GS2025-22

Exploring the use of geoanalytics to enhance landscape-integrated geochemical interpretations of lake sediments at the regional scale in northern Manitoba (NTS 64F, G, J, K)

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In Brief:

- High quality lake sediment geochemistry data from northwestern Manitoba was recently re-analysed covering ~52,660 square kilometers
- Machine learning-enhanced critical mineral prospectivity maps are being developed by investigating the relationship between lake sediment geochemistry and surficial sediments

Citation:

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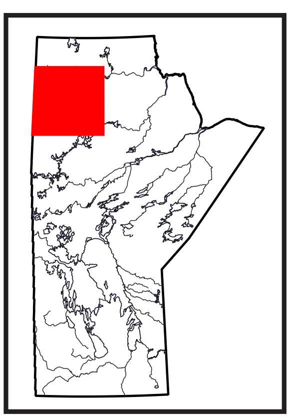

Summary

The objective of this study is to apply novel machine-learning prospectivity algorithms to recently reanalyzed lake-sediment geochemistry datasets in northern Manitoba. This investigation will involve the compilation and synthesizing of the current body of information available on the surficial geology and Quaternary processes, which are critical components influencing chemical signals in the lake-sediment dataset. In addition, other factors that may influence the lake-sediment chemistry, such as bedrock geology, will be incorporated. Initial findings of the data compilation and literature review suggest there is a notable control on spatial expression of chemical patterns caused predominantly by glaciolacustrine sediment coverage.

Introduction

Geochemical surveys at regional scale are designed to cover vast regions with an appropriate sampling density. Traditionally, this would involve an area covering several 1:250 000 scale National Topographic System (NTS) map sheets, with a sampling density of approximately 0.01 to 0.5 samples per square kilometre (Hosseini-Dinani et al., 2019). Results were then used to delineate prospective areas for further mineral exploration. Large regions of northern Manitoba were surveyed under the National Geochemical Reconnaissance Program starting in 1975 and largely concluded by the late 1980s. The original lake-sediment analytical results used atomic adsorption spectroscopy (AAS) and colorimetric analytical methods.

In the 40 to 50 years since the original analysis, significant advancements in analytical chemistry have been achieved and the archived lake-sediment sample material was reanalyzed in 2022 and 2023 using modern analytical methods. The original archived sample material was analyzed by Bureau Veritas facilities in Vancouver, British Columbia. A total of 65 elements were determined using inductively coupled plasma–mass spectrometry (ICP-MS) following digestion of 0.5 g of material by a modified aqua regia (1 HNO_3: 1 HCl: 1 H_2O). Additionally, 35 elements were determined by instrumental neutron activation analysis (INAA) of a 30 g sample (Amor et al., 2024a, b; Bourdeau, 2024). The reanalysis of lake-sediment data within the study area was completed in 2023 (Amor et al., 2024a). The final goal of the study is to generate landscape-integrated geochemical prospectivity maps enhanced by the application of machine learning (ML) algorithms to delineate areas of critical-mineral potential.

Study area

The study area encompasses a total of 3852 sites over an area of approximately 52 680 km^2 across four 1:250 000 scale NTS map sheets of northwestern Manitoba (Figure GS2025-22-1a, b). The area of interest is located 16 km north of the town of Lynn Lake and includes the First Nation communities of Tadoule Lake and Lac Brochet.

Methodology

There are four core components of this study: 1) geochemistry, 2) surficial geology and landscape-process history, 3) bedrock geology and mineralization and 4) machine-learning strategy. Geochemistry of the surface environment will be evaluated based on the available lake-sediment chemical data.

