Introduction and summary

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Abstract: This bulletin summarizes surficial geology knowledge and data produced by the Geo-mapping for Energy and Minerals (GEM) program in the last decade and provides an updated understanding of the nature, distribution, and history of surficial deposits in various glacial terrain types of Canada's North. The advancement in various aspects of surficial geology and the evolution of certain concepts and methods form the subject of the papers that make up this bulletin. Specifically, the papers discuss the status of surficial geology mapping in northern Canada and the development of standards to facilitate map release; highlights from selected GEM surficial geochemical and indicator mineral surveys and the establishment of protocols for drift prospecting; and the revised glacial histories and surficial geology in various regions, from the Mackenzie Mountains to the Labrador coast. This introductory paper to Bulletin 611 describes the scope of the publication and provides a summary of major surficial geology contributions to the GEM program in northern Canada. Remaining knowledge gaps and outstanding issues suggest ideas for future research topics and regions of interest that could inform decisions on mineral exploration and land-use management.

Résumé : Le présent bulletin offre une synthèse des connaissances et des données sur la géologie des formations superficielles produites par le programme Géocartographie de l'énergie et des minéraux (GEM) au cours de la dernière décennie, et fournit une compréhension mise à jour de la nature, de la distribution et de l'histoire des dépôts superficiels dans divers types de terrains glaciaires du nord du Canada. Les progrès réalisés dans divers aspects de la géologie des formations superficielles et l'évolution de certains concepts et méthodes font l'objet des articles qui composent ce bulletin. Plus précisément, on y traite de l'état de la cartographie géologique des formations superficielles dans le nord du Canada et de l'élaboration de normes visant à faciliter la diffusion des cartes; des faits saillants de certains levés géochimiques et de minéraux indicateurs réalisés dans le cadre du programme GEM ainsi que de l'établissement de protocoles pour la prospection glacio-sédimentaire; et de la révision de l'histoire glaciaire et de la géologie des formations superficielles dans diverses régions, des monts Mackenzie à la côte du Labrador. Cet article d'introduction au Bulletin 611 décrit la portée de la publication et fournit un résumé des principales contributions en géologie des formations superficielles au programme GEM dans le nord du Canada. Les lacunes dans les connaissances et les questions en suspens laissent entrevoir des sujets de recherche future et des régions d'intérêt qui pourraient éclairer les décisions en matière d'exploration minérale et de gestion de l'utilisation des terres.

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INTRODUCTION

The surface of the Canadian landscape as we know it today largely results from geological processes that occurred during the last 2.6 Ma because of Quaternary glaciations. Relict surfaces that formed earlier in late Tertiary time are important in the northwest part of the country, especially in the Yukon, but they have been considerably modified during subsequent glaciations by glacial and fluvial processes. Glaciations, caused by pronounced climatic changes, are responsible for the erosion of the substratum, deposition of unconsolidated surface materials, and the rise and fall of sea level. In Canada's North, surface materials form extensive and often thick deposits, concealing bedrock and potential mineral resources it might contain, filling valleys and lowlands traversed by sparse infrastructure, or shaping the ground surface underlain by permafrost on which communities are established.

There is a long and rich history of Quaternary research and fieldwork by the Geological Survey of Canada (GSC) in the vast and remote areas of Canada's North. One of the last co-ordinated efforts to integrate knowledge about glacial deposits of northern Canada was captured as part of the Decade of North American Geology volume and maps on the Quaternary geology of Canada and Greenland (Fulton, 1989). Much work and research have been accomplished since the publication of that authoritative synthesis on the surficial geology of Canada at a regional scale. The Geo-mapping for Energy and Minerals (GEM) program, launched in 2008 to modernize and update our geological knowledge of Canada's North, was completed on March 31, 2020. Phases 1 (2008–2013) and 2 (2014–2020) of GEM produced new, publicly available, regional-scale geoscience knowledge on the surficial geology of a number of areas in northern Canada. New GEM knowledge and data produced in the 12 years of GEM-1 and GEM-2 have helped us to better understand the nature, distribution, and history of surficial deposits in Canada's North. This compendium bulletin summarizes a number of major contributions to the GEM program on the surficial geology of northern Canada and identifies gaps in knowledge and outstanding issues for future work.

