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PREPRINT 1

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Abstract

The GEM program has facilitated the availability of new and converted surficial geology maps and associated digital datasets for large sectors of northern Canada, leading to about 70% of the north being mapped and digitally available. Development of the Surficial Data Model (SDM) and Canadian Geoscience Map (CGM) series have streamlined the publication process and created a common standard digital map format and geodatabase. Based on traditional and more recent remote predictive mapping methodologies, there are now three types of surficial geology CGM maps produced: Surficial Geology, Reconnaissance Surficial Geology, and Predictive Surficial Geology. The considerable number of new surficial geology maps published during GEM-1 and GEM-2, as well as upcoming map publications, has resulted in an increase of 12% map coverage north of 60˚, constituting a significant and lasting legacy of the GEM Program.

Résumé

Le programme GEM a facilité la disponibilité de nouvelles cartes géologiques des formations superficielles, de cartes converties et d'ensembles de données numériques connexes pour de grands secteurs du Nord du Canada, ce qui a entraîné la cartographie et la disponibilité numérique d'environ 70 % du Nord. L'élaboration du modèle de données de géologie des formations superficielles et de la carte géoscientifique canadienne a simplifié le processus de publication et créé un format de carte numérique standard commun et une géodatabase. Basé sur les méthodologies de cartographie traditionnelles et prédictives plus récentes, il existe maintenant trois types de cartes de géologie des formations superficielles: la géologie des formations superficielles, la géologie des formations superficielles reconnaissance, et la géologie des formations superficielles prédictive. Le nombre considérable de nouvelles cartes géologiques de surface publiées au cours de GEM-1 et GEM-2, ainsi que les publications cartographiques à venir, a entraîné une augmentation de 12 % de la couverture cartographique au nord de 60˚, ce qui constitue un héritage important et durable du programme GEM.

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1. INTRODUCTION

The gathering of geoscientific information to map the geology of the country has been a key activity of the Geological Survey of Canada since its foundation in 1842. It took twenty-two years to produce the first national-scale geological map (Logan, 1864) followed one year later by the first surficial geology map depicting the distribution of unconsolidated glacial and post-glacial deposits between Lake Superior and Gaspé (Logan, 1865). This map represented the first step at demonstrating the importance of surficial geology mapping for the economic development of the landmass that was to become Canada after the Confederation in 1867.

Although the objective of this introduction is not to present a complete historical perspective and evolution of surficial geology mapping at the GSC, we summarize below some of the major milestones which impacted the interpretation of the surficial geology landscape of Canada to bring into perspective the new mapping efforts accomplished as part of the GEM Program. Our summary is meant to complement the historical perspective on surficial geology mapping at the GSC presented by Fulton (1993) in a special issue of the Canadian Journal of Earth Sciences dedicated to the 150th anniversary of the GSC.

The first surficial geology maps were produced without aerial imagery of any sort. They were based on field work and ground observations along the highways of the time: rivers, lakes, marine shorelines and rare roads. The themes addressed were varied. Some were more academic such as a map showing three positions of a Keewatin dispersal centre northwest of Hudson Bay in a GSC report by Tyrrell (1897), largely based on the measurements of glacial striations along river ways in the core of the ice sheet. Although Tyrrell's map does not classify as a surficial geology map, it was the first glacial history reconstruction of the Laurentide Ice Sheet depicted on a map and derived from surficial geology observations. Other GSC surficial projects and their related products clearly had objectives related to the development of natural resources, such as maps illustrating surficial geology elements of the Klondike gold fields in the unglaciated part of the Yukon by Johnston (1900, 1905).

The availability of airphotos in the 1950's marked a major milestone on the interpretation of the Canadian landscape by surficial geologists. The bird's eye view of the land surface allowed the observation of landforms that could not be deciphered from a point of observation on the ground. Ultimately, this led to a wide range of surficial geological observations obtained by over 140 geologists of the GSC and provincial departments which were compiled on the first Glacial Map of Canada by Wilson et al. (1958). This benchmark product influenced and demonstrated the value of airphotos for mapping the surficial geology. A decade later, Prest et al. (1968) presented an updated version of the Glacial Map of Canada resulting from a compilation effort of existing maps and from the colossal task of interpreting surficial geology landforms and sediments with airphotos for previously unmapped parts of the country. The map is still abundantly cited in the scientific literature today depicting a broad view of the main surficial geology elements of the country such as unglaciated areas, the large expanses of land covered by various glacial, glaciofluvial, glaciolacustrine and marine sediments, general glacial lineation patterns, and some dominant moraines of the Laurentide Ice Sheet such as Sakami and St. Narcisse in Québec, Cree Lake in Saskatchewan, The Pas in Manitoba and Chantrey in Nunavut.

Twenty seven years later, surficial geology mapping conducted throughout Canada by provincial, territorial and the federal geological surveys was compiled into the Surficial Materials Map of Canada by Fulton (1995). This compilation product largely relied on the basic foundation of interpreting the land surface from airphotos confirmed by field work and ground observations. In parallel to the production of surficial maps showing polygons, lines and points of all surficial geology elements, derivative maps depicting ice front retreat positions, ice flow patterns and specific landforms were constructed from various surficial geology datasets. The maps of the paleogeography and ice margin chronology of North America by Dyke and Prest (1987) and Dyke et al. (2003), and the glacial features map around the Keewatin Ice Divide by Aylsworth and Shilts (1989), are examples of such products.

Throughout the years, airphotos have been progressively augmented by other types of remote imageries. The advent of multiple types of satellite imageries and topographic data (Landsat, Radarsat, digital elevation model-DEM) progressively became of common use to interpret landform continuums that could not easily be identified on airphotos because of their extensive size, and surface materials. Certain aspects of the ground conditions provided from specific spectra of satellite images (e.g. moisture, vegetation cover) contributed valuable data for the interpretation of the surficial sediments. In the last ten years, an increase availability of images created by the light detection and ranging method (LIDAR) has provided an unprecedented view of the land surface without the obstruction from a canopy cover. So far unnoticeable subtle features at the land surface can now be mapped from LIDAR imagery in an unparalleled level of detail. However, the availability of large coverage of LIDAR images dominantly remain restricted to the southern populated regions. For areas north of 60˚, the recently available ArcticDEM generated with high-resolution satellite images (PGC, 2019) represents a breakthrough for detailed geomorphological mapping in the Canadian Arctic.

Since the early days of surficial geology mapping in Canada, surficial geology projects and field activities in northern Canada have been completed by the Geological Survey of Canada, the Yukon Geological Survey, the Northwest Territories Geological Survey and the Canada-Nunavut Geoscience Office. Surficial geology maps were produced to address a wide range of questions and issues from glacial history and sea level reconstructions, mineral exploration, evaluation of natural hazards, permafrost studies, granular resources, environmental assessments, infrastructure development (e.g. roads, pipelines, hydro lines), hydrogeology, and more. Despite these efforts, extensive landmass of northern Canada remained unmapped until the early 21st century. Given the necessity of modern geoscience information required for the sustainable and responsible economic development of the North, the federal government financially invested in the mapping of the North by implementing the Geo-mapping for Energy and Minerals Program (GEM), a 12 years (2008-2020) initiative led by Natural Resources Canada.

The completion of the GEM program has facilitated the availability of surficial geology maps and associated datasets for large sectors of northern Canada in a common standard format. Prior to the GEM Program, surficial geology maps were produced in different formats and styles which restrained their utility across large areas and territorial boundaries. Through the GEM program, standardization of surficial geology data was accomplished by: 1) the digital compilation of existing surficial geology maps to modern formats, 2) mapping of "white-space" areas by conventional airphoto interpretation and field-based studies, supported by satellite imagery and DEM visual interpretation, and 3) mapping using remote sensing imagery in an attempt to predict the surficial geology elements (remote predictive mapping - RPM). Early in this surficial geology mapping effort, it became clear that there was a need to provide surficial geology data in a consistent structured digital format so that the information could be used to its full potential. Such requirement was the foundation for the development of a Surficial Data Model (Deblonde et al., 2012) which we describe in the next section of this chapter (Section 2).

The current extent of surficial geology mapping north of 60°, which combines pre-GEM and new maps produced in the 12 years of GEM-1 and GEM-2 projects, is described in Section 3. A large part of the new maps relied on stereoscopic analysis of airphotos augmented by field work and interpretation of remote imageries. In addition to this "classical" approach, much effort was devoted to the development of remote predictive mapping (RPM) methods largely based on automated interpretation of remote imageries, a form of machine learning. Comparison of the human and machine products has enabled the development of automated tools with at least a regional efficiency for some surface materials. We review progress accomplished with the RPM method by the GSC and collaborators in Section 4.

2. SURFICIAL DATA MODEL: IMPLEMENTING A STANDARD DATA STRUCTURE FOR PUBLICATION

History

The first surficial geology maps of the GSC were using symbols generally recognized by the international scientific community. For example, the extent of sediment types was shown with colored polygons by Logan (1865) and striations were depicted as a straight line crossed by a bow-shape line near the end pointing in the down-ice direction by Tyrrell (1897). The style and type of information depicted on the surficial geology maps and their legend have greatly evolved since these first two maps. Fulton (1993) provides an historical perspective on the evolution of mapping system and legend style used on surficial geology maps. Throughout this evolution, the need for consistency of information represented on geological maps produced by the GSC was first officially recognized in a guide to authors for the preparation of maps and reports (Cairnes and Rice, 1957). Since then, a series of "Guide to authors" with variable amounts of material related to the symbology and format of legends of geological maps have been produced by the GSC (Rice and Harker, 1961; Blackadar et al., 1975, 1979; GID Editorial Board, 1998; Weatherston et al., 2016). More detailed mapping standards at the GSC were included in Debain et al. (1972) and various Geological Survey of Canada (1975, 1984, 1990) reports. Similar guides were prepared by provincial geological surveys (e.g. Ryder and Howes, 1984; Resources Inventory Committee, 1996; Howes and Kenk, 1997).

