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OPEN FILE 9169

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2024

Canada

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Canada geological map compilation

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Abstract

The Canada Geological Map Compilation (CGMC) is a database of previously published bedrock geological maps sourced from provincial, territorial, and other geological survey organizations. The geoscientific information included within these source geological maps was standardized, translated to English, and combined to provide complete coverage of Canada and support a range of down-stream machine learning applications. Detailed lithological, mineralogical, metamorphic, lithostratigraphic, and lithodemic information was not previously available as one national-scale product. The source map data was also enhanced by correcting geometry errors and through the application of a new hierarchical generalized lithology classification scheme to subdivide the original rocks types into 35 classes. Each generalized lithology is associated with a semi-quantitative measure of classification uncertainty. Lithostratigraphic and lithodemic names included within the source maps were matched with the Lexicon of Canadian Geological Names (Weblex) wherever possible and natural language processing was used to transform all of the available text-based information into word tokens. Overlapping map polygons and boundary artifacts across political boundaries were not addressed as part of this study. As a result, the CGMC is a patchwork of overlapping bedrock geological maps with varying scale (1:30,000-1:5,000,000), publication year (1996-2023), and reliability. Preferred geological and geochronological maps of Canada are presented as geospatial rasters based on the best available geoscientific information extracted from these overlapping polygons for each map pixel. New higher resolution geological maps will be added over time to fill data gaps and to update geoscientific information for future applications of the CGMC.

1.0 Introduction

Bedrock geological maps are visual representations of the solid rock that occurs at, or near, the land surface. Accurate and detailed bedrock information is critical for a range of applications, including mineral potential, groundwater, geohazards, geothermal, engineering and construction, environmental impacts, geoscientific research, and education. The Geological Survey of Canada (GSC) published its first "Geological Map of Canada" prior to confederation, which included parts of the northeastern U.S. and the southeastern provinces of modern-day Canada (Logan, 1864). Multiple bedrock geological map compilations have since been published that provide complete coverage of Canada's land and offshore areas at variable levels of detail and reliability (Canada Bureau of Geology and Topography, 1945; Douglas, 1969; Geological Survey of Canada, 1884, 1955, 1962; Logan, 1869; Reed et al., 2005; Rice, 1955; Van Hise, 1896; Wheeler et al., 1996; Willis, 1906; Young, 1913, 1924). Over time, paper-based bedrock geological maps have evolved into digital databases with geoscientific information stored as attributes that are linked to geospatial polygons. Geoscientific data reported in these types of digital formats are essential for down-stream applications that require Geographic Information Systems (GIS) and other modes of geospatial analysis (Harrison et al., 2011; Reed et al., 2005; Wheeler et al., 1996).

The most recent geological map of Canada was published by Wheeler et al. (1996), and the digital data accompanying this seamless 1:5M scale paper-based map has since become one of the most downloaded products available from the Natural Resources Canada publication database. Some of the standardized attributes accompanying the paper map include geological provinces and domains, generalized geology, major and minor rock types, geological ages, and metamorphic grade. Each of these attributes were reported in French and English to improve accessibility. The Wheeler et al. (1996) map was subsequently used as one of the foundational pieces for the 1:5M scale Geologic Map of North America (Reed et al., 2005). Hoffman (2015) provides a historical account of John O Wheeler's life and the fundamental geoscientific research underpinning both of these remarkable contributions.

Provincial, territorial, and other geological survey organizations have made significant progress since Wheeler et al. (1996) to improve the quality and detail of bedrock geological map databases in their jurisdictions. Most of these more recently published map databases were completed at larger map scales (1:30,000-1:2,000,000) relative to the 1:5M national-scale compilation, revealing much more geological detail. The higher accuracy and precision of geological contacts within these more detailed maps is important for the large parts of Canada that are characterized by complex bedrock geology or to include small igneous intrusions that are difficult to visualize on paper-based maps at the national-scale. Recent geological map databases have also made significant progress on capturing more detailed geoscientific information including rock type, ages, mineralogy, metamorphic, lithostratigraphic, lithodemic data and descriptions of outcrops supporting the preferred map interpretation. None of this detailed information has previously been available at the national-scale. Moreover, the geospatial databases accompanying these more recent bedrock geological maps are published with their own data model and the geoscientific information associated with each geospatial polygon has never been standardized and combined into one digital product.

The Canada Geological Map Compilation (CGMC) is a research product that translates, edits, standardizes, and combines geoscientific information from 32 previously published geodatabases to address that knowledge gap (Table 1). Data included within the CGMC are presented in a series of folders that are named after their corresponding file format. Standardized geoscientific information associated with overlapping map polygons is reported as a database with geospatial information in a GeoPackage file format (i.e., “gpkg” folder). The same information is also reported in a non-spatial CSV file format for machine learning applications (i.e., “csv” folder). This CSV format includes the original and edited polygon coordinates in well-known text format (WKT) that can be converted back to geospatial polygons as required. Seven electronic tables (cgmc_table_01:cgmc_table_07) containing the definitions for the standardized geoscientific data and vocabularies with linkages to international data standards like GeoSciML (v2016.01) are reported as Microsoft Excel file formats. Continued progress on these types of international data standards (e.g., North America Data Model, GeoSciML, and INSPIRE) have the potential to greatly increase the interoperability of geospatial databases in the future (Laxton, 2017; Sen & Duffy, 2005). Spatial indexing is also used to construct new geological and geochronological maps of Canada based on the best available geoscientific information for each map pixel. The preferred geological and geochronological maps are presented as geospatial rasters in a GeoTIFF format with a colour key (i.e., “geotiff” folder) and publication-ready coloured images in JPEG format (i.e., “jpeg” folder).