SUMMARY

More than 1 700 000 km^2 of Canada's North, including large parts of the Northwest Territories and Nunavut and the northern parts of British Columbia, Saskatchewan, Manitoba, Quebec, and Newfoundland and Labrador, have been covered by numerous surficial geology GEM projects (Fig. 1). The advancement in various aspects of surficial geology and the evolution of certain concepts and methods form the subject of this bulletin, a companion to the other GEM synthesis bulletins. Following this introduction, which describes the scope and approach of this bulletin, Kerr et al. provide a general overview of the status of surficial geology mapping north of 60°N. The GEM program made available new digital surficial geology maps for large sectors of northern Canada, resulting in an increase of 12% in mapping cover and leading to about 70% of the North being mapped and digitally available. Kerr et al. describe the development of the Surficial Data Model (SDM) and the Canadian Geoscience Map (CGM) series to facilitate the production of surficial geology maps in a common standard format, and they review improvements in the accuracy of remote predictive mapping methods that complement and support the classical surficial geology mapping approach. Kerr et al. also provide a complete list of GEM surficial geology maps and a list of GEM publications on the remote predictive mapping of surficial materials.

A significant buildup of rigorous surface compositional data sets occurred as part of the GEM program. The paper by McClenaghan et al. provides highlights from selected GEM surficial geochemical and indicator mineral surveys and case studies conducted around known mineral deposits in lake sediments, stream sediments, stream waters, lake waters, and tills across approximately 1 000 000 km^2 of northern Canada, including areas of interest for mineral exploration. The paper draws attention to areas with anomalous concentrations of elements and/or indicator minerals that are indicative of bedrock mineralization for a broad range of commodities and to the development of new mineral exploration models and surficial protocols. McClenaghan et al. list all publications that report GEM geochemical and mineralogical data and describe the surficial sample media and analytical methods used.

The following five papers summarize different aspects of the glacial history in selected areas (Fig. 1). These papers provide a comprehensive review and integration of legacy and new surficial data sets in a number of regions studied before or during the GEM program and stretching from the Mackenzie Mountains to the Labrador coast. Authors approached each regional paper differently. Duk-Rodkin and

