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CARIBOU: A HIERARCHICAL DATABASE SYSTEM FOR COMPILING DIGITAL GEOLOGICAL INFORMATION

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ABSTRACT

*Digital map compilation faces many challenges, particularly when working on a regional or provincial scale. The Catalogue of Rock Information and Boundary Unification (CARIBOU) project combines elements of hierarchical and relational databases to facilitate the collection of geological information in a standardized classification system to eliminate many common compilation issues across map sheets and jurisdictional boundaries (*e.g.*, variable map scales, naming conventions, border faults). The database is built on parent–child relationships to organize geological units in a ranked hierarchy, allowing for the grouping and displaying of units at different ranks. The data catalogue is structured with fields to compile all available information for a geological unit and assign the unit a new map label for reclassification during map compilation.*

The user must first compile a digital mosaic of regional geology, choosing the most representative geological information for each area. Following this, each polygon of the mosaic is given a unique polygon identifier. CARIBOU then accepts the list of polygon identifiers and remaps the original map labels to new labels, ensuring unit consistency across the mosaic. As all the rank information is appended from the catalogue, the level of detail can then be controlled directly in a geographic information system (GIS) software, allowing for the creation of regional compilations and custom thematic maps at varying scales, whilst preserving the original polygons and source information. Although the current development is limited to internal bedrock geology compilations, CARIBOU could eventually be implemented alongside the Geoscience Atlas to enable wider distribution and access.

INTRODUCTION

Geological maps are, by their nature, subjective interpretations of underlying geological information. As such, many factors can influence the map-making process, including individual geologists' biases or specializations, the project scope, the scale of mapping and existing knowledge at the time of mapping (Colman-Sadd, 2003). Therefore, it is unlikely that map units spanning multiple map sheets will be continuous, much less share a consistent unit label, even when mapped by the same individual. This presents challenges towards map compilation, particularly when working on a regional or provincial scale, and compilers must often make calculated decisions on the inclusion of certain units or features based on their own criteria of geological significance.

Many national and global-scale geological databases have been attempted in recent years (*e.g.*, Hartmann and Moosdorf, 2012; Horton *et al.*, 2017; Lawley *et al.*, 2024) and several provincial jurisdictions across Canada have recently released, or are in the process of releasing, updated bedrock geology map compilations (*e.g.*, Maxeiner *et al.*, 2021; Colpron, 2022; Roy, 2023). However, the most recent 1:1 000 000-scale (1:1M) geological map compilations by the Geological Survey of Newfoundland and Labrador (GSNL) were completed by Colman-Sadd *et al.* (2000) and Wardle *et al.* (1997) for Newfoundland and Labrador, respectively; almost three decades old and in need of revisions with the acquisition of recent data. In addition to these 1:1M compilations, a multi-scale detailed digital map of Newfoundland was published to the Geoscience Atlas by Crisby-Whittle (2012), while the only portion of Labrador in the Geoscience Atlas with a similar level of detail is the work of Gower (2019), covering the eastern Makkovik and Grenville provinces. Most of the geology of Labrador is only digitally available *via* the 1:1M compilation, which does not accurately represent all the compiled data for the region (*e.g.*, Ryan, 1990; Wardle, 1993, 1994).

The decision by GSNL to begin production of revised 1:1M-scale geological maps of the province coincided with the opportunity to develop a detailed geology dataset, which led to the Catalogue of Rock Information and Boundary Unification (CARIBOU) initiative: a hierarchical database designed both to catalogue geological information and to facilitate the publishing of map compilations at different scales in a GIS environment. The design philosophy of CARIBOU follows that of the GeoLegend database

(Colman-Sadd *et al.*, 1997; Colman-Sadd, 2003) while integrating a ranked hierarchical system to preserve unit relationships across different map scales.

SYSTEM OVERVIEW

The CARIBOU database is housed in Microsoft Access, and the GIS component is performed in ArcGIS Pro with data hosted in a file geodatabase and associated tables. CARIBOU uses a combination of a hierarchical and relational data structure, using parent–child relationships to develop a hierarchy of units in a tree structure while supplementary information, such as geochronology and references, is stored in separate tables and related to the main lithology records through a primary key. Other information (*e.g.*, class and rank names, tectonic zones, geologic time scales) are stored in immutable look-up tables and related to the main table through primary-foreign key relationships. A full entity-relationship diagram of CARIBOU is shown in Figure 1.

DATA CATALOGUE

A major challenge with the current GSNL data-storage method is the fragmentation of geological information across published maps, current research volumes, peer-reviewed journal articles and industry reports. While this