2.0 Data

2.1 Source map information

Reference information for each source map is reported in Table 1. Users of the CGMC are referred to those original sources for more information and to access the most up to date information. Map data included within CGMC can be linked back to their source dataset using the row number of the original map polygons (i.e., SOURCE_FID). The source feature-identifier number is unique for each source map. Each source map was also assigned a unique reference identifier (i.e., SOURCE_REFERENCE_ID) based on the publication year, publisher abbreviation, and publication name (Table 1). This source reference identifier will be managed over time to make sure that it remains unique as new geological maps are added to the CGMC. The “SOURCE_FID” and “SOURCE_REFERENCE_ID” are also combined to generate a persistent identifier (PID) that is unique for each map polygon included in the CGMC (Table 2). The calculated PID will remain fixed and unique, even as new geological maps are added to the CGMC over time, and can be used as a key for database join operations as required. The “SOURCE_FID”, “SOURCE_REFERENCE_ID”, and “PID” are mandatory geospatial attributes (Table 2). Other mandatory attributes that provide source information include publication year, maximum mapping scale, minimum mapping scale, source geometry, and full bibliographic reference (Table 2). Optional source information includes the digital object identifier (DOI), which was unavailable in some cases (Table 2). All missing source map information is reported as “unknown”. All geospatial polygons are transformed to the Canada Atlas Lambert coordinate reference system (EPSG:3978). Index maps showing the spatial extent of each source geological map are presented in Fig. 1.

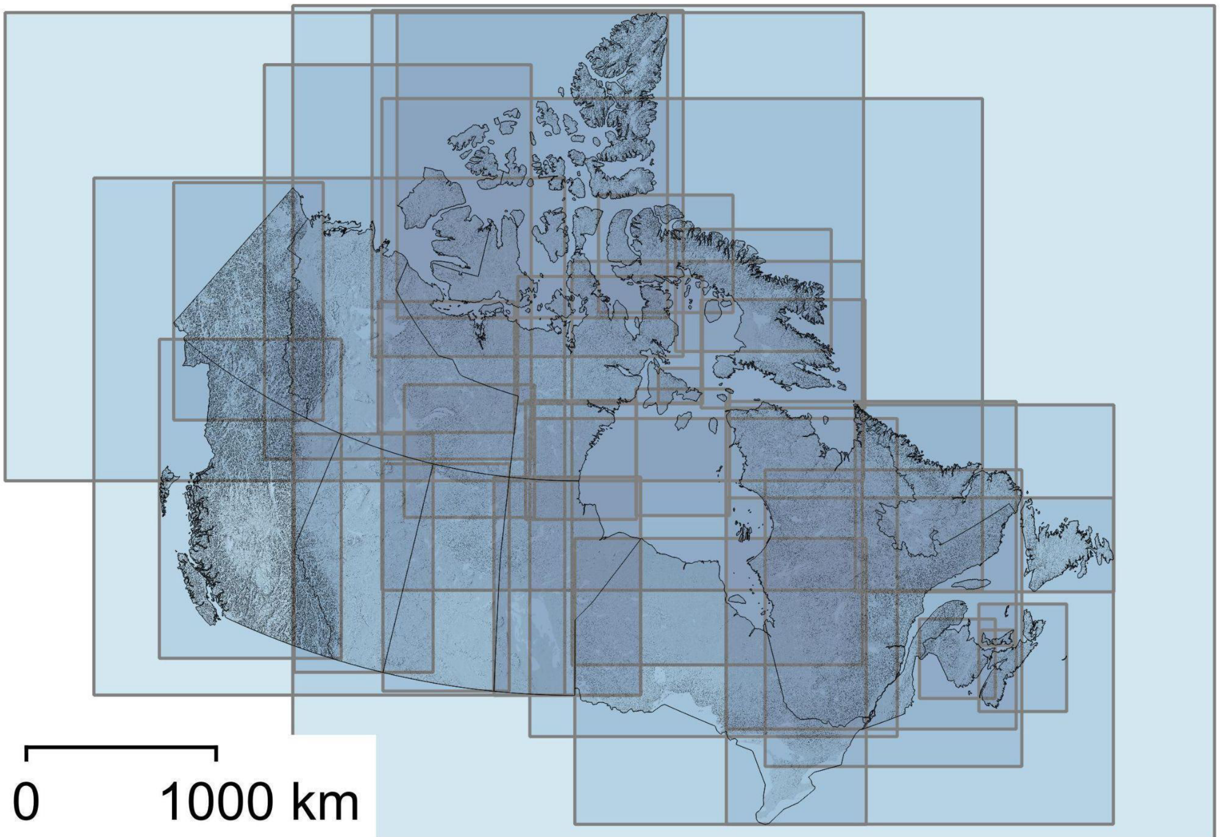

Figure 1: Spatial coverage for geological source maps included in the CGMC (n = 32).

2.2 Lithological information

Three different methods are used to standardize lithological information included in the source maps. First, all of the available geoscientific information is used to re-classify each map polygon into 35 generalized lithologies (i.e., LITHOLOGY_CLASSIFICATION; Table 3). These generalized lithologies are subdivided into: (1) “igneous”, (2) “sedimentary”, and (3) “metamorphic” rocks classes (Table 3). Map polygons that do not fit within these broad classes are described as “other”. Generalized lithologies are based on the interpreted protolith wherever primary sedimentary and/or igneous features are recognized from the available text data. As a result, the CGMC is an interpretative bedrock geological map of rock protoliths. In contrast, “metamorphic” rocks are reserved for map polygons that are missing primary sedimentary and/or igneous features. The reliability of the rock descriptions to interpret these generalized lithologies is captured using the Tikoff et al. (2023) semi-quantitative uncertainty scale within the “LITHOLOGY_CLASSIFICATION_UNCERTAINTY” attribute (i.e., certain, 100%; compelling, 75%, presumptive 50-75%, suggestive 25-50%, permissive, <25%, no evidence, 0%; Table 2). The LITHOLOGY_CLASSIFICATION and LITHOLOGY_CLASSIFICATION_ UNCERTAINTY are mandatory attributes.