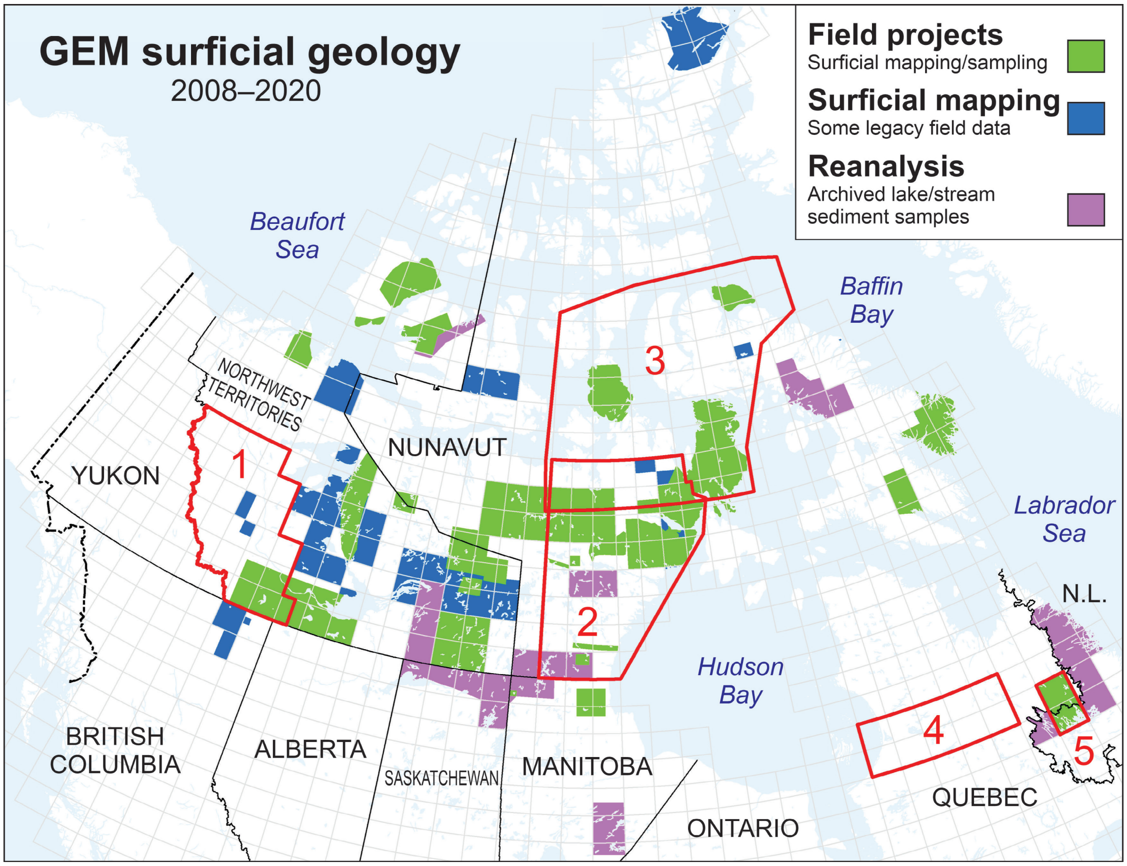

Figure 1. Location of GEM surficial geology projects in northern Canada. Field projects include surficial geology mapping, thematic research, and surficial geochemical and indicator mineral surveys (lake and stream sediments and waters, till, eskers) covered in Kerr et al. (this volume) and McClenaghan et al. (this volume). New surficial geology mapping was also completed in some areas using legacy field data. Archived samples were reanalyzed under GEM (mainly lake and stream sediments — *see* McClenaghan et al. (this volume)). Various aspects of the regional glacial history are reported for selected areas outlined in red on the map: 1 = Duk-Rodkin and Barendregt (this volume); 2 = McMartin, Campbell et al. (this volume); 3 = Tremblay and Lamothe (this volume); 4 = Parent (this volume); and 5 = Rice et al. (this volume).

Barendregt's paper covers a large region of western Northwest Territories, framed by the Canadian Shield to the east, northern Interior Plains in its central part, and the Cordillera to the west. It summarizes the Quaternary history of the Mackenzie Mountains and foothills. The glacial history accompanies a map of varying glacial limits, important stratigraphic sites, and locations depicting remnant features of preglacial landscapes. The other four papers cover regions underlain by the Canadian Shield at the core of the continent, forming plains and low-relief hills. The paper by McMartin, Campbell et al. gives an overview of new glacial geomorphological mapping in the Keewatin region of central mainland Nunavut that is based on high-resolution remote imagery, legacy maps, and the integration of large volumes of ground-based data sets. Various glacial landsystems are identified, many of which are entirely new and others of which are significantly modified or updated. The paper provides links to an external scientific paper and an accompanying geodatabase of mapped glaciogenic features, standardized field data sets, and interpreted glacial landsystems. The paper by Tremblay and Lamothe synthesizes ice-flow patterns and chronology in the Boothia–Lancaster ice-stream catchment area using previous and new field-based evidence (striations, glacial erratics, cold-based terrain characteristics) and remote onshore and offshore data. Subglacial thermal regimes, glacial dynamics, and ice-flow events are reconstructed. The paper by Parent summarizes ice-flow history and dynamics in the core region of the Quebec–Labrador sector of the Laurentide Ice Sheet in central Quebec. The summary is based on a regional survey of small-scale features, such as crosscutting glacial striae or faceted bedrock surfaces; and large-scale features, such as eskers, streamlined landforms, and crag-and-tail ridges. The paper also examines the regional dispersal of distinctive indicator clasts (Sakami Formation) in glacial and glaciofluvial sediments. The complex successions of flow patterns in this region provide exceptional examples of polyphase glacial dispersal patterns, ranging from linear and palimpsest dispersal trains to ice-divide migrations. Rice et al., using detailed surficial mapping and till provenance studies, document the relative chronology and erosional intensity of ice-flow events of the south Core Zone area in east-central Quebec and western Labrador. The paper offers important insights into how subglacial conditions fluctuated throughout glaciation and affected the geomorphology of the region, and it discusses the resulting local glacial dispersal patterns.

