Status of surficial geology mapping in northern Canada

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Abstract: The Geo-mapping for Energy and Minerals (GEM) program has facilitated the availability of new and converted surficial geology maps and associated digital data sets for large sectors of northern Canada, leading to about 70% of the North being mapped and digitally available. Development of the Surficial Data Model and Canadian Geoscience Map (CGM) series has 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 the two phases of the GEM program, as well as upcoming map publications, has resulted in an increase of 12% in map coverage north of 60°, constituting a significant legacy of the GEM program.

Résumé : Le programme Géocartographie de l'énergie et des minéraux (GEM) a facilité la disponibilité de nouvelles cartes et de cartes produites par la conversion de cartes existantes de la géologie des formations superficielles, ainsi que des ensembles de données numériques afférents, pour de vastes secteurs du nord du Canada, ce qui fait qu'environ 70 % du Nord est désormais cartographié et que les résultats sont disponibles numériquement. L'élaboration du Modèle de données pour les formations superficielles et l'instauration de la série des Cartes géoscientifiques du Canada ont permis d'optimiser le processus de publication et de créer un format normalisé commun de carte numérique et de géodatabase. Sur la base des méthodes de cartographie classique et celles plus récentes de télécartographie prédictive, il existe maintenant trois types de cartes de la géologie des formations superficielles dans la série des Cartes géoscientifiques du Canada, à savoir la géologie des formations superficielles, la géologie de reconnaissance des formations superficielles et la géologie prédictive des formations superficielles. Le nombre considérable de nouvelles cartes de la géologie des formations superficielles publiées au cours des deux phases du programme GEM, 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 du programme GEM.

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INTRODUCTION

The gathering of geoscientific information to map the geology of the country has been a key activity of the Geological Survey of Canada (GSC) since its foundation in 1842. It took 22 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 postglacial deposits between Lake Superior and Gaspésie (Logan, 1865). This map represented the first step in demonstrating the importance of surficial geology mapping to the economic development of the landmass that was to become Canada after 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, some of the major milestones that impacted the interpretation of the surficial geology landscape of Canada are summarized below to bring into perspective the new mapping efforts accomplished as part of the Geo-mapping for Energy and Minerals (GEM) program. This 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 fieldwork 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 in nature, 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 rivers in the core of the ice sheet. Although Tyrrell's map does not fall under the classification of surficial geology map as such, 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 Yukon by Johnston (1900, 1905).

The availability of airphotos in the 1950s marked a major milestone in 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 bench-mark 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 of existing maps and from the colossal task of interpreting surficial geology landforms and sediments from 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 Saint-Narcisse in Quebec, Cree Lake in Saskatchewan, The Pas in Manitoba, and Chantrey in Nunavut.

Twenty-seven years later, data from surficial geology mapping conducted throughout Canada by provincial, territorial, and federal geological surveys were compiled into the Surficial Materials of Canada map by Fulton (1995). This compilation product largely relied on the foundation of interpreting the land surface from airphotos confirmed by fieldwork 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 data sets. The maps of the paleogeography and ice-margin chronology of North America by Dyke and Prest (1987) and Dyke et al. (2003), aa well as the map of the glacial features around the Keewatin Ice Divide by Aylsworth and Shilts (1989), are examples of such products.

Throughout the years, the usefulness of airphotos has been progressively augmented by the addition of other types of remote imagery. The advent of multiple types of satellite images and topographic data (Landsat, RADARSAT, digital elevation model or DEM) progressively led to their being commonly used in the interpretation of landform continuums that could not easily be identified on airphotos because of their extensive size and surficial materials. Certain aspects of the ground conditions provided by specific spectra of satellite images (e.g. moisture, vegetation cover) contributed valuable data for the interpretation of the surficial sediments. In the past 10 years, an increase in the availability of images created by the light detection and ranging (lidar) method has provided an unprecedented view of the land surface without the obstruction created by the canopy cover. Subtle features of the land surface that had so far been unnoticeable could now be mapped from lidar imagery at an unparalleled level of detail. However, the availability of lidar images offering coverage of large areas currently remains dominantly restricted to the southern populated regions. For areas north of 60°, the recently available ArcticDEM, generated using high-resolution satellite images (Polar Geospatial Center, 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 GSC, 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 including 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), and hydrogeology. Despite these efforts, extensive areas of the northern Canadian landmass remained unmapped until the early twenty-first century. Given the necessity of acquiring the 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 GEM program, a 12-year (2008–2020) initiative led by Natural Resources Canada.

The completion of the GEM program has facilitated the availability of surficial geology maps and associated data sets 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 limited their usefulness across large areas and territorial boundaries. Through the GEM program, standardization of surficial geology data was accomplished by 1) digitally converting a compilation of existing surficial geology maps to modern formats; 2) mapping 'white-space' areas using 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, also known as 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 a requirement was the foundation for the development of a 'Surficial Data Model' (Deblonde et al., 2012), which is described below.

A large part of the new maps produced in the 12 years of GEM-1 and GEM-2 projects (*see* Appendix A) relied on stereoscopic analysis of airphotos, to which was added the results of fieldwork and interpretation of remote imagery. In addition to this 'classical' approach, much effort was devoted to the development of RPM methods largely based on automated interpretation of remote images, a form of machine learning. Comparison of the human and machine products has enabled the development of automated tools that are efficient, at least at the regional scale, for some surficial materials. The progress accomplished by the GSC and collaborators using the RPM methods is reviewed further below (*see* 'Remote predictive mapping of surficial materials and landforms' section).

SURFICIAL DATA MODEL: IMPLEMENTING A STANDARD DATA STRUCTURE FOR PUBLICATION

History

The first surficial geology maps of the GSC used symbols generally recognized by the international scientific community. For example, the extent of sediment types was shown with coloured polygons by Logan (1865), and striations were depicted as a straight line crossed by a bow-shaped 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 legends have greatly evolved since these first two maps. Fulton (1993) provided an historical perspective on the evolution of mapping systems and legend styles used on surficial geology maps. Throughout this evolution, the need for consistency in the 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 publications entitled *Guide to Authors*, containing 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 GSC reports (1975, 1984, 1990). 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 1970s to the late 1990s, 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 (R.J. Fulton, unpub. rept., 1998).

Prior to the GEM program, the GSC released surficial geology maps as three distinct product types: Preliminary maps, Open File maps, and A-series maps. Examples of these maps can be viewed in Natural Resources Canada's online catalogue of publications at https://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 1990s. 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 digitally produced coloured maps designed for quick release. These were also considered preliminary surficial geology maps typically associated with ongoing 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.

The outcome of discussions on 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 migrated to the GEM-1 Information Management project as part of the Tri-T Surficial Geology Compilation and GeoMap Flow activities (Kerr et al., 2008, 2009). Throughout 2008 and 2009, a preliminary surficial-mapping data model (geodatabase and common legend) was developed by a group of GSC researchers (A. Plouffe, D.E. Kerr, I. McMartin, L.A. Dredge, A.S. Dyke, M. Parent, S.J. Paradis, D.R. Sharpe, A. Duk-Rodkin, D.A. St-Onge, D.H. Huntley) and publication staff (D. Everett, O.E. Inglis, G. Buller, C. Deblonde, A.J. Weatherston, A. Moore, L. Robertson, D. Giroux, B. Brodaric).

