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ABSTRACT

Surficial geology maps provide important geoscience information for geological reconstructions, mineral exploration and development, and land use planning. In this study, remote predictive mapping was used to derive a predictive surficial geology map for Marian River NTS 85-N, which straddles the Slave, the Bear-Slave and the Interior Platform geological provinces. The predictive map was generated using radiometrically balanced LANDSAT 7 imagery (collected in 2001) and knowledge from airphoto interpretations, fire history, elevation models, field observations and legacy datasets. This Open File contains graphical and digital geo-referenced versions of the predictive maps. A printable version of the predictive surficial geology map is provided in pdf format (map scale 1:125 000).

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

INTRODUCTION

Despite the detailed knowledge of bedrock geology in the mineral-rich Slave, Bear-Slave and Interior Platform geological provinces, knowledge of surficial materials and surficial geology remain rudimentary in most of these regions. The lack of this geoscience information limits the ability to identify terrain risks associated with various surficial materials along proposed and existing infrastructure corridors (e.g. northern roads). Surficial maps also play a vital role in mineral exploration (e.g. drift prospecting and bedrock mapping), and in the identification of granular aggregate materials.

The Geological Survey of Canada of Natural Resources Canada has begun to use Remote Predictive Mapping (RPM) to map surficial materials (Grunsky et al., 2006; Brown et al., 2007; Harris, 2008; Stevens et al., 2013) and bedrock (Harris et al., 2010) over large areas where existing geological knowledge is insufficient. These RPM map products provide a first order assessment of surficial materials and bedrock, which can guide traditional field mapping and provide regional information for geotechnical investigations and mineral exploration.

A remote predictive surficial geology map has been produced for the Marian River map sheet NTS 85-N, as part of research conducted through Great Slave-TRACS (Transportation Risk in the Arctic to Climatic Sensitivity) and GEM (Geo-mapping for Energy and Minerals. This Open File contains graphical and digital geo-referenced versions of the predictive maps for Marian River NTS 85-N. A printable surficial geology map for NTS 85-N is provided in pdf format at a scale of 1:125 000. A preliminary surficial geology map of the northern half of NTS 85-K was also produced using the same statistics as 85-N and is presented as a raw model output in this open file.

Regional Surficial Geology

The Marian River map sheet (NTS 85-N) is located on the boundaries of the Slave, Bear-Slave and Interior Platform geological provinces of the Northwest Territories. The terrain mainly consists of exposed bedrock, open to dense forests of black spruce, jack pine, and paper birch mixed with marshes, fens and peat bogs in low-lying areas. This region is located within the extensive discontinuous zone of permafrost. Forest fires occur throughout the map sheet as shown in Figure 1. The geology of the map sheet (Figure 1) is split diagonally between Proterozoic granites of the Canadian Shield region to the North-east and Paleozoic dolomites, shales and limestone of the Plains region to the south-east (Vincent, 1989).

Regional geological studies indicate that the last glacial episode occurred in the Late Wisconsin, which reached its maximum extent about 18,000 years ago. The Yellowknife region was ice covered to about 11,000 BP and became ice-free by about 10,000 BP (Dyke and Prest, 1987). Paleo ice flow was to the southwest, as evident by striae and fluted bedrock measurements (Kerr, 2006) and the orientation of eskers and drumlinoid features. With the retreat of ice in the region, a large glacial lake (Glacial Lake McConnell) occupied the Great Bear and Great Slave Basins, up to an elevation of about 280 m (Craig, 1965; Smith, 1994) in the western part of the basin, to 320-335 m in the

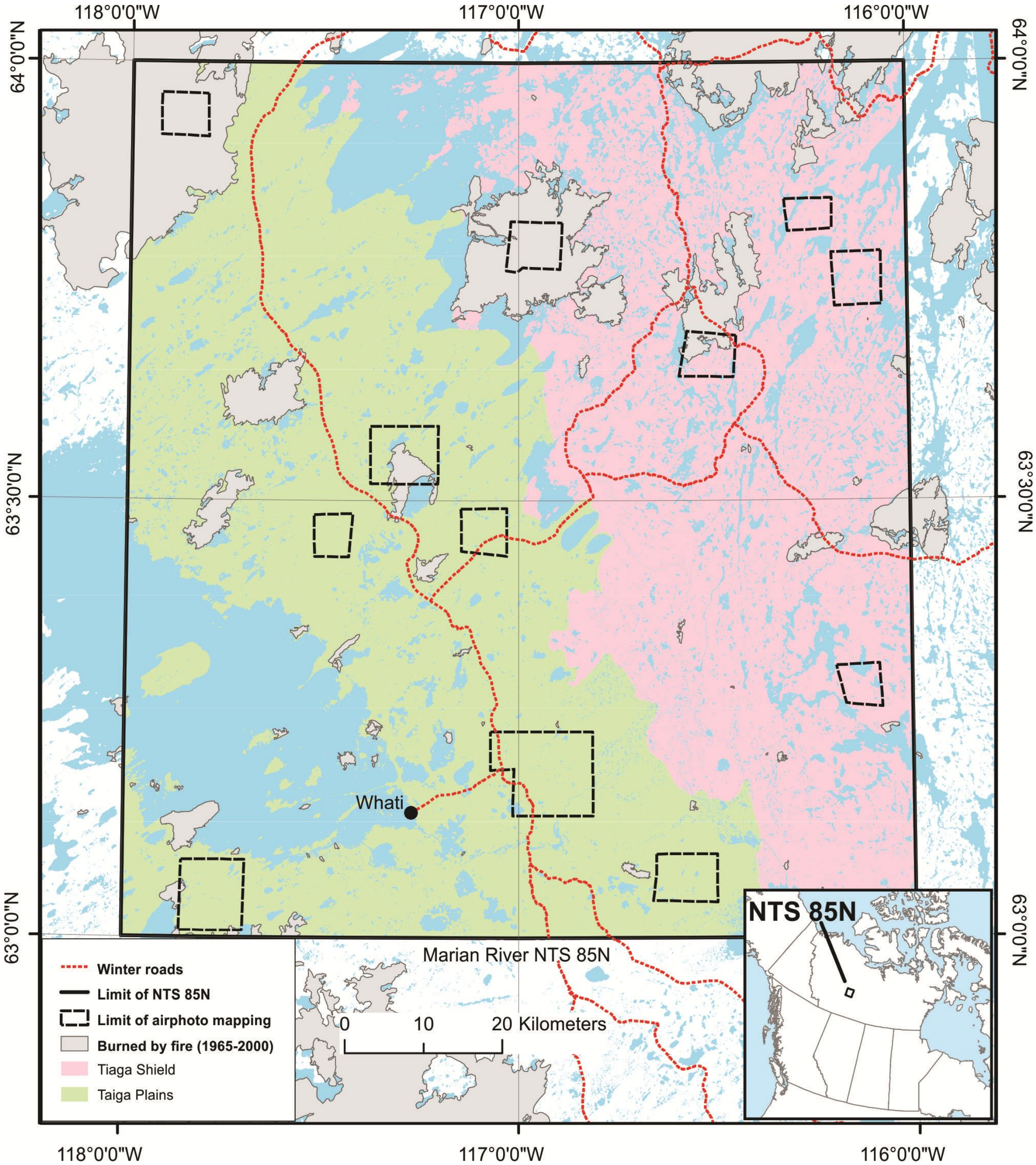

Figure 1. Study area showing the location of Marian River NTS 85-N (solid back line) and the limit of air photography mapping used for development of training areas (dashed black line).

eastern section of the basin (Kerr et al., 2014), resulting in the deposition of fine-grained glaciolacustrine sediments. Wave-washed bedrock and reworked glacial and glaciofluvial sediments are also present.

Existing surficial maps for this area include information at a national scale 1:5M (Fulton, 1995) and a regional scale at 1:1M (Aylsworth and Shilts, 1989). However because of their scale, these maps are inadequate for most applications, such as geological reconstructions, mineral exploration, resource development and government land use planning. A predictive surficial materials and surficial geology map has been recently published for Yellowknife NTS 85J (Stevens et al., 2012) and Hearne Lake NTS 85I (Stevens et al., 2013), located to the southeast of the present study area.

Remote Predictive Mapping (RPM)

Remote predictive mapping (RPM) integrates multiple remote sensing datasets to classify surficial geology units based on statistically robust models built from user defined training areas (Figure 2). The integration of multiple types of remotely sensed data attempts to improve the accuracy of the mapping by increasing the distinction between each training class (surficial geology type). From these predictive maps and field data, predictive surficial geology maps can be generated to infer the origin and environment into which the sediment was deposited.

A predictive map does not represent geological truth, but rather an estimate of what may be present on the ground, based on the signatures derived from the interpreted data (geophysical, geochemical, remotely sensed). Traditional geological maps derived from airphoto interpretation are used in this process to construct the classification models and independently validate the resulting map. It should be recognized that all maps, including those based on airphoto interpretations, inherently contain some form of spatial and/or classification error.

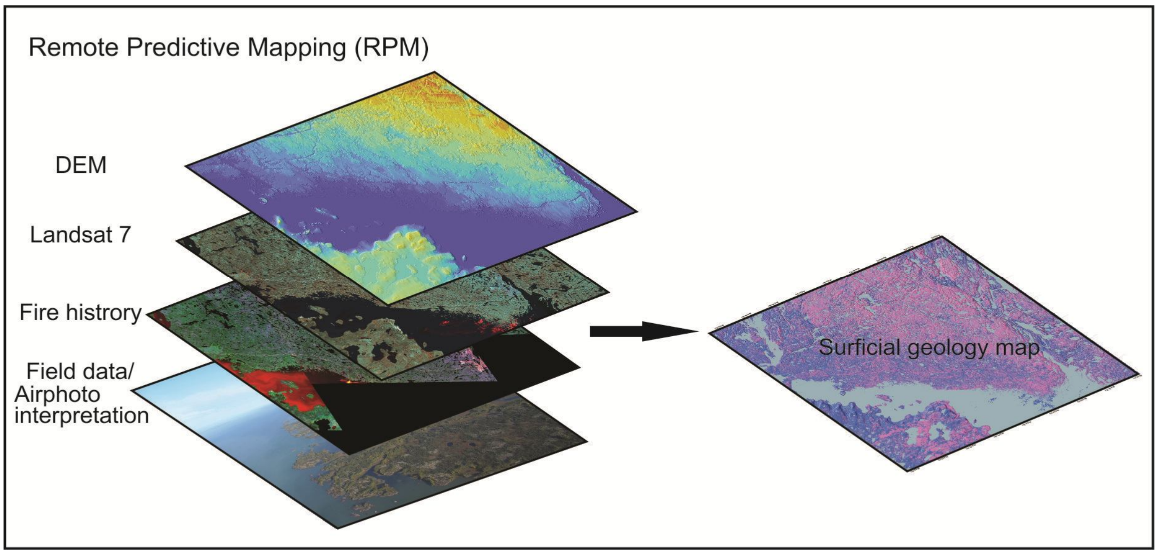

Figure 2. Schematic diagram showing the integrations of multiple remotely sensed datasets used to produce surficial geology maps. The data layers used in the analysis are based on the availability and usefulness of various sources of data (after Stevens et al., 2013).

REMOTE PREDICTIVE MAPPING APPROACH (NTS 85-N)

The RPM methodology adopted for mapping NTS 85-N was based on the availability of remote sensing data and the authors' field experience of surficial materials and geology found in the region (Figure 3). The classification approach involved the use of a decision-tree model calibrated on multiple training classes mapped using air photographs. The resulting model was used to predict surficial geology by applying the training classes to satellite imagery, fire history map and a digital elevation model (DEM) for the 85-N map area. Decision-tree methodology was chosen as the classification algorithm due to its ability to handle large training datasets irrespective of their statistical distributions. Decision-tree models are non-parametric classifiers that have an advantage of being able to use both categorical and continuous independent data for classification unlike the maximum likelihood classification method. The See5™ (http://www.rulequest.com/index.html) decision tree algorithm uses a combination of cross validation and boosting. Cross validation generates error statistics on a holdout sample from a single trial, and boosting reduces model errors by weighting the incorrectly classified cases more heavily in the subsequent trial runs. This process is repeated for the specified number of trials using a different random holdout sample each time. The final boosted map is generated using the majority prediction from all trials.

Data

Mapping was undertaken using multiply LANDSAT 7 imagery taken in 2001 (normalized bands 2,3,4,5,7) which was downloaded from Glovis (http://glovis.usgs.gov/) All scenes were pre-screened by Glovis so only minor cloud and cloud shadow were present. Mid-summer acquisition dates were chosen when vegetation is at peak greenness to facilitate normalizing radiometry among scenes and to ensure stable radiometric signatures representing each surficial class. Native projection was Universal Transverse Mercator (UTM) zone 12 with Datum WGS 84 for Glovis. All scenes were projected to the common UTM zone 12 and ellipsoid GRS 1980 to correspond to the mapsheet projection.

Scenes were radiometrically balanced using Thiel-Sen robust regression on each spectral band in adjacent overlap regions between scenes (Olthof et al., 2005). Scenes were mosaiced into the mapsheet extent that included extra data on all four sides to reduce edge errors. They were first mosaiced east to west and south to north and then again into separate channels in the opposite order to generate two separate mosaics with each one representing one of two overlap regions between scenes. The final mosaic was produced by selecting pixels in overlap regions based on the maximum Normalized Difference Vegetation Index (NDVI = (NIR-Red) / (NIR+Red)) that is used to preferentially select clear-sky pixels over cloud and cloud shadow.

Entropy of each primary LANDSAT band was calculated using a 7x7 pixel moving window in order to provide local texture of the reflectance values. The use of entropy bands or surface roughness has been shown to increase the transformed divergence values between surficial materials (Stevens et al. 2012).

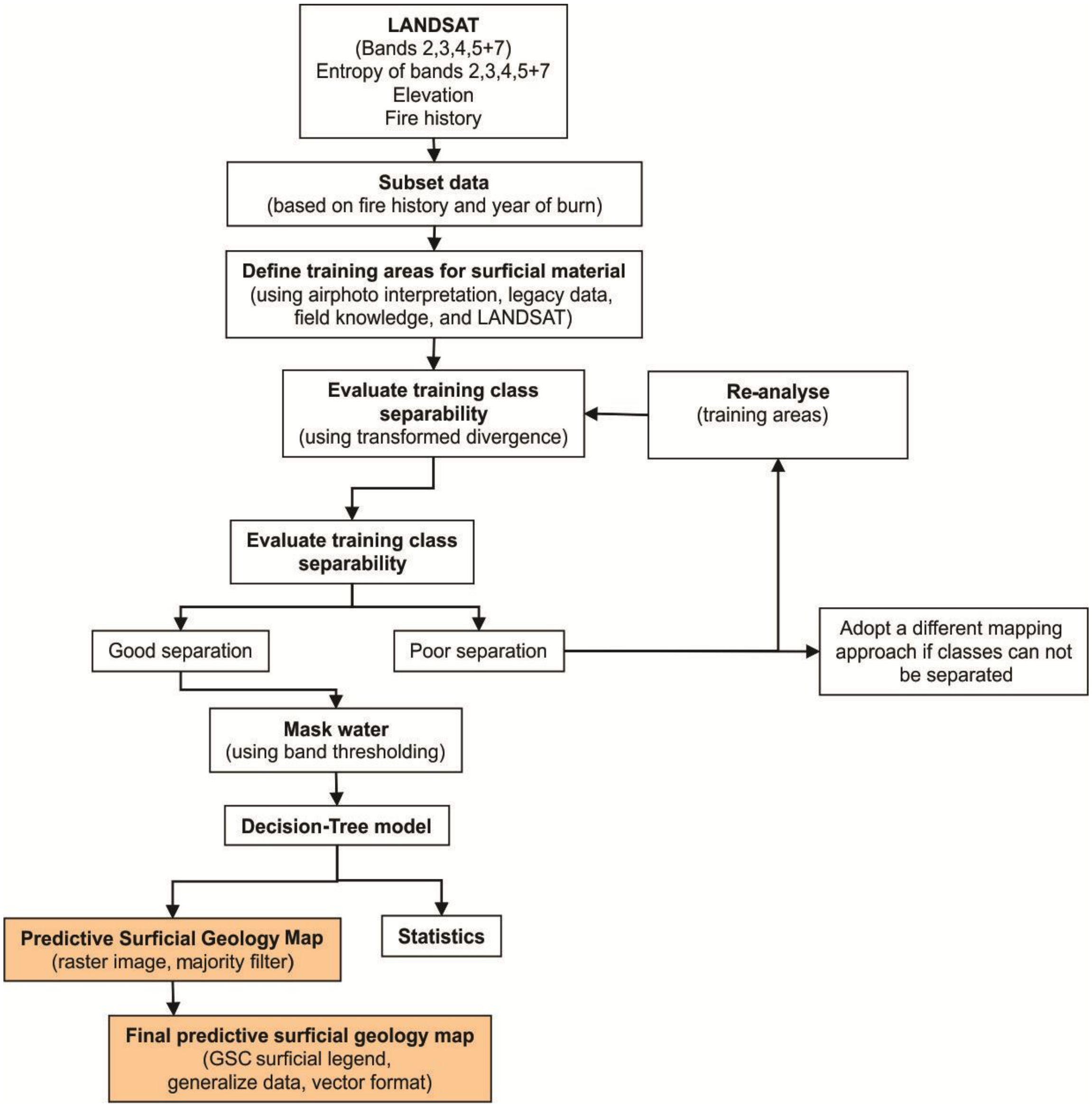

Figure 3. Flow chart describing general remote predictive mapping approach used in this study (after Stevens et al., 2012).

Water bodies were masked from the LANDSAT imagery using the near infrared channel (band 4) and with thresholding applied to DN (digital numbers) <40. The derived mask may also included cloud shadows and some wetlands with water at the surface. The selected mask was then merged to water polygons from the NTDB (Geogratis (http://www.geogratis.gc.ca)) to complete the water mask layer.

Elevation data in the form of a digital elevation model (DEM) was downloaded from Geogratis (http://www.geogratis.gc.ca) as 1:50k NTS grids in lat/long projection with a resolution between 0.75 and 3 arc seconds that was set at 30 m when projected to UTM. Fire history was obtained from the Northwest Territories Centre for Geomatics (http://www.geomatics.gov.nt.ca). Polygons representing forest fires burn areas that proceeded the Landsat acquisition dates were gridded at 30 m resolution. Fires dates ranged from 1965 to 2000. The location of the burn areas is presented in figure 1.

A total of 12 bands of data was used to produce the surficial geology map, including normalized bands 2-5+7 and entropy of bands 2-5+7, a 30 m digital elevation model and fire history (Table 1).

Table 1. Description of data bands used to map surficial geology

LANDSAT 7	
Band 2 (TM2)	records reflected green energy (λ=0.52-0.60 microns)
Band 3 (TM3)	records reflected red energy (λ=0.63-0.69 microns)
Band 4 (TM4)	records reflected near infrared energy (λ=0.76-0.90 microns)
Band 5 (TM5)	records short wave infrared energy (λ=1.55-1.75 microns)
Band 7 (TM7)	records short wave infrared energy (λ=2.08-2.35 microns)
LANDSAT 7 texture	
Entropy 2 (Tex2)	Band 2 calculated over a 7x7 pixel moving window
Entropy 3 (Tex3)	Band 3 calculated over a 7x7 pixel moving window
Entropy 4 (Tex4)	Band 4 calculated over a 7x7 pixel moving window
Entropy 5 (Tex5)	Band 5 calculated over a 7x7 pixel moving window
Entropy 7 (Tex7)	Band 7 calculated over a 7x7 pixel moving window
Fire history	Fire burn history from 1965 to 2000
DEM	30 m DEM

Training data

Traditional air photography interpretation of surface geology was performed to establish representative training classes of surficial geology (Figure 1 and Table 2). The final training classes were based on the outcome of air photograph interpretation, legacy data, and field experience in the region. Field survey of surficial geology was also conducted from helicopter in June of 2012. Information gained from this field work was used in the development of the training areas.

The statistical separation between training classes was determined for each surficial material prior to classifying the LANDSAT 7 imagery. The statistical separability of training classes was assessed using transformed divergence (TD), which is determined from the distance between mean reflectance value for each class in the N-dimensional space (Richards, 1986)

$$Dij = \frac{1}{2} tr((Ci - Cj)(Ci^{-1} - Cj^{-1})) + \frac{1}{2} tr((Ci^{-1} - Cj^{-1})(\mu_i - \mu_j)(\mu_i - \mu_j)^T)$$

where *i* and *j* are the two signatures (classes) being compared, *Ci* is the covariance matrix of signature I, μ_i is the mean vector of signature I, *tr* is the trace function (matrix algebra) and *T* is the transposition function. The transformed divergence is expressed as

$$TD_{ij} = 2000\left(1 - \exp\left(\frac{-D_{ij}}{8}\right)\right)$$

Table 2. Surficial geology classes used as training data for image classification. The GeoCode corresponds to the digital numbers embedded within the digital surficial geology data product accompanying this Open File (RPM_NTS mapsheet 85-N.tif).

GeoCode	Surficial material classes	Number of polygons	Number of pixels
1	Glaciolacustrine (GL)	48	2943
2	Till veneer (Tv)	31	1587
3	Bedrock (R)	94	2313
4	Lacustrine (L)	43	3737
5	Till (T)	29	20379
6	Organic (O)	37	1588

The TD provides an exponentially decreasing weight to increasing distances between the classes and describes the relative degree of separation between classes (Table 3).

Table 3. Relative degree of separation for transformed divergence.

Transformed divergence	Relative degree of seperation
0.1 – 1.0	very poor separation
1.0 – 1.5	poor seperability (marginal)
1.5 – 1.9	moderate seperability
>1.9	good seperability

All classes exhibit moderate separability or good seperability (Table 4). Moderate separability occurs between till veneer – glaciolacustrine, till veneer – organic and till veneer – till. The lower results between till veneer and those listed are likely due to similarities in surface vegetation.

Table 4. Matrix of transformed divergence for all the training classes for LANDSAT bands 2-5+7, entropy, fire history and elevation.

Transformed Divergence Matrix

	GL	O	T	R	Tv	
O	1.93					
T	1.99	1.90				
R	2.00	1.97	1.90			
Tv	1.68	1.70	1.83	1.95		
L	2.00	1.96	2.00	1.99	2.00	L

Classification and Post Processing

The predictive surficial geology map produced in this report was based on the Boost trial of the decision-tree methods in See5™. As mentioned earlier, the boost trial incorporates information from the previous 10 trial runs in order to minimize classification errors. All of the trial runs were applied to the normalized LANDSAT 7 bands (2-5+7), entropy (bands 2-5+7), a DEM and burn maps. Each repetition was run with a random sample of 75% of the training data for model input while withholding 25% for validation. Results from the model runs are presented in Table 5. The total number of cases is 32,547.

Table 5. List of all trial runs for the decision-tree model along with errors in cell counts and percentage.

Trial #	# Errors	% Error
0	154	0.47
1	1295	3.98
2	1348	4.14
3	753	2.31
4	890	2.73
5	952	2.93
6	780	2.40
7	671	2.06
8	791	2.43
9	1083	3.33
Boost	9	0.03

The predictive surficial geology map was subsequently generalized in order to conform to cartographic standards for a 1:125 000 map sheet. The generalization process included 3 iterations of a 3x3 pixel majority filter, conversion of the data from raster to vector format and removal of polygons less than 15,300 m^2 (17 pixels). Polygons below this minimum size threshold were replaced with the neighboring classes using the expand tool in ArcGIS.

Special treatment was given to predicted bedrock in regions and outcrops to maintain the spatial distribution of small discrete outcrops without overloading the map sheet with bedrock clusters. Predicted bedrock polygons smaller than 15,300 m^2 were converted to points using the centroid command in ArcGIS. This produced over 83,000 bedrock outcrops with some clusters being extremely dense. In order to thin out outcrop density but maintain the spatial information, a thinning method was employed. Any bedrock outcrops within 60 m buffer were merged together and a new centroid was created as a single point. This method reduced the density of bedrock outcrops to just over 43,000 points. Table 6 provides a description of the final surficial geology classes predicted for 85-N map sheet.

Table 6. Surficial geology units used for mapsheet NTS 85-N.

GeoCode	Surficial Geology Unit	Description of Surficial Geology Unit
1	GL	Glaciolacustrine sediments: undifferentiated silt and clay, may include small areas of till veneer, variable thickness
2	Tv	Till veneer: poorly sorted silt to gravel diamicton, may be modified by glaciolacustrine and meltwater processes, may contain small bedrock outcrops and glaciolacustrine veneer, variable thickness but generally <2 m
3	R	Bedrock: undifferentiated, may be overlain by discontinuous cover of till veneer, glaciolacustrine veneer and isolated glaciofluvial patches
4	L	Lacustrine sediments: undifferentiated, exposed sediment surrounding modern lakes, variable thickness
5	T	Till undifferentiated: poorly sorted silt to gravel diamicton, variable thickness but generally >2 m
6	O	Organic deposits: undifferentiated fen, bog and floating aquatic vegetation

Glaciolluvial sediments were not included as a surficial unit in the Decision Tree model and subsequently are excluded as a unit in the final surficial geology maps. The classification model used in this study is not conducive to identifying the spatial pattern of glacio-fluvial deposits such as eskers and drumlins. The model also experienced difficulty distinguishing between bedrock and exposed dry soil surround water bodies, organic and lacustrine deposits. For the final surficial geology map, all predicted bedrock occurrences within 90 m of water, lacustrine or organic material were deleted and replaced by surrounding surficial geological units.

REