglas and Norris, 1961), Landry (dominantly limestone; Douglas and Norris, 1961), Bear Rock (carbonate breccia; Hume and Link, 1945), and Hume (fossiliferous limestone and argillaceous limestone; Basset, 1961) formations. These remain useful map units for the Devonian carbonate platform succession and are retained on GEM program maps. One modification made in the Colville Hills (Fallas, 2017a, b, c, d; Gouwy et al., 2017a) was the use of the term 'Bear Rock assemblage' (after Morrow, 2012) for the interval including Bear Rock, Arnica, and Landry formations, to indicate uncertainty regarding the exact distribution of each of these units in an area of generally poor exposure. It is also uncertain whether any Delorme Group strata are present in the Colville Hills, but if present, they would be included in the 'Bear Rock assemblage' unit.

The Middle Devonian succession can be mapped discontinuously along the northern Mackenzie Mountains front and in the Franklin Mountains. On Operation Norman maps, these strata were assigned, in ascending order, to: Hare Indian Formation (shale, commonly with a calcareous and bituminous basal member; Kindle and Bosworth, 1921); Ramparts Formation (limestone; Kindle and Bosworth, 1921) or Kee Scarp Formation/Member (bioclastic limestone; Stelck, 1944; Hume and Link, 1945; Hume, 1954); and Canol Formation (dark, siliceous shale; Basset, 1961). Maps produced during the GEM Program use the Hare Indian, Ramparts, and Canol formations as separate units where all three are present. Where limestone of the Ramparts Formation is absent, and shales of the Hare Indian and Canol formations are difficult to distinguish, these units are combined as the Horn River Group (see Pugh, 1983, for history of usage), a term not used during Operation Norman (Figure 7). Late Devonian Imperial Formation (Link, 1921; Hume and Link, 1945) is applied on GEM maps in the same manner as on Operation Norman maps, for a succession of sandstone and shale with minor conglomerate and fossiliferous limestone. Caldwell (1964) reviewed the complicated nomenclatural history of this unit. GEM bedrock mapping also extended the distribution of a local carbonate marker within the Imperial Formation, the Jungle Ridge Member (Stelck, 1944; Hume and Link, 1945; Hume, 1954), to the west flank of the Franklin Mountains (Fallas and MacNaughton, 2013; Fallas et al., 2013b, c).

During the first phase of the GEM program, field support was provided for a graduate thesis on the sedimentology and stratigraphic packaging of the Imperial Formation, based on exposures along the eastern edge of the Mackenzie Mountains (Acker, 2013). Also see Hadlari et al. (2009) for a regional study of the Imperial Formation. Summaries of additional work Devonian stratigraphy (P.B. Kabanov, work in progress; see also Kabanov et al., 2016) and conodont biostratigraphy (S.A. Gouwy, work in progress; see also Gouwy et al., 2017b) during the second phase of GEM are currently in preparation.

Northeast of the Mackenzie Mountains, Cretaceous and younger siliciclastic strata were identified on the Operation Norman maps using various formal and informal terms (Figure 7). Subsequent stratigraphic work (Yorath and Cook, 1981; Dixon, 1999) established formal terminology from the Lower Cretaceous Martin House Formation to the Upper Cretaceous to Paleocene Summit Creek Formation. This formal terminology generally has been used on GEM program maps, although sparse outcropping strata with poor biostratigraphic control east of the Colville Hills are treated as an undivided Cretaceous unit. Most units are found anywhere Cretaceous strata are preserved, although the Sans Sault Member of the Arctic Red Formation is only recognizable on the west flank of the Franklin Mountains, and its stratigraphic equivalent, the Mahony Lake Formation, is restricted to the east side of the Franklin Mountains. The youngest units, East Fork and Summit Creek formations, are restricted to the southeast portion of the study area, in Brackett Basin (Figure 8). For a recent overview of Cretaceous stratigraphy in the project area and adjacent regions, see Fallas et al. (in press, b). During the GEM Program, graduate projects were completed dealing with the sedimentology and stratigraphy of the Martin House Formation (Davison, 2011) and with aspects of the region's Cretaceous biostratigraphy (Bell, 2018). Additionally, some attention was given to the sedimentology and petroleum geochemistry of oil-stained Cretaceous outcrops in the Colville Hills (Fallas et al., 2015c; Jiang et al., in press).

A NOTE ON SUBSURFACE STUDIES

Although the present report focuses on studies carried out in relation to bedrock mapping, both phases of the GEM Program in the Mackenzie region included subsurface components. Key elements of this work are briefly summarized here. Much of the subsurface work reflected the goal of improved oil and gas exploration success in Mackenzie Plain and Great Bear Plain (e.g., Hannigan et al., 2011), although efforts to unravel regional tectonostratigraphic evolution were also significant. From the former perspective, Hu and Hannigan (2009) provided an important evaluation of reservoir petrophysics for key stratigraphic intervals (Cambrian to Cretaceous) in numerous industry wells. The study by Hadlari et al. (2009) on the Upper Devonian Imperial Formation (referred to above) incorporated subsurface data (wireline logs and reflection seismic profiles). Dixon (2011) reported on core-based subsurface correlations in the Devonian to Carboniferous clastic-wedge succession (Imperial and Tuttle formations), and a graduate project by Raska (2017) sought to apply 3D subsurface modelling methods to the geological structure of the Devonian beneath Mackenzie Plain. Additional subsurface studies on Devonian facies and stratigraphy during the second phase of GEM will be summarized in a report by P.B. Kabanov (work in progress).