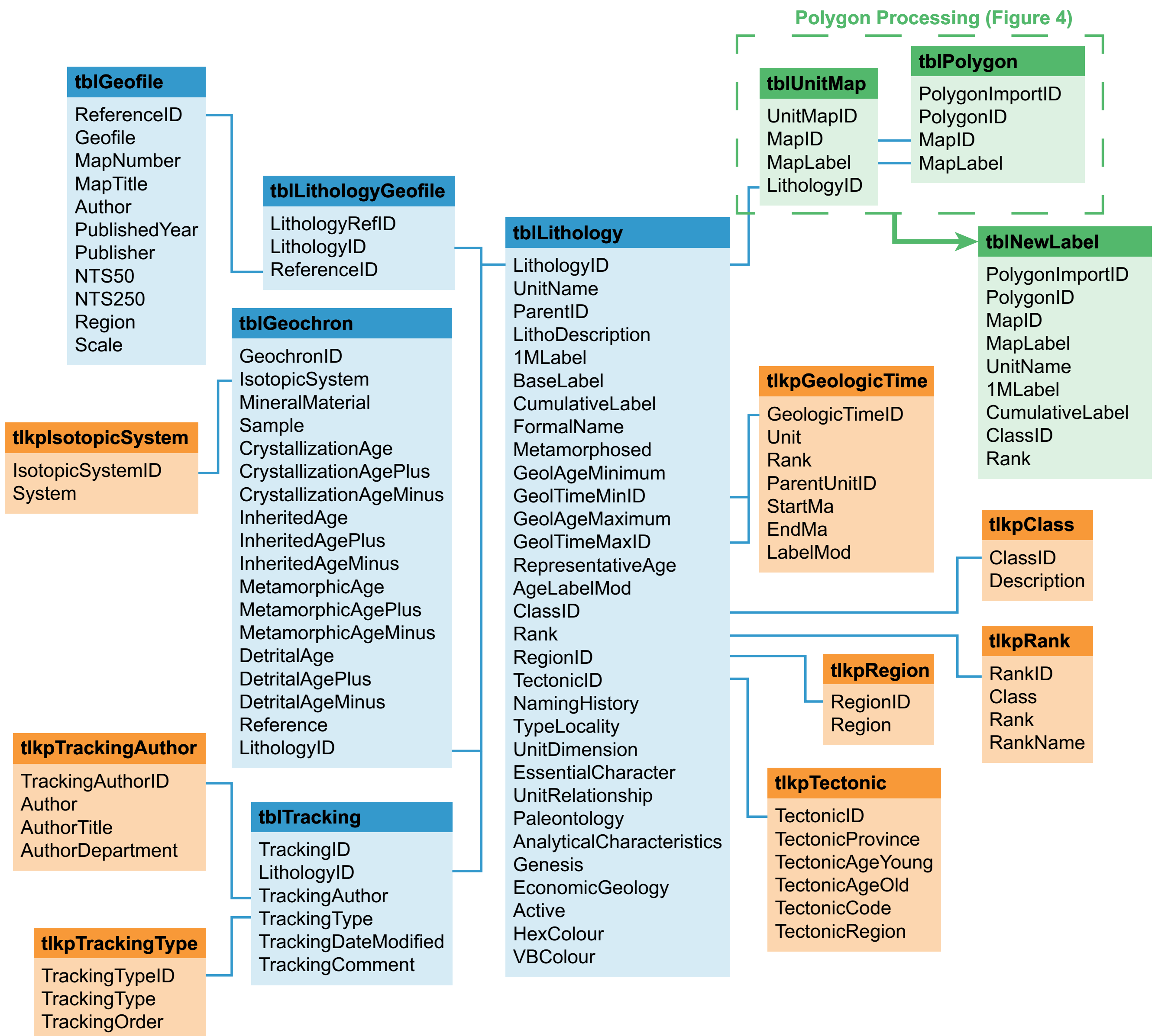


Figure 1. *Detailed entity-relationship diagram of CARIBOU. Data entry tables are shown in blue, and lookup tables in orange. Green tables relate to the polygon import and export processing.*

information can be accessed *via* index in the public-facing Geoscience Atlas, this only provides a spatial catalogue of information and may include dozens of records that are irrelevant to the user. The CARIBOU data library is instead structured to compile and present all current information for each geological unit, to be maintained concurrently with GSNL data releases. CARIBOU utilizes the Cooperative Lithodemic And Stratigraphic System (CLASS), proposed by Maxeiner *et al.* (2024) and summarized in Table 1, to both eliminate issues with compiling lithological units across map boundaries within the province and ensure harmonization on a national, or even global, scale (*e.g.*, GeoSciML, OneGeology). This system adapts the nomenclature used by the North American Stratigraphic Code (NASCN, 2021), British Columbia Geological Survey (Cui *et al.*, 2017) and British Rock Unit Classification System (BRUCS; Gillespie and Leslie, 2021), where each class of rock is given a formal ranking from 1 (supergroup and non-stratiform equivalencies) to 7 (bed or flow and non-stratiform equivalencies) across four major class divisions, which can generally be seen as increasing in complexity moving from left to right (Class A–D). This scheme is a major improvement to the GeoLegend application (Colman-Sadd *et al.*, 1997), particularly in areas of Labrador, where despite many geological units being non-stratiform, they can still be contained in a hierarchical taxonomy.