From approximately the late 70's to the late 90's, a surficial geology legend review committee was in place at the GSC to ensure that the consistency, logic, and minimal content of the legend was respected (Fulton, 1993). The committee verified that basic information such as unit texture, thickness and general description were included in the map unit description. In 1998, R.J. Fulton produced an unpublished report on the standards and protocols for surficial geology mapping which strongly recommended a letter-based mapping system based on deposits genesis (Fulton, 1998).

Prior to the GEM Program, the GSC released surficial geology maps under three product types: Preliminary series, Open Files and A-series. Examples of these maps can be viewed on-line at geoscan.nrcan.gc.ca. The preliminary maps were typically black and white or two-colour maps reproduced on National Topographic System (NTS) map sheets. This type of paper map was used until the early 1990's. Their simple, hand-drawn style (i.e. black and white with no or limited colour) allowed easy reproduction and relatively fast publication processes. Open File maps ranged from hand-drawn maps to later digital coloured maps designed for quick release. These were also considered preliminary surficial geology maps typically for on-going projects. Following a project completion, the final authoritative maps were released as A-series coloured maps which required two scientific and one editorial reviews. In some cases, A-series maps were compiled from and produced at a smaller scale than Open File or Preliminary maps.

Discussions of regional surficial geology map compilations (Kerr and Knight, 2005; McMartin et al., 2006) and a GSC surficial geology common legend were consolidated in 2008 within the North of 60° Surficial Geology Compilation Project, under GSC's Northern Resources Development Program, and then moved to the GEM-1 Knowledge Management Program as part of the Tri-T Surficial Geology Compilation and GeoMap Flow projects (Kerr et al., 2008, 2009). Throughout 2008-2009, a preliminary Surficial Mapping Data Model (geodatabase and common legend) was developed by a group of GSC researchers (Alain Plouffe, Daniel Kerr, Isabelle, McMartin, Lynda Dredge, Art Dyke, Michel Parent, Serge Paradis, Dave Sharpe, Alejandra Duk-Rodkin, Denis St-Onge, David Huntley) and publication staff (Dave Everett, Evelyn Inglis, Guy Buller, Christine Deblonde, Allison Weatherston, Andrew Moore, Louis Robertson, Denis Giroux, Boyan Brodaric).

Facilitation of the map publication process and the development of a common data structure were two objectives of GEM-1 Knowledge Management Program. The Surficial Data Model (SDM) was proposed as a key tool for standardization of map units, symbols, and datasets associated with surficial geology maps to be published as part of GEM, but also to be used by mappers in other GSC Programs.

Creation of the Surficial Legend Committee

In 2010, a Surficial Legend Committee (SLC) was created at the GSC to develop the scientific language and the data structure of the SDM, under the GeoMap Flow GEM-1 project. The SLC continued to expand the original SDM of 2008-09. Regular weekly to monthly meetings brought different mapping experts from all regions of Canada (Alain Plouffe, Daniel Kerr, Michel Parent, Denis St-Onge, David Huntley), and GIS expertise (Dave Everett, Evelyn Inglis, Guy Buller, Christine Deblonde, Allison Weatherston, Andrew Moore). Subsequent members were added, including Rod Smith, Janet Campbell, Robert Cocking, Sean Eagles, and Louis Robertson.

As part of the SDM development and issuing discussions, the following process was established for the SLC: 1) each of the surficial geologist member has a vote, and the majority rules; 2) technical members have a veto (in the case where proposed additions/changes cannot be done from a technical point of view); and 3) if an issue arises that should be sent to the broader mapping community, it will be, and a decision will be made on a 51% majority vote of the SLC.

In 2012, the SLC published its first version of the SDM which is considered the first national common surficial geology legend (Deblonde et al., 2012). Since then, it has been updated on a periodic basis based on requests from mappers (Deblonde et al., 2014, 2017, 2018, 2019; Cocking et al., 2015, 2016). Up to 2015, the list of changes contained many revised or additional legend features, but since 2016, the number of requests has been low (5 or less changes per year). From the onset, it was clear that the SDM was to be a live database which would require periodic changes and additions based on the wide expertise and demand of all mappers. As such, the SLC created a form to submit proposed changes or additions to the SDM which are to be evaluated by the SLC. The objective is to promote an open discussion between the SLC and the mappers. To optimize the review process and to avoid constant changes to the SDM that would affect map production, the proposed changes are to be submitted by November 1st of each year and their review completed by December 1st. Changes to the SDM are then published by March 31st.

The main objective of the SDM is to standardize the terminology and symbology of surficial geology maps that ultimately facilitate map production, and the compilation of data from different sources. In the past, surficial geology maps were strictly paper products but, with the advent of personnel computers, field digital devices and geographic information systems came the demand for vector data depicted on the maps. The publication of digital data associated to a surficial geology map provided an opportunity to include additional information that otherwise could not be depicted on a paper map (e.g. field notes attached to features).

Structure of the Surficial Data Model

The SDM incorporates both the traditional visual characteristics of a geological map and the digital geoscience data used to create it, integrating field observations and interpretations of airphotos and other remote imagery (satellite, digital elevation models). The use of consistent surficial geological map units, standard line and point symbols, and overlay patterns, enables the timely compilation and publication of geological maps.

The SDM includes three broad components: 1) map units represented by coloured polygons and line boundaries; 2) geomorphological features represented by overlay polygons, lines, and points; and 3) field observations, measurements and/or samples represented by points. The SDM does not include elements that are depicted on figures in the margin of a surficial geology map, or on thematic maps such as ice-flow or drift thickness maps.

Map units are shown at the top of the map legend and listed in a chronological order with the youngest unit at the top and the oldest at the bottom, typically bedrock. The most common order of map units is presented in Table 1. This typical order of map units may need to be adapted to a particular map area. Line and point symbols are placed below the map units. Like the map units, they are listed in order of age with the youngest at the top. Units formed in subglacial settings are older than those associated with ice-marginal processes, which are assumed to be older than features associated with proglacial environments. Glacial features are assumed to be older than glaciolacustrine and/or glaciomarine features. Post-glacial features and those associated with active processes (permafrost, landslides, avalanche tracks, etc.) are the youngest. Items that do not have a geological time connotation (e.g. sample site, gravel pit, field station) are placed at the bottom of the list. By convention, geological contacts are placed at the top of the symbol list. Symbol order can be modified from the default order suggested in the SDM, following the geological particularity of a map area.

Map unit

A map unit is defined as an area of the earth surface underlain by material of a single genesis, nature, and/or thickness. The limit of a map unit is defined by a combination of field and remote observations (e.g. airphotos) which include but are not limited to geomorphology, tone, texture, patterns, landform association, composition, vegetation, feature orientation, and geometry. These attributes are then used to infer the genesis, the environment of deposition, and the relative geological age of the deposits that make up the unit.

Each map unit has a unique designator and an associated colour. The map unit designator uses a combination of upper- and lower-case letters and numbers (Fig. 1). One or two upper-case letters define the primary genesis of the material or process (Table 1). The upper-case letter(s) is followed by one or two lower-case letters that reflect a category defined by morphology (e.g. hummocky), environment of deposition (e.g. nearshore sediments) or thickness (e.g. veneer) (Fig. 1).

Numbers placed beside the category designator can be used for sub-categories defined by geological processes (e.g. landslide deposits related to retrogressive thaw flow or rotational slump), depositional environment (e.g. subaerial and subaqueous outwash fan sediments), sediment composition (e.g. calcareous till blanket) or sedimentary structure (e.g. stratified and unstratified talus scree sediments) (Fig. 2).

In some parts of Canada, recourse to geological events may be required to differentiate map units. In such instances, lower case letters are placed in front of the map unit designator to define the geological events which could be geochronological (e.g. Late Wisconsin versus Holocene), depositional or erosional (e.g. Amundsen glaciation, Tuk Phase ice advance), or related to provenance (e.g. Laurentide Ice Sheet versus Cordilleran Ice Sheet) (Fig. 3).

Table 1. *Map unit letter designators.*

Map unit designator	Map Unit	Subcategory
	Glacial Ice or Snowpack	
Isn	Snowpacks	
I	Glacier or icefield or icecap	
	Anthropogenic deposits	
H	Undifferentiated	
	Organic deposits	
Owf	Fen deposits	
Owb	Bog deposits	
Ows	Salt marsh	
Ov	Veneer	
Ob	Blanket	
O	Undifferentiated deposits	
	Eolian sediments	
El	Loess	
Er	Dunes	
Ev	Veneer	
E	Undifferentiated sediments	
	Colluvial and mass-wasting deposits	
Cf	Fan sediments	
Ca1	Apron or talus scree deposits	Stratified
Ca2	Apron or talus scree deposits	Unstratified
Ca	Apron or talus scree deposits	Unspecified
Cz1	Landslide deposits	Avalanche
Cz2	Landslide deposits	Mud flow
Cz3	Landslide deposits	Retrogressive thaw flow
Cz4	Landslide deposits	Rotational landslide
Cz5	Landslide deposits	Translational landslide
Cz	Landslide deposits	Unspecified
Cg	Rock glacier	
Cv	Veneer	
Cb	Blanket	
C	Undifferentiated deposits	
	Alluvial sediments	
Ap	Floodplain sediments	
Af	Fan sediments	
Ai	Intertidal or estuarine sediments	
At	Terraced sediments	
Av	Veneer	
Ab	Blanket	
A	Undifferentiated sediments	
	Lacustrine sediments	
Lr	Beach sediments	
Ld	Deltaic sediments	
Ln	Littoral and nearshore sediments	
Lo	Offshore sediments	
Lv	Veneer	
Lb	Blanket	
L	Undifferentiated sediments	
	Marine sediments	
Mt	Terraced sediments	
Mr	Beach sediments	
Md	Deltaic sediments	
Mi	Intertidal sediments	
Mn	Littoral and nearshore sediments	
Mo	Offshore sediments	
Mv	Veneer	
Mb	Blanket	
M	Undifferentiated sediments	
	Glaciomarine sediments	
GMr	Beach sediments	
GMd	Deltaic sediments	
GMi	Intertidal sediments	
GMn	Littoral and nearshore sediments	
GMo	Offshore sediments	
GMf	Submarine outwash-fan sediments	
GMm	Submarine moraine complex	
GMv	Veneer	
GMb	Blanket	
GM	Undifferentiated sediments	