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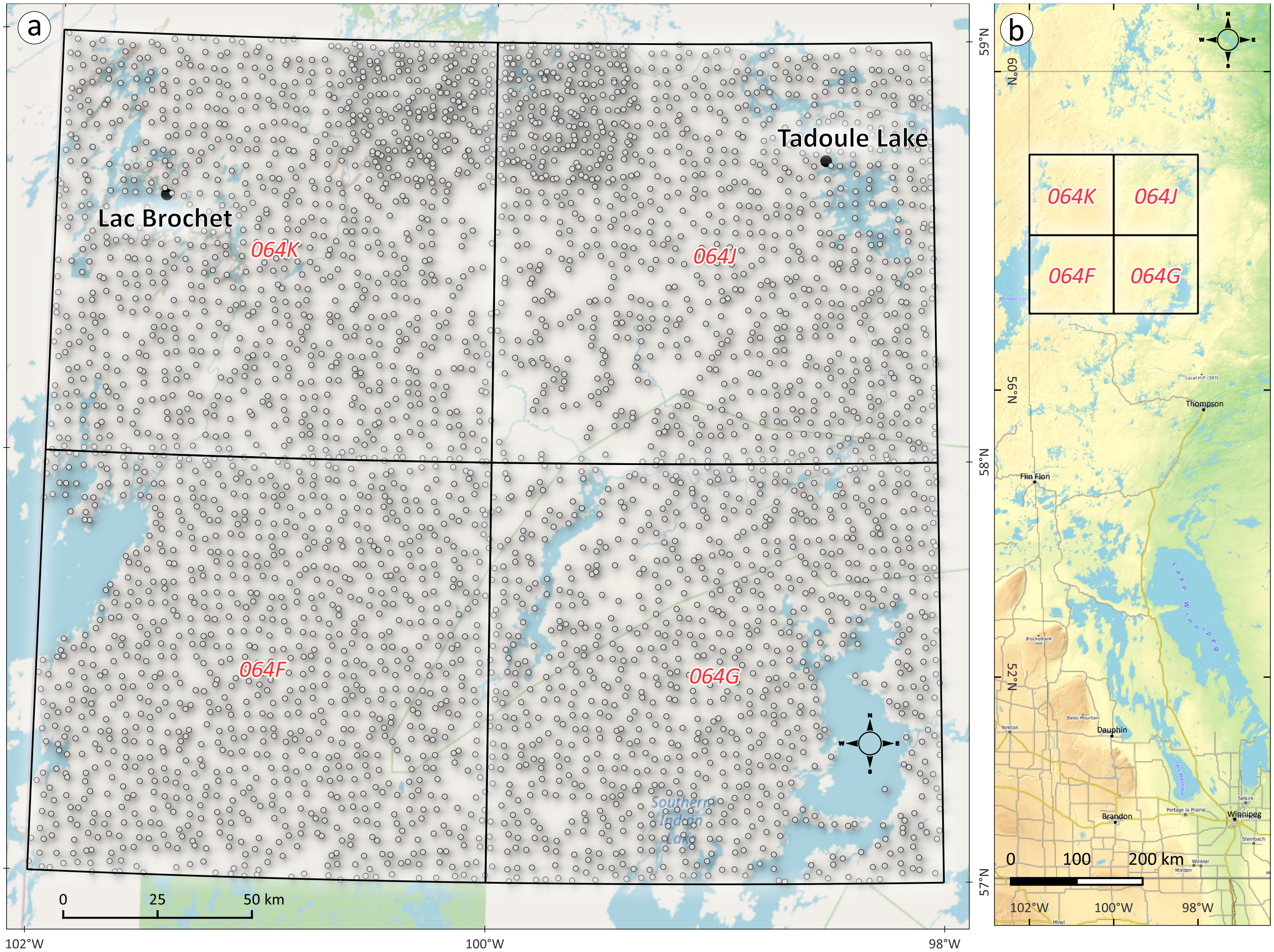

Figure GS2025-22-1: *Study area (NTS 64F, G, J, K) in northern Manitoba showing **a)** the location of lake-sediment samples (white dots) collected by the Geological Survey of Canada in the mid-1970s and 1980s; **b)** regional location within the province of Manitoba. Base maps sourced from Open Street Map (www.openstreetmap.com) and U.S. Geological Survey (2014).*

These chemical maps are indirect detection tools of potential mineral resources for the region but can be critical indicators of potential when combined with geophysical or other remote sensing data. The lake-sediment chemistry will be complemented by the integration of bedrock and/or till chemical data that is available in the literature.

The landscape surface, or biosphere, serves as the medium in which the lake-sediment sample is hosted. The character, distribution and movement or modification through time should be considered during the interpretation of the chemical data. Relevant terrain mapping and glacial history research will be included in the interpretation of the data and subsequent ML-enhanced prospectivity strategies. Other relevant factors, such as the organic content of each sample, regional hydrology and landforms potentially impacting migration of chemical elements (e.g., watersheds) will also be considered.

Bedrock geology is the primary origin of chemical signals in surficial sediments. It is important to understand the nature, chemistry and distribution of major rock units that may have been eroded by glacial ice or meltwaters. Bedrock geology mapping will be compiled and all documented mineral occurrences will be interrogated in preparation for the machine-learning prospectivity workflows that follow.

A selection of supervised and unsupervised ML algorithms will be evaluated for their suitability to lake-sediment geochemical datasets. Supervised algorithms such as linear regression, logistic regression, decision trees/random forest and gradient boosting will be considered for cases where map values may be predicted based on a set of known factors (e.g., predicting landscape/landform type from Sentinel-2 [European Space Agency, 2025] spectral data and topography). Unsupervised algorithms, such as clustering (e.g., hierarchical density-based spatial clustering of applications with noise [HDBSCAN]) and dimensionality reduction (e.g., principal component analysis), will also be leveraged for pattern recognition and predictive modeling where data labels are available or readily known. Finally, the cumulative workflow will aim to apply the ML algorithms to identify subtle signatures embedded within a wide range of geological and ecological data inputs that have a direct impact on lake-sediment chemistry. Whenever possible, the data-driven strategy will be described in written scripts using Python coding language, in Python notebook(s) or in GIS software plug-in extensions for public use.

The current priority is the synthesis of available surficial geology maps and interpretation of landscape modification since the Pleistocene. The landscape and surficial materials will directly drive how the geochemical data is interpreted and will also provide a fundamental understanding of data layers that become available for later ML-model design.