Prior to importing and relabelling digital polygons, the unit must first exist in CARIBOU. Figure 2 shows how information is entered into CARIBOU. Class, rank and parent unit information under the unit summary segment is necessary to construct the ranked unit hierarchy, which updates dynamically as the parent–child relationship grows through populating CARIBOU with more lithological units. Other fields, such as tectonic zone or essential character (*i.e.*, igneous, sedimentary, *etc.*), allow for the development of small-scale thematic maps (*e.g.*, “lithofacies” or “tectonic assemblage” maps; Colman-Sadd, 2003). Essential character is considered as the representative descriptor of a unit on a smaller scale. Geochronology, references and data-tracking tables are related to the main lithology form through one-to-many or many-to-many relationships, allowing for multiple entries in each of these tables that are connected to each lithology. Other unit details, such as economic geology and paleontology, are included but are not required fields. The main lithology table contains a self-referential relationship to indicate the parent unit’s Lithology ID (Figure 3). By hosting the library in this relational data structure, queries can be constructed to search and filter for specific data. For example, a user may design a query to return a list of all geological units referenced by a specific map or identify all units in Labrador that contain the word “nickel” in the economic geology field.

Map labels are presented both as standalone codes and as cumulative labels that build from the parent unit’s map label (Figure 3). For example, if the Epsilon Assemblage is given the code “E” and the Zeta Lithodeme, a subunit of the Epsilon Assemblage, has the base label “z”, the cumulative label for the Zeta Lithodeme would therefore be coded as “Ez”. If the age of unit is constrained, a representative age prefix (*i.e.*, “O” for units of Ordovician age or “S” for Silurian age) can be appended to the label. A 1M label field is included if the compiler overrides the cumulative labels with a predetermined unit code or to correlate a unit with an existing small-scale map.

Due to the parent–child relational framework of the database, data-storage ambiguity and redundancy is greatly reduced, while enabling relationship flexibility and data inheritance. For example, a rank 4 unit (*e.g.*, formation) does not necessarily need to belong to a rank 3 unit (*e.g.*, subgroup) to be part of a rank 2 or 1 unit (*e.g.*, group or supergroup). Additionally, an important feature of CLASS

Table 1. CLASS hierarchy proposed by Maxeiner *et al.* (2024)

Rank	Class A Supracrustal rock units	Class B Strongly metamorphosed supracrustal rock units	Class C Intrusive rock units	Class D Mixed-class rock units
1	Supergroup	Superassemblage	Supersuite	Supercomplex
2	Group	Assemblage	Suite	Complex
3	Subgroup	Subassemblage	Subsuite	Subcomplex
4	Formation	Lithodeme	Pluton, swarm, composite intrusion*	Migmademe
5	Member	Lithostrome	Dyke, sill, intrusion	Migmastrome
6	Submember	Sublithostrome	Not formally defined	Submigmastrome
7	Bed, flow	Layer	Not formally defined	Not formally defined

Note: *composite or layered intrusions are not explicitly defined at this rank by Maxeiner *et al.* (2024) but added here for clarification