Facilitation of the map publication process and the development of a common data structure were two objectives of the GEM-1 Information Management project. The Surficial Data Model (SDM) was proposed as a key tool for standardization of map units, symbols, and data sets 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 GEM-1 GeoMap Flow project. The SLC continued to expand the original 2008–2009 version of the SDM. Regular weekly to monthly meetings brought together different mapping experts from all regions of Canada (A. Plouffe, D.E. Kerr, M. Parent, D.A. St-Onge, D.H. Huntley) and GIS expertise (D. Everett, O.E. Inglis, G. Buller, C. Deblonde, A.J. Weatherston, A. Moore). Subsequent members were added, including I.R. Smith, J.E. Campbell, R.B. Cocking, S. Eagles, and L. Robertson.

As part of the development of the SDM and issuing discussions, the following process was established for the SLC: 1) each of the committee members who is a surficial geologist 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 subsequently be made based on a 51% majority vote of the members of the SLC who are surficial geologists.

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 (five or fewer 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 on which proposed changes or additions to the SDM could be submitted for evaluation 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 1 of each year and their review completed by December 1; changes to the SDM are then published by March 31.

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 personal computers, field digital devices, and geographic information systems came the demand for vector data depicted on maps. The publication of digital data associated with 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 such as satellite and digital elevation models or DEMs. 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 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. Postglacial features and those associated with active processes (permafrost, landslides, avalanche tracks) 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 uppercase and lowercase letters and numbers (Fig. 1). One or two uppercase letters define the primary genesis of the material or process (Table 1). The uppercase letter(s) is followed by one or two lowercase 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 subcategories 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, lowercase letters are placed in front of the map-unit designator to define the geological events that could be geochronological (e.g. -Wisconsinan versus Holocene), depositional or erosional (e.g. Reid Glaciation, Tuk Phase ice advance), or related to provenance (e.g. Cordilleran Ice Sheet versus Laurentide Ice Sheet) (Fig. 3).

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 all are of Late Wisconsinan 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 Wisconsinan 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, subcategories, 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 for 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 that consists of 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 colour 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 by a forward slash (‘/’) that separates the two units based on their stratigraphic order (top unit first; 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 that only appear as secondary or underlying units in complex and stratigraphic-relationship designators.

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, and depositional environment. A typical entry would read, for example, ‘Glaciolacustrine nearshore sediments: well sorted fine sand with minor silt;

Table 1. Map-unit letter designators.

Map-unit designator	Map unit	Subcategory
	Glacial ice or snowpack	
Isn	Snowpacks	
I	Glacier or ice field or ice cap	
	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	

Table 1. (cont.)

Map-unit designator	Map unit	Subcategory
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	
	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

Table 1. (cont.)

Map-unit designator	Map unit	Subcategory
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	

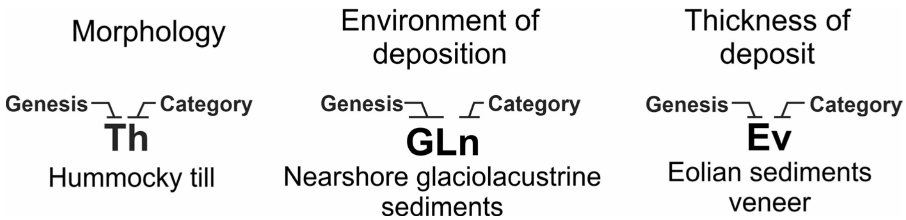

Figure 1. Map-unit designators use a combination of uppercase and lowercase letters and numbers. One or two uppercase letters define the primary genesis of the material or process followed by one or two lowercase letters that reflect a category defined by morphology, environment of deposition, or thickness.

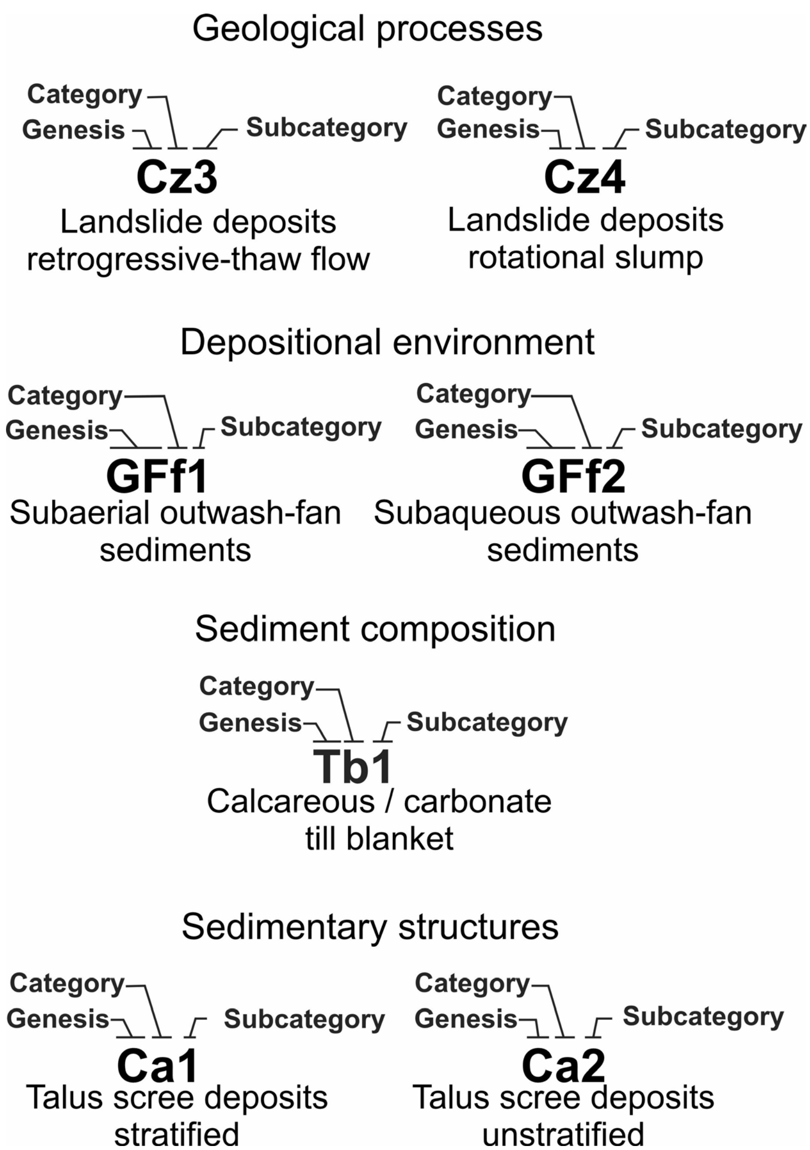

Figure 2. In the map-unit designator, a number placed beside the category designator can be used for subcategories defined by geological process, depositional environment, sediment composition, or sedimentary structure.