Second, all individual rock types present within the source maps are listed in order of decreasing abundance where that information was provided and/or the order of first appearance in the absence of any other information (i.e., LITHOLOGY_01 to LITHOLOGY_10). Igneous, sedimentary, and metamorphic lithologies have been re-classified to formal names wherever possible to improve search (describe below). A complete list of unique lithologies and the most closely matching GeoSciMl vocabulary is reported in Table 4. The LITHOLOGY_01 to LITHOLOGY_10 attributes are optional. Almost all source map polygons contained fewer than ten rock types. Future versions of CGMC may need to expand the number of LITHOLOGY attributes as required. Missing rock types are reported as “unknown”.

Third, all of the available text data, including the original rock types, are converted to word tokens using natural language processing (described below). A semicolon is used as the separator for each word token. All description fields were checked for spelling prior to natural language processing. All lithological text data is reported in lowercase.

2.2.1 Igneous rocks

Igneous rocks are subdivided into 13 generalized lithology classes based on their mode of origin (i.e., intrusive versus extrusive) and composition (Table 3). Extrusive igneous rocks are fine-grained and are further subdivided into igneous_extrusive_alkalic (e.g., phonolite, tephrite, basanite), igneous_extrusive_felsic (e.g., rhyolite), igneous_extrusive_intermediate (e.g., andesite), and igneous_extrusive_mafic (e.g., basalt). Undivided, extrusive igneous rocks of uncertain and/or mixed composition are classified as “igneous_extrusive” for the purposes of the generalized lithology classification. Extrusive igneous rock types (LITHOLOGY_01:LITHOLOGY_10) included in the source maps are re-classified to lithologies following the International Union of Geological Sciences (IUGS) total alkali silica (TAS) diagram wherever possible (Le Maitre et al., 2002). For example, rocks originally described as “mafic volcanics” are re-classified as “basalt” in CGMC (Table 4). Volcaniclastic rocks are grouped with the appropriate extrusive rock composition for the LITHOLOGY_CLASSIFICATION; whereas the “igneous_extrusive” class is used for undivided volcaniclastic rocks of uncertain composition. Previously published volcaniclastic rock classification systems were not used as part of the present study because these more precise rock names were often missing from the source datasets and many of the proposed rock names have multiple definitions (Cas & Wright, 1988; Fisher, 1961, 1966; Frolova, 2008; White & Houghton, 2006). As a result, all volcaniclastic rock types (e.g., tuff, ash, lapilli, lapillistone, lapilli tuff, tuff breccia, pyroclastic breccia, volcanic breccia, volcaniclastic, agglomerate) in the source datasets are re-classified to “volcaniclastic rock” within the CGMC (Table 4). The original volcaniclastic rock types that are based on one or more of the formalized volcaniclastic rock classification schemes are maintained in the tokens attribute. Qualifiers were used to interpret the LITHOLOGY_CLASSIFICATION, but were not used to infer the LITHOLOGY_01:LITHOLOGY_10 attributes unless they inferred a specific rock type (e.g., mafic, intermediate, and felsic volcanics implies basalt, andesite, and rhyolite, respectively; Table 4).

Intrusive igneous rocks are all coarse-grained and further subdivided into compositional sub-groups, including igneous_intrusive_felsic (e.g., granite), igneous_intrusive_intermediate (e.g. diorite), igneous_intrusive_mafic (e.g., gabbro), igneous_intrusive_ultramafic (e.g., peridotite). The “igneous_intrusive” class is used for undifferentiated igneous intrusive rocks of uncertain origin (Table 3). Many of these poorly documented igneous intrusions were inferred from geophysical surveys. Two additional igneous intrusive classes are used for specific rocks types based on their historic importance as a textural field description (i.e., igneous_intrusive_pegmatite) and/or because of their poor fit into the four main compositional groups (i.e., igneous_intrusive_anorthosite; Table 3). The original igneous intrusive rock types are re-classified within the LITHOLOGY_01:LITHOLOGY_10 attributes to follow the International Union of Geological Sciences (IUGS) quartz-alkali feldspar-plagioclase-feldspathoid (QAPF) and mafic-ultramafic diagrams wherever possible (Streckeisen, 1976). For example, rocks originally classified as a “granitoid” are re-classified as “granite” in CGMC (Table 4). Qualifiers were used to interpret the LITHOLOGY_CLASSIFICATION attribute, but were not used to indicate the presence of specific intrusive igneous rock lithologies (e.g., granitic, granitized, and granite-like were not used to infer granite as a lithology for the LITHOLOGY_01:LITHOLOGY_10 attributes; Table 4).