Table 1. *Map unit letter designators (continued).*

	Glaciolacustrine sediments	
GLr	Beach sediments	
GLd	Deltaic sediments	
GLn	Littoral and nearshore sediments	
GLo	Offshore sediments	
GLf	Subaqueous outwash-fan sediments	
GLm	Subaqueous moraine complex	
GLh	Hummocky sediments	
GLv	Veneer	
GLb	Blanket	
GL	Undifferentiated sediments	
	Glaciofluvial sediments	
GFp	Outwash plain sediments	
GFt	Terraced sediments	
GFf1	Outwash fan sediments	Subaerial
GFf2	Outwash fan sediments	Subaqueous
GFf	Outwash fan sediments	Unspecified
GFh	Hummocky sediments	
GFc	Ice-contact sediments	
GFk	Kame terrace	
GFr	Esker	
GFv	Veneer	
GFb	Blanket	
GF	Undifferentiated sediments	
	Glacial sediments	
Tg	Rock-glacierized moraines	
Th1	Hummocky till	Carbonate/calcareous
Th	Hummocky till	Unspecified
Tm1	Moraine complex	Carbonate/calcareous
Tm	Moraine complex	Unspecified
Tr1	Ridged till; moraine	Carbonate/calcareous
Tr	Ridged till; moraine	Unspecified
Ts1	Streamlined till	Carbonate/calcareous
Ts	Streamlined till	Unspecified
Tp1	Till plain	Carbonate/calcareous
Tp	Till plain	Unspecified
Tx1	Weathered till	Carbonate/calcareous
Tx	Weathered till	Unspecified
Tv1	Veneer	Carbonate/calcareous
Tv	Veneer	Unspecified
Tb1	Blanket	Carbonate/calcareous
Tb	Blanket	Unspecified
T	Undifferentiated sediments	Unspecified
	Weathered bedrock or regolith	
Wv1	Veneer	Carbonate/calcareous
Wv	Veneer	Unspecified
Wb1	Blanket	Carbonate/calcareous
Wb	Blanket	Unspecified
W1	Undifferentiated regolith	Carbonate/calcareous
W	Undifferentiated regolith	Unspecified
	Volcanic deposits	
Vpy	Pyroclastic sediments	
V	Undifferentiated volcanic deposits	
	Undifferentiated deposits	
U	Undifferentiated deposits	
	Bedrock	
R1	Sedimentary	
R2	Igneous	
R3	Metamorphic	
R	Undifferentiated	

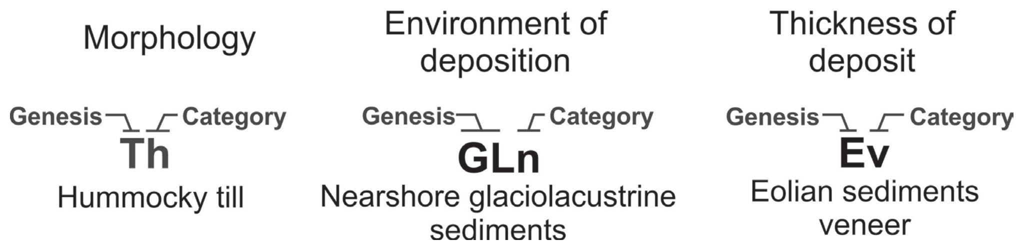

Figure 1. *Map unit designators use a combination of upper- and lower-case letters and numbers. One or two upper-case letters define the primary genesis of the material or process followed by one or two lower-case letters that reflect a category defined by morphology, environment of deposition, or thickness.*

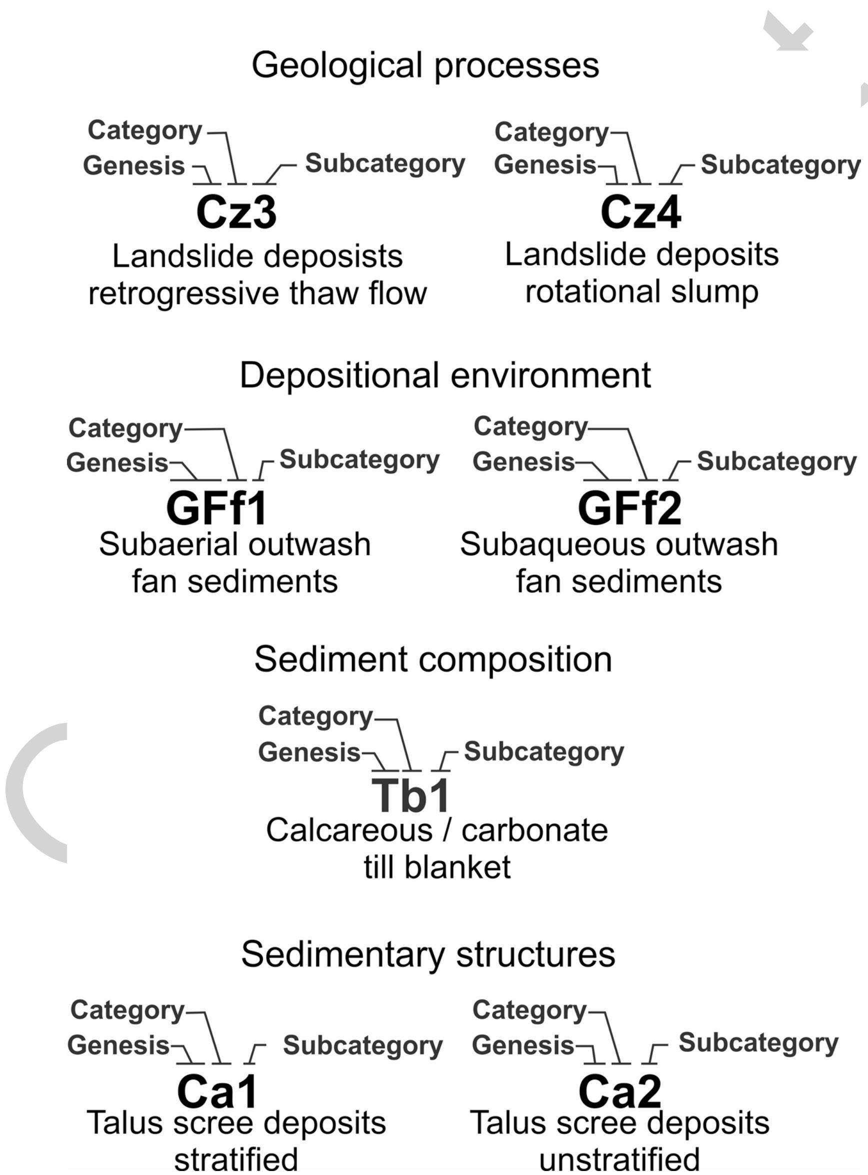

Figure 2. *In the map unit designator, a number placed beside the category designator can be used for sub-categories defined by geological processes, depositional environment, sediment composition or sedimentary structure.*

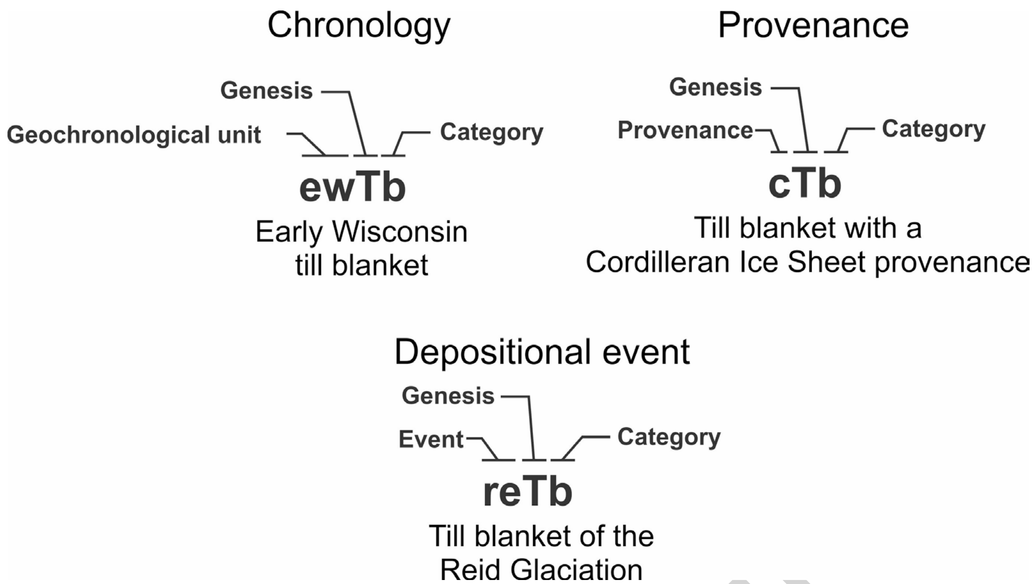

Figure 3. *Lower case letters placed in front of the map unit designator define a geological event. Geological events are depositional, erosional, or defined by geochronology or provenance.*

To avoid unnecessary long map unit designators, the geological event does not need to be added if all units on the map belong to the same geological event. For example, the label "lw" is not required on till units of a single map if they are all of Late Wisconsin age. Similarly, if two identical map units of different geological event-attributes are present in a map area, the prefix is only placed on one of them. For example, in a region with a Late Wisconsin and a Neoglacial till blanket, map-unit designators should be Tb and nTb, respectively, as opposed to lwTb and nTb. The reader is referred to the map unit poster in Deblonde et al. (2018) for the latest and complete list of map units including categories, sub-categories, and geological events included in the SDM.