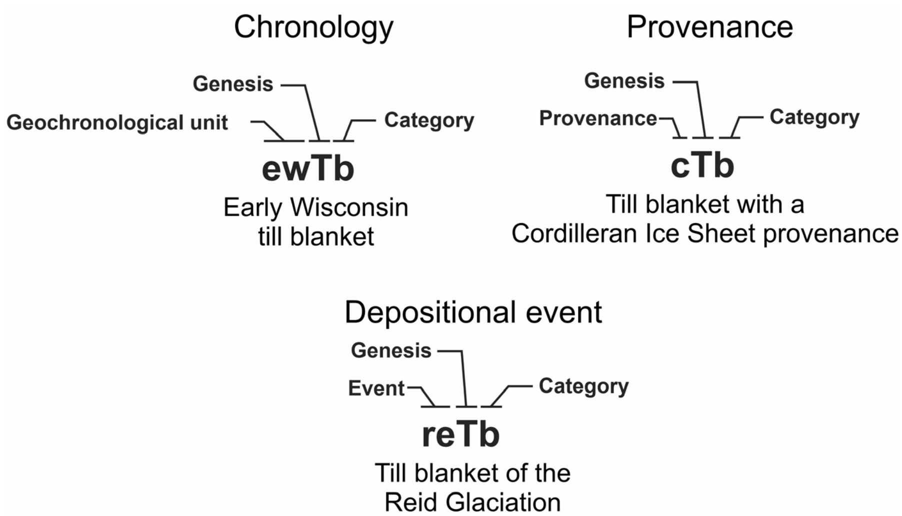

Figure 3. Lowercase letters placed in front of the map-unit designator define a geological event. Geological events are depositional, erosional, or defined by geochronology or provenance.

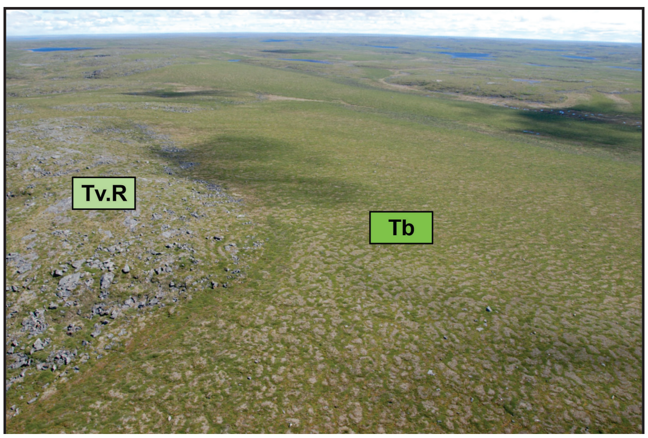

Figure 4. Complex map-unit designators are used when two map units are too small to be mapped separately. A maximum of two units separated by a dot are shown in order of importance (most abundant unit first). This example from the eastern Northwest Territories shows a complex unit of till veneer interspersed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

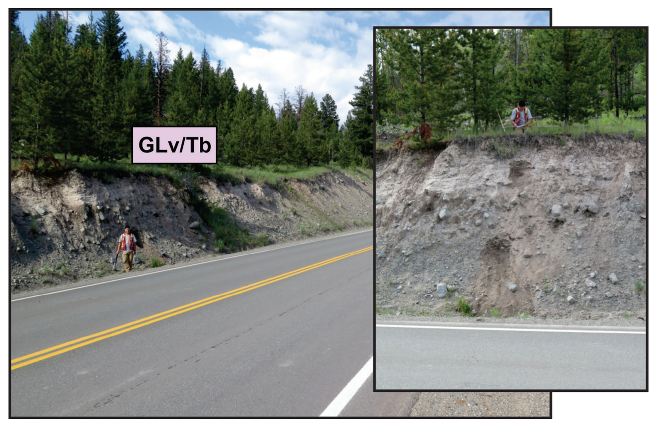

Figure 5. A stratigraphic relationship between two map units is shown by a forward slash ('/') that separates the two units following their stratigraphic order (top unit first). A polygon with a stratigraphic map-unit designator is coloured according to the overlying unit. This example from south-central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

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, DEMs). Geomorphological features are represented as overlay polygons, lines, and points symbols (Fig. 6, 7, 8).

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.

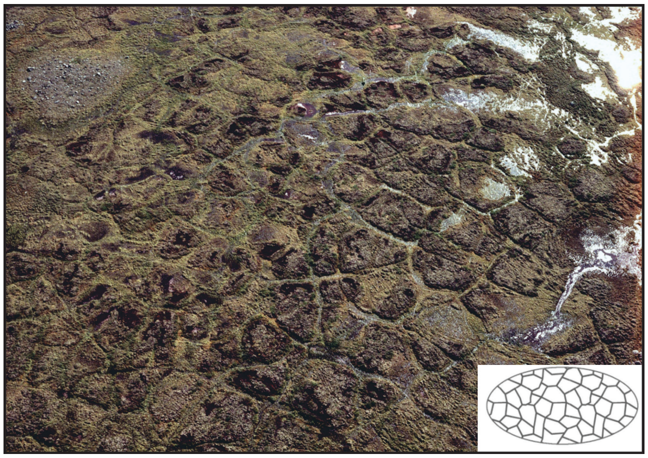

Figure 6. Patterned ground, such as these ice-wedge polygons from the central Slave Province in the Northwest Territories, is represented by an overlay polygon (lower right corner) on a map. Photograph by D.E. Kerr. NRCan photo 2019-280

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

As in the case of map units, geomorphological features are classified according to their genesis and environment of deposition, which include 11 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 with the map. For example, dune point symbols can include subset attributes related to the dune type (e.g. longitudinal, parabolic, or unspecified);

Figure 8. Areas of outcrops too small to be mapped as polygons are represented as point symbols. 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

11 subtypes of patterned grounds and 6 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 (e.g. 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 clast orientations 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.

As for geomorphological features, additional information to the point symbol can be included in the published digital data. For example, the list of microforms 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. nonsorted circles, sorted circles, ice-wedge polygons), or the meltwater erosional forms observed on bedrock (muschelbrüche, sichelwannen, comma forms, spindle flutes, furrows) can all be transferred from the field notes to the digital data associated with a map.

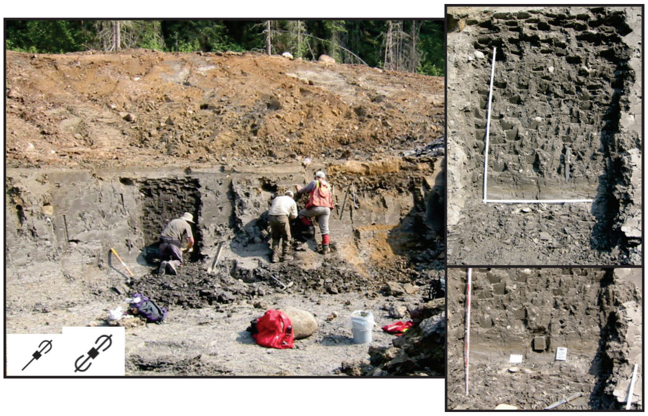

Figure 9. Field observations such as till fabrics can be represented by oriented point symbols. This example of a till fabric site from northwestern Alberta shows the point symbol oriented in the ice-flow direction (lower left corner). Photograph by C. Kowalchuck. NRCan photo 2019-287, -288, -289

Map production since the SDM

The SDM was designed in co-operation with staff of the Mapping Information Branch (MIB) of Natural Resources Canada and researchers working on the GEM-1 GeoMap Flow project, which transitioned into the GEM-2 Science Language and Symbology Development activity. The 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 that are no longer published. The principal goals of the CGM series are to

- integrate the SDM with map production so that the outputs are derived from a standard geodatabase;
- add greater consistency to GSC map information, making outputs easier to use;
- 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;
- replace the older Preliminary, Open File, and A-series map series with a standardized, and more flexible, CGM series; and
- ensure that the print- and GIS-ready versions are released simultaneously and that the GIS version contains all available digital information, including field notes.

