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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8836**

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sediment-hosted Zn-Pb mineral systems**

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CanadaThe wordmark for Canada, with a small red maple leaf icon positioned above the letter 'a'.



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Datasets to support prospectivity modelling for sediment-hosted Zn-Pb mineral systems

Introduction

Sedimentary basins are prospective for a wide range of critical raw materials and improved mineral exploration targeting in these settings has the potential to reduce future supply chain disruptions. Herein we report public geoscience datasets that are used in Lawley et al. (in press) to generate prospectivity models across Canada, the U.S., and Australia for Mississippi Valley-type (MVT) and clastic-dominated (CD) Zn-Pb deposits and their associated critical raw materials (e.g., Cd, Ga, Ge, Sb, and In). Modelling was completed as part of the Critical Minerals Mapping Initiative (CMMI) between the Geological Survey of Canada (GSC), the United States Geological Survey (USGS), and Geoscience Australia (GA). As discussed below, all public geoscience datasets included within this study are spatially indexed using a discrete global grid system (DGGS) and combined into a datacube (Lu et al., 2018). Data in this combined form can be used to address multiple geoscience research areas (e.g., prospectivity modelling, land-use planning, remote predictive mapping, and cumulative environmental impact assessments). The relatively coarse resolution of the DGGS used (hexagon area of 5.16 km²) is best suited for reconnaissance and/or continent-scale applications. Geological and geophysical datasets, training data used for prospectivity modelling, and supporting information are reported in Tables 1–4.

Data processing

All data processing and spatial operations to prepare geological and geophysical datasets for prospectivity modelling were completed in R (R Core Team, 2021) using mostly the “tidyverse” (Wickham et al., 2019), “sf” (Pebesma, 2018), and “raster” packages (Hijmans and van Etten, 2012). The first step in data processing was to import and convert individual spatial data layers in vector (e.g., continent names, country names, states/provinces/territories names, terrane names, geological map units, geological properties, geological periods) and raster (e.g., geophysics and proximity surfaces) formats into a common coordinate reference system (CRS; latitude and longitude are reported in degrees using the WGS84 datum; EPSG4326) and resolution (Table 1). This study uses the H3 DGGS (Uber Technologies Inc, 2020) developed by Uber and released as open source (Apache 2 license) to convert latitude and longitude coordinates to a unique H3 address. This hierarchical and hexagon-based DGGS provides complete global coverage at multiple resolutions. All raster and vector datasets were spatially indexed using resolution 7 of the H3 DGGS, which corresponds to 98,825,162 unique H3 addresses for the globe, with an average hexagon area of 5.16 km², and average hexagon edge length of 1.22 km. Zonal statistics for converting raster data with geographic coordinates to the H3 DGGS were completed using the “exactextractr” package; whereas vector datasets were converted to raster objects using the “fasterize” package prior to spatial indexing. All H3-related data operations used the “h3jsr” package, which provides an R binding to a variety of useful neighbourhood and address lookup functions that are built for the H3 DGGS.

Training data

Mineral deposits and occurrences that were used as training data are based on previously published compilations (Hoggard et al., 2020) and updated databases in Canada (e.g., provincial and territorial), the United States (e.g., Alaska Resource Data File, ARDF; Mineral Resources Data System, MRDS; USMIN), and Australia (e.g., OZMIN and MINLOC). Active mining operations, past-producing mines, and advanced-stage exploration projects were classified as deposits for the purposes of the present study; whereas prospects, showings, and anomalous drill intercepts were defined as mineral occurrences. Methods for filtering deposits and occurrences varied somewhat for each data source, but generally consisted of using major commodities (e.g., Zn, Pb) and available descriptions of lithologies and mineralization to subdivide the training data into two mineral systems (i.e., MVT and CD). Deposits and occurrences that shared some similarities with these mineral systems but were difficult to classify because of the limited available information, or were of uncertain economic significance (e.g., geochemical soil anomaly, mineralized float), were classified as “Unknown” and excluded from model training. Duplicate deposits contained within individual databases were removed wherever possible using their names and locations. However, mineral occurrences with duplicated names were not removed since individual deposits may be associated with multiple mineral occurrences.