Five types of geological boundaries are available to define the limit of map units (Cocking et al., 2015 and later version of the SDM). Defined, approximate and inferred boundaries follow the bedrock geology mapping nomenclature with a decreasing level of confidence of the map-unit boundary from defined to approximate to inferred. Concealed boundaries are used in rare localities where a previously mapped area is now flooded following the construction of a dam and reservoir. Lastly, arbitrary boundaries through water are used to close polygons under water bodies. Arbitrary boundaries are not depicted in the map legend and are only visible in the digital version of map documentation.

For some regions, the complex surficial geology may include units too small to be mapped individually given the scale used. In such instances, a complex unit designator can be used which contains a maximum of two map units separated by a dot (Fig. 4). The units are shown in order of importance and the polygon on the map contains the color of the most abundant unit.

In addition to complex units, stratigraphic relationships between map units may be observed and required on surficial geology maps in some regions or projects. This could be of importance in a mapping project that targets granular resources and where a veneer of glacial lake sediments overlies glaciofluvial aggregates. The stratigraphic relationship can be shown with a forward slash ('/') that separates the two units following their stratigraphic order (Fig. 5). A polygon with a stratigraphic map unit designator is coloured according to the overlying unit. All map units must be described in the legend, including units which only appear as secondary or underlying units in complex and stratigraphic relationship designators.

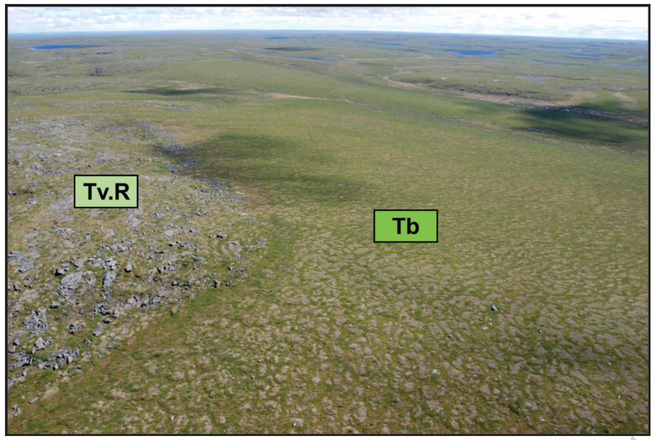

Figure 4. *Complex map unit designators are used when two map units are too small to be mapped separately. A maximum of two units separated by a dot are shown in order of importance (most abundant unit first). This example from the eastern Northwest Territories shows a complex unit of till veneer interspersed with outcrops (Tv.R) beside a till blanket (Tb). Photograph by P.X. Normandeau. NRCan photo 2019-283*

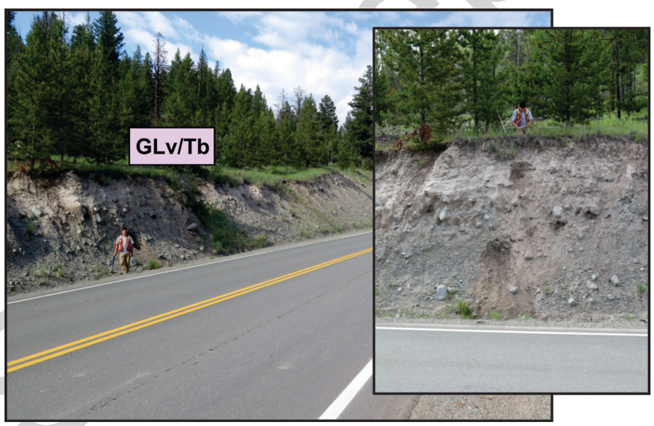

Figure 5. *A stratigraphic relationship between two map units is shown with a forward slash ('/') that separates the two units following their stratigraphic order (top unit first). A polygon with a stratigraphic map unit designator is coloured according to the overlying unit. This example from south-central British Columbia shows a veneer of glaciolacustrine sediments (GLv) overlying a till blanket (Tb). Photograph by A. Plouffe. NRCan photo 2019-285 and 2019-286*

The map-unit legend contains the description of the material for all units depicted on the map according to the basic elements described below. The style of the map-unit description varies from short summaries to longer descriptive text depending on mappers' preference. However, basic elements and their order include: map-unit name, grain size (texture), structure, range of thickness, geomorphology, stratigraphic relationships, depositional environment, and other characteristics. For example: Glaciolacustrine nearshore sediments: well sorted fine sand with minor silt; massive to stratified; 1 to 3 m thick; generally forms flat to gently rolling surfaces; typically overlies till; deposited in shallow water depth, near wave base, in a former glacial lake; more abundant on north facing slopes.

Geomorphological features (polygons, lines, and points)

Geomorphological features regroup landforms, sediments or site locations interpreted from observations made on imagery (e.g. airphotos, satellite imagery, digital elevation models). Geomorphological features are represented as overlay polygons, lines and points symbols (Figs. 6, 7, 8).

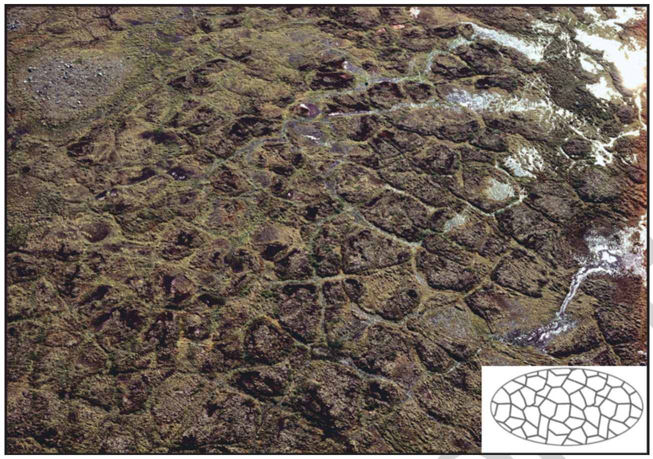

Figure 6. *Patterned ground such as these ice-wedge polygons from the central Slave Province in the Northwest Territories is represented by an overlay polygon (lower right corner) on a map. Photograph by D.E. Kerr. NRCan photo 2019-280*

Figure 7. *Beach crests such as these beaches developed on a glaciofluvial deposit from the eastern Northwest Territories are represented by line symbols (lower right corner). Photograph by P.X. Normandeau. NRCan photo 2019-284*

The choice of points, lines or overlay polygons to represent geomorphological features is a question of scale. Typically, a point symbol is a feature too small to be drawn to scale on the map (e.g. outcrop, small gravel pit). A line symbol is typically drawn to scale. For example, the length of a line on the map representing an esker or a symbol related to an ice-flow movement (e.g. flutings, drumlins, crag-and-tails) reflects the length of the landform on the imagery. Symbols related to ice-flow movements can also be represented as oriented point symbols with a constant length for landforms too short to be shown to scale and for the inclusion of landforms derived from legacy maps.

Figure 8. *Areas of outcrops too small to be mapped as polygons are represented by a point symbol. This example from the central Slave Province shows the point symbol for outcrops in the lower right corner. Photograph by D.E. Kerr. NRCan photo 2019-281*

Similar to map units, geomorphological features are classified according to their genesis and environment of deposition which include eleven groups: anthropogenic, bedrock, eolian, glacial and ice-contact, ice-movement indicators, mass-wasting, paleodrainage, paleogeography, permafrost and periglacial, shoreline and miscellaneous features. A geomorphological feature can have the same genesis and age as the underlying map unit (e.g. an esker represented as a line symbol within a glaciofluvial map unit) but could also be of a different genesis and age (e.g. small dunes represented as point symbols on a glaciofluvial terrace).

Some of the data attached to a geomorphological feature may not be depicted on the map but can be captured in the digital information associated to the map. For example, dune point symbols can include subset attributes related to the dune type (e.g. longitudinal, parabolic or unspecified); eleven sub-types of patterned grounds and six types of minor moraines can be documented; relative age of ice-flow indicators observed on imagery such as flutings or drumlins can be recorded digitally; and specific notes or the level of confidence about a point or line symbol can be included by the mapper. Similarly, point and line symbols too tightly spaced to be shown at the scale of the paper map can be included in the digital data.

Field observations

Field observations are represented by point symbols that contain the observations and measurements recorded in a field-data collection tool (i.e. GANFELD) or on paper and later digitized. For example, a till fabric can be depicted by a symbol on the map (Fig. 9) and the actual measurements of clasts orientation included with the digital data attached to the map. For mappers and map users, there is no obvious distinction between a field observation and a geomorphological feature point symbol. Simply said, both appear as point symbols on the map. However, field observations are kept separate to maintain a relation between the data structure of the field-data collection tool and the SDM, which facilitates the transfer of field data during map production.

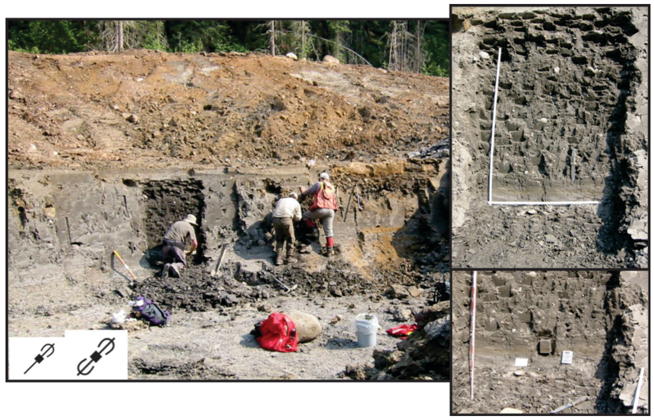

Figure 9. *Field observations such as till fabrics can be represented by an oriented point symbol. This example of a till fabric site from northwest Alberta shows the point symbol oriented in the ice-flow direction (lower left corner). Photograph by C. Kowalchuck. NRCan photo 2019-287, 2019-288, and 2019-289*

As for geomorphological features, additional information to the point symbol can be included in the published digital data. For example, the list of micro-forms observed at a striated site (e.g. mini crag-and-tail, striations, chattermarks, grooves, nail-heads, boulder pavement striations), the specific type of patterned ground (e.g. non sorted circles, sorted circles, ice-wedge polygons, etc.), or the meltwater erosional forms observed on bedrock (muschelbruchen, sichelwannen, comma forms, spindle flutes, furrows, etc.) can all be transferred from the field notes to the digital data associated to a map.