Reflection seismic studies were an important component of both phases of GEM. This included a regional overview of subsurface Phanerozoic structure (MacLean, 2012), a study of the complex structural evolution of the Keele Arch (MacLean et al., 2014, 2015) that is discussed further below, and a major restudy of the tectonic and stratigraphic evolution of the Cambrian succession in the subsurface of the project area (MacLean, 2011a, b). This last provided the impetus for additional regional studies on the Cambrian System. A preliminary core study of reservoir facies in the Mount Clark Formation beneath the Colville Hills (Herbers et al., 2016) was followed by a regional core and wireline study of the Mount Clark and Mount Cap formations, which formed the basis of a graduate project (Sommers, 2018) that currently is being prepared for external publication. This thesis project was designed to build upon outcrop-based studies of Cambrian stratigraphy from the first phase of GEM (MacNaughton et al, 2013; Hamel and MacNaughton, 2013), in particular by erecting a sequence-stratigraphic framework for the succession. Trilobite faunas previously collected from industry cores (e.g., Macqueen and Mackenzie, 1973) have been the subject of a preliminary reassessment (Morgan, 2019), which suggests that updated Cambrian biozones can be applied to the succession for greater biostratigraphic precision. The subsurface work complements a second, outcrop-based graduate project (M. Bouchard, work in progress) dealing with outcrop exposures around the Brock Inlier and in the eastern Mackenzie Mountains (Bouchard and Turner, 2017a, b). The goal of this combined effort is to provide an updated stratigraphic framework for the Mount Clark and Mount Cap formations from where they onlap the east flank of Mackenzie Arch to their preservational zero edge against the Brock Inlier.

STRUCTURAL GEOLOGY

The Mackenzie region project areas of the GEM program encompass a significant portion of the northern Foreland Belt of the Canadian Cordillera (Norris, 1985). Structures associated with both pre-Laramide and fold-and-thrust style deformation of the Laramide Orogeny are recognized from the Mackenzie Mountains to the Colville Hills (Figure 1) within the study area. Summary overviews of the regional structural geology have been presented by Norris (1985), Cook (in McMechan et al., 1991), Hyndman et al. (2005), and Martel et al. (2011).

Pre-Laramide Structures

Structures formed during the Cretaceous to Eocene Laramide Orogeny dominate the Mackenzie region (Eisbacher, 1981; Cook, in McMechan et al., 1991). However, within the GEM study area there are also structures with a demonstrable pre-Laramide history. In a regional study beneath the northern plains, Cook and MacLean (2004) used reflection-seismic data to document a series of subsurface contractional and extensional faults, with associated folding, affecting Paleo- and Mesoproterozoic sedimentary and metasedimentary successions that constitute 'basement' to the region's Neoproterozoic to Paleocene strata. These basement structures were interpreted to have varying trends, although approximately northward trends are common. Aitken and Cook (1974a) documented another set of faults, presumed by them to be normal faults, trending north-northwest (340-360°), and cutting Neoproterozoic strata in the Mackenzie Mountains. They noted that map relationships indicate these antecedent faults were active before Upper Cambrian strata were deposited, and they suggested that the lack of involvement of Rapitan Group or younger strata indicates these faults may have formed before Rapitan deposition. Eisbacher (1981) documented a set of normal faults affecting strata of the Coates Lake and lower Rapitan groups in the Mackenzie Mountains. Fault trends vary with latitude, from northeastward near 63°N, to northward at 64°N, and northwestward at 65°N,. These faults were interpreted to be syndepositional to the Coates Lake and Rapitan Groups. Young et al. (1979) assigned these syndepositional faults to the Hayhook Orogeny. As part of GEM program research, north to north-northeast trending, Early to mid-Cambrian normal faulting has been documented in the subsurface of Mackenzie Plain, Franklin Mountains, and Colville Hills (MacLean, 2011b; MacLean et al., 2014; 2015). Syndepositional normal faulting in Middle Cambrian Nainlin Formation was also documented within the Mackenzie Mountains (Figure 12) (MacNaughton and Fallas, 2014; Fallas et al., 2016). The dominant north-northwest trend of these faults is coincident with the antecedent faults of Aitken and Cook (1974a), and in some cases, they are the same features.