Remote sensing and spectral analysis

Remote sensing satellites can map vast regions of the Earth quickly and consistently. This study will make use of Sentinel-2 multispectral data acquired from the Copernicus Browser web platform operated by the European Space Agency. This dataset comprises tiles of multiband spectral raster data split into individual raster images of each spectral band. The raw data will be processed to remove data that reflects biomass or vegetation signals and isolate bare soil or mineral signals (Rikimaru et al., 2002; Phiri et al., 2020; Mzid et al., 2021). The base soil index shown in the figure below (Figure GS2025-22-2a, b) was developed for a different landscape, ecology and climate to that present in the study area and, therefore, additional landscape features, such as recent wildfire residues, must be considered when evaluating results (M. Rinne, pers. comm., 2025). The final processed datasets will be evaluated individually in relationship to other landscape variables, digital elevation models (DEMs) and Quaternary geology, but will also be included in future ML workflows.

Digital elevation modelling

The morphology of the landscape surface provides significant insight into past processes. Access to a high-resolution and accurate surface map based on remotely acquired data is fundamental for predictive terrain mapping. Light detection and ranging (LiDAR) point-cloud datasets (LAZ file format) are considered the most valuable in terms of detailed (0.5–1 m resolution) terrain mapping; however, the acquisition of LiDAR data is costly and resource intensive. Commercial satellite-based alternatives acquired from public and private sources, such as the Airbus