Map production since the SDM

The SDM was designed in cooperation with the Mapping Information Branch (MIB) and GEM-1's GeoMap Flow (GMF) project, which is now GEM-2's Geological Data Flow (GDF) project. SDM is fully integrated into the GSC's new digital Canadian Geoscience Map (CGM) series, which replaces the traditional A-series maps, Open File maps, and Preliminary maps which are no longer published. The principal goals of the Canadian Geoscience Map series are to: 1) integrate the SDM with map production so that the outputs are derived from a standard geodatabase; 2) add greater consistency to GSC map information making outputs easier to use; 3) streamline the release of print-ready and GIS-ready data from surficial and bedrock field mapping projects by implementing an appropriate level of cartographic effort; 4) replace older Preliminary, Open File and A-Series map series with a standardized and more flexible CGM series; and 5) ensure that the print- and GIS-ready versions are released simultaneously and that the GIS version contains all available digital information including field notes. Canadian Geoscience Maps are published with a printable file (.pdf) and with digital attributes: map units, points, lines, overlays and field data. A published map is no longer simply viewed as a traditional paper (hard copy) product but as digital datasets.

Classification of surficial geology CGM maps

The recent increase in GSC surficial geology mapping activity, primarily as part of the GEM program, as well as new mapping methodologies, necessitated a way to easily and clearly identify different types of surficial geology CGM map products. Three different naming conventions for surficial geology CGM map titles were adopted in 2012 by the GSC's Surficial Legend Committee, Geomap Flow (GMF) managers (GEM-1 and GEM-2), and MIB.

The three types of surficial geology maps and associated titles were designed to help the user differentiate between the different styles/methodologies of mapping, for example, when viewing them in a list of references/citations. All map types conform to the Surficial Data Model (SDM) on the basis of vector-based polygons and geomorphological lines, points and overlays.

Surficial Geology: This type of map is generally based on expert-knowledge airphoto interpretation, and may include analysis of supporting satellite imagery and digital elevations models (DEM). Airphoto interpretation focusses on map unit/deposit genesis, texture, thickness, structure, morphology, depositional or erosional environment, ice flow and meltwater direction, age/cross-cutting relationships, landscape evolution and associated geological features, complemented by additional overlay modifiers, points and linear features following the SDM. Systematic fieldwork across the entire map area is an essential component, incorporating various digitally-captured data from ground truthing. Samples of sediment and other materials are also typically systematically collected for geochemical, mineralogical or age-dating analyses. Selected legacy data may also be added to the map. Figure 10 is an example of a new CGM surficial geology map at 1:100 000 scale compiled for a GEM-1 project.

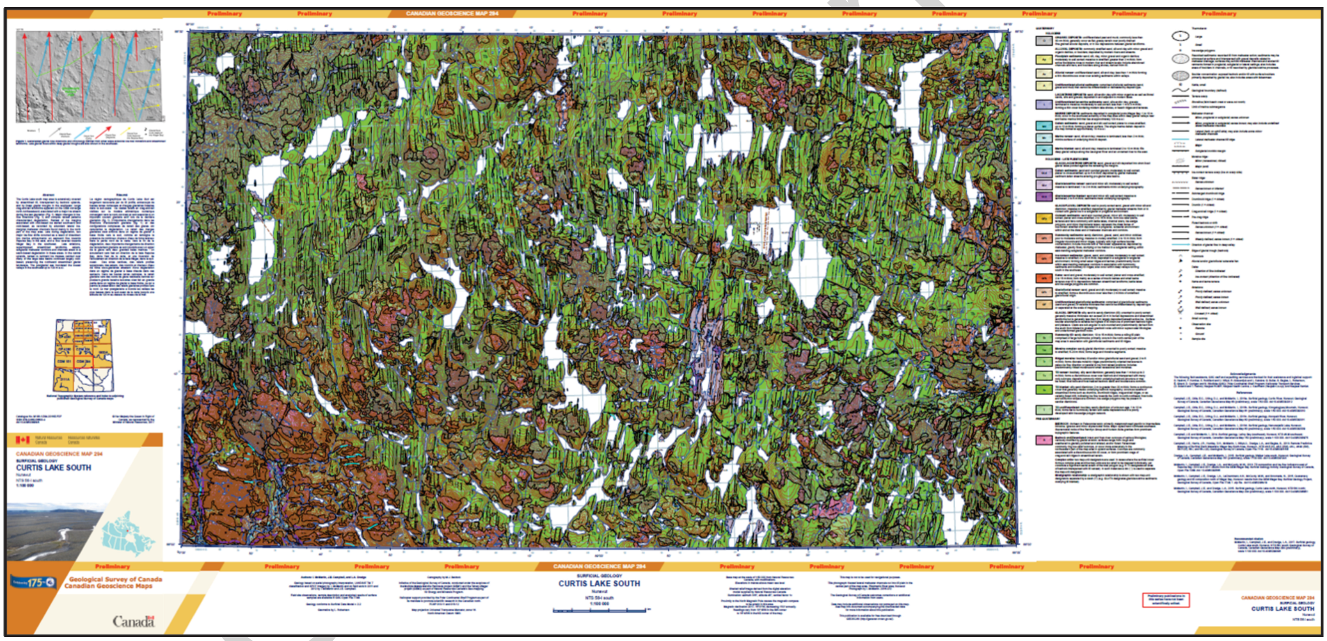

Figure 10. *An example of a CGM surficial geology map from the Curtis Lake south area, Nunavut, compiled for a GEM-1 project at 1:100 00 scale (McMartin et al., 2017). The map compilation is based on systematic fieldwork (~10-km site spacing), detailed airphoto interpretation and analysis of satellite imagery and DEMs.*

Reconnaissance Surficial Geology: This type of map is based on expert-knowledge airphoto interpretation (may include interpretive satellite imagery, DEMs), with limited or no fieldwork. Airphoto interpretation includes map unit/deposit genesis, texture, thickness, structure, morphology, depositional or erosional environment, ice flow and meltwater direction, age/cross-cutting relationships, landscape evolution and associated geological features, complemented by additional overlay modifiers, points and linear features following the SDM. Selected legacy data may also be added to the map.

Predictive Surficial Geology: This type of map is derived from one or more methods of remote predictive mapping (RPM) using different satellite imageries, spectral characteristics of vegetation and surface moisture, machine processing and classification algorithms and DEMs. The map is produced after raster data are converted to vector, with the addition of some expert-knowledge airphoto interpretation (using training areas or post-verification areas). Varying degrees of non-systematic fieldwork may support the mapping process, and the addition of any relevant legacy data is added where available.

Accompanying marginal notes, abstract, or credit notes on every CGM map clearly define how the map was derived. In addition, the National Topographic System (NTS) map sheet number is added to the title and citation for greater ease of locating maps geographically.

Summary

The GSC Surficial Data Model serves to implement a standard data structure for compiling surficial geology maps that will benefit research scientists, government project managers, communities and the mineral exploration industry. It allows consistency in the structure of surficial geology information that has a wide range of applications from the search and inventory of granular resources, the location of potential natural hazards, various environmental concerns, mineral exploration methods, climate change, to academic research. The SDM will facilitate future surficial geology compilations which could reach a national and potentially an international coverage and could gain web accessibility similar to the widely used satellite imageries.

3. NATURE AND EXTENT OF SURFICIAL GEOLOGY MAPPING NORTH OF 60˚

Surficial geology compilation

One of the main objectives of the GEM Program was to develop and populate a surficial geoscience database of source maps to provide access to multi-scale surficial geoscience data in support of responsible northern resource exploration and economic development, and land use issues (Kerr et al., 2009). This was initiated in the Tri-Territorial Surficial Compilation GEM-1/GEM-2 Project, with the creation of a digital compilation and queriable geodatabase of new and existing surficial geology maps of Northwest Territories, Nunavut, and Yukon (Kerr and Eagles, 2010, 2011, 2012, 2014; Kerr et al., 2013).

The development of a standard surficial geology legend (SDM) ensured the implementation of common map units and symbols, and facilitated new Quaternary geology mapping and correlation of map units at all scales (see Section 2 above). Conversion of legacy (previously published) surficial maps to the new legend was the first step in making the database more queriable.

Mapping progress

Prior to GEM-1, the nature and distribution of surficial sediments and general Quaternary knowledge was known for about 58% of the territorial land mass north of 60˚ (Fig. 11). In the decades leading up to GEM-1, surficial geology mapping focussed mainly on regions of known and potential economic interest and resource development (oil, gas, minerals etc.), as well as of geoscientific interest where sufficient knowledge was lacking. GEM-1 contributed just over 6% of mapping knowledge in targeted areas (Fig. 12), and GEM-2 will add another 6% of mapping knowledge in areas adjacent to GEM-1 and in new research areas (Fig. 12). The total area of the North mapped principally by GSC/NRCan is about 70%, representing a knowledge increase of 12% of the North in the last 12 years (Fig. 13), through a combination of 'Surficial Geology', 'Reconnaissance Surficial Geology', and 'Predictive Surficial Geology' maps (see Appendix 1 for a list of GEM surficial geology maps).