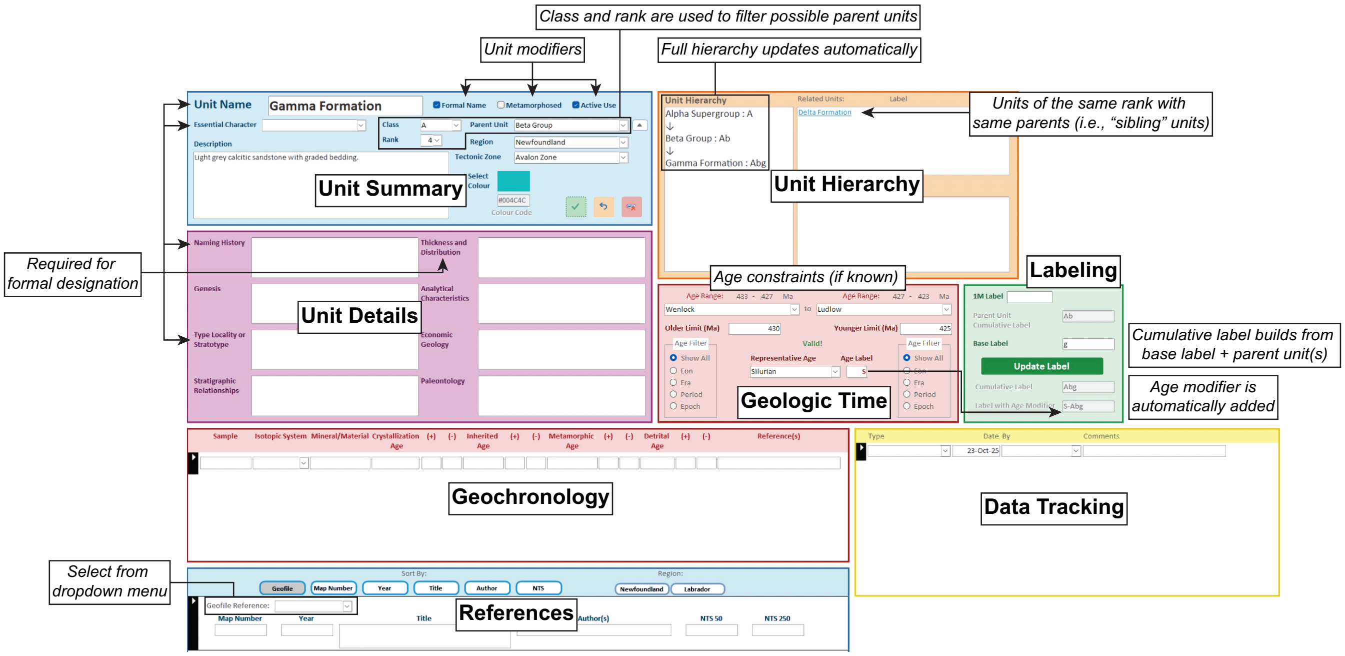
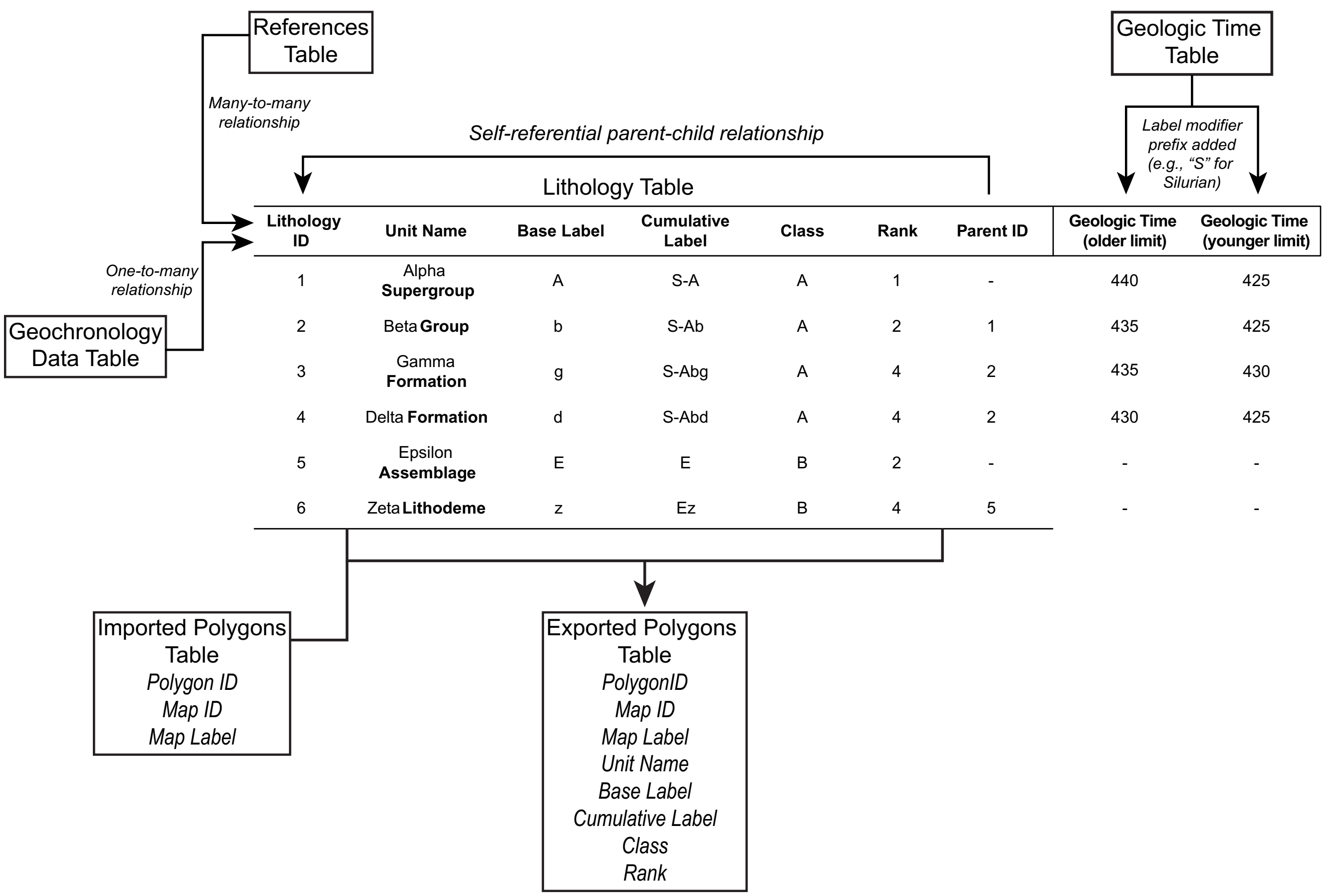


Figure 2. *CARIBOU data entry form.*



Lithology ID	Unit Name	Base Label	Cumulative Label	Class	Rank	Parent ID	Geologic Time (older limit)	Geologic Time (younger limit)
1	Alpha **Supergroup**	A	S-A	A	1	-	440	425
2	Beta **Group**	b	S-Ab	A	2	1	435	425
3	Gamma **Formation**	g	S-Abg	A	4	2	435	430
4	Delta **Formation**	d	S-Abd	A	4	2	430	425
5	Epsilon **Assemblage**	E	E	B	2	-	-	-
6	Zeta **Lithodeme**	z	Ez	B	4	5	-	-

Figure 3. *Simplified relationship diagram of CARIBOU using fictitious units. Note that not all fields or tables from CARIBOU are included in the diagram.*

is the ability to blend classes together: a formation (class A) may belong to an assemblage (Class B), although this should only be considered as a function of increasing complexity, moving from classes A to D across Table 1 rather than D to A (Maxeiner *et al.*, 2024). CARIBOU accounts for these exceptions by permitting the user to select any higher ranked unit in the same class, not only units of the immediate higher rank or of the same class. The direct relationships permit object-oriented inheritance: users do not need to populate all “ancestor” fields (ranks 1–7) for a given unit, as all higher-ranked units are inherited from the immediate parent unit (*e.g.*, the Alpha Supergroup is inherited as the grandparent unit of the Gamma Formation, through the parent Beta Group, Figure 3). The suitability of a hierarchical structure to store parent–child relationships is also evident when considering a complete lithological tree: a formation can be a constituent of one group, but a group can contain many formations.