2.2.2 Sedimentary rocks

Sedimentary rocks are subdivided into six generalized lithology classes based on bulk composition and/or grain size (i.e., sedimentary_siliclastic, sedimentary_siliclastic_coarse, sedimentary_fine, sedimentary_chemical, sedimentary_chemical_carbonate, sedimentary_chemical_ evaporite; Table 3). Siliciclastic rocks comprise silica-based clasts that are generally devoid of carbonate minerals. Dozens of classification systems have been proposed to classify siliciclastic rocks based on grain size, composition, texture, depositional environment, and/or transport mechanisms (Crook, 1960; Dickinson, 1970; Dott, 1964; Folk, 1954, 1980; Garzanti, 2019; Klein, 1963; Lazar et al., 2015; Lundegard & Samuels, 1980; Macquaker & Adams, 2003; Okada, 1971; Pettijohn, 1954; Picard, 1971; Shepard, 1954; Spears, 1980; Stow, 1981). The use and misuse of these classification schemes presents significant challenges for national-scale compilations that include observations from hundreds of geoscientists over many decades. As a result, the current study focuses on re-classified the dozens of possible siliciclastic rock types into four lithologies based on grain size: (1) breccia, (2) conglomerate, (3) sandstone (e.g., arenite, arkose, psammite, greywacke, wacke, grit, orthoquartzite, and locally quartzite); and (4) mudrock (e.g., siltstone, mudstone, claystone, shale, slate, argillite, and pelite; Table 4). Qualifiers were excluded during the re-classification process (e.g., sandy, silty, muddy) to focus the re-interpretation of siliciclastic rock types on the root word for the LITHOLOGY_01:LITHOLOGY_10 attributes. The reduced number of siliciclastic lithologies makes search easier and all of the original rock types are included in the tokens attribute for more precise, albeit mixed, nomenclature.

Chemical sedimentary rocks form by biological and chemical processes and comprise a diverse suite of rock types that are re-classified as three generalized lithologies. Limestone is the most common chemical sedimentary rock and comprises mostly calcite and/or aragonite ($CaCO_3$). Calcium-bearing limestone was differentiated from magnesium and calcium-bearing dolostone [$CaMg(CO_3)_2$] wherever possible based on the available text data for the LITHOLOGY_01:LITHOLOGY_10 attributes (Table 4). Dolomite was re-classified as dolostone for consistency (Table 4). However, limestone and dolostone are combined as “sedimentary_chemical_carbonate” for the generalized lithology classification (Table 3). Multiple classification have been proposed to classify limestone and other carbonate rock types based on grain size, clast type, texture, diagenetic processes, and depositional environments (Bissell & Chilingar, 1967; Dunham, 1962; Folk, 1959; Wolf, 1960; Wright, 1992). The rock types presented in these classification system were re-classified to limestone as part of the current study to improve search (e.g., calci-mudstone, mudstone, wackestone, packstone, grainstone, boundstone, bindstone, crystalline, floatstone, rudstone, bafflestone, framestone) within the LITHOLOGY_01:LITHOLOGY_10 attributes (Table 4). Siliciclastic rocks with qualifiers that imply a significant proportion of carbonate minerals are also re-classified to limestone to further limit the number of possible lithologies for search purposes (e.g., micrite, marl, and lime are all used to infer limestone as a lithology rather than a siciclastic rock; Table 4).

Evaporites form in marine environments and/or lakes and represent the second generalized lithology sub-division of chemical sedimentary rocks (Table 3). Calcite, gypsum, anhydrite, halite, and potash are the dominant minerals that precipitate from solution and concentrate to form evaporite deposits. In many cases, the presence of evaporite deposits and exhalites had to be inferred from mineral names rather than rock types. Qualifiers were used for the LITHOLOGY_CLASSIFICATION, but were not used to infer specific lithologies (e.g., evaporitic is not used to infer evaporite for LITHOLOGY_01:LITHOLOGY_10).

The remaining "sedimentary_chemical" generalized lithology classification comprises a diverse range of other chemical and/or biological rock types, including chert, iron formation, phosphorite, barite, and coal (Table 3). These rocks tend to be intercalated with fine siliciclastic and/or extrusive igneous rocks in sediment-starved depositional settings, but, in detail form by a variety of different chemical and/or biological processes. With the exception of iron formation (e.g., taconite, banded iron formation, BIF), most of these lithology types are taken directly from the source descriptions and without further modification (Table 4). Qualifiers were used for LITHOLOGY_CLASSIFICATION, but were not used not used to infer specific lithologies (e.g., cherty is not used to infer chert for the LITHOLOGY_01: LITHOLOGY_10 attributes).

2.2.3 Metamorphic rocks

Metamorphic rock types are subdivided into 11 generalized lithology classes and are restricted to rock types that lack primary igneous and/or sedimentary features (Table 3). Generalized metamorphic rock classes are based on a combination of textural (i.e., granoblastic versus foliated) and mineralogical features. Each class is based on established names in the scientific literature, although the precise definition of metamorphic types is known to vary depending on the informal classification system used. The "metamorphic_charnockite" class is a type of granofels that includes a variety orthopyroxene-, quartz- and feldspar-bearing rocks that form at granulite-facies metamorphic conditions (e.g., charnockite, enderbite, mangerite, and opdalite; Table 3). The "metamorphic_ migmatite" generalized lithology class also forms at granulite facies metamorphic conditions, but unlike charnockite, is based on texture rather than mineralogy (Table 3). Other granofels metamorphic rocks include eclogite (i.e., rocks comprising garnet and pyroxene), amphibolite (i.e., rocks comprising mostly amphibole), marble (i.e., rocks comprising mostly calcite), and quartzite (i.e., rocks comprising mostly quartz), which are classified based on their observed mineralogy (Table 3). These granofels metamorphic rock types may occur across a wide range of pressures and temperatures conditions. In contrast, foliated metamorphic rocks are classified into "metamorphic_gneiss" and "metamorphic_schist" based on their texture (Table 3). The "metamorphic_gneiss" class is further subdivided into orthogneiss and paragneiss based on the most likely igneous or sedimentary protolith, respectively. All other strongly foliated metamorphic rocks are classified as "metamorphic_schst" regardless of grain size (e.g., schist, phyllite; Table 3). Historic metamorphic rock names, or metamorphic rocks within the same group, were simplified into standard lithologies as required for the LITHOLOGY_01:LITHOLOGY_10 attributes (Table 4).