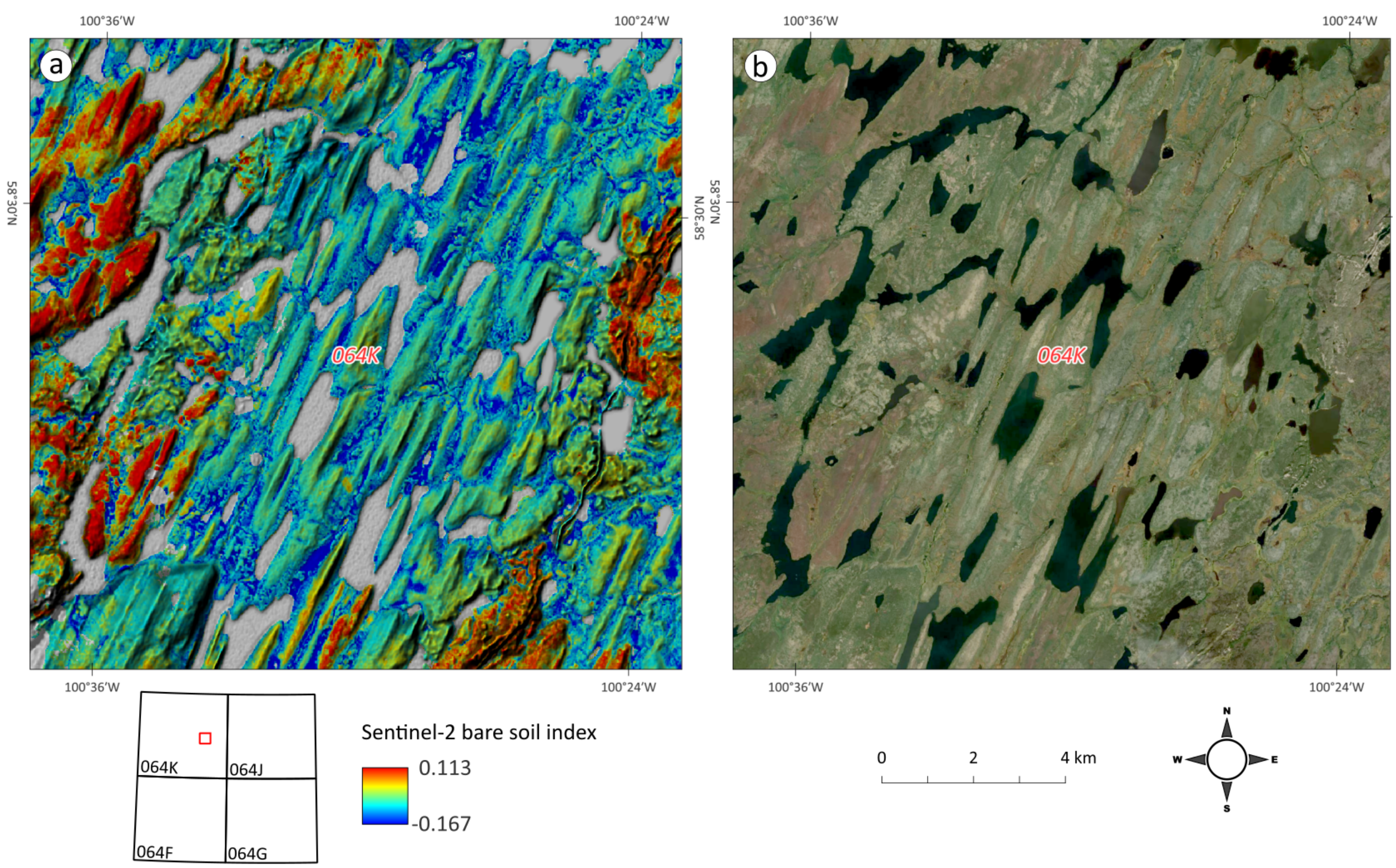

Figure GS2025-22-2: Image of a small region along the eastern margin of NTS area 64K in northern Manitoba, showing ***a)*** *the bare soil index calculated from Sentinel-2 spectral data overlaid on a hillshade Copernicus DEM at 30 m resolution, in which the red colours are most likely bare soil and the dark blue, least likely to be bare soil;* ***b)*** *satellite imagery of the same area. Data over waterbodies have been masked. Copernicus Sentinel-2 data (European Space Agency, 2025) processed by the European Space Agency (ESA) and accessed from the Copernicus Browser at https://browser.dataspace.copernicus.eu/. Figure produced using Copernicus WorldDEM-30 (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved). Image from Microsoft® Bing™ Maps service 2025).*

WorldDEM™ 5 m digital terrain model (DTM) or Maxar GeoEye-1 half-metre multispectral satellite imagery, can provide reasonable (1–30 m resolution) data for terrain analysis at a much lower fixed cost than LiDAR. However, it should be noted that these are not true bare earth ground-surface elevations and can be affected by thick and tall vegetation. Thus, optically-derived photogrammetric surface models are not as reliable for terrain analysis but can potentially be improved using mathematical models (Liu et al., 2014).

This study makes use of data from the Shuttle Radar Topography Mission (SRTM) distributed by the U.S. Geological Survey (U.S. Geological Survey, 2014) and the Copernicus products distributed by the European Space Agency (European Space Agency, 2025) to provide a continuous base layer for geographic interpretation (Figure GS2025-22-3). Each raster dataset has a cell size of approximately 30 by 30 m, making it suitable for large-scale regional interpretations. Additional detailed mapping may be completed with the acquisition of a commercially available product such as WorldDEM Neo data, which features a pixel resolution of up to 5 m and is suitable for vegetated areas as it utilizes modern technology (i.e., interferometric synthetic aperture radar) that can achieve near bare-earth elevations (Airbus Defence and Space, 2025).

In recent years, digital archeologists have been publishing innovative processing algorithms designed to be applied to LiDAR datasets to enhance subtle small-scale features thought to represent evidence of past human activity (Kokalj and Hesse, 2017). These same DEM processing algorithms will be applied to the DEM assembled for this study area to enhance subtle features (a few hundred metres minimum due to 30 m pixel resolution). A