The CGMs 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 data sets.

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, created the need to identify easily and clearly different types of surficial geology CGM map products. Three naming conventions for surficial geology CGM map titles were adopted in 2012 by the SLC of the GSC, Geomap Flow 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 as, for example, when viewing them in a list of references/citations. All map types conform to the 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; it may include analysis of supporting satellite imagery and DEMs. Airphoto interpretation focuses on map unit/deposit genesis, texture, thickness, structure, morphology, depositional or erosional environment, ice-flow and meltwater direction, age/crosscutting relationships, landscape evolution, and associated geological features, complemented by additional overlay modifiers, points, and linear features based on 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 radiometric age 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.

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/crosscutting relationships, landscape evolution, and associated geological features, complemented by additional overlay modifiers, points, and linear features based on 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 RPM methods using different satellite imagery, 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 postverification areas). Varying degrees of nonsystematic fieldwork may support the mapping process, and relevant legacy data are added where available.

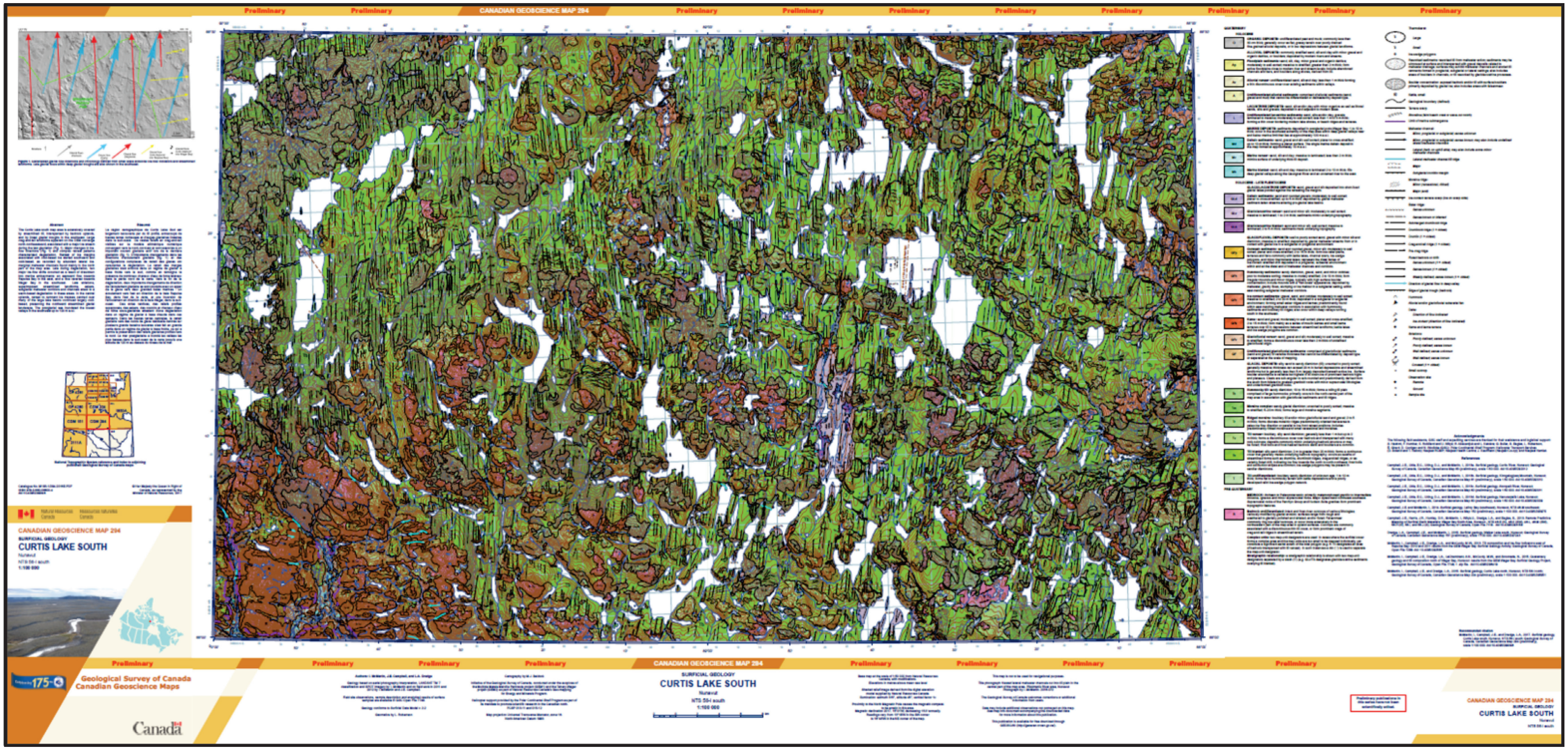

Figure 10. An example of a Canadian Geoscience Map series surficial geology map from the area south of Curtis Lake, Nunavut, compiled for a 1:100 000 scale project undertaken during the first phase of the Geo-mapping for Energy and Minerals program (McMartin et al., 2017). The map compilation is based on systematic fieldwork (~10 km site spacing), detailed airphoto interpretation, and analysis of satellite imagery and digital elevation models.

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

Summary

The GSC SDM 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, or the location of potential natural hazards, the choice of appropriate mineral exploration methods, and the study of various environmental concerns and 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 that of the widely used satellite imagery.

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 multiscale surficial geoscience data in support of responsible northern resource exploration and economic development and resolution of land-use issues (Kerr et al., 2009). This was initiated as part of the Tri-T Surficial Compilation activity, which ran during both phases of the GEM program, with the creation of a digital compilation and queryable geodatabase of new and existing surficial geology maps of the Northwest Territories, Nunavut, and Yukon (Kerr and Eagles, 2010, 2011, 2012, 2014; Kerr et al., 2013).

The development of a standard surficial geology legend (the 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* previous section). Conversion of legacy (previously published) surficial maps to the new legend was the first step in making the database more queryable.

Mapping progress

Prior to GEM-1, the nature and distribution of surficial sediments and general Quaternary history were known for about 58% of the territorial landmass north of 60° (Fig. 11). In the decades leading up to GEM-1, surficial geology mapping focused mainly on regions of known and potential economic interest and resource development (oil, gas, minerals), as well as of geoscientific interest where sufficient knowledge was lacking. Phase 1 of the GEM program contributed just over 6% of mapping knowledge in targeted areas (Fig. 12), and GEM-2 added 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 through either GSC or NRCan programs is currently about 70%, representing an increase of 12% in mapping knowledge of the North in the last 12 years (Fig. 13), through a combination of 'surficial geology', 'reconnaissance surficial geology', and 'predictive surficial geology' maps.