2.2.4 Other

Unconsolidated sediments and/or rocks that are not readily described as either igneous, metamorphic or sedimentary are re-classified into five additional classes, including other_fault (e.g., cataclasite, mylonite, pseudotachylite), other_hydrothermal (e.g., veins, metasomatic rocks), other_melange (e.g., melange), other_unconsolidated (e.g., unconsolidated to semi-consolidated sediments), and other_unknown (e.g., unmapped areas, ice, water, and rock of uncertain origin; Table 3). The "other" classes contain the broadest range of original rock names that had to be re-classified to facilitate search. For example, the "fault rock" lithology is used for the LITHOLOGY_01: LITHOLOGY_10 attributes to re-classify dozens of original fault rock names that may or may not correspond to the multiple fault rock classifications that have been developed over the years (Higgins, 1971; Killick, 2003; Sibson, 1977; Woodcock & Mort, 2008). Similarly, veins and other forms of hydrothermal alteration that completely obscure the protolith lithology are re-classified to the "metasomatic rock" lithology. Correctly interpreting the origin of these types of hydrothermally altered rocks is challenging with the available information, and the protolith is used for the generalized lithology classification wherever possible. The melange class comprises matrix-supported breccias containing blocks of mixed lithologies that tend to be associated with continental margins. The diapiric, structural, and/or sedimentary process responsible for producing melange are sufficiently distinct from faults (and other generalized lithology classes) to warrant their own class (Festa et al. 2010). However, we note that melange has been used as a descriptive term and lithology within the source maps and the concept has also evolved over time. The unconsolidated class includes glacial and other surficial sedimentary deposits. All of the original names used to describe these surficial deposits are re-classified to "unconsolidated material" lithology for the LITHOLOGY_01:LITHOLOGY_10 attributes because the CGMC is intended to be applied as a compilation of bedrock geoscientific information (Table 4). Finally, the unknown class is used to re-classify all unmapped areas and rocks of uncertain origin. All of the original geoscientific words used to describe map polygons are preserved as word tokens for additional context.

2.3 Geochronological information

Geochronological information is standardized and subdivided following the International Chronostratigraphic Chart (ICC) developed by the International Commission on Stratigraphy (ICS; v 2023/09)(Cohen et al., 2013). No attempt was made to correct source maps for the changing definitions of the ICC over time. Maximum and minimum ages are reported using the most precise time subdivisions available in the source maps, with more general time subdivisions imputed accordingly. For example, a sedimentary rock deposited in the "Cambrian" period is assigned to the "Paleozoic" era and "Phanerozoic" eon by default, even if the more generalized age subdivisions were not included in the source maps. However, the epoch and age for a rock deposited in the "Cambrian" is classified as "unknown". Map polygons with one age are reported with identical maximum and minimum age information. Translating source map data to the ICC also required "Tertiary" to be re-classified as "Paleogene" and "Neogene". Similarly, ages reported as "Precambrian" in the source maps are translated to maximum and minimum ages of "Archean" and "Proterozoic", respectively. Maximum and minimum absolute ages and their uncertainties are reported as is and may correspond to intrusions are dykes that are younger than their host rocks. As a result, absolute ages may be inconsistent with the other age information provided in the ICC format. All missing geochronological information is reported as "unknown". Text-based geochronological information is reported in title case.

2.4 Mineralogical information

Mineralogical information is taken directly from the source maps using the list of official mineral names published by the International Mineralogical Association and Commission on New Minerals, Nomenclature and Classification (CNMNC; January 2023) wherever possible. However, a large number of exceptions to these formalized mineral names were required based on what was available in the source maps, including commonly used mineral groups (i.e., biotite, amphibole, garnet, pyroxene, and serpentine). Historic mineral names were converted to their corresponding mineral group (i.e., hornblende = amphibole; hypersthene = orthopyroxene) to improve search. Special qualifiers used to describe metamorphic and/or hydrothermal alteration were converted to mineral groups wherever possible (e.g., biotitized = biotite). All missing mineralogical information is reported as “unknown”.

2.5 Metamorphic information

Maximum and minimum metamorphic facies are based on information contained in the source maps and subdivided into standardized facies, including hornfels, zeolite facies, prehnite–pumpellyite facies, greenschist facies, amphibolite facies, granulite facies, blueschist facies, and eclogite facies (Schmid et al., 2007). For map polygons that report one metamorphic grade, the “METAMORPHIC_MAXIMUM” and “METAMORPHIC_MINIMUM” attributes contain the same information. As a result, the “METAMORPHIC_MAXIMUM” attribute is likely more informative for the large number of map polygons that do not report a range of pressure and temperature conditions. Granulite and eclogite rocks are used to infer granulite and eclogite facies metamorphism, respectively, even if metamorphic grade was missing from the source maps. Amphibolites were not used to infer amphibolite facies metamorphism because multiple geological processes can produce amphibole-rich rocks and their mode of origin was rarely described in the source data. Moreover, qualifiers used to describe metamorphic facies are excluded from the standardized metamorphic information because of the possibility that these terms were used inconsistently over time (e.g., upper, middle, lower, low, medium, high). All missing metamorphic information is reported as “unknown”. Text-based metamorphic information is reported in lower case.