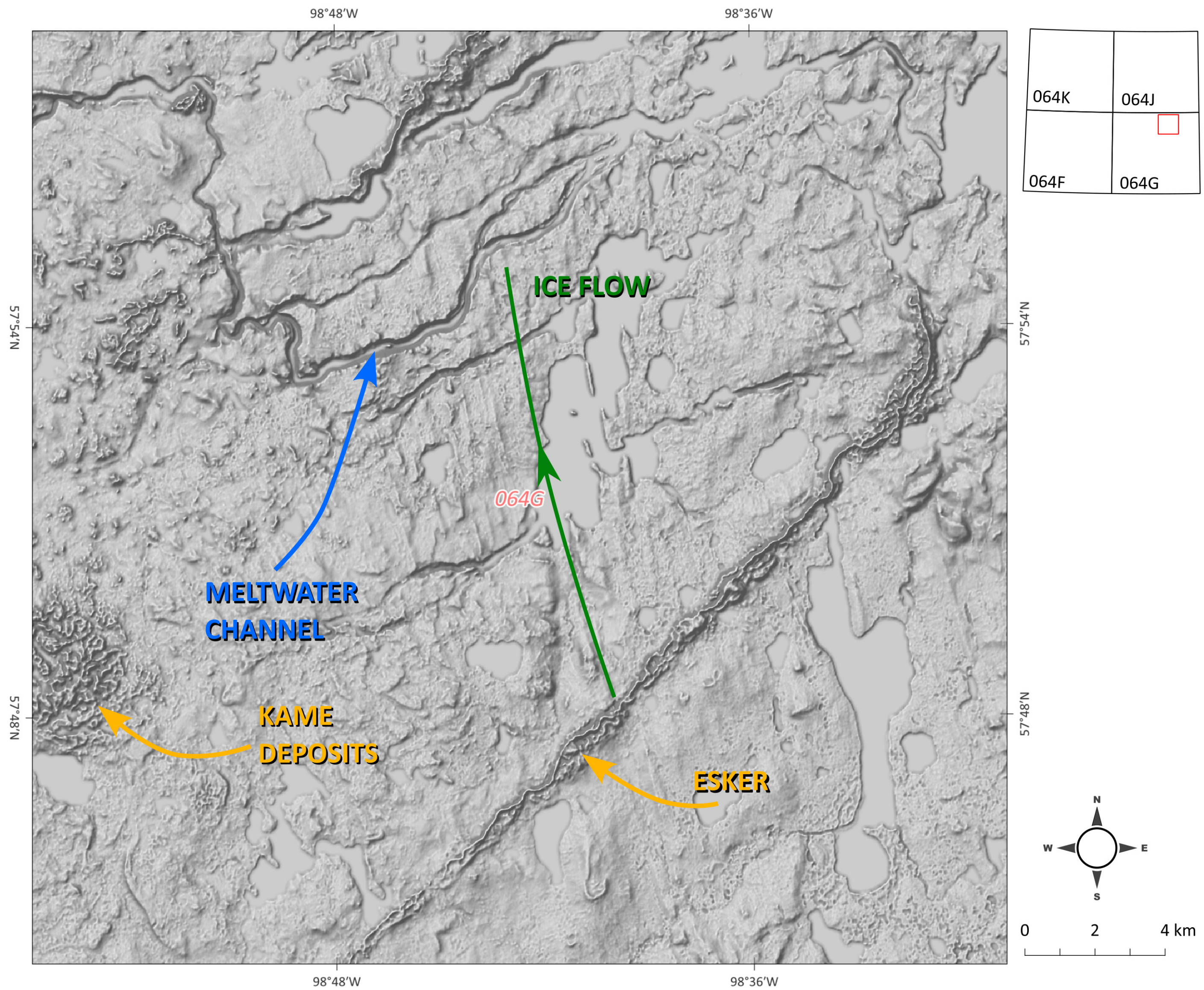

Figure GS2025-22-3: Image of a small portion of NTS area 064G in northern Manitoba (location shown on inset) from the Copernicus 30 m DEM. The image illustrates streamlined landforms that indicate an ice-flow event (oriented approximately north-south), followed by the deposition of esker and kame deposits, and finally major erosional channels that were created as proglacial waterbodies migrated in response to fluctuations in ice position and accumulations of glacial deposits. Figure produced using Copernicus WorldDEM-30 (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved).

future consideration for the DEM data layer is to generate apparent drainage catchments for waterbodies as a potential metric for use in machine-learning modelling.

Surficial landforms and Quaternary history

The surficial sediments that overlie bedrock are the most important variable in the interpretation of lake-sediment chemistry. The lake sediment is an accumulation of fine- to very fine-grained silt, clay and organic material thought to be representative of the waterbody catchment area. The chemistry of the glacial sediments is a first-order factor in the lake-sediment chemistry results and can potentially be directly related to its bedrock source, albeit influenced by mixing through the various phases of glacial transport. It is important to reiterate that landforms developed from the earliest phases of ice advance and retreat (e.g., esker and kame deposits, beachlines and glaciolacustrine basins) may often, but not always, be adjusted by subsequent phases of advancing ice. This will contribute to local chemical heterogeneity that is reflective of the reworking processes associated with glacial melt and retreat, which can obscure the original bedrock signal. Lastly, it is important to consider surficial sediment thickness when interpreting regional geochemical data. Regions with thicker surficial sediments generally have less chemical relation to the underlying bedrock (Cummings and Russell, 2018). The most southeastern area of the study is generally recognized as being overlain by glaciolacustrine sediment that, in certain locations, is observed to reach at least 5 m in thickness (T. Hodder, pers. comm., 2025).

In glaciated terrains, the surficial landforms are primarily related to erosion and deposition by ice or to proglacial water bodies that formed as glaciers waxed and waned. A large volume of research has been conducted across northern Manitoba and southern Nunavut to map major landforms and interpret glacial events (Trommelen et al., 2014; Gauthier et al., 2019; Amor et al., 2024a; Hodder et al., 2024). These studies have demonstrated that there has been a complex multiphase regime of ice-flow advance and retreat in the region, with ice advances from the north and southeast at different times in the past (Figure GS2025-22-4). However, it should be noted that the ice-flow