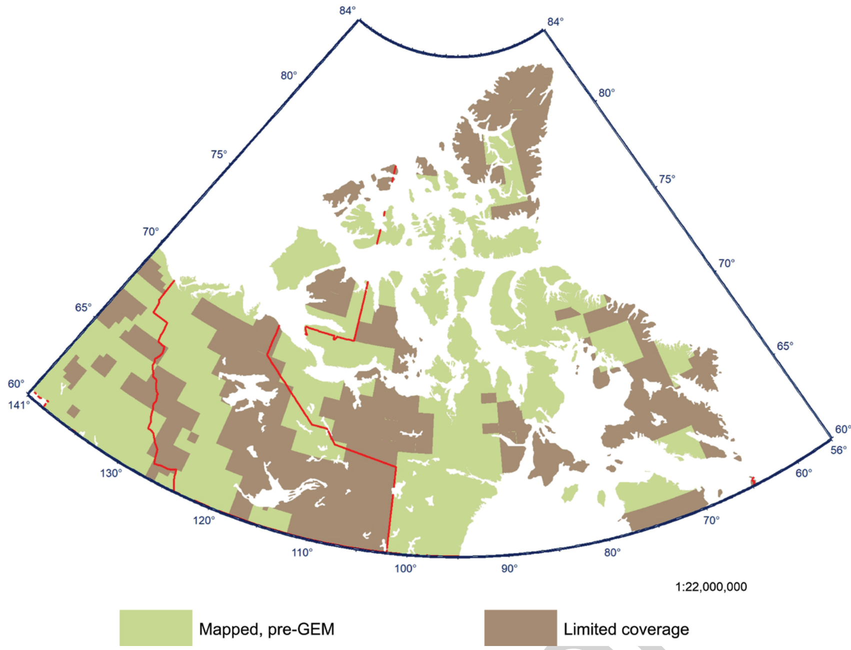

Figure 11. *Surficial geology map coverage north of 60˚ prior to the start of GEM in 2008. About 58% of the territorial land mass north of 60˚ was mapped.*

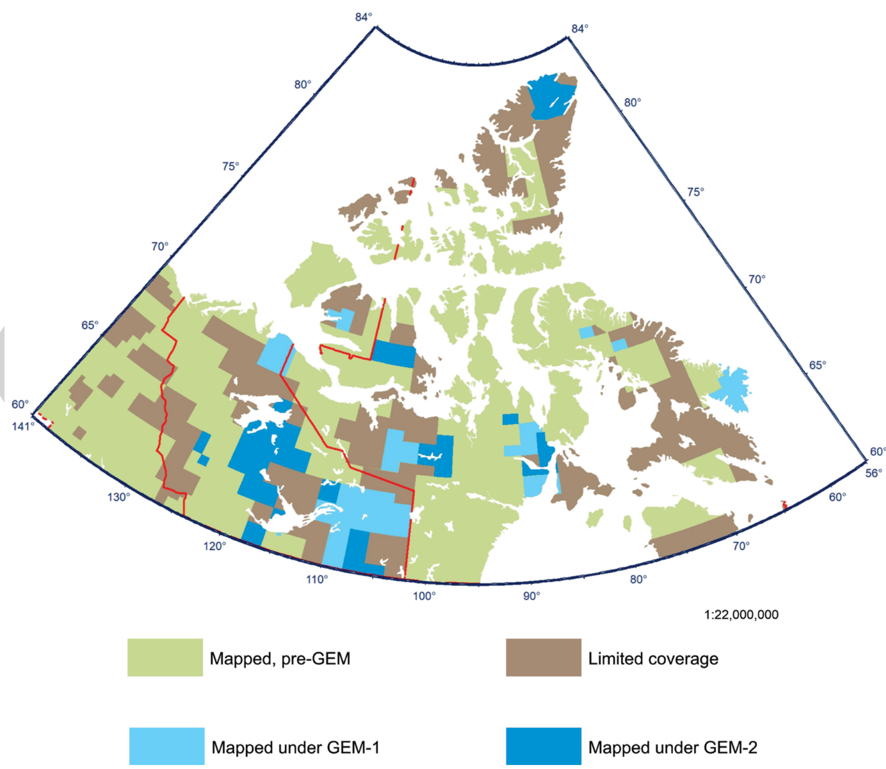

Figure 12. *New GEM-1 and GEM-2 surficial geology map coverage north of 60˚. Surficial geology maps under compilation but not released yet are included. GEM-1 and GEM-2 contributed to about 12% of new mapping knowledge in targeted areas since the beginning of the GEM Program.*

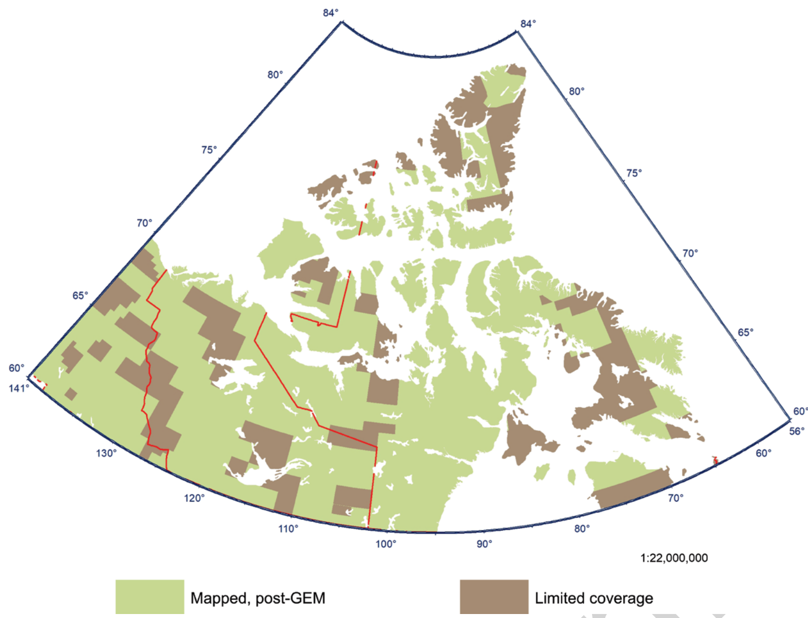

Figure 13. *Surficial geology map coverage based on all GSC and Territorial programs. About 70% of the territorial land mass north of 60˚ is mapped.*

Future mapping

Digital, standardized surficial geoscience maps are broadly valued resources for land use, exploration and research. Over the last 60 years, systematic mapping has reduced knowledge gaps to the point where they represent about 30% of the north, generally representing areas which were once isolated, difficult to access, or under-investigated for a number of reasons from a Quaternary science perspective. As local geoscience needs arise and resources permit, these areas will likely be infilled at the required scale of mapping using the SDM. All mapping approaches, from traditional airphoto interpretation to remote predictive mapping techniques, followed by field surveys, will ensure that data is acquired and transferred with seamless effort using the Surficial Data Model.

4. REMOTE PREDICTIVE MAPPING (RPM) OF SURFICIAL MATERIALS AND LANDFORMS

Overview

Historically, surficial geology maps at the GSC have been produced by experienced Quaternary mappers using their expert knowledge of airphoto interpretation and terrain analysis (based on 3-D morphology, texture, tone, etc.,) combined with field observations and a regional understanding of the glacial history of the area mapped. The map feature compilation and interpretation consist of estimating the sediment/deposit spatial distribution, genesis, texture, thickness, structure, morphology, depositional or erosional environment, ice-flow direction, nature and direction of meltwater drainage, age relationships, landscape evolution and associated geological features. Currently at the GSC, these features are defined by map unit polygons, and complemented by additional overlay polygons, points and linear features, selected from over 275 different geological elements in the Surficial Data Model (see Section 2 above; Deblonde et al., 2017). Typically a preliminary airphoto interpretation is completed prior to ground verification during fieldwork. The preliminary geological map is then revised with the new field-based data. The interpretation can also be compiled after the fieldwork is completed and surface sample composition and ages are acquired. Satellite imagery and DEM data are often used to complete the interpretation and mapping process.

Prior to the GEM program, the GSC began to investigate using remote predictive mapping (RPM) as a method to map surficial materials, in a non-SDM format, over large areas in remote regions (e.g. Grunsky et al., 2006, 2009; Harris, 2007; Harris et al., 2006, 2008; Brown et al., 2007, 2008). Grunsky et al. (2006, 2009) produced the first published RPM study at the GSC. Training areas were used to perform a maximum likelihood classification using combined multibeam radar (RADARSAT-1), multispectral satellite imagery (Landsat TM-7) and a regional digital elevation model (DEM) to produce a predictive map of surficial materials for the Shultz Lake area of Nunavut (NTS 66A). These authors concluded that, although there were limitations to the mapping accuracy (correctly predicting materials present at any one location), this RPM approach could be useful as a predictive map tool for ground follow-up surficial mapping and mineral exploration programs.

With the availability of improved imageries, DEMs and datasets, studies within the GSC have continued to investigate remote predictive mapping as an experimental tool, including machine-based techniques and protocols. Over the last 10 years, GSC scientists and Canadian Centre for Mapping and Earth Observation (CCMEO) colleagues have been developing new methodologies to address the lack of sufficient surficial geoscience knowledge in unmapped areas of the Canadian North (see Appendix 2 for a list of GEM RPM surficial materials publications).

Predictive surficial materials maps (Fig. 14) can provide an estimate of the surficial earth materials present on the ground based on their spectral signatures derived from interpreted data. Surficial materials, defined generally on the basis of texture, composition, moisture content and vegetation, with no context of genesis, may include organic deposits, sand and gravel, boulders, diamictons, fine-grained sediments, and bedrock exposure. RPM studies can also help improve our understanding of glaciated landscapes, provide a framework for ice flow and mineral dispersal investigations at regional scales, as well as other types of ecological research and land-use planning. The materials-based features (units, objects or structures) observed and interpreted on a raster image do not necessarily correspond to how these same features would be classified by the more traditional airphoto interpretation or in the field by a geologist. These materials-based raster images (classification maps; Fig. 14) do not represent a surficial geology map in the traditional sense of landscape evolution, which includes information related to genesis, environment of deposition, age and landform relationships and associations, stratigraphic relationships or postglacial and glacial features and processes.