As much of northern Labrador has historically been mapped only at a reconnaissance scale, many lithological units lack a formal designation for their name. For a unit to have a formal designation (*i.e.*, proper title case), it must be described in a peer-reviewed report or journal article with naming history, type locality, unit distribution, characteristics and essential character (NASCN, 2021). CARIBOU accepts informal names into the database and provides fields to record all mandatory information to define a formal unit. Formalization of a unit after its initial entry into CARIBOU can be easily recorded through the data tracking table (Figure 2).

POLYGON COMPILATION

The GIS component of CARIBOU functions similar to the GeoLegend application (Colman-Sadd *et al.*, 1997). The database relies first on an existing map compilation or digital mosaic of representative polygons over a continuous geographical extent. Often, a geographical region will have several adjacent or overlapping maps, and the map compiler must decide on which map to designate as the representative geology. Following Colman-Sadd (2003), there are three main criteria to consider: age, scale and geological focus. More recent maps typically include information from older maps compiled together with new data, so are generally preferable. Additionally, the most detailed source map is generally preferable, as these maps typically contain more information on geological subdivisions and more accurate contacts. Finally, many mapping projects focus on detailing specific map units in a study area, while peripheral rocks may be more generalized and may have been mapped in greater detail in another source. Continuity of adjacent maps also bears consideration; it may be tempting to prefer compiling maps by a particular author, particularly if those maps cover a large geographical area and/or share a unit legend. Although this may ease the initial compilation process, these maps may eventually become superseded, and the integration of new geological information should not be restricted solely to maintain continuity of obsolete maps.

The user first selects definitive or representative polygons for a geographical area, and the GIS assigns unique polygon identifiers to each polygon in the area (Figure 4). This list of identifiers, along with their original map name and unit label, are imported into CARIBOU, where the unique combination of the original “Map ID” and “Map Label” fields are converted to a new standardized label that corresponds with a geological unit inside CARIBOU. This unique combination ensures that all equivalent rock units are standardized even across multiple maps. After joining the lithological information fields, the list of polygon identifiers is exported back into the GIS and used to construct map compilations while retaining the original information of each map. It is evident in Figure 4 that units 1, 2 and 3d of Map NL01 correspond to units 18, 16 and 17 of Map NL02, respectively. Rather than selecting either map as the definitive source and merging the polygons, CARIBOU appends the new labels of Ap, SDp and gBd to the polygons of both maps, along with the lithological information housed in the data library. Polygons can then be symbolized across map boundaries while ensuring their source information is not lost in the compilation process. Integration with the Mineral Occurrence Data System (MODS) is also possible at this point, as spatial queries can be created between the MODS point data and the newly created polygons to produce a list of mineral occurrences within each geological unit.

Border faults commonly occur during map compilations and are often difficult to resolve by the compiler. While small misalignments across map boundaries may be fixed with manual effort, abrupt unit changes across map boundaries are commonplace, particularly in regions mapped to variable levels of detail. CARIBOU makes no attempt to fabricate solutions to these issues, but by implementing CLASS as a standardized hierarchical system, these issues can be minimized. Colman-Sadd (2003) remarks that boundary mismatches represent sources of information themselves and recommends that linework of compiled maps remain untouched by the compiler. Using Figure 4 as an example, Unit 19 of Map NL02 is not mapped on Map NL01, resulting in a border fault in Unit kGt in the merged map. However, if units kGt and gBa are grouped in the same parent unit under CLASS, they can be generalized together in the final stages of map production.