Future mapping

Digital, standardized surficial geoscience maps are broadly valued resources for land use, exploration, and research. Over the past 60 years, systematic mapping has reduced knowledge gaps to the point where they represent about 30% of the North, generally consisting of areas that 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 RPM techniques, followed by field surveys, will ensure that data are acquired and transferred with seamless effort using the SDM.

REMOTE PREDICTIVE MAPPING 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 three-dimensional morphology, texture, tone), 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, complemented by additional overlay polygons, points, and linear features selected from over 275 different geological elements in the SDM (*see* 'Surficial Data Model: implementing a standard data structure for publication' section; Deblonde et al., 2017). Typically, a preliminary airphoto interpretation is completed prior to ground verification

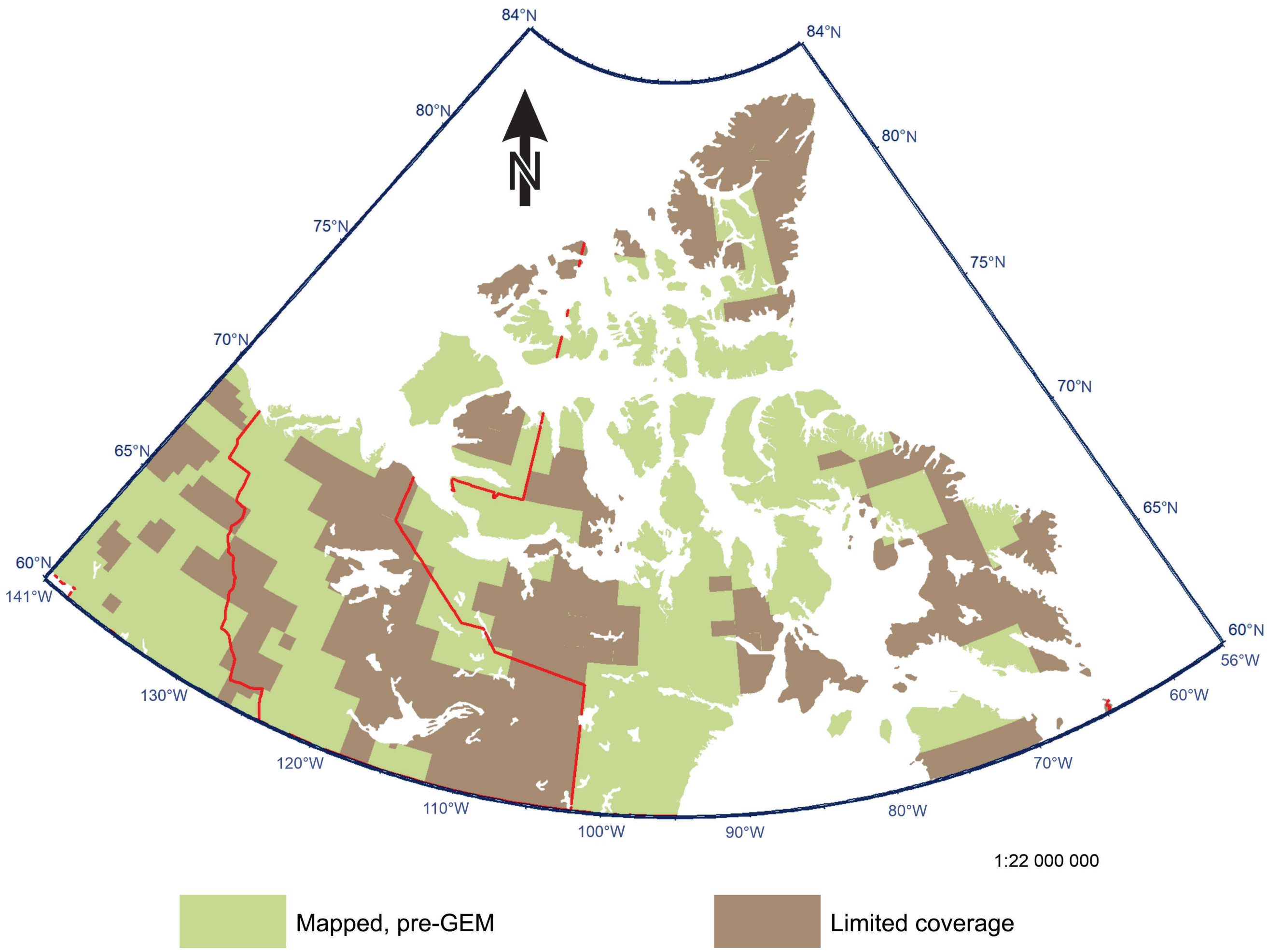

Figure 11. Surficial geology map coverage north of 60° prior to the start of the Geo-mapping for Energy and Minerals program (GEM). About 58% of the territorial landmass north of 60° (in green) was mapped prior to 2008. Areas in brown represent areas about which little is known.

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 had begun to investigate using 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; Brown et al., 2007, 2008; Harris 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 7 ETM+), and a regional DEM to produce a predictive map of surficial materials for the Shultz Lake area (NTS 66-A) of Nunavut (Grunsky et al., 2006). 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 imagery, DEMs, and data sets, studies within the GSC have continued to investigate RPM as an experimental tool, including machine-based techniques and protocols. Over the past 10 years, GSC scientists and Canada Centre for Mapping and Earth Observation colleagues have been developing new methodologies to address the lack of sufficient surficial geoscience knowledge in unmapped areas of the Canadian North (*see* Appendix B for a complete list of GEM surficial-material RPM publications).

Predictive surficial-material 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,