2.6 Lithostratigraphic information

Lithostratigraphic information is standardized into “supergroup” (i.e., two or more groups), “group” (i.e., two or more formations), “formation” (i.e., the primary unit of lithostratigraphy), “member” (i.e., a named lithological subdivision of a formation), “bed” (i.e., a named distinctive layer in a member or formation), and “flow” (i.e., the smallest distinctive layer in a volcanic sequence) following the guidelines of the International Stratigraphic Guide (ISG) and North American Stratigraphic Code (NASC)(ISSC, 2000; Murphy & Salvador, 1999; NASC, 1983, 2005, 2021; Salvador, 1994). Each of these terms is restricted for igneous and sedimentary rocks that conform to the law of superposition as described by the ISG and NASC. All other lithostratigraphic names that did not conform to the ISG and NASC nomenclature are reported within the LITHOSTRATIGRAPHIC_OTHER attributes. For some geological maps, lithostratigraphic information had to be sourced from separate electronic tables and joined to the polygons using an alphanumeric code. Lithostratigraphic names and parent-child relationships were not-reinterpreted as part of the current study. Inferring parent-child relationships from the standardized lithostratigraphic information is therefore not advised. For example, multiple formation names may or may not correspond to the same group name, even for the same map polygon. Biostratigraphic, allostratigraphic, and pedostratigraphic information were not standardized, but all text-based information extracted from the source maps is maintained in the word tokens attribute. All missing lithostratigraphic information within the standardized attributes are reported as “unknown”. Text-based lithostratigraphic is reported in title case

The standardized lithostratigraphic data were also joined with the Lexicon of Canadian Geological Names on-line database (Weblex; https://weblex.canada.ca) wherever possible based on the standardized name and locality (i.e., province and/or territory). The Weblex database provides significantly more information on the status, location, age, lithology, and history of lithostratigraphic names across Canada. The expanded rock descriptions included in the Weblex database are particularly important for the down-stream natural language processing applications (Lawley et al., 2023). New names are being added to the Weblex database by users over time and so linkages with lithostratigraphic names as part of CGMC will need to be updated in future publications. All Weblex information is reported as is and in the same casing as the online database so that the long-form English names can be used as a join key to link the CGMC and Weblex for down-stream applications. Missing Weblex information is reported as “unknown”.

2.7 Lithodemic information

Lithodemic information is restricted to rocks that do not conform to the law of superposition (Gillespie & Leslie, 2021; Hattin, 1991; NASC, 1983, 2005, 2021). Source maps include this kind of lithodemic information as mappable assemblages of metamorphic, igneous, and/or highly deformed rocks of special significance. However, lithodemic naming schemes are not as formalized as the lithostratigraphic nomenclature and source maps contain a large number of names that do not conform to any known standard (Gillespie & Leslie, 2021; NASC, 1983, 2005, 2021). As a result, lithodemic names were treated as is and grouped into “supercomplex” (i.e., two or more complexes), “complex” (i.e., an association between two or more intrusive, highly deformed, and/or highly metamorphosed rocks), “supersuite” (i.e., two or more suites), and “suite” (i.e., an association between two or more intrusive, highly deformed, and/or highly metamorphosed rocks). All other informal lithodemic names (e.g., series, zones, swarms, plutons, sills, dykes) were combined into the LITHODEMIC_OTHER attributes. The rank and significance of these “other” lithodemic names is highly variable. More research is needed to formally classify lithodemic information at the national-scale (Gillespie & Leslie, 2021). Similar to the lithostratigraphic information described above, individual map polygons may contain multiple lithodemic names that are unrelated. Text-based lithodemic information is reported in title case. Standardized lithodemic information is joined with the Weblex database wherever possible. All Weblex information is reported as is. Missing lithodemic information is reported as “unknown”.

3.0 Natural language processing methods

All text processing was completed using the “tidytext” (Silge & Robinson, 2016), “deeplr” (https://github.com/zumbov2/deeplr), and “tidyverse” (Wickham et al., 2019) in R (R Core Team, 2024). First, text data from each source map was concatenated into a single attribute. The concatenated text data was then transformed to lowercase word tokens (Silge & Robinson, 2016). Numbers, punctuation, spaces, and tokens with fewer than three characters were removed as part of the tokenization process (Lawley et al., 2023). Unique word tokens were then extracted and translated to English using the DeepL application programming interface (https://www.deepl.com). Text outputs from the DeepL API were manually inspected to identify errors introduced during the translation process and to create a list of uninformative word tokens (i.e., stop words). A large number of stop words correspond to rock mapping codes within the source datasets. People, place, and animal names were added to the list of stop words to focus downs-stream NLP research on geoscientific information. A standard list of English stop words (n = 1,149) was also used to remove uninformative word tokens from further analyses (e.g., he, she, they)(Silge & Robinson, 2016). The translated, corrected, and filtered word tokens were then concatenated for each PID ("TOKEN_ENGLISH"). Overall, the CGMC corpus comprises 5,141,215 word tokens in total and 4,430 unique word tokens. Missing text data is reported as "unknown". All word tokens are reported in lower case and separated by a semi-colon.