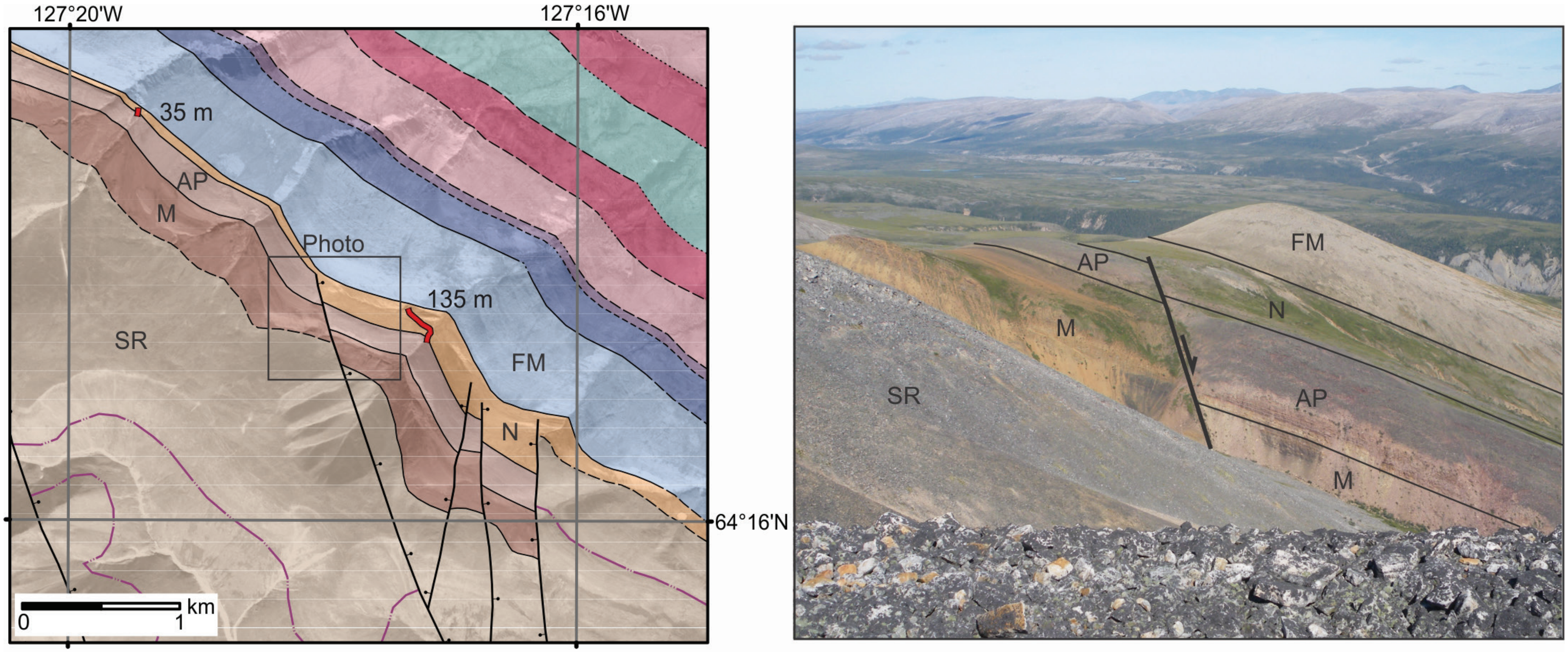

Figure 12. *Evidence of Cambrian motion on pre-Laramide faults. On left, map interpretation of Fallas and MacNaughton (2014c). Labelled units include Neoproterozoic Katherine Group: Shattered Range Fm (SR), McClure Fm (M), Abraham Plains Fm (AP), Middle Cambrian Nainlin Fm (N), and Cambro-Ordovician Franklin Mountain Fm (FM). Pre-Laramide normal faults cut Katherine Group and Nainlin Formation, whereas overlying Franklin Mountain Formation is not offset by the fault. Measured sections through the Nainlin Formation are shown on the map as red lines with measured thickness of unit annotated. Black box indicates area of illustrated photo. Field photo on right looks north-northwest along the down-to-the-east normal fault shown on map. Units are labelled with the same abbreviations as on the map. Satellite imagery from Planet Labs Geomatics Corp.*

Laramide Structures

The majority of structures mapped within the study area formed during the development of the Canadian Cordillera. In the present context, the term Laramide Orogeny is used herein to indicate contractional deformation during Cretaceous to Eocene time. The timing of Laramide deformation in the study area is based on multiple lines of evidence: the presence of sediment derived from the Cordillera in Late Cretaceous strata (Hadlari et al., 2014), the presence of Cretaceous bentonites indicating volcanic activity in the region (Thomson et al., 2011), and the involvement of Cretaceous to Paleocene units in Laramide folding. This timing is further supported by a GEM program thermochronological study showing uplift on thrust faults in the Mackenzie Mountains from the mid-Cretaceous to Eocene (Breker, 2012; Powell et al., 2016; Powell, 2017).