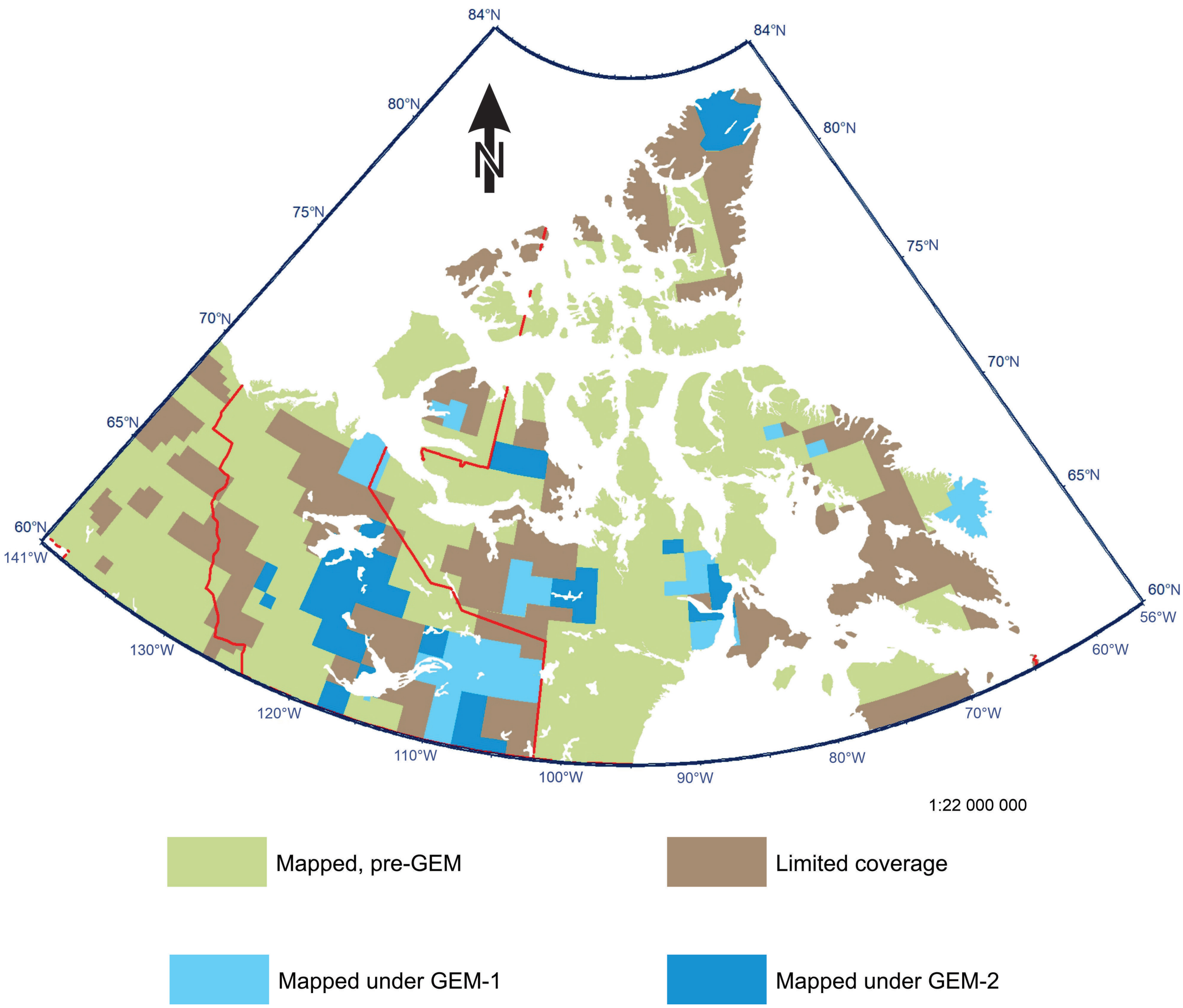

Figure 12. New surficial geology map coverage north of 60° produced during both phases of the Geo-mapping for Energy and Minerals program (GEM-1 and GEM-2). Surficial geology maps under compilation but not released yet are included. The combined mapping output of GEM-1 and GEM-2 contributed to about 12% of new mapping knowledge in targeted areas since the beginning of the GEM program.

with no context of genesis, may include organic deposits, sand and gravel, boulders, diamictons, fine-grained sediments, and exposed bedrock. Relying on RPM studies can also lead to a better understanding of glaciated landscapes and 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 material-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 by a geologist in the field. These material-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, as well as processes.

Surficial-material RPM examples

In this section, a number of key surficial-material RPM studies completed as part of the GEM program are summarized to illustrate methods used to produce several different products, namely classification maps of surficial materials, predictive surficial-geology maps, and predictive classification maps created using artificial intelligence. Additional RPM studies not discussed are listed in Appendix B.

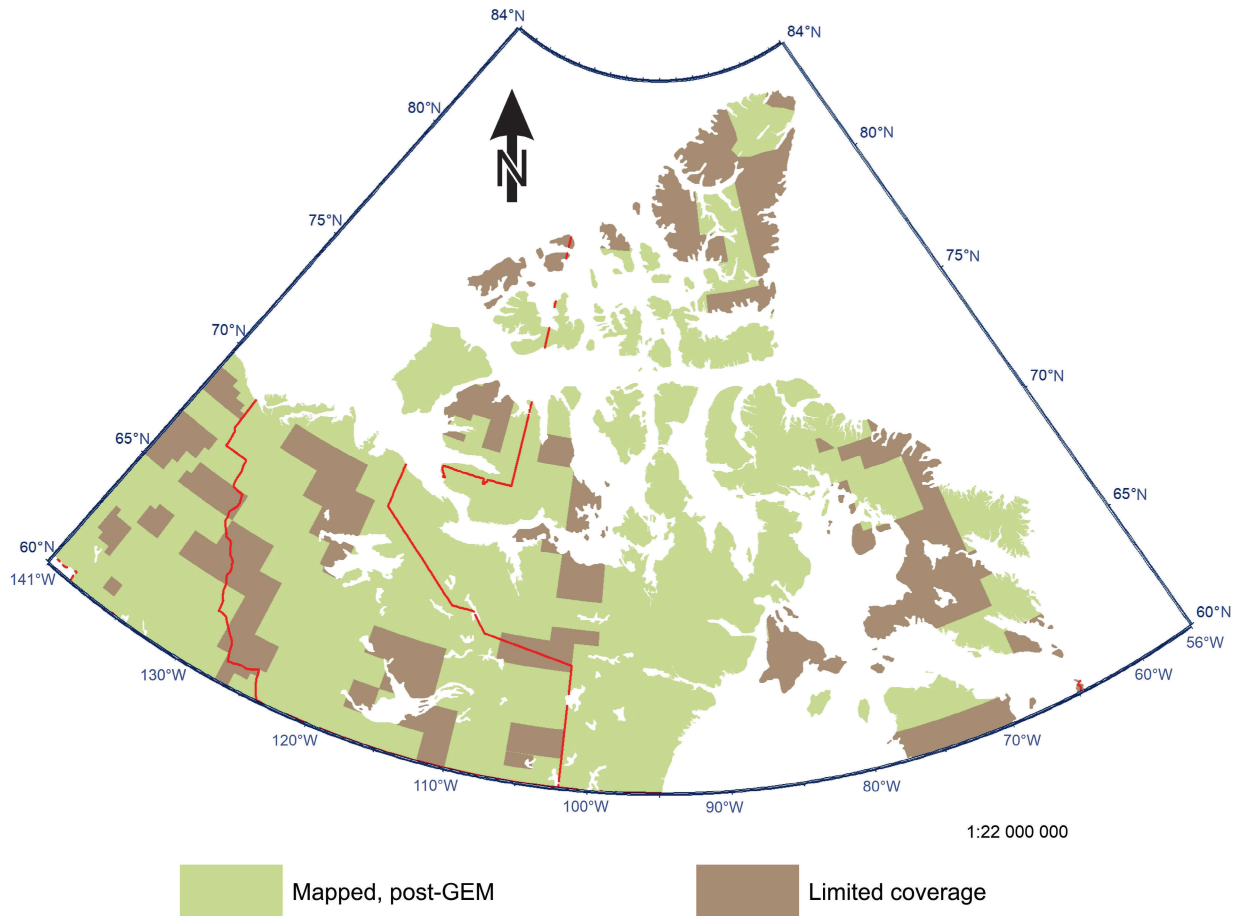

Figure 13. Surficial geology map coverage based on all Geological Survey of Canada and territorial programs. About 70% of the territorial landmass north of 60° is now mapped.