OUTSTANDING ISSUES

The papers in this bulletin summarize major contributions in the fields of surficial geology and geochemistry, but they describe only part of the research accomplished through the GEM program. Nevertheless, they include key elements of a continued effort to understand the nature and composition of surficial materials and to recognize the main problems associated with reconstructing the history of glaciations in northern Canada. Here we present a brief overview of what we consider to be some of the knowledge gaps and outstanding issues in Canada's North as summarized from the papers presented here. We provide ideas for future research topics and regions of interest that could inform decisions on mineral exploration and land-use management in upcoming geoscience programs in support of a strong northern economy.

Major developments in the reconstruction of paleo-ice sheets and understanding of ice-sheet dynamics have occurred since the 1980s. These developments have been supported by an increase in empirical data used to constrain the interpretation of ice-sheet evolution (e.g. Stokes et al., 2015). In northern Canada, the glacial geological record from onshore and offshore areas has also been significantly augmented during that time, including during the GEM program, which resulted in an increase of 12% in the surficial geological mapping cover north of 60°N (*see* Kerr et al., this volume). Nevertheless, about 30% of northern regions remain essentially unmapped, which not only hampers mineral exploration, but also limits our ability to develop more accurate paleo-ice-sheet reconstructions, assess terrain risks associated with various surficial materials, and identify critical aggregate resources. In particular, large tracts of Baffin Island, Victoria Island, and the Queen Elizabeth Islands, as well as parts of the Yukon, central mainland Nunavut, and central mainland Northwest Territories, have limited surficial geology map coverage other than in national-scale compilations (Prest et al., 1968; Fulton, 1995). These areas generally represent some of the most poorly accessible regions of Canada's North and are underinvestigated from a Quaternary science perspective for a number of reasons. The prioritization of these areas for future mapping will depend on geoscience needs, priorities of northern communities and stakeholders, and the available resources of impending scientific programs. To fill the existing gaps, all mapping approaches — from visual interpretation of aerial photographs and high-resolution remote imagery to machine-learning techniques and spatial recognition — must aim for the highest accuracy. The methods developed for remotely mapping landforms and surface materials will result in detailed and accurate geological maps only if the methods are supported and validated by field-based, high-quality data and incorporated with expert knowledge.

The coverage of publicly available geochemical and indicator mineral data in Canada's North considerably increased during the GEM program, and together with data from previous GSC and territorial surveys, now represents about two thirds of northern Canada (*see* McClenaghan et al., this volume). However, large areas underlain by prospective rocks, in places covered by thick sequences of glacial sediments or having little information on provenance, have yet to be assessed. These areas include parts of the western Northwest Territories underlain by Paleozoic bedrock, the Slave Craton, the western Churchill geological province, and the northern Superior Craton.

In addition to new surveys, reanalysis of GSC archives in some of these areas using modern analytical methods will provide valuable and cost-efficient means of mineral-potential mapping. Improved and evolving GSC protocols for collection and analysis of surface materials, combined with the development of leading-edge data-driven methods using multiscale and multidisciplinary data sets, will streamline the compilation, integration, and analysis of the data that will support new opportunities for mineral exploration and for environmental baseline assessments. Future directions in geochemical research at the GSC should include an investigation of how portable field and laboratory geochemical methods can better deliver regional geochemical survey results. The expansion of mineral suites and mineral chemistry studies for fertility assessments around known mineral deposits, as well as the continued testing of automated mineralogical analysis of indicator minerals in all fractions of surficial sediments, particularly the fine-grained (<0.25 mm) matrix portion, is also needed.

Additionally, enhanced comprehension of glacial sediment provenance, stratigraphy, and dispersal patterns is required in various glacial terrain types. Specifically, studies in areas affected by complex ice-flow dynamics and changing basal thermal regimes, such as areas once covered by ice streams, under former ice divides, or comprising weathered landscapes preserved under cold-based conditions, will enable a better interpretation of geochemical anomalies and selection of appropriate surface exploration methods.