Laramide deformation is recognized throughout most of the study area, but varies in the types of structures, level of detachment, strata involved, and structural trends. These variations can be characterized for each physiographic region (Figure 1) as belonging to a particular structural domain (Fallas, 2013e). Laramide structures include thrust faults (northeast directed faults cutting through strata at angles between 0° and 45°, regardless of present-day dip), backthrusts (southwest directed faults with the same geometry as thrust faults), reverse faults (faults cutting through strata at >60°, typically with steep fault-plane dips), and minor strike-slip faults. Northwest-trending thrust faults are the dominant fault type in the Mackenzie Mountains (Figure 13A), Mackenzie Plain, and Franklin Mountains, and are present to a lesser degree in the Colville Hills. Northwest- or west-trending backthrusts are present in the Mackenzie Mountains, the northwest margin of Mackenzie Plain, and in the Franklin Mountains (Figure 13B). North- to north-northwest-trending reverse faults are the dominant fault type in the Colville Hills and the eastern Franklin Mountains; they are also present as a minor fault type within the Mackenzie Mountains (Figure 13C). West-, northwest-, and north-trending folds are present throughout the deformed belt and are the dominant Laramide structures northeast of the Plateau Fault in the Mackenzie Mountains (Figure 13D), as well as in Mackenzie Plain, Brackett Basin, and Colville Hills. Where thick packages of resistant carbonate or quartz sandstone are involved in folding, larger folds with wavelengths of 5-25 km dominate the structural style (Figure 13B, D). Near the Yukon – Northwest Territories border in the Mackenzie Mountains, shale-dominated Selwyn Basin strata fold at multiple scales with wavelengths of tens to hundreds of metres (Figure 13E). North- to north-northwest-trending normal faults are common in the Mackenzie Mountains but typically are found in Neoproterozoic and Cambrian strata and therefore generally are interpreted as pre-Laramide structures (Figure 12). Normal faults typically have smaller displacements (a few metres up to 300 m) as compared to contractional Laramide faults (hundreds of metres up to a few kilometres).

Laramide folds and faults in the Mackenzie Mountains are detached at multiple stratigraphic levels, with major structures exploiting weak, commonly shaly or evaporitic strata in the Neoproterozoic Tsezotene Formation, the Ten Stone or Snail Spring formations of the Little Dal Group (Figure 13A), the Twitya Formation, and the Sheepbed Formation. An additional detachment level must be present below the Tabasco Formation, but is not exposed in the Mackenzie Mountains. Minor folds are also detached in the Devonian Landry and Hume formations. Major structures in Mackenzie Plain, Brackett Basin, Franklin Mountains, and Colville Hills are detached within evaporitic strata of the Cambrian Saline River Formation (Figure 13F). One such structure in Brackett Basin, forming the MacKay Range, was studied in detail as a student project during the GEM program (Proks, 2012).