Surficial materials RPM examples

In this section we summarize below a number of key surficial materials RPM studies completed as part of the GEM Program to illustrate methods used to produce several different products, namely classification maps of surficial materials, predictive surficial geology maps and the use of artificial intelligence to produce predictive classification maps. Additional RPM studies not discussed are listed in Appendix 2 at the end of this chapter.

Surficial materials classification maps

Under GEM, GSC researchers sought to improve the ability to remotely map surficial materials through development and/or application of new algorithms and incorporation of other imageries and datasets. RPM mapping of surficial earth materials northwest of Hudson Bay in Nunavut was undertaken as part of the Wager Bay Surficial Geology GEM-1 Activity (Wityk et al., 2013; Campbell et al., 2013). A mosaic comprising seven separate LANDSAT TM 7 images was prepared for the classification of surficial materials. Training areas representative of 12 surficial material classes were identified through the use of airphoto interpretation, LANDSAT imagery and field knowledge of the mapping area. Fifty percent of the training set was randomly chosen to produce the prediction and the remaining 50% was used to validate the prediction. The statistical separability of the training areas with respect to spectral reflectance was evaluated by an expert RPM researcher using transformed divergence analysis. Water bodies and cloud cover were masked to lower the confusion level. The Robust Classification Method (RCM) based on 60 repetitions was used to classify the LANDSAT imagery producing a number of predictive maps of surficial materials. These maps were first statistically analysed via a confusion matrix and associated measures of accuracy, then geologically evaluated through the use of airphotos in concert with field observations. The mapping of surficial materials using LANDSAT data was not without problems (e.g. radiometrically unbalanced imagery) but did generate useful predictive maps that served to focus and guide more detailed field mapping studies, as well as providing information on surficial materials in extensive areas that could not be field mapped. Although it did not have a high overall classification accuracy (46.3%), the ”best classification” map provided the most realistic predictive map. Incorporation of field knowledge and the expertise of Quaternary geologists was critical to the production of raster-based predictive maps of surficial materials.

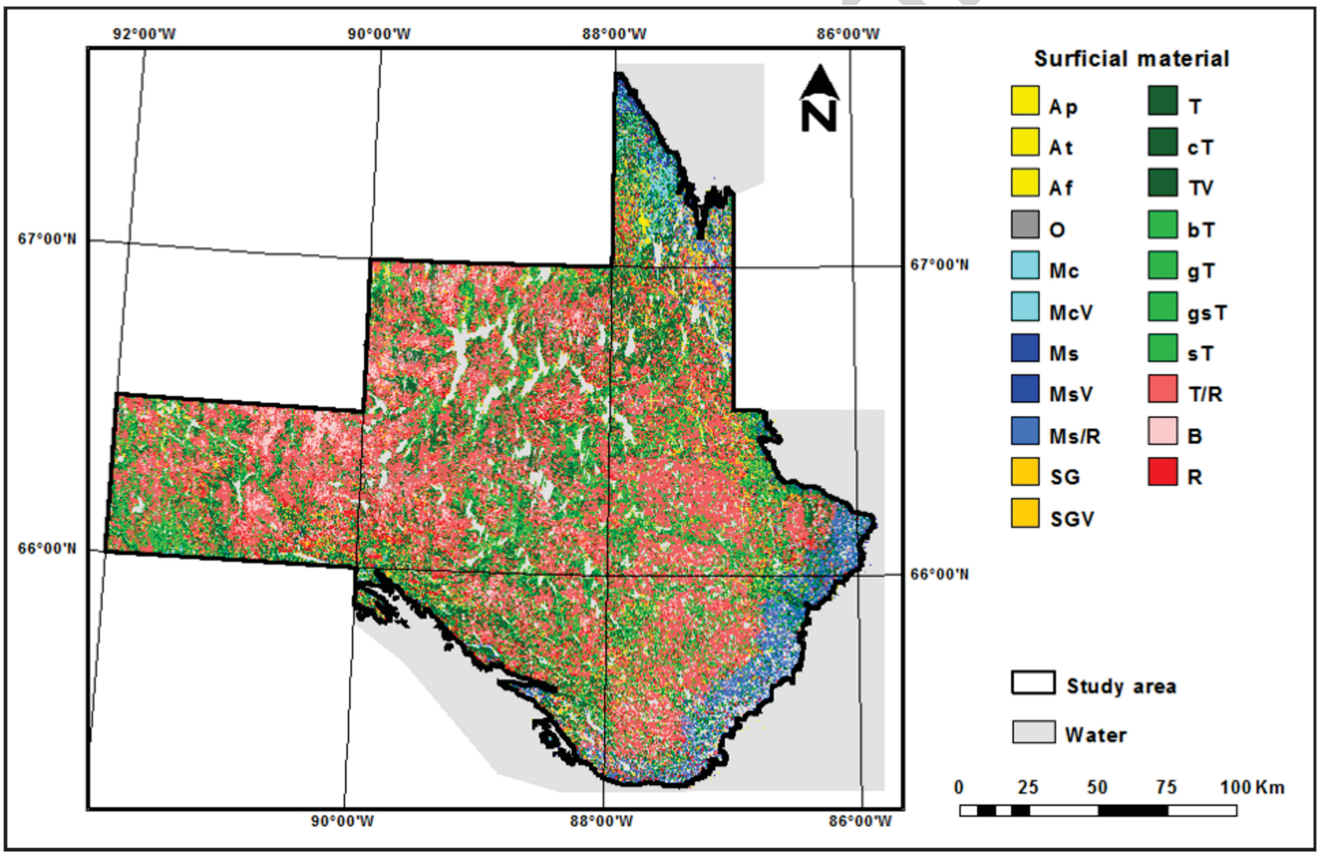

Figure 14. *An example of a RPM surficial materials classification map. Random Forests classifier was applied to a combination of satellite imageries and topographic data using the All-polygon script to produce a classification map of the Wager Bay North project area (Byatt et al. 2019a). Classes consisted of: alluvial plain (Ap), alluvial terrace (At), flooded alluvium (Af), organics (O), offshore silt and clay (Mc), offshore silt and clay with vegetation (McV), marine sand (Ms), marine sand with vegetation (MsV), thin marine sand (Ms/R), sand & gravel (SG), sand & gravel with vegetation (SGV), thick till (T), carbonate-rich till (cT), thick till with dense vegetation cover (TV), bouldery till (bT), gravelly till (gT), gravelly sandy till (gsT), sandy till (sT), thin till (T/V), boulders (B), bedrock (R).*

More recent mapping in the Wager Bay area as part of the Tehery-Wager GEM-2 Project (Fig. 14) sought to improve on the previous work (Byatt et al., 2019a) and to extend the coverage south of Wager Bay (Byatt et al., 2015, 2019b). Byatt et al. (2019a, 2019b) produced predictive surficial maps with 21 (north) and 22 (south) material classes by applying a non-parametric classifier, Random Forests (RF), to a combination of RADARSAT-2 C-HH and C-HV with Landsat-8 OLI, DEM, and slope data. Validation (mapping) accuracies were determined by comparing the resulting maps to more than 1000 field sites. By adding RADARSAT-2 dual-polarized images and using the All-polygon script of RF, the classification overall accuracy increased to 98.1%. Adding RADARSAT-2 data in the classification also increased the validation accuracy to above 85% for the majority of the classes. This study produced similar but improved classification maps with respect to Campbell et al.'s (2013) work.

Predictive surficial geology maps

Predictive surficial geology maps are comprised of surficial unit polygons that infer the origins and environments into which the sediments were deposited but generally do not include. For this type of RPM map, the surficial materials classifications have been generalised and grouped into unit polygons using machine processing, expert knowledge and limited field and/or legacy data to conform the geological map polygons to the Surficial Data Model. The two examples of publications discussed below include raster (surficial materials classification map) and vector data (surficial geology map) in the SDM format.

One of the early predictive surficial geology maps was produced in the Yellowknife area (Stevens et al., 2012a) as part of the Tri-Territorial (Tri-T) Surficial Compilation GEM-1 Knowledge Management Project and the Transportation Risk in the Arctic to Climatic Sensitivity activity in the Climate Change Geoscience Program. The initial surficial materials classification map was based on 20 repetitions of the robust classification methods using Maximum Likelihood Classification applied to the normalized LANDSAT bands 2, 3, 4, 5 and 7. Separate classification was performed on the northeast and southwest portions of the map sheet. The surficial materials map was generalised in order to conform to cartographic standards for a 1:125 000 scale map. The generalisation included 3 iterations of a 3x3 pixel majority filter (smoothing), the conversion of data from raster to vector format and removal of polygons less than 15,300 m^2 (17 pixels). The generalized surficial units were converted to predictive surficial geology units based on knowledge gained from airphoto interpretation and field observations and legacy data (such as adding glacial striations from reconnaissance maps or bedrock maps, and other field data).

A comparison between the remote predictive surficial materials and the interpreted airphoto for two training areas for the Yellowknife study shows the RPM map effectively captures the type and general locations of the different sediments that have been mapped from airphotos. Locally, RPM techniques resulted in a higher level of detail than by airphoto interpretation; this was due to the simple nature of the geology (bedrock outcrops and fine-grained glaciolacustrine sediments in depressions) as well as the detailed scale of the satellite imagery. However, airphoto interpretation was more effective in delineating the boundary between certain sediment types that have distinct surface expression and morphology (e.g. eskers, drumlinoids, beach ridges).

In the Rae map region (NTS 85-K), a more robust methodology was developed as part of the Mackenzie GEM-2 project in the Northwest Territories (Kerr et al., 2016). The classification approach involved the use of the Boost mode of the decision-tree methods in See5TM calibrated on training classes developed from expert airphoto interpretation, and on an unsupervised classification of the LANDSAT 7 satellite imagery. Training areas were selected in burned and unburned areas. The resulting training classes were used in the decision-tree model to predict surficial geology by applying the training classes to satellite imagery, a digital elevation model (DEM), and DEM texture. Decision-tree methodology was chosen as the classification algorithm due to its ability to handle large training datasets irrespective of their statistical distributions. The final RPM and boosted maps were generated using the majority prediction from all trials. In the development of the surficial materials and predictive surficial geology map, forest fire history and vegetation cover resulted in reduced accuracy, and did not permit clear distinctions between classes according to expert airphoto interpretation. Consequently, traditional airphoto interpretation was utilized to produce the final surficial geology map.