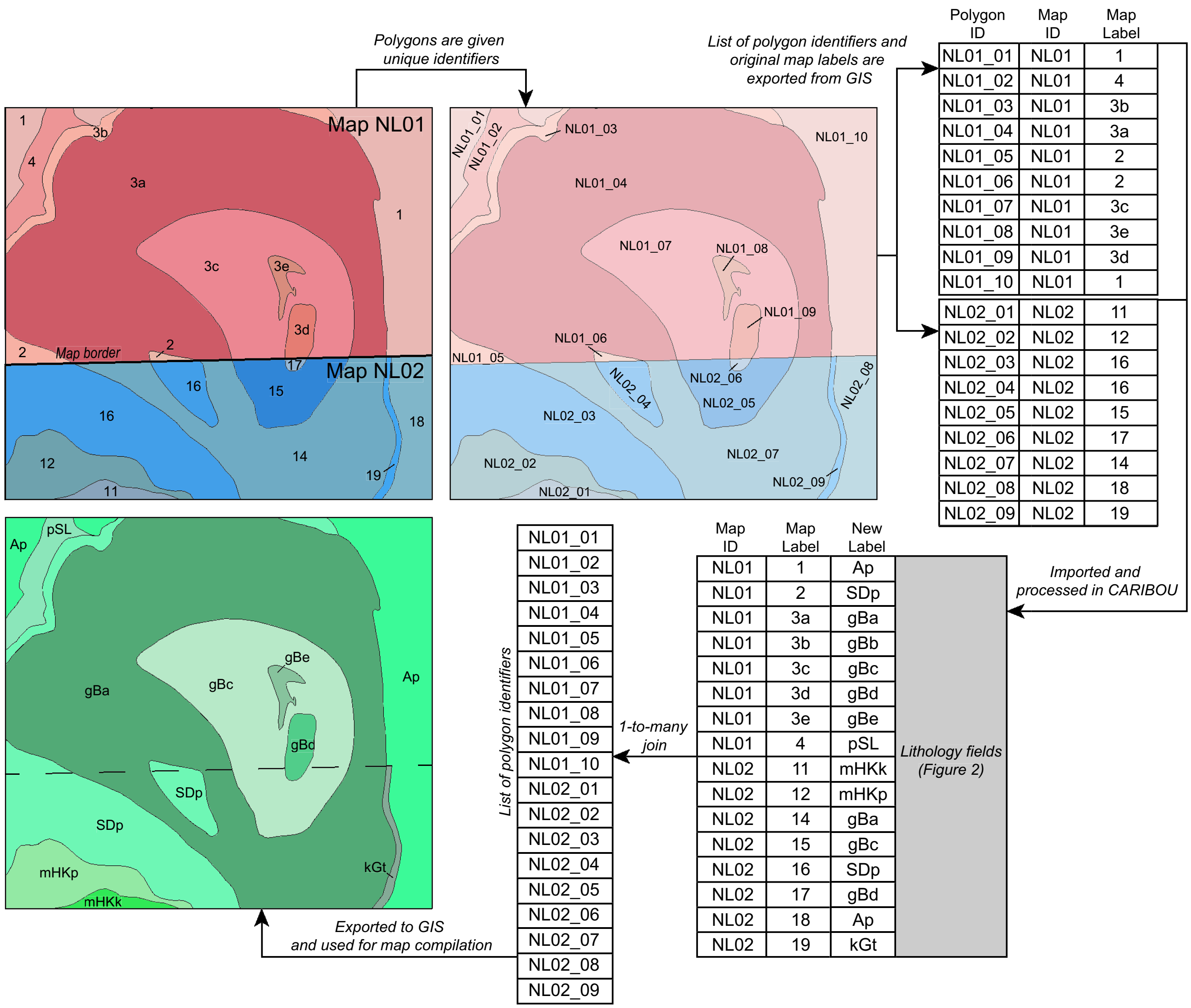


Figure 4. *Polygon compilation workflow applied to adjoining maps. Maps NL01 and NL02 are modified from Ermanovics* et al. *(1997) and Ryan (1990). Map colours and labels are arbitrarily chosen to symbolize different polygons and are not intended to represent specific lithologies.*

APPLICATION OF CARIBOU: NAIN PLUTONIC SUITE

As part of the Labrador 1:1M map revisions, the region was subdivided into smaller map compilation areas to narrow the scope of the project. One area, comprising the Nain Plutonic Suite (NPS) and surrounding area (NTS map areas 14C–F) was first compiled by Ryan (1990) and recently recompiled as a simplified map (*see* Hinchey *et al., this volume*). The NPS is a Mesoproterozoic anorthosite–mangerite–granite–charnockite (AMGC) suite that covers approximately 20 000 km^2 and intrudes along the suture of the Archean Nain Province and Archean to Paleoproterozoic Churchill Province, typically comprising Mesoproterozoic supracrustal metasedimentary units and gneisses (Ryan, 1990).

Figure 5 shows a simplified segment of the geology of the Nain Plutonic Suite and demonstrates how the CARIBOU and CLASS systems can be applied to non-stratiform regions. The Hettasch and Kiglapait composite intrusions are mapped as large intrusive bodies with defined subunits and are placed at the rank 4 level, with the subunits of these composite intrusions placed at rank 5. All intrusive bodies would be considered Class C units (Table 1). The full hierarchy of Class C members of the NPS of Figure 5 is recorded in Table 2, demonstrating how CARIBOU uses CLASS to handle non-stratiform units. Note that although some of