Geological data

Bedrock geological data for the U.S. were taken from the State Geologic Map Compilation (SGMC) digital database of the conterminous United States (Horton et al., 2017) and the Geologic Map of Alaska (Wilson et al., 2015). Geological data for Canada comprises 20 previously published provincial, territorial, and other smaller scale geological maps that were combined as part of the current study (Colman-Sadd et al., 1990; Wardle et al., 1997; de Kemp and Scott, 1998; Viljoen et al., 1999; PEI Department of Environment Energy and Forestry, 2002; Fisher and Poole, 2006; St-Onge et al., 2006; Tella et al., 2007; Ontario Geological Survey, 2011; Prior et al., 2013; Pehrsson et al., 2014; GeoNB, 2015; Harrison et al., 2016; Cui et al., 2017; Okulitch and Irwin, 2017; Saskatchewan Mining and Petroleum GeoAtlas, 2018; Skulski et al., 2018; Yukon Geological Survey, 2018; Stublely and Irwin, 2019; SIGÉOM, 2020). Missing data from these individual provincial, territorial, and other Canadian geological maps were imputed with the seamless, 1:5 million scale national geology database as required (Wheeler et al., 1996). However, individual map units have not been reconciled across state, provincial, territorial and/or other map boundaries. As a result, geological data from the U.S. and Canada should be considered as a patchwork of individual maps with boundary artefacts. In contrast, geological data for Australia is seamless and was taken from the 1:1 million scale national geology database (Raymond et al., 2012). All source map datasets are provided in Table 1.

Rock classifications from all 24 source maps were then subdivided into four types (i.e., sedimentary, igneous, metamorphic, and other) and 31 sub-types based on all of the available geological information, including major and minor rock types and descriptions wherever possible (i.e., rock descriptions of variable length were available for Alaska, Canada, and Australia; Table 2). This reclassification process is somewhat subjective and,

in many cases, multiple rock types and subtypes were appropriate for map units comprising multiple lithologies. For example, metamorphosed rocks presented a significant challenge and were mapped as their dominant protolith if rock descriptions contained primary sedimentary and/or igneous features. All other map units were re-classified according to their dominant lithology, which, in many cases, had to be inferred from the order of rock types that appeared in the descriptions. Dictionaries created as part of the current study were also used to search through major and minor rocks types and available descriptions to map the presence or absence of up to 17 geological properties (i.e., coarse clastic, fine clastic, calcareous, carbonaceous, evaporitic, cherty, red beds, sedimentary, ultramafic to mafic composition, intermediate composition, felsic composition, pegmatitic, alkali, igneous, schistose, gneissose, and anatectic; Table 3). In Canada, rock descriptions were expanded by matching formation names to the WEBLEX database (Lexicon of Canadian Geological Names on-line) wherever possible.

Geological periods are based on the 23 geological map compilations described above and were re-formatted and compiled as part of the current study. Geological ages are based on the maximum and minimum period defined in the source map data, which, for the purposes of this study, were assumed to reflect the current International Chronostratigraphic Chart (ICS) maintained by the International Union of Geological Sciences (IUGS) at the time of writing. No attempt was made to correct source-map data for the changes that have occurred to the ICS over time, except for the obsolete “Tertiary” period, which was re-classified into the Paleogene and Neogene. Mapped rock units with “Precambrian” ages were assumed to have maximum and minimum ages corresponding to the Paleoproterozoic and Cambrian, respectively, since Eoarchean rocks are exceptionally rare. Source map data that only contained geological eras (i.e., Cenozoic, Mesozoic, Paleozoic), were re-formatted to their respective maximum and minimum periods. Rocks covered by young glacial sediments represented a particular challenge during the process of re-formatting source map data and it is possible that some minimum ages are anomalously young in glaciated areas.

Reformatted geological age data from all 23 geological maps were also used to estimate the paleolatitude of rocks at the time of their deposition and/or emplacement. Paleogeographic reconstructions are based on Scotese (2021), which was completed and published as part of the PALEOMAP project (<https://www.earthbyte.org/paleomap-paleoatlas-for-gplates/>). Paleo-latitude and -longitude were calculated based on the “pole of inaccessibility” for each tectonic plate included within the PALEOMAP model (i.e., the farthest point from each plate boundary) and tracked through geological time using the GPlates web application programming interface (Muller et al., 2018). Calculated paleo-latitudes and -longitudes for large tectonic plates are subject to relatively large uncertainties. For example, the North America craton was tracked from a single pole (i.e., modern latitude and longitude of 53° and -91°, respectively). The PALEOMAP model places most of North America and Australia at low paleolatitude prior to the assembly of the supercontinents Gondwana and/or Pannotia during the latest Neoproterozoic (Scotese, 2021), which is broadly consistent with other previously published paleogeographic reconstructions even if the precise configuration of tectonic plates remains an active area of research (Dalziel, 1997; Evans, 2013). The core of the North American continent did not migrate to more northern latitudes until after the break-up of Pangea at ca. 175 Ma (Scotese, 2021).