Though our understanding of regional aspects of the Quaternary geology of northern Canada has progressed since the start of the GEM program, there are still several factors limiting a more precise interpretation of the glacial record. These factors, common to many Quaternary research projects in glaciated terrains, are amplified by the sheer size and remoteness of Canada's North. Two of these factors are the inadequate mapping of glacial geomorphology at a detailed scale (e.g. with ArcticDEM); and the uneven distribution and poorly integrated field observations from years of northern research by government and academia. Although compilation work has advanced in a large area of central mainland Nunavut (*see* McMartin, Campbell et al., this volume) and southwestern Northwest Territories (Duk-Rodkin and Barendregt, this volume) and is in progress around the Gulf of Boothia (Tremblay and Lamothe, this volume), the acquisition, integration, and synthesis of large volumes of detailed and well-structured data sets need to continue in regions covered by the GEM program and beyond. Another factor is the difficulty in establishing chronological and stratigraphic relationships of the glacial sediments. The scarcity of dated materials in the glacial units, the poorly accessible stratigraphy frozen in permafrost or partially preserved along riverbanks, and the limitations of current dating methods all play a role. Though western Northwest Territories and Yukon have been more widely studied and glaciations are better constrained, our ability to produce reconstructions of glaciations predating the last one, to define events of the last glaciation, or to identify patterns and styles of deglaciation over the Canadian Shield has been more limited. Other complicating factors in interpreting glacial histories and evaluating glacial transport are the complexity and variable intensity of erosional and depositional processes and events, potentially separated by nonglacial events or changing subglacial thermal conditions. Such interplay results in glacial sediment composition inherited from previous events or not reflecting a simple history determined by mapping only the most recent landforms and striations (*see* Parent, this volume; Rice et al., this volume).

Some of the uncertainties and interpretation problems associated with the Laurentide Ice Sheet history mentioned above could be tested and perhaps resolved in key areas of the North. One of these areas is a vast and poorly accessible region straddling the Slave and western Churchill provinces at the boundary between Northwest Territories and Nunavut. This area was at the centre of a major ice dome of the Laurentide Ice Sheet and hosts a large zone of relict landscapes of unknown age or significance (e.g. Campbell et al., 2019), the terminus of the Dubawnt Lake Ice Stream (McMartin, 2017; Campbell et al., 2019), and poorly dated major ice retreat positions at the MacAlpine Moraine System (Dyke et al., 2003; Dalton et al., 2020). Additionally, the timing and subglacial conditions associated with the eastern extent of the Laurentide Ice Sheet, near the Labrador coast, remain poorly constrained (e.g. Dalton et al., 2020). More detailed work focusing on the abundant ice streams in this region and more data constraining the age of ice retreat would significantly improve our understanding of the eastern Laurentide Ice Sheet. An examination of the glacial record in these areas, including geomorphological mapping using high-resolution imagery supported by new geochronological data and targeted glacial sediment sampling, would form a solid basis for further refinement of the glacial history of Canada's North and provide the appropriate framework for mineral exploration. Similar compilations and research projects in other portions of the territories and northern parts of provinces would improve the resolution of the proposed reconstructions and increase our understanding of sediment provenance in key regions of northern Canada with mineral potential.

It is hoped that this bulletin will serve as a source of information by providing the references to published work on those regions covered by the GEM program and that the themes discussed here will stimulate new ideas and provide a starting point for future research in Canada's North.

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It is impossible to do justice to the various individual projects and activities carried out during the GEM program, but we have endeavoured to provide at least a summary of some of the major scientific contributions. Federal, territorial, and provincial geological surveys, as well as academia, have contributed to this bulletin. The papers have undergone internal and external reviews by GSC researchers (Alain Plouffe, Roger Paulen, Dan Kerr, Pierre-Marc Godbout, Rod Smith, Janet Campbell, Éric Boisvert), former or current GSC emeritus scientists (Jean Veillette, Art Dyke, Bob Garrett, Lionel Jackson), and external partners from academia (Martin Ross) and industry (Steve Cook), and we thank all of them for their thorough comments and suggestions.

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