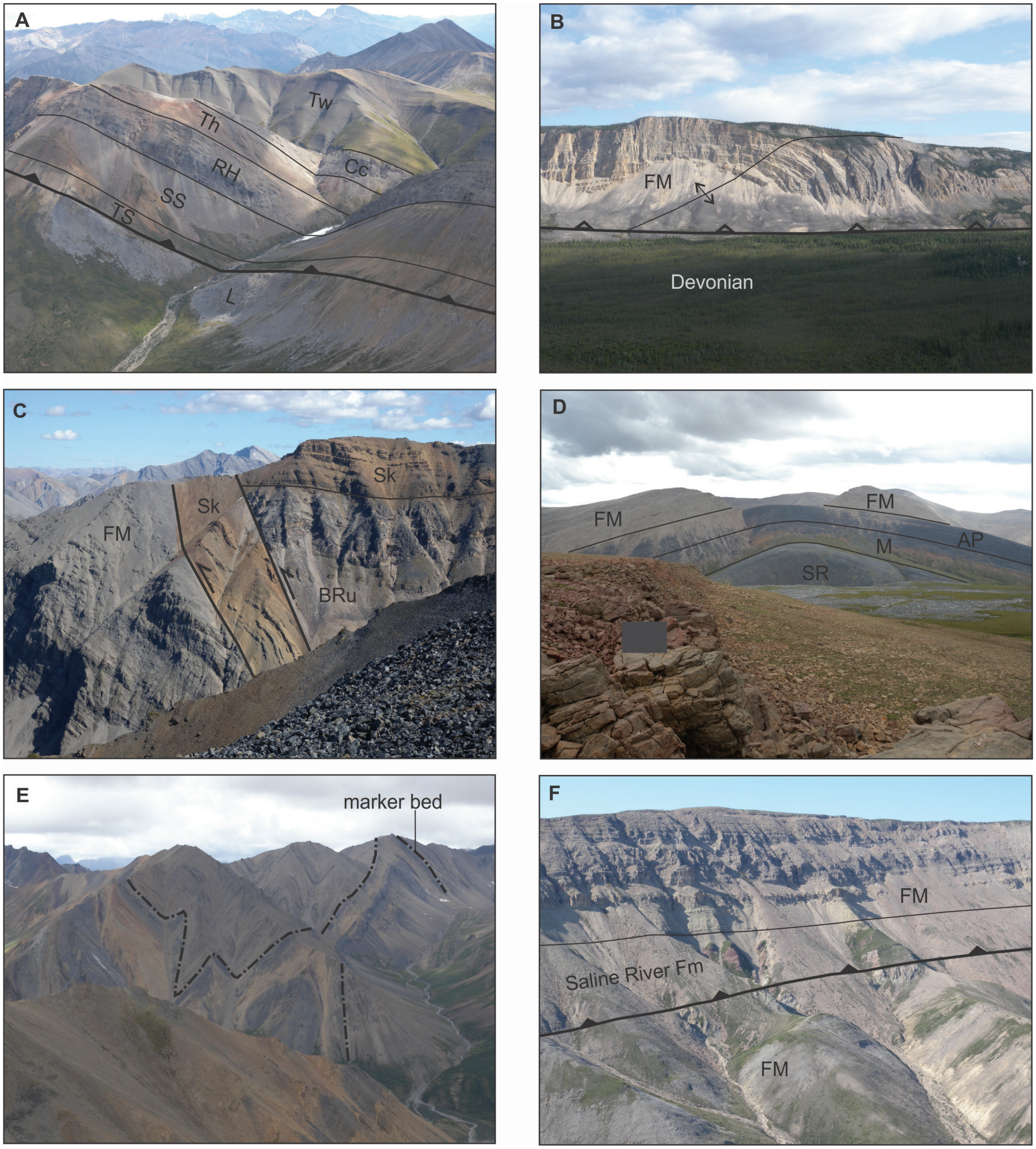

Figure 13. *Laramide structures. A. Looking south at the Plateau Fault in Bonnet Plume Lake map area (NTS 106B). Thrust detachment lies within evaporite of the Ten Stone Formation. B. Looking northeast at backthrust and anticline on Brokenoff Mountain in Norman Wells map area (NTS 96E). C. Looking southeast at reverse faults in Bonnet Plume Lake map area. D. Looking southeast along the McDermott anticline in the Carcajou Canyon map area (NTS 96D). E. Looking northwest at tight folds in carbonate and shale of the Sekwi Formation, eastern Nadaleen River map area (NTS 106C). F. Looking southwest at thrust splay in the Norman Range of the Franklin Mountains, Norman Wells map area. Thrust detachment lies within evaporite of the Saline River Formation. Abbreviations: Ten Stone Fm (TS), Snail Spring Fm (SS), Ram Head Fm (RH), Thundercloud Fm (Th), Coppercap Fm (Cc), Twitya Fm (Tw), Landry Fm (L), Franklin Mountain Fm, (FM), Sekwi Fm (Sk), Backbone Ranges Fm, upper mbr (BRu), Shattered Range Fm (SR), McClure Fm (M), Abraham Plains Fm (AP).*

A characteristic of many reverse faults in the study area is evidence of a pre-Laramide extensional history (Fallas, 2013e). In the Mackenzie Mountains, faults with normal stratigraphic offset can be traced into faults with reverse offset (see the Conundrum Fault of Fallas and MacNaughton, 2014c), and stratigraphic relationships show that some reverse faults have thicker successions in the hanging wall, indicating that the hanging wall was once the down-dropped side of the fault. The dominant trend of reverse faults, near 340°, also matches the dominant trend of mapped normal faults of the Hayhook Orogeny and Cambrian extensional phase. In the subsurface of Mackenzie Plain, Brackett Basin, Franklin Mountains, and Colville Hills, reflection seismic data show a similar inversion of stratigraphy on major steeply dipping reverse faults (i.e., thicker stratigraphic successions in the hanging wall) cutting through the detachment level in the Saline River Formation, and connecting with structures in the underlying Proterozoic strata (MacLean et al., 2014; 2015). In this manner, the Mackenzie Trough (for location, see Figure 8) was inverted during the Laramide Orogeny as the second phase of the Keele Arch along the eastern Franklin Mountains and Colville Hills.

Difficulties in resolving the details of some stratigraphic intervals, notably the Katherine Group, Little Dal Group, Backbone Ranges Formation, and Road River Group, led previous mappers to leave these intervals partly or completely undivided on reconnaissance maps. Improved understanding of stratigraphic detail since the 1970's, and particularly during the GEM program, has facilitated subdividing such thick successions (>500 m thick) based on consistent lithological variations. In turn, these stratigraphic refinements have locally revealed new structural details, and in some cases allowed for the recognition of structures previously overlooked. One example of this is the northwest extent of the Canyon Fault in the Carcajou Canyon map area (NTS 96D), where an undivided 'lower division' of the Katherine Group disguised the trace of the Canyon Fault and led Aitken et al. (1974) to interpret a termination just north of the Carcajou River. Mapping of the subdivisions of the Katherine Group during the GEM program (Figure 14) demonstrated the continuation of the Canyon Fault to the northwest margin of the map area (Fallas and MacNaughton, 2014a). In other instances, correcting earlier misidentifications of units led to the revision of previously mapped faults, or the new identification of faults (Figure 15). Accurate mapping of units and structures has implications for identifying prospective versus non-prospective areas for mineral exploration. For example, previous maps in some cases misidentified Ediacaran Sheepbed Formation as lower Paleozoic Road River Group (Aitken and Cook, 1974b). In the Yukon portion of Selwyn Basin, thin-bedded silty carbonate of the Road River Group is a host for Carlin-type gold deposits (Arehart et al., 2013), and similar Road River Group lithologies are potential targets for Carlin-type gold exploration in the project area (Fischer, 2018). However, suitable lithologies for Carlin-type mineralization are not known to be present in the Sheepbed Formation. Thus, misidentification of Sheepbed Formation as Road River Group (Figure 16) could be a significant exploration risk, with the potential to send mineral exploration companies into non-prospective areas.