Fault data compilations were taken from global (Chorlton, 2007; Styron and Pagani, 2020), national (Raymond et al., 2012) and the Geologic Map of North America digital databases (Reed et al., 2005). No attempt was made to remove duplicate faults prior to converting fault traces to a proximity surface. Small deviations between fault traces from different databases are not expected to have a major impact on the prospectivity results at the largest spatial scales. Proximity to passive margins and black shales are based on the global compilations of Bradley (2008) and Granitto et al. (2017), respectively.

Geophysical data

Seismic datasets were sourced from a combination of active, controlled-source seismic refraction and passive teleseismic surveys. Depth estimates for the seismogenic Moho (i.e., depth to the Mohorovičić discontinuity) were taken from national datasets [i.e., Canada, Schetselaar and Snyder (2017); conterminous United States, Shen and Ritzwoller (2016); Alaska, Zhang et al. (2019); Australia, Kennett et al. (2011)] and the global models of Szwillus et al. (2019), Reguzzoni and Sampietro (2015), and Laske et al. (2013). Seismic velocities in the upper mantle and teleseismic-based estimates for the lithosphere-asthenosphere boundary are from Debayle et al. (2020), Hoggard et al. (2020), and Priestley et al. (2018). High seismic velocities tend to be associated with old, cold, and melt-depleted cratonic lithosphere within the interiors of continents, which contrasts with the relatively slow seismic velocities of lithospheric regions modified through interaction with younger asthenospheric melts. These sharp contrasts in seismic velocities, coupled with rapid changes in lithospheric thickness, can be used to map the morphology of tectonic plates and the deepest pathways of melts and/or fluids within the lithosphere. Focusing of mantle-derived fluids and melts into the overlying crust may also be reflected by rapid changes in crustal thickness (i.e., Moho depth).

Gravity datasets were sourced from a combination of satellite-, airborne-, and ground-based surveys. Satellite-based gravity surveys include data acquired as part of the European Space Agency (ESA) Gravity Field Steady-State Ocean Circulation Explorer (GOCE) mission and their derivative products that emphasizes the curvature and shape of anomalies, as described in Ebbing et al. (2018). The gravity derivative products reported herein were calculated from the grid of merged national gravity databases for Canada, Alaska, and the conterminous United States (Phillips et al., 1993; Saltus et al., 2008; Geological Survey of Canada, 2017) and from the grid of the Australian gravity data (Lane et al., 2020) using identical data processing procedures available in the Geosoft Montaj software. For Canada, Alaska, and the conterminous U.S., re-processing involved merging gravity datasets to a 2 km grid to create a seamless Bouguer anomaly grid across most of North America. The combined Canada-U.S. grid was then merged with the Bouguer anomaly grid for Australia, prior to calculating the horizontal gradient magnitude (HGM) for all three countries using the methodology of Cordell (1979). Re-processed gravity grids (i.e., HGM of the Bouguer gravity) and their upward-continued (30 km) versions highlight the edges of density sources at shallow to deeper depths, respectively. In addition to the grids and their derivatives, points tracking the HGM gravity maxima were calculated for both the Bouguer gravity and its upward-continued

field (Phillips, 2007). The proximity to these tracks in map pixels, also referred to as gravity “worms”, act as a proxy for steeply dipping geologic structures and contacts between rocks with varying densities.

Magnetic data were sourced from modern (Alaska Division of Geological and Geophysical Surveys, 2016; Miles and Oneschuk, 2016) and legacy surveys (e.g., North America magnetic map; Ravat et al., 2009) to create an updated and merged residual magnetic anomaly map of North America. The merged residual magnetic anomaly data were reduced-to-the-magnetic north pole (RTP) using a differential RTP methodology (Arkani-Hamed, 2007) implemented in the Geosoft Montaj software. An identical workflow was followed to create an RTP grid and derivative products from the residual magnetic anomaly map of Australia (Minty et al. 2019). Several derivative products were also calculated from the RTP grids as part of the current study using identical procedures described in Phillips (2007). This included the first vertical derivative (1VD) to evaluate and map magnetic contrasts in the shallow crust. The edges of shallow magnetic sources were further highlighted by calculating the horizontal gradient magnitude (HGM) of the pseudo-gravity field RTP data. Proximity to the tracks of the maxima of HGM pseudo-gravity, or “worms”, was an additional derivative product calculated from the RTP data. To evaluate the influence of deep magnetic-sources on the basin-hosted mineral systems, long-wavelength anomalies were calculated from the RTP grids via matched filtering using the methodology described in Syberg (1972) and implemented using code developed by Phillips (2007). The long wavelength RTP anomalies were transformed to pseudo gravity and the HGM calculated from this field to emphasize boundaries and edges of deep magnetic-sources. Proximity to “worms”, which track the maxima HGM, act as proxies to map the edges of the deep magnetic sources within the deep- to mid-crust.