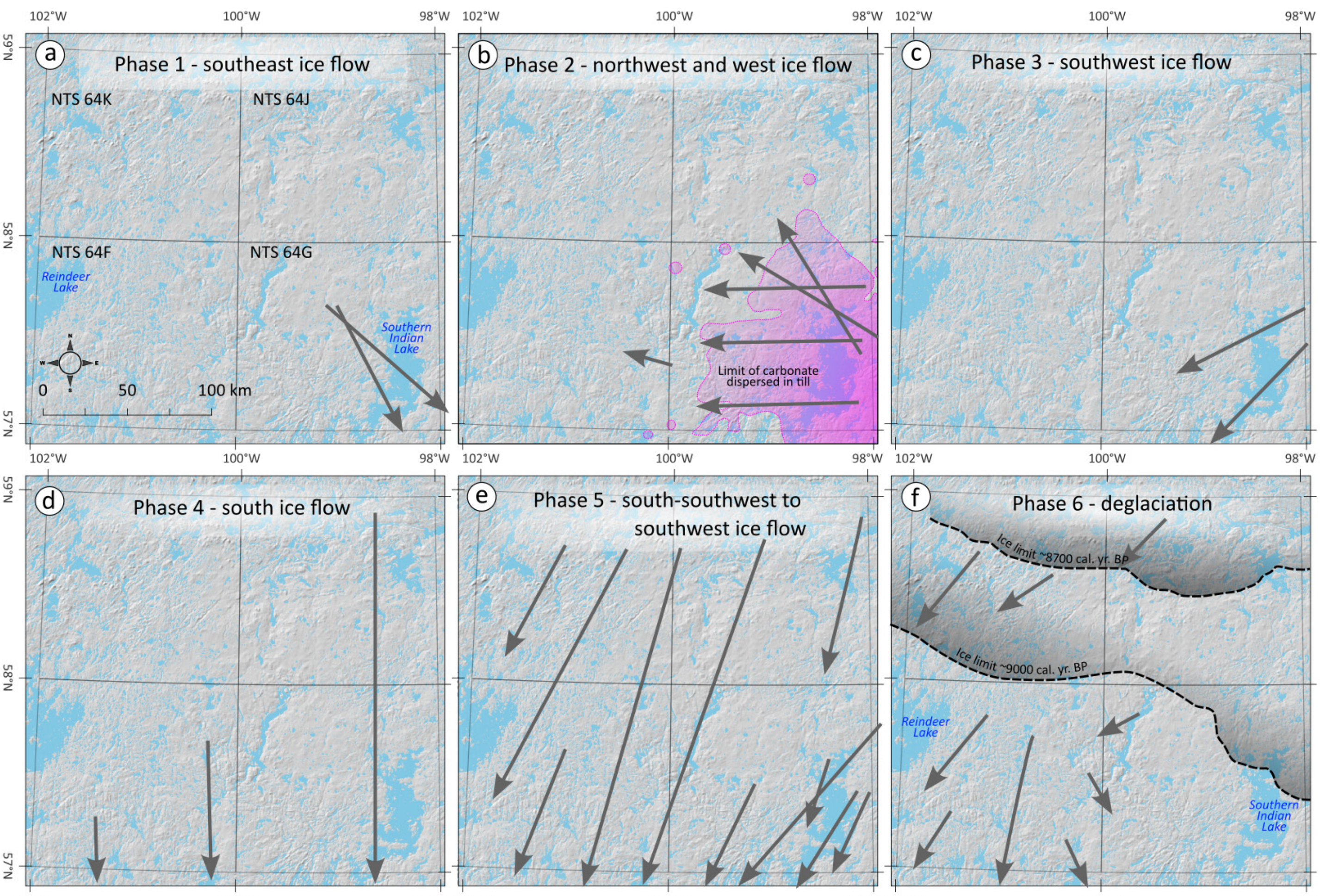

*Figure GS2025-22-4: Series of maps illustrating the phases of ice flow across the study area in northern Manitoba based on field mapping and satellite-image interpretation: **a)** ice flow in phase 1predominantly from the north; **b), c)** resurgence of ice from the east-southeast in phases 2 and 3 presumed to have transported carbonate clast-rich till over much of NTS area 064G; **d)** return of ice flow southward in phase 4; **e)** southwestward ice flow in phase 5; **f)** final phase of glacial retreat. Figure modified from Gauthier et al., 2019; Amor et al, 2024a. Base hillshade topography produced using Copernicus WorldDEM-30 (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved).*

history is not thought to be consistent across all four NTS areas that are the focus of this study.

The compilation and synthesis of literature pertaining to the Quaternary history of the area is ongoing and is being undertaken in conjunction with representatives at the Manitoba Geological Survey (MGS) and the Geological Survey of Canada (GSC). Currently all data from the literature is being compiled in a QGIS workspace, including all published spatial vector data. Where required, older vector data based on coarse resolution data will be remapped to the resolution of the Copernicus 30 m DEM. It is important to complete this process before applying a machine-learning modelling strategy since all core variables should initially be adequately quantified and the data problem well defined.

A compilation of relict beach ridges observed remotely is being undertaken with the support of the MGS. Surface maps from previous investigations are being synthesized (e.g., Figure GS2025-22-5a, b; Dredge and Nixon, 1981, 1982; Dredge et al., 1982a, b; Nixon et al., 1982; Richardson et al., 1982; DiLabio et al., 1986; Kaszycki and Way Nee, 1989). The relict beach ridges are a direct indicator of the limits of past proglacial lakes that formed at the margin of the Laurentide Ice Sheet, such as glacial Lake Agassiz (Teller, 1987). These large proglacial lakes received significant sediment input from the melting ice sheet, and silt and clay deposited within these lakes certainly contribute to masking the geochemical signals. Preserved beach ridges are most well developed near the centre of the area covered by the four NTS map sheets, indicating a period of time character-