4.0 Preferred geological and geochronological maps of Canada

All spatial operations were completed in R using the "sf" (Pebesma, 2018), "terra" (Hijmans et al., 2022), "fasterize" (https://github.com/ecohealthalliance/fasterize), and "tidyverse" (Wickham et al., 2019) packages. Virtual machines were used for the most memory intensive operations, typically using the EC2 M5 instances available through Amazon Web Services (https://aws.amazon.com), Posit Workbench, and SageMaker (Joshi, 2020). Spatial indexing is based on Google's hierarchical S2 discrete global grid system (DGGS), which partitions the planet into quadrilaterals at variable spatial resolutions (http://s2geometry.io). The CGMC uses resolution 15 of the S2 DGGS, which corresponds to 6B quadrilaterals globally. Each quadrilateral at this resolution corresponds to an approximate edge length and area of 290 m and 79,173 m^2, respectively (http://s2geometry.io/resources/s2cell_statistics). Canada was partitioned into S2 cells based on the simplified 1:10M scale national shoreline polygon downloaded from Natural Earth (https://www.naturalearthdata.com). Approximately 121,194,444 S2 cells cover the Canadian landmass at resolution 15, although this number can vary depending on the level of shoreline detail used to calculate the terrestrial limits of the map area. The process of spatial indexing could be repeated at higher (few mm), or lower (1,000s of km), S2 resolutions depending on the down-stream application and the available computing resources. Each of the 32 bedrock geological maps were spatially indexed source maps using the same methodology. The "best-available" spatially indexed source map for each S2 cell was then extracted based on the following heuristic: (1) map polygons with "permissive" lithological classification uncertainty were removed. This filtering step removed map polygons that were inferred from geophysics and buried under Phanerozoic cover in Manitoba; (2) lithology rank (i.e., other_unknown = 1; other_unconsolidated = 1; other_fault = 2, other_hydrothermal = 2, other_melange = 2; all others = 3) was sorted in descending order. This sorting step decreases the likelihood that unmapped areas are included in the preferred geological map; (2) LITHOLOGY_CLASSIFICATION_UNCERTAINTY was sorted in descending order to prioritize map polygons with low classification uncertainty; (3) SOUCE_SCALE_MAXIMUM was sorted in ascending order to prioritize source maps with the most geological detail; and (4) SOURCE_YEAR was sorted in descending order to prioritize the most recent information; and (5) LITHOLOGY_CLASSIFICATION was sorted in alphabetical order. This heuristic is intended to identify the best-available geoscientific information for each S2 cell and was used to construct the preferred geological map of Canada (Fig. 2). The same method was used to create the preferred geochronological map of Canada, although an extra step was required to remove source data with missing age information prior to sorting the S2 cells (Figs. 3 and 4). For visualizing purposes, the preferred geological and geochronological maps of Canada were rasterized to a 200 by 200 m square grid and exported in a GeoTIFF file format. The colour attributes for each GeoTIFF file are provided within the cgmc_geotiff folder.

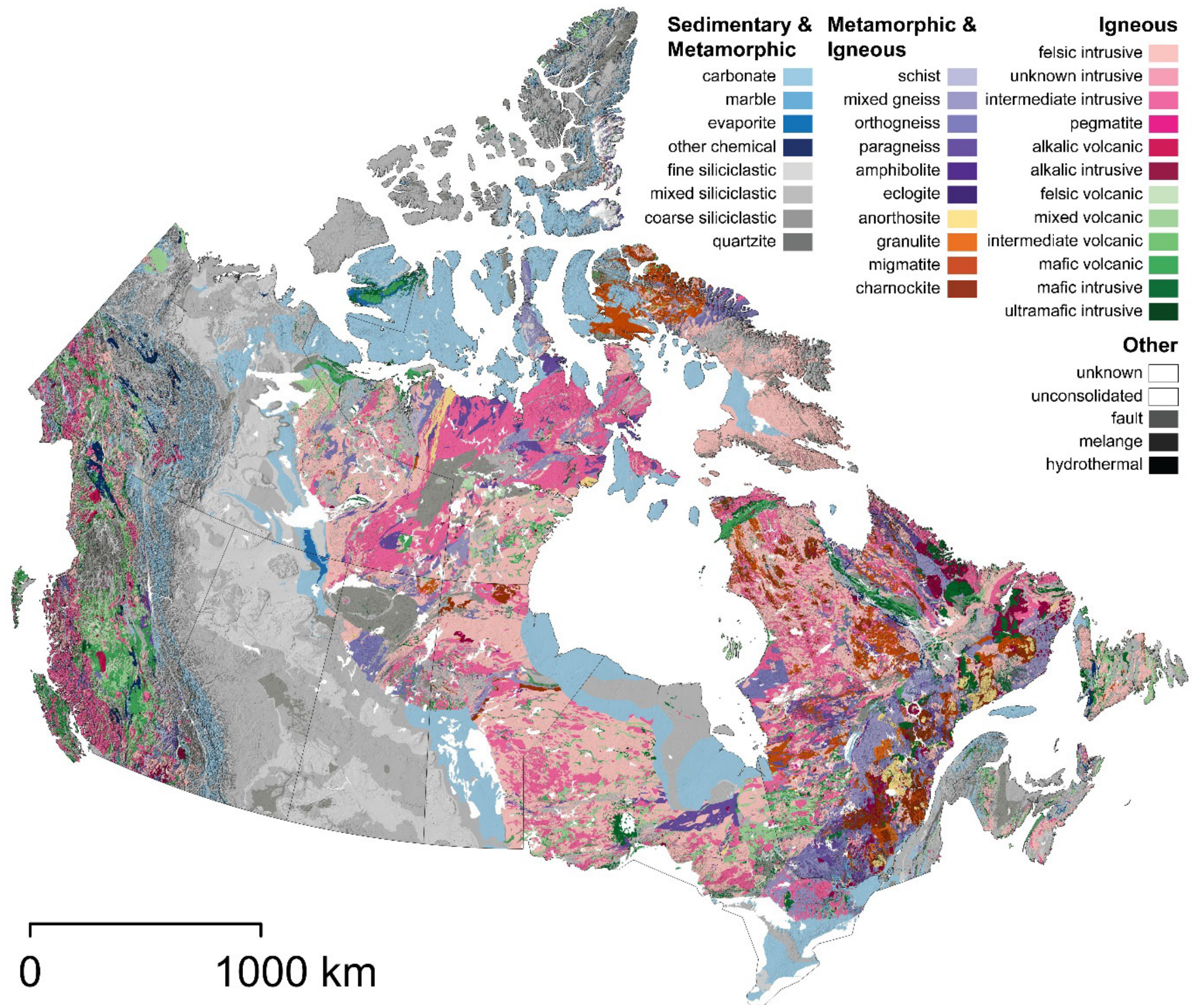

Figure 2: New geological map of Canada based on the best available geoscientific information extracted from the CMGC and superimposed on a hillshade raster image.