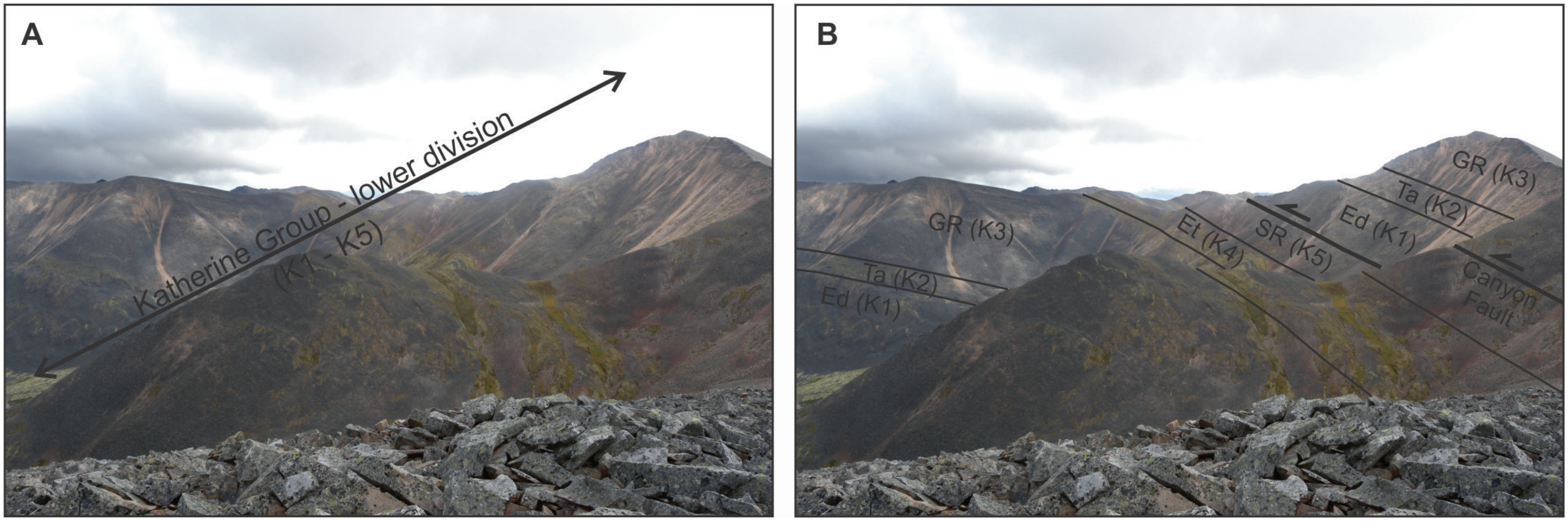

Figure 14. *Revised structural interpretation resulting from subdivision of the Katherine Group. A. View looking southeast at undivided lower Katherine Group of Operation Norman (Aitken et al., 1974), with no interpreted fault, in northwest Carcajou Canyon map area (NTS 96D). B. Extension of the Canyon Fault recognized by mapping the formations of the Katherine Group (Fallas and MacNaughton, 2014a). Abbreviations: Eduni Fm (Ed), Tawu Fm (Ta), Grafe River Fm (GR), Etagochile Fm (Et), Shattered Range Fm (SR). Informal K1 to K5 designations for the lower division of the Katherine Group of Aitken et al. (1978) also shown for reference.*