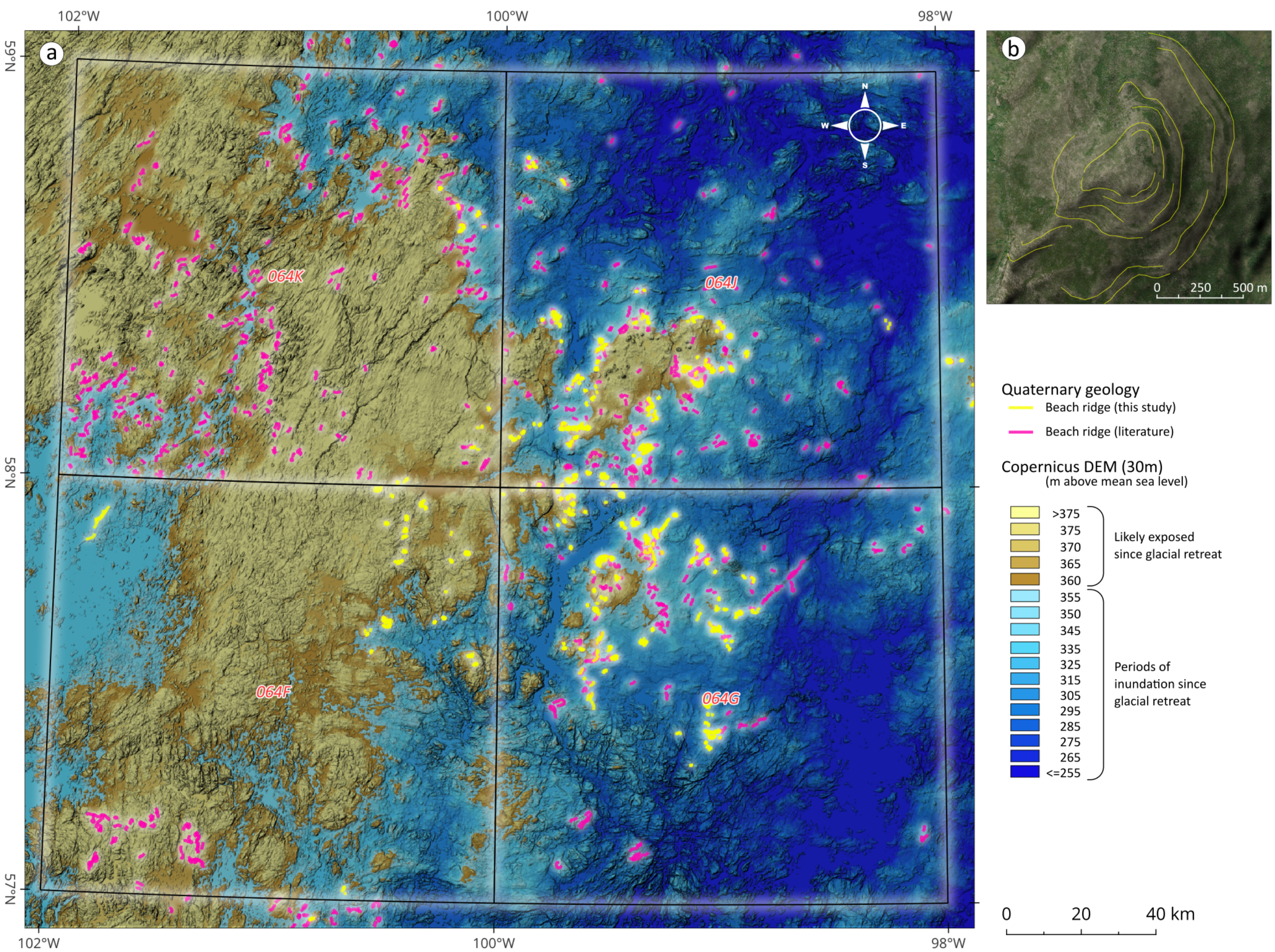

Figure GS2025-22-5: ***a)*** *Map of the study area in northern Manitoba showing the Copernicus 30 m DEM (European Space Agency, 2025). Beach ridges mapped in this study are shown as yellow polylines and beach ridges compiled from literature are shown as pink polylines. The majority of identified beach ridges cluster around 350–360 m elevation. The patterns of beach-ridge development may assist in delineating areas that were not exposed to extended periods of inundation and glaciolacustrine sedimentation. The digital elevation model was colour adjusted such that the brown to blue transition occurs at ~355 m elevation, which aligned with the mean elevation of the majority of visible beach ridges and may represent limits of subaerial exposure at ca. 8000 years ^{14}C BP.* ***b)*** *Satellite image showing a small mound with several relict beach ridges; yellow lines are interpreted as beach-ridge segments. Base hillshade topography produced using Copernicus WorldDEM-30 (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved). Image from Microsoft Bing Maps service 2025.*

ized by sustained proglacial lake levels (Figure GS2025-22-5a, b). Although beach ridges themselves are not a significant control of lake-sediment geochemistry, the patterns of beach-ridge development may assist in delineating local areas that were not exposed to extended periods of inundation and glaciolacustrine sedimentation. An intended outcome of the project is to also synthesize published surficial geology maps of the study area.

Geochemical data

The exploratory data analysis of the geochemical dataset has been limited, as additional work will require classifying surficial material into groups (or domains) and identifying the hydromorphic and mechanical dispersion vectors; however, preliminary analysis indicates chemical patterns that are of interest. For example, a map of lake-sediment nickel concentration reveals a relationship with mapped beaches, with samples recovered from elevations above the reconstructed beach ridges showing overall lower nickel values (Figure GS2025-22-6a, b). This pattern suggests glaciolacustrine sediments associated with Lake Agassiz may be more clay rich or organic rich and act as a more effective metal-retention medium. This will be explored further in the future, along with additional compilations of the INAA results and the original survey results to achieve a complete database that will assist in completing the research program.