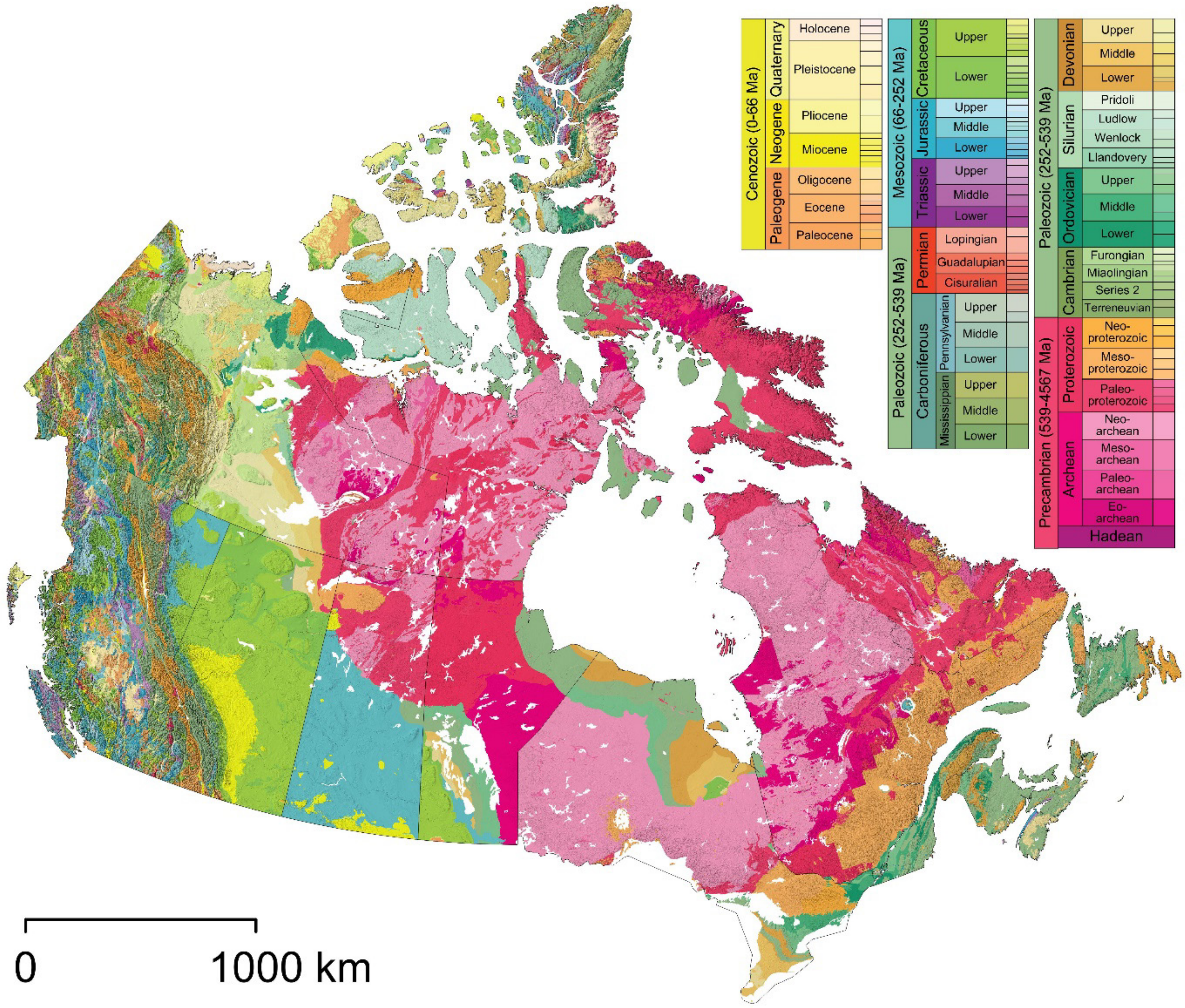

Figure 3: New geochronological map of Canada based on the best available geoscientific information extracted from the CMGC and superimposed on a hillshade raster image. Colours are based on the ICS chart for each of the finest-resolution and minimum ages available in the source maps.

Summary

The CGMC translates, standardizes and combines previously published bedrock geoscientific information to provide complete coverage of Canada as one digital product. Detailed lithological, mineralogical, lithostratigraphic, and lithodemic data published within geological map databases had not previously been available at the national-scale. The geoscientific information included within the CGMC reflects the progress made by provincial, territorial, and other geological survey organizations since the seamless 1:5M scale bedrock geological map of Canada was published by Wheeler et al. (1996). These more modern geological surveys have been acquired by hundreds of geoscientists over many decades and at great financial expense. Users of the CGMC are encouraged to seek out the source map data for all of the additional information that is not included in the present study (e.g., point and line data, supplementary documents, and images). Provincial and territorial geological survey organizations provide the most current bedrock geoscientific information for their jurisdictions. The

CGMC is a research product that is intended for national-scale mineral potential, groundwater, geohazards, geothermal, and environmental assessments. Over time, new higher resolution bedrock geological maps will be added to the CGMC in priority places to improve the performance of down-stream machine learning applications.

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