Integrated predictive surficial geology map

As part of SMART Mapping GEM-1 Knowledge Management project, a 1: 250 000 predictive surficial geology map of Washburn Lake, eastern Victoria Island was compiled using a new mapping method that integrates a RPM analysis, visually interpreted imagery and regional-scale ground truth data (Sharpe et al., 2018). The main stages of this classification included: a) data input from ~3–4 LANDSAT ET M+ images (30 m resolution), tiled into a mosaic, SPOT panchromatic imagery (5 m pixel size), and interpretation of landforms from satellite imagery and airphotos; b) training data relating spectral signatures (material, vegetation, and slope, linked to variation in surface moisture) to areas of distinctive terrain using this imagery; c) image classification using a Random Forests (RF) classifier; d) a surface materials map integrating spatial variability and surface materials and using expert knowledge of texture, landforms, and process; and e) map evaluation using field observations and photos, as well as completed mapping. The final surficial geology map (raster and vector formats) consists of surficial map unit polygons with landforms superimposed.

Application of artificial intelligence

Recent advancements in RPM looked to assess the potential of deep neural networks to improve surficial geology mapping in the South Rae GEM-2 Project in southern Northwest Territories (Latifovic et al., 2018). This new method can provide an objective surficial materials layer that experts can use to direct their mapping and assist with interpretation beyond and between field observation sites. The study investigated the ability of convolution neural networks (CNN) to predict surficial geology classes under two sampling scenarios. In the first scenario, a CNN used samples (training areas) collected over the area to be mapped and at ground observation sites. In the second scenario, a CNN trained over one area was applied to locations where the available samples were not used in training the network. The evaluation of the CNNs in both scenarios was carried out using black and white airphotos, Landsat 8 L1G TM/ETM+ reflectance time series imagery, and high-resolution DEM data over five areas within the Abitau Lake map sheet (NTS 75B). Contrary to most of the above studies, this region is heavily forested. The thick vegetation masks the spectral signature of the surface materials. The time series Landsat mosaic provided a means to remove much of the effects of forest burns. The CNN generated an average accuracy of 76% when locally trained. However, for independent test areas (i.e., trained over one area and applied over other), accuracy dropped to 59-70% (av. 68%) depending on the classes selected for mapping. In comparison to the more widely used Random Forests machine learning algorithm, deep learning CNN represents an improvement in accuracy of 4% producing better results for less frequent classes with distinct spatial structure. Both the classification and mapping accuracies were significantly improved upon by the use of CNN as noted by the surficial geologist's assessment through airphoto interpretation and field work.

Landform RPM mapping

In recent years, mapping of drift lineations and other glacial landforms (e.g. eskers, moraines) at different scales in Canada's North based on remotely sensed data such as satellite imageries and digital elevation models has been the focus of many studies both within and outside GEM project areas (Boulton and Clark, 1990; Clark, 1997; De Angelis, 2007; De Angelis and Kleman, 2005, 2007, 2008; Greenwood and Kleman, 2010; Kleman et al., 2002, 2010; Shaw et al. 2010a-b; Broscoe et al., 2011; Storrar et al., 2013; Margold et al., 2015; Storrar and Livingstone, 2017). Under the GEM-1 Remote Predictive Mapping project, two studies took different approaches to mapping glacial landforms in northern Canada. Shaw et al. (2010a-b) produced a national-scale glacial flowline map of Canada based solely on visual interpretation of glacial landforms using two satellite datasets: Landsat 7 ETM+ imagery (30 m resolution) and Shuttle Radar Topography Mission digital elevation model (SRTM- 90m resolution DEM). North of 60° latitude, only Landsat data were used for the compilation. No existing data or maps were incorporated into the predictive map. It was recognised that the RPM map and resulting model contained uncertainties due to geological complexity, the data scale and source, and lack of ground truthed data (Shaw et al., 2010a).

Broscoe et al. (2011) investigated to use of automated semi-quantitative mapping of glacial landforms. Eskers were chosen to test the utility of this approach. Using ArcGIS and an esker detection module coded in Python, the 1:50 000 scale Canadian digital elevation data (CDED) were smoothed using user defined filter windows. A difference surface was produced that emphasizes ridge areas and was used to create polygons. Results from two test areas in the barrens of the Northwest Territories indicated eskers with adequate relief, size and peakedness could be extracted from CDED DEM data using GSC legacy vector esker line data (Aylsworth and Shilts, 1989) as a training set and air photo interpretation for visual checks. Due to the low resolution of the DEM data, the method used only captured larger eskers but refinements to this method with higher resolution DEMs would likely be successful in delineating significant portions of esker networks in unmapped areas of northern Canada.

Key advances, successes and issues with RPM of surficial materials

Both the classification and mapping accuracies of remote predictive surficial materials maps are extremely variable from region to region, and are largely dependent on data quality and quantity, the nature and complexity of the surficial materials as well as the classification method used. It is generally accepted that RPM is not an alternative procedure to traditional mapping methods for producing detailed and accurate geological maps. An additional constraint is the difficulty in relating surficial materials classes to surficial geological units in the Surficial Data Model, and interpreted landforms to point and linear features, and the resulting effects on conceptual glacial history models. RPM of surficial materials and landforms does provide however a new knowledge layer than can complement data derived from airphoto interpretation or other visual interpretation using expert knowledge.

Byatt et al. (2019a, 2019b) demonstrated that classification accuracies can be improved with the use of radiometrically balanced images, use of newer Landsat imagery, introduction of RADARSAT 2 imagery, DEM and slope data into the model, optimizing the number of materials classes, and the use of a more robust classification algorithm (RF).

Despite the reduced accuracy due to forest cover in the South Rae region, deep learning CNN provided a potential means to address some of the limitations for surficial geology RPM. Latifovic et al. (2018) suggest that for future surficial geology mapping, deep learning CNNs could provide initial predictions that are refined by the surficial geologist and fed back into the model in an ongoing cycle, thus reducing error and adapting the method to new or local conditions. This would integrate the knowledge of geological experts and ideally reduce the human subjectivity in the final map products. All studies stress that radiometrically balanced spectral imagery and input of expert geological knowledge are imperative for producing more accurate maps. Furthermore, it is stressed that RPM is a mapping tool to aid the surficial geologist and augment conventional mapping methods.

When the confidence in the RPM data is relatively high and classification maps show both high classification and mapping accuracies, a 'predictive surficial geology' map may be produced following the Canadian Geoscience Map (CGM) and Surficial Data Model formats. Conversion of predictive raster-based surficial materials to vector-based surficial geology is done through GIS procedures with input by an experienced Quaternary geologist who uses a combination of expert analysis, a review of legacy publications and archival data, in addition to the detailed training and validation sites identified during the RPM analyses. After careful assessment for accuracy, these types of products can be produced as first order maps in unmapped areas or areas of limited knowledge. They are not meant to replace actual field-based mapping activities and the resultant, more scientifically robust, geological maps completed by airphoto interpretation, particularly where there is field validation.

Although landform compilations based on remotely sensed data identified patterns of streamlining and various other glacial features, the lack of ground truthing in these studies has frequently resulted in misinterpretation of certain glacial landforms, bedrock features mistaken for glacial drift features, and/or simplification of ice flow patterns. Such misinterpretations have prevented a proper interpretation of the glacial history and dynamics of the Laurentide Ice Sheet. With expert knowledge of the region and DEMs of greater resolution (e.g. LIDAR, ArcticDEM) and appropriate imagery, future mapping of glacial landforms will certainly improve (see McMartin et al., Chapter xx of this Synthesis). Development of machine-based spatial recognition and analysis will also provide a useful automated tool to assist with landform compilations.

Large tracts of Canada's north remain unmapped with respect to surficial geology. The lack of this geoscience information limits the ability to identify and assess terrain risks associated with various surficial materials, identify aggregate resources and hampers mineral exploration. The RPM methodology that combines combined machine-automated learning techniques, field data, visual interpretation of remotely sensed imagery (satellite interpretation/analysis of landforms), and airphoto training areas will improve surficial mapping over extensive regions of largely unmapped terrain. These RPM map products provide a first order assessment of surficial materials, which can guide traditional field mapping and provide regional information for geotechnical investigations and mineral exploration.

5. SUMMARY

The considerable number of surficial geology maps recently published in Northern Canada constitute a significant and lasting legacy of the GEM Program. Published and upcoming maps will result in an increase of 12% map coverage for areas north of 60˚. The push to develop more accurate Remote Predictive Mapping techniques of surficial materials during the GEM Program is also a noteworthy contribution. Method development will continue to improve and with new satellite imagery (i.e. RadarSAT Constellation) and high resolution DEMs (i.e. ArcticDEM) becoming widely available, RPM methods will contribute to increase the surficial geology map coverage north of 60˚ in the near future. In addition, the implementation of the GSC Surficial Data Model is a major outcome that serves to implement a standard data structure to facilitate surficial geology map production and benefit end users. The SDM allows consistency in the structure of surficial geology information that has a wide range of applications for topics concerned with granular resources, natural hazards, environmental application, mineral exploration, climate change, and academic research. The SDM and CGM formats will facilitate future compilations for national and international coverages which could gain web accessibility similar to the widely used satellite imagery (i.e. Google Earth).

6. ACKNOWLEDGEMENTS

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Appendix 1. GEM surficial geology maps*

**Note from the Volume editor: All GEM maps from north and south of 60° are included (as of May 10, 2021).*

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Appendix 2. GEM RPM surface materials publications

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