Economic considerations

The work described herein plays a small part in the final goal of applying machine-learning–enhanced and landscape-integrated geochemical prospectivity to mapping for critical minerals in a remote region of northern Manitoba. This work builds on geochemical sampling, recent Quaternary mapping and sample reanalysis, the aim of which is to generate sophisticated maps of commodity and deposit-style prospectivity as a support to critical-mineral exploration. Mineral prospectivity maps are an important tool for mineral exploration and can also be used for effective land-use planning.

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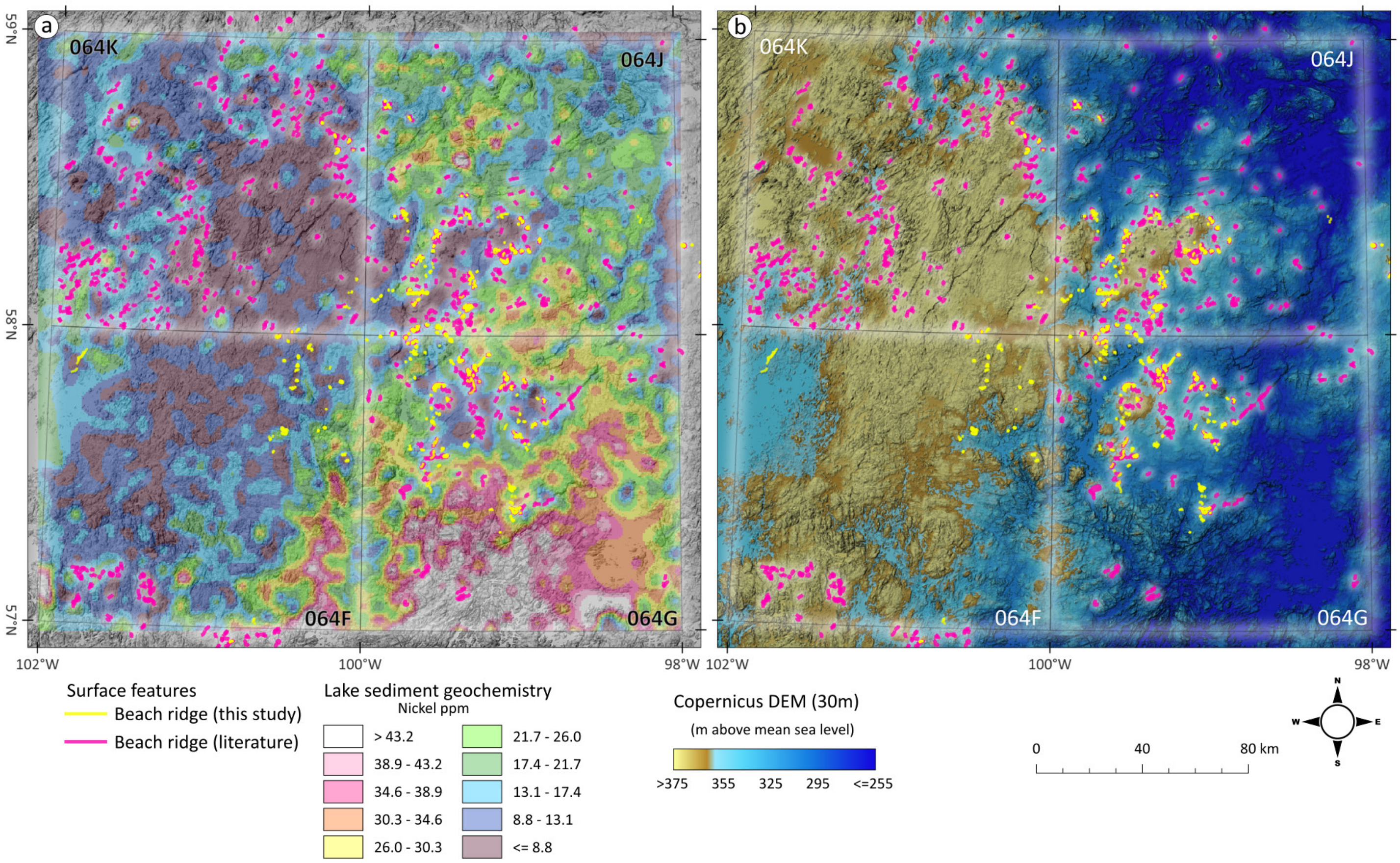

***Figure GS2025-22-6: S**eries of maps of the study area in northern Manitoba showing **a)** nickel concentration in lake-sediment samples (after aqua-regia digestion); **b)** a reconstruction of Lake Agassiz in the map area. There is a notable spatial relationship between these features, where nickel concentrations in lake sediment without paleolake coverage tend to be lower. Base hillshade topography produced using Copernicus WorldDEM-30 (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved).*

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