Datacube

The datacube is reported in a tabular format containing 97 columns and 5,164,970 rows (Table 4). Each row represents a unique H3 address; whereas each column represents a different geological or geophysical dataset. Header names are located in the first row of Table 4. All values are comma-separated. The combined dataset was filtered to remove H3 cells containing more than 70% missing data. All remaining missing values are represented as NA. The entire datacube can be imported into a GIS environment using the longitude and latitude for the approximate center of each H3 cell or the calculated polygon geometries in well-known-text format (WKT). Both options for locating H3 cells in a GIS environment are based on the WGS84 datum (EPSG4326). Some software and web-based applications can also recognize the H3 address names by default, including kepler.gl. However, depending on the available computer resources, it may be easier to filter or subset Table 4 prior to importing into GIS or web-based applications using a variety of packages that are available in high-level programming languages, including python (e.g., pandas) and R (e.g., tidyverse). For example, the following R code (R Core Team, 2021) provides an example of how to read Table 4, filter by country, and then export the filtered data as a csv file using the group of packages included within the tidyverse (Wickham et al., 2019):

```

#Load the required packages into R
#Tidyverse is a group of packages that includes readr and dplyr
library(tidyverse)

#Read Table 4 as a csv file into R using the readr package
cmmi <- readr::read_csv("filepath here")

#Filter the dataset using the country name and the dplyr package
#Country names include "Canada", "United States of America", and "Australia"
cmmi_filter <-      cmmi %>%
                    dplyr::filter(Country_Majority == "Canada")

#Export filtered data to csv using the readr package
readr::write_csv(cmmi_filter, "filepath here")

```

Table 4 can also be filtered by province name (n.b. this data column includes province, state, and territory names) and then exported to further reduce the file size for plotting in GIS:

```

#Load the required packages into R
#Tidyverse is a group of packages that includes readr and dplyr
library(tidyverse)

#Read Table 4 as a csv file into R using the readr package
cmmi <- readr::read_csv("filepath here")

#Filter the dataset using the province name and the dplyr package
#Use the OR operator to filter H3 cells within Ontario or Quebec
cmmi_filter <-      cmmi %>%
                    dplyr::filter(Province_Majority == "Ontario" |
                                   Province_Majority == "Quebec")

#Export filtered data to csv using the readr package
readr::write_csv(cmmi_filter, "filepath here")

```

The complete list of province, state, and territory names is taken from Natural Earth (www.naturalearthdata.org) and can be listed in R to provide additional filtering options:

```

#Load the required packages into R
#Tidyverse is a group of packages that includes readr
library(tidyverse)

#Read Table 4 as a csv file into R using the readr package
cmmi <- readr::read_csv("filepath here")

#View unique character names for each province, state, and territory
unique(cmmi$Province_Majority)

```

File size can be further reduced to improve performance by filtering and then selecting a subset of datasets for export in R:


```

#Load the required packages into R
#Tidyverse is a group of packages that includes readr and dplyr
library(tidyverse)

#Read Table 4 as a csv file into R using the readr package
cmmi <- readr::read_csv("filepath here")

#Filter the dataset using the province name and the dplyr package
#Use the OR operator to filter H3 cells within Ontario or Quebec
#Select a subset of datasets using the dplyr package
cmmi_filter <-      cmmi %>%
                    dplyr::filter(Province_Majority == "Ontario" |
                                   Province_Majority == "Quebec") %>%
                    dplyr::select(H3_Address, H3_Geometry, Longitude_EPSG4326,
                                   Latitude_EPSG4326, Province_Majority)

#Export filtered and selected data to csv using the readr package
readr::write_csv(cmmi_filter, "filepath here")

```

The increasing availability of spatial data packages in python (e.g., GeoPandas) and R (e.g., sf) also allow spatial operations to be completed programmatically rather than in a traditional GIS environment. Spatial data packages are better suited for manipulating larger datasets and can be used to convert Table 4 into a spatial object for further analysis and visualization. Lovelace et al. (2019) provides a free resource for people interested in learning more about geocomputation with R.

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Table 1: Datasets and sources

Table 2: Descriptions of rock types and sub-types

Table 3: Vocabularies used for mapping rock properties

Table 4: Spatially indexed geological and geophysical datasets

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