Surficial-material 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 imagery and data sets. Mapping of surficial earth materials using RPM methods northwest of Hudson Bay in Nunavut was undertaken as part of the GEM-1 Wager Bay Surficial Geology activity (Campbell et al., 2013; Wityk et al., 2013). A mosaic comprising seven separate Landsat 7 ETM+ images was prepared for the classification of surficial materials. Training areas representative of 12 surficial-material classes were identified using 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 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 analyzed using a confusion matrix and associated measures of accuracy, then geologically evaluated using airphotos combined 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, which were used 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 were critical elements of the production of raster-based predictive maps of surficial materials.

More recent mapping in the Wager Bay area (Fig. 14) as part of the GEM-2 Tehery–Wager project sought to improve on previous work (Byatt et al., 2019a) and to extend the coverage south of Wager Bay (Byatt et al., 2015, 2019b). Byatt et al. (2019a, b) produced predictive surficial-material maps with 21 (north) and 22 (south) material classes by applying a nonparametric Random Forests (RF) classifier to a combination of RADARSAT-2 C-band HH and HV satellite image data with Landsat 8 OLI, DEM, and slope

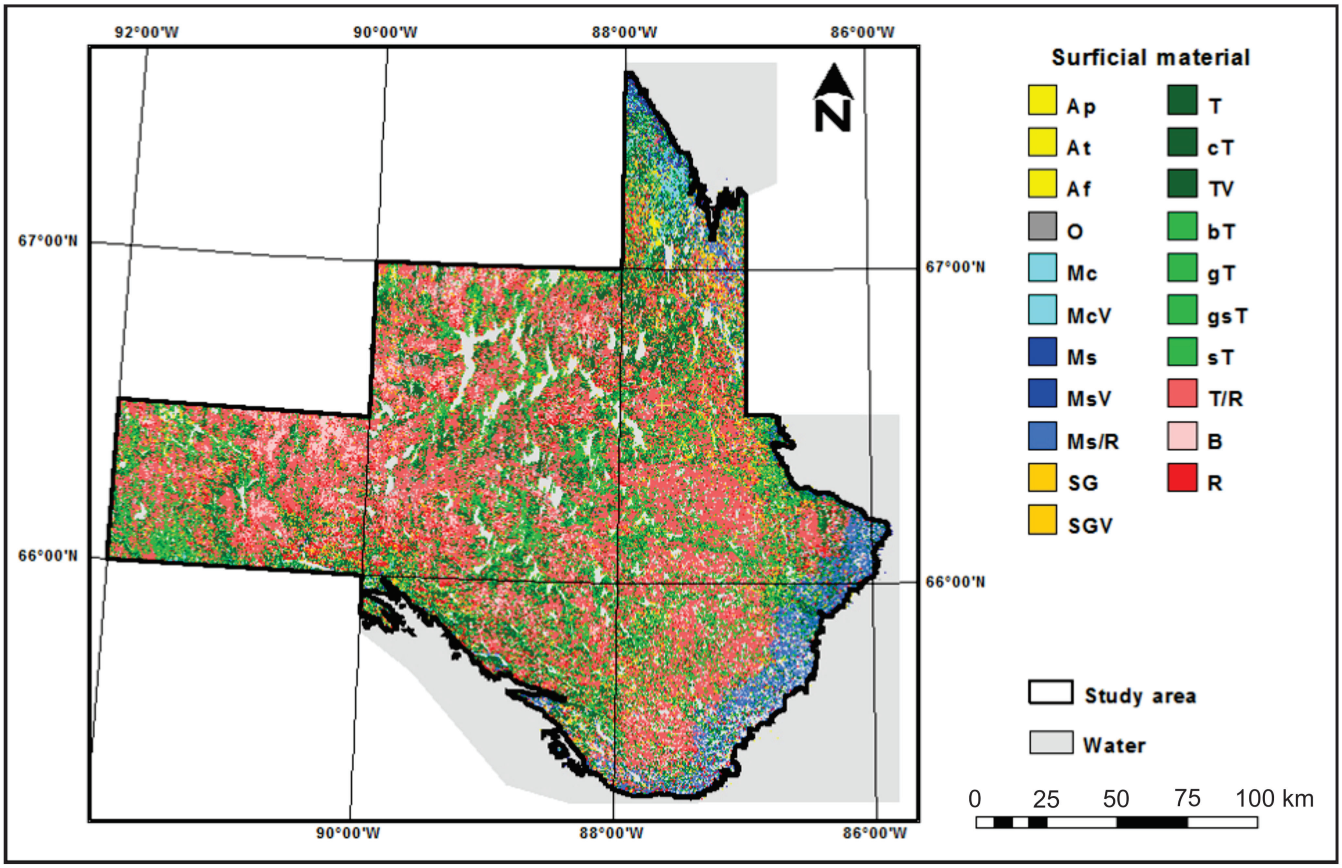

Figure 14. An example of a surficial-material classification map produced using remote predictive mapping methods. A Random Forests (RF) classifier was applied to a combination of satellite imagery and topographic data using the *All-polygon* version of RF to produce a classification map of the Wager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

data. Validation (mapping) accuracies were determined by comparing the resulting maps to more than 1000 field sites. Adding dual-polarized RADARSAT-2 images and using the *All-polygon* version of RF increased the overall accuracy of the classification to 98.1% (Byatt et al., 2019a). Adding RADARSAT-2 data to the classification also increased the validation accuracy to above 85% for most of the classes. This study produced similar but improved classification maps with respect to the work presented in Campbell et al. (2013).

Predictive surficial geology maps

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

One of the early predictive surficial geology maps was produced in the Yellowknife area (Stevens et al., 2012) as part of the Tri-T Surficial Compilation activity of the GEM-1 Information Management project and the Transportation Risk in the Arctic to Climatic Sensitivity activity in the Climate Change Geoscience program. The initial surficial-material classification map was based on 20 repetitions of the robust classification method using maximum likelihood classification applied to the normalized Landsat bands 2, 3, 4, 5, and 7. Separate classification was performed on the northeastern and southwestern portions of the map area. The surficial-material map was generalized to conform to cartographic standards for a 1:125 000 scale map. The generalization included three iterations of a 3 × 3 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, field observations, and legacy data (such as adding glacial striations from reconnaissance maps or bedrock maps and other field data).

A comparison between the surficial materials identified using RPM methods and the interpreted airphoto for two training areas of 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 that achieved through 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 boundaries between certain sediment types that have distinct surface expression and morphology (e.g. eskers, drumlinoids, beach ridges).

In the Rae map area (NTS 85-K), a more robust methodology was developed as part of the GEM-2 Mackenzie 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 See5, a data mining tool, 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 DEM, and DEM texture. Decision-tree methodology was chosen as the classification algorithm due to its ability to handle large training data sets 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, not only did forest-fire history and vegetation cover result in reduced accuracy but they also hindered establishing clear distinctions between classes according to experts in airphoto interpretation. Consequently, traditional airphoto interpretation was used to produce the final surficial geology map.