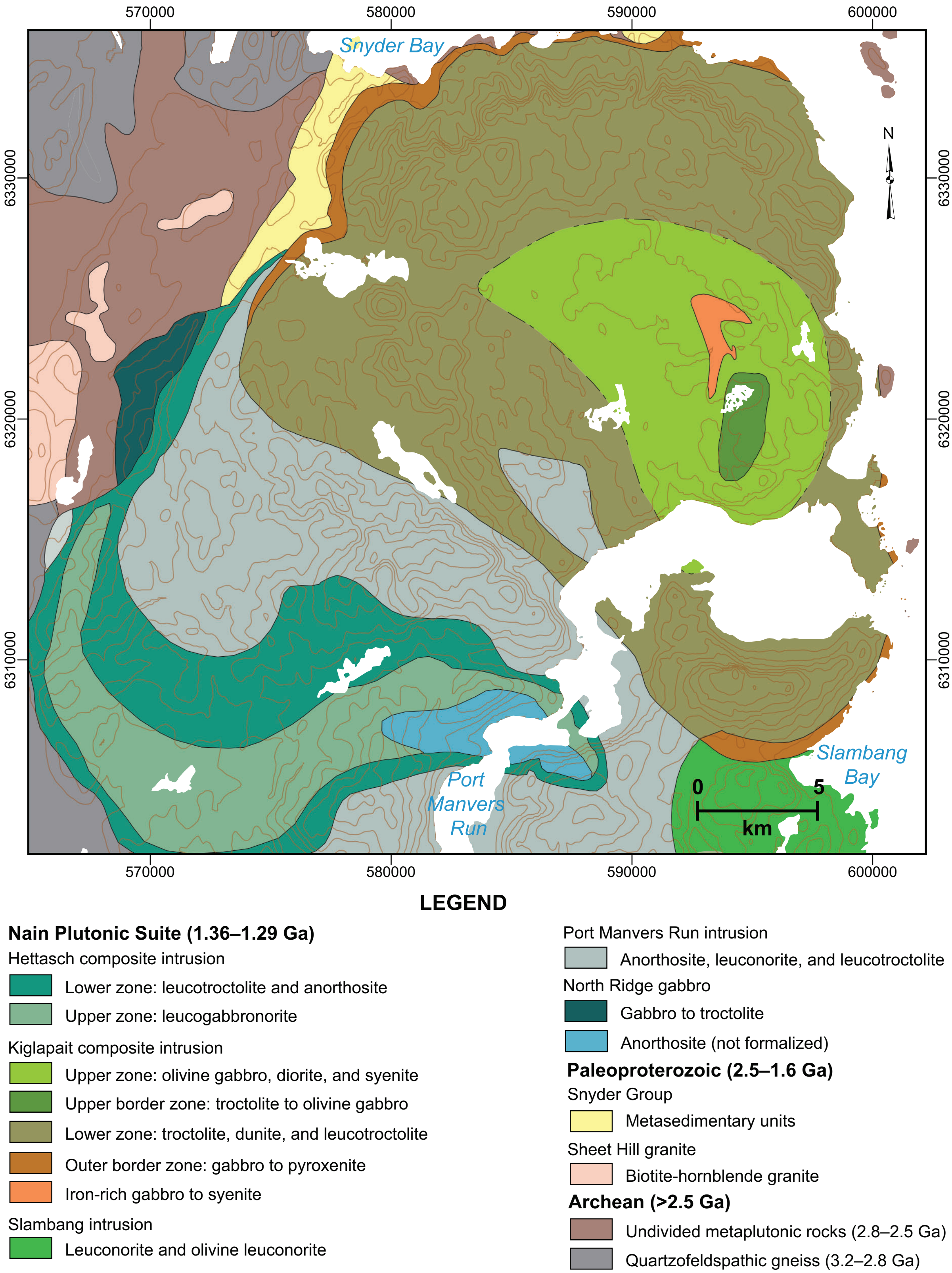


Figure 5. *Generalized geology of a section of the Nain Plutonic Suite and surrounding rocks, Labrador. NTS map areas 14C/13, 14, 14F/03 and 04, modified from Ryan (1990). All units of the NPS are generalized to rank 5 (intrusion-level).*

Table 2. Application of CLASS to units of the Nain Plutonic Suite

Rank 1 Supersuite	Rank 2 Suite	Rank 3 Subsuite	Rank 4 Pluton/composite intrusion/swarm	Rank 5 Dyke/sill/intrusion	Rank 6 Not formally defined	Rank 7 Not formally defined
			Kiglapait composite intrusion	Upper zone Upper border zone Lower zone Outer border zone Iron-rich gabbro		
Unnamed at this level	Nain Plutonic Suite		Hettasch composite intrusion	Lower zone Upper zone		
				Slambang intrusion North Ridge gabbro Port Manvers Run intrusion Anorthosite (not formalized)		

Note: According to CLASS, the Kiglapait and Hettasch "composite intrusions" would fall under Rank 5, as they are not formally defined plutons. However, due to the historic interchangeability of these terms in Labrador, these have been placed as Rank 4 units due to being composed of identifiable subunits

the larger named intrusions (*e.g.*, Port Manvers Run intrusion) may fit the lithodemic nomenclature for a rank 4 pluton (Gillespie and Leslie, 2021), they are mapped here only as informally named intrusions and are thus placed at rank 5. If further work resulted in the formalization of these intrusions as plutons, either single- or composite-phase, these would be elevated to rank 4 (*i.e.*, Port Manvers Run Pluton). Furthermore, if the Port Manvers Run Pluton was hypothetically found to contain discrete, mappable subunits, those subunits might get placed at the intrusion level (rank 5), either formally or informally. The parent–child relationship structure in CARIBOU can handle this flexibility and is therefore well-equipped to incorporate the results of future detailed mapping projects. If the desired map was produced at a scale at which to group all NPS members together (*i.e.*, suite-level regional map), those subunits can be easily generalized as a cohesive body and contacts between the subunits would be dissolved (Figure 6). By appending the full ranked hierarchy to each polygon, CARIBOU provides compilers the information and tools to make decisions about individual polygons and map units directly in the GIS environment.

FUTURE DIRECTION

CARIBOU is designed to be scalable for future work – not only to support the ongoing 1:1M recompilation project, but also to integrate detailed information from future high-resolution mapping campaigns. This initiative would be a multi-phase project; currently, CARIBOU is still in an early proof-of-concept phase, with a limited, but scalable, scope. The primary focus is on bedrock geology relationships to complement the provincial map recompilation projects, but surficial geology integration is planned for a future release.

Short-term goals include (1) a legend designer to directly handle the potentially large and cumbersome amount of map units of compilation projects, (2) increasing the functionality of the polygon import feature to handle more complex and uncommon situations (*e.g.*, compound map labels, map labels with special characters, *etc.*), and (3) allowing for polygon export at multiple user-defined levels of detail. Additionally, developing advanced geospatial tools to ease the integration of new polygons from future mapping projects would help to reduce map boundary issues by automatically handling topological problems (*e.g.*, Cui, 2021).

The essential objective of CARIBOU is to catalogue and document as much information about the geology of the province in a harmonized system. Therefore, unifying CARIBOU with the Geoscience Atlas would present the catalogue in an interactive, public-facing environment. This is a critical long-term goal and would represent a large milestone in the accessibility of geological data in the province, not only for internal GSNL use, but especially for wider distribution to the public.

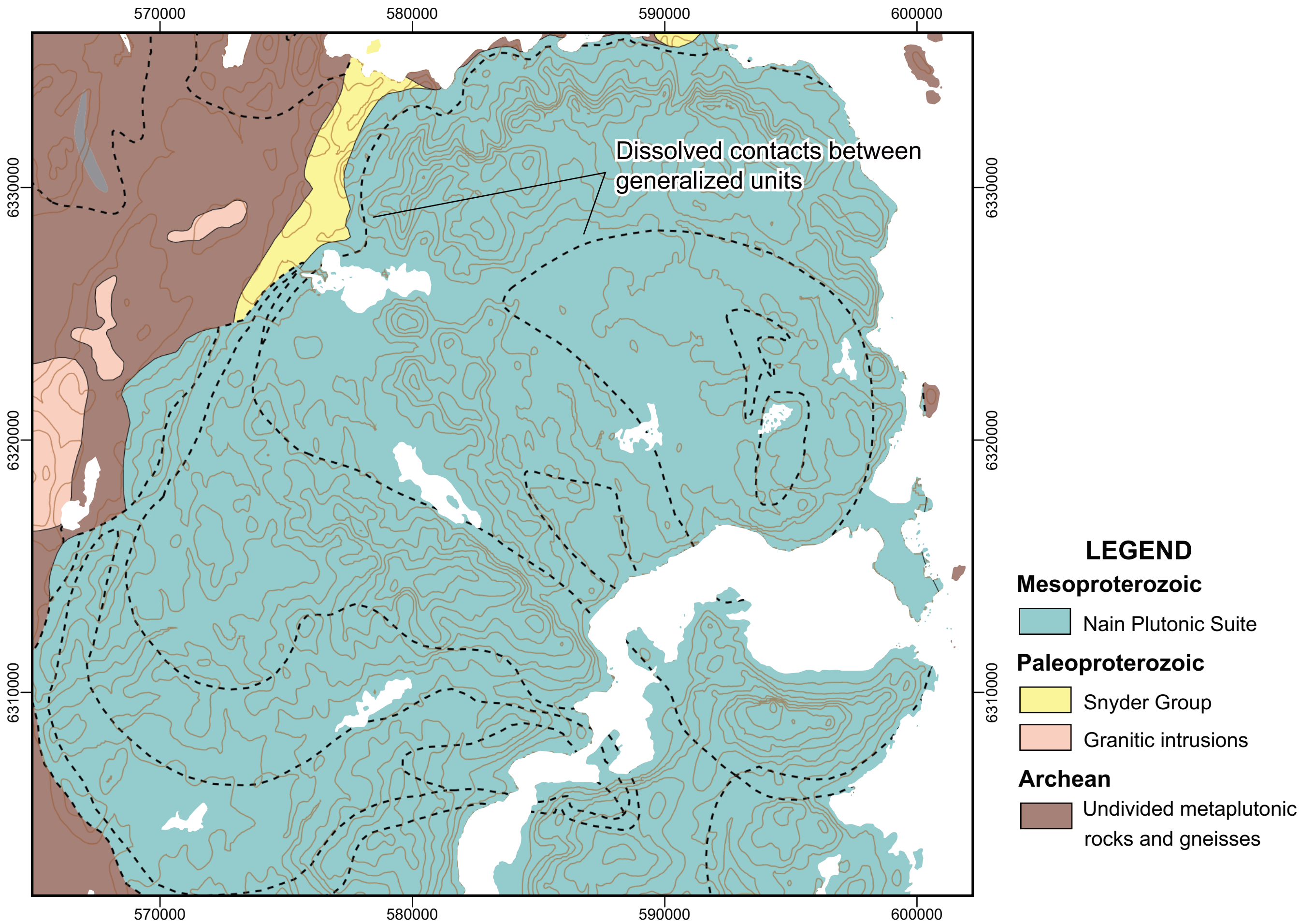


Figure 6. *Generalized geology of a section of the Nain Plutonic Suite and surrounding rocks, generalized to rank 2 (suite-level). Modified from Figure 5.*

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