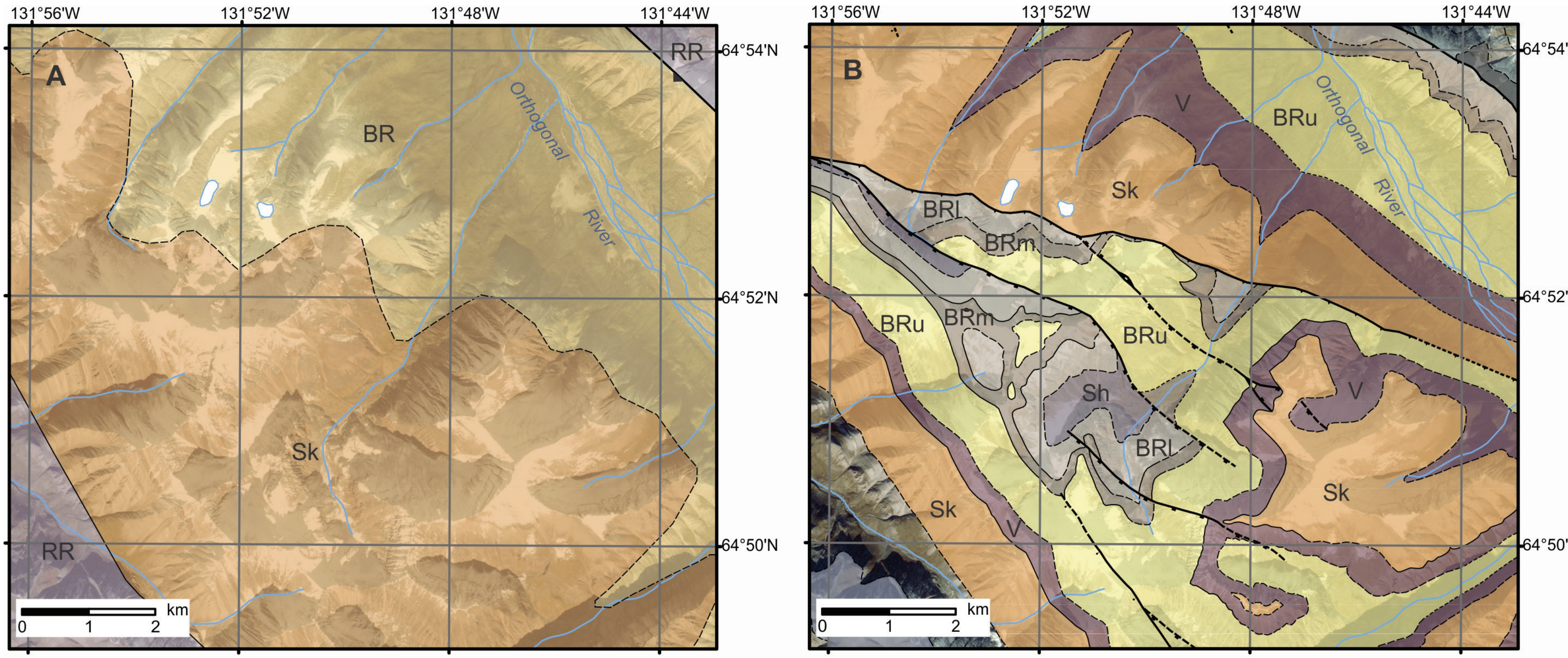

Figure 15. *Geological interpretations of northwest Bonnet Plume Lake map area (NTS 106B). A. Interpretation of Blusson (1974) showing an un-faulted succession southwest of Orthogonal River. B. Revised interpretation based on GEM program mapping with thrust (triangle symbol), reverse (rectangular symbol), and normal (tic and circle symbol) faults identified. Abbreviations: Sh = Sheepbed Fm, BR = Backbone Ranges Fm, (BRl, BRm, BRu = lower, middle, and upper members respectively), V = Vampire Fm, Sk = Sekwi Fm, and RR = Road River Group. Satellite imagery from Planet Labs Geomatics Corp.*

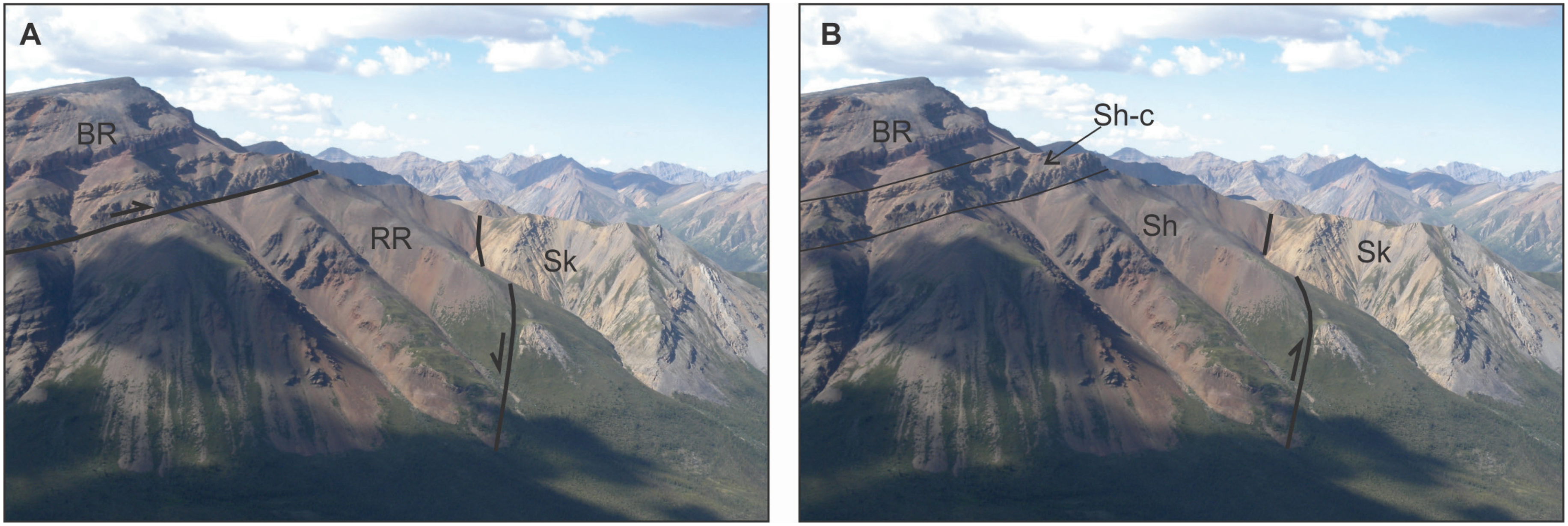

Figure 16. *Reinterpreted structural relationships in northeast Bonnet Plume Lake map area (NTS 106B). A. View looking west at Operation Norman interpretation (Aitken and Cook, 1974b) of unnamed thrust fault and normal fault (arrows indicate fault motion). Abbreviations: Backbone Ranges Fm (BR), Road River Fm (RR), Sekwi Fm (Sk). B. Revised interpretation from GEM program work of a single thrust fault based on the recognition of Sheepbed Fm (Sh) and the 'Sheepbed carbonate' (Sh-c) underlying the Backbone Ranges Fm.*

REVIEW OF HIGHLIGHTS

During the two phases of the GEM Program in the Mackenzie region, GSC scientists and collaborators remapped nearly 92,000 km^2 of territory. To date, eighteen new bedrock geology maps have been published at 1:100 000 or 1:250 000 scales, and six additional maps are currently in preparation (Figure 4B). In addition to bedrock mapping, geophysical mapping covered nearly 13,000 km^2 in the Mackenzie Valley (airborne gravity survey; Dumont, 2009) and 48,300 km^2 in the Mackenzie Mountains (airborne aeromagnetic survey; Kiss, 2018). As of mid-2019, scientists affiliated with the GEM Program have published at least 38 GSC reports on Mackenzie region geology, augmented by at least 5 relevant reports published by other government agencies, and 17 peer-reviewed articles in journals or books. Also of note are the new biostratigraphic and other data contained in at least 36 internal GSC Palaeontological Reports (see Appendix). Important summaries of Mackenzie region geology generated during the GEM Program include: Hannigan et al. (2011) on oil and gas potential of the mainland Northwest Territories, including an overview of regional geology; MacLean (2011b) on the Cambrian in the subsurface; Morrow (2012, 2018) on regional Devonian stratigraphy; Fallas et al. (in press, a) on the Cambrian to Devonian Mackenzie Platform east of the Mackenzie Mountains; and Fallas et al. (in press, b) on Mesozoic and Cenozoic geology east of the Mackenzie Mountains.

Prior to GEM, the state of bedrock geology maps across the Mackenzie Mountains and Interior Plains was uneven and largely based on reconnaissance studies conducted a half-century ago, particularly Operation Norman. Although GEM mapping demonstrated the large-scale reliability of the earlier generation of maps, it also provided an opportunity to take advantage of scientific and technological advances. The advent of GIS technology facilitated incorporation of legacy data from government (Fallas et al., 2015a) and industry sources (Finley et al., 2017) into the project geodatabase, lending additional value to the work of earlier geologists. Modern methods of field data collection permit near-instantaneous incorporation of mapping and stratigraphic data into the geodatabase. The use of the geodatabase in the field was a boon for on-the-ground planning of mapping strategies and daily work goals. Of similar importance was access to high-resolution, colour satellite imagery for much of the region, which also has been invaluable for post-field map compilation. The delivery of underlying observations with map interpretations allows the user to assess the reliability of published interpretations, reinterpret the geology, and/or reuse the observations in new research.

The most obvious visual change in the new generation of maps may be the use of updated stratigraphic nomenclature that post-dates Operation Norman. As discussed above, these revisions affect essentially every geologic system from the Tonian to the Paleocene. Stratigraphic innovations published during GEM include: formalization of lithostratigraphy for the Mackenzie Mountains Supergroup (Long and Turner, 2012; Turner and Long, 2012); recognition of greater stratigraphic complexity in the Ediacaran-Cambrian transition (MacNaughton et al., 2018; MacNaughton and Fallas, 2018, in press), studies of which are still ongoing; revisions to the Cambrian stratigraphy of eastern Mackenzie Mountains (e.g., MacNaughton et al., 2013), including formalization of the new Nainlin Formation (MacNaughton and Fallas, 2014); clarification of the internal stratigraphy of the Cambro-Ordovician Franklin Mountain Formation (Turner, 2011); and the use of biostratigraphy to resolve issues in mapping the Bear Rock Formation and related units in the Colville Hills (Gouwy et al., 2017).

The GEM Program provided an important opportunity to update the Operation Norman generation of maps, not least because the work could be conducted in more detail than was possible during the earlier reconnaissance programs. By comparison, fieldwork for Operation Norman was limited to three summer field seasons. GEM mapping on a subset of the Operation Norman maps included six field seasons of 3-6 weeks each, plus two shorter seasons of 1-2 weeks. As a result, geological boundaries have been traced on the ground and structures mapped in greater detail than was possible for earlier workers. Such revisions have identified additional faults, with associated implications for estimates of shortening across the Mackenzie Mountains, fault-controlled mineralization, and tectonic history. Greater stratigraphic and structural detail is also aiding in ongoing revisions to understanding the tectono-stratigraphic evolution of the Mackenzie region.

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