Integrated predictive surficial geology map

As part of the SMART Mapping activity of the GEM-1 Information Management project, a 1:250 000 predictive surficial geology map of the Washburn Lake area on eastern Victoria Island, Nunavut, was compiled using a new mapping method that integrates an RPM analysis, visually interpreted imagery, and regional-scale ground truth data (Sharpe et al., 2018). The main stages of this classification included

- data input from approximately three or four Landsat 7 ETM+ images (30 m resolution) tiled into a mosaic, panchromatic SPOT imagery (5 m pixel size), and interpretation of landforms from satellite imagery and airphotos;
- training data relating spectral signatures (material, vegetation, and slope, linked to variation in surface moisture) to areas of distinctive terrain using this imagery;
- image classification using an RF classifier;
- a surficial-material map integrating spatial variability and surficial materials and using expert knowledge of texture, landforms, and process; and
- 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 sought to assess the potential of deep neural networks to improve surficial geology mapping in the GEM-2 South Rae project in the southern Northwest Territories (Latifovic et al., 2018). This new method can provide an objective surficial-material 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 convolutional neural networks (CNNs) to predict surficial geology classes under two sampling scenarios. In the first scenario, CNNs used samples (training areas) collected over the area to be mapped and at ground observation sites. In the second scenario, CNNs trained over one area were 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+ time-series reflectance imagery, and high-resolution DEM data over five areas shown on the Abitau Lake map sheet (NTS 75-B: Latifovic et al., 2018). Unlike the regions in most of the studies previously discussed, this region is heavily forested. The thick vegetation masks the spectral signature of the surficial materials. The time-series Landsat mosaic provided a means to remove much of the effects of forest burns. The CNNs generated an average accuracy of 76% when locally trained. However, for independent test areas (i.e. trained over one area and applied over another), accuracy dropped to between 59% and 70% (av. 68%), depending on the classes selected for mapping. In comparison to the more widely used RF machine-learning algorithm, deep-learning CNNs represent an improvement in accuracy of 4%, producing better results for less frequent classes with distinct spatial structure. Both the classification and mapping accuracies significantly improved when CNNs were used, as subsequently noted in the assessment made by a surficial geologist using airphoto interpretation and fieldwork.

Landform mapping using RPM methods

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 imagery and DEMs has been the focus of many studies, both within and outside GEM project areas (Boulton and Clark, 1990; Clark, 1997; Kleman et al., 2002, 2010; De Angelis and Kleman, 2005, 2007, 2008; De Angelis, 2007; Greenwood and Kleman, 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 data sets: Landsat 7 ETM+ imagery (30 m resolution) and a Shuttle Radar Topography Mission DEM (90 m resolution). North of latitude 60°N, only Landsat data were used for the compilation. No existing data or maps were incorporated into the predictive map. It was recognized 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 the use of automated semiquantitative techniques to map glacial landforms. Eskers were chosen to test the utility of this approach. Esri ArcGIS and an esker-detection module written in Python were used, and the 1:50 000 scale Canadian digital elevation data (CDED) were smoothed using user-defined filter windows. A difference surface that emphasized ridge areas was produced and used to create polygons. Results from two test areas in the barrens of the Northwest Territories indicated that eskers with adequate relief, size, and peakedness could be extracted from CDED DEM data using legacy GSC vector esker-line data (Aylsworth and Shilts, 1989) as a training set and airphoto 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-material 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 on 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-material classes to surficial geological units of the SDM, and interpreted landforms to point and linear features, and the resulting effects on conceptual glacial-history models. However, RPM of surficial materials and landforms does provide a new knowledge layer that can complement data derived from airphoto interpretation or other visual interpretation using expert knowledge.

Byatt et al. (2019a, b) demonstrated that classification accuracies can be improved with the use of radiometrically balanced images and newer Landsat imagery; the introduction of RADARSAT-2 imagery, as well as DEM and slope data, into the model, thus 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 CNNs provided a potential means to address some of the limitations to surficial geology RPM. Latifovic et al. (2018) suggested 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 level of 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, the studies emphasize that RPM is a mapping tool meant to aid the surficial geologist and enhance 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 CGM and SDM 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 and 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 product 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 complemented by airphoto interpretation, particularly where field validation is provided.

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, DEMs of greater resolution (e.g. lidar, ArcticDEM), and appropriate imagery, future mapping of glacial landforms will certainly improve (*see* McMartin et al., this volume). 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 not only limits the ability to locate aggregate resources and to identify and assess terrain risks associated with various surficial materials, but also hampers mineral exploration. The RPM methodology that combines machine-automated learning techniques, field data, visual interpretation of remotely sensed images (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 help guide traditional field mapping and provide regional information useful for geotechnical investigations and mineral exploration.

SUMMARY

The considerable number of surficial geology maps recently published in northern Canada constitutes a significant legacy of the GEM program (Appendix A). Published and upcoming maps will result in an increase of 12% map coverage for areas north of 60°. The push to develop more accurate RPM techniques of surficial materials during the GEM program was 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 the increase in surficial geology map coverage north of 60° in the near future. In addition, the implementation of the GSC SDM is a major outcome that will allow the development of a standard data structure designed 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 in matters related to 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 that achieved by the widely used satellite imagery (i.e. Google Earth).

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Appendix A – GEM surficial geology maps

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Geological Survey of Canada, 2018. Surficial geology, Berlinguet Inlet and Bourassa Bay, Nunavut, NTS 47-G and 57-H; Geological Survey of Canada, Canadian Geoscience Map 339 (Surficial Data Model v. 2.3 conversion of Map 1960A), scale 1:250 000. https://doi.org/10.4095/306465

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Geological Survey of Canada, 2018. Surficial geology, Rock River, Yukon – Northwest Territories, parts of NTS 116-I and 116-P; Geological Survey of Canada, Canadian Geoscience Map 357 (Surficial Data Model v. 2.3 conversion of Map 11-1982), scale 1:100 000. https://doi.org/10.4095/308210

Geological Survey of Canada, 2018. Surficial geology, Boothia Peninsula, Nunavut, NTS 57-A, D, F, G and parts of 47-B, 57-B, C, E, 67-D, E, H; Geological Survey of Canada, Canadian Geoscience Map 358 (Surficial Data Model v. 2.3 conversion of Map 1570A), scale 1:500 000. https://doi.org/10.4095/308366

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Geological Survey of Canada, 2018. Surficial geology, Fort Simpson, Northwest Territories, NTS 95-H; Geological Survey of Canada, Canadian Geoscience Map 369 (Surficial Data Model v. 2.3.14 conversion of Preliminary Map 3-1978), scale 1:125 000. https://doi.org/10.4095/308384

Geological Survey of Canada, 2019. Surficial geology, Mistake River, Nunavut, NTS 56-L; Geological Survey of Canada, Canadian Geoscience Map 175 (Surficial Data Model v. 2.3.14 conversion of Preliminary Map 6-1981), scale 1:250 000. https://doi.org/10.4095/311262

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Appendix B – GEM surficial-material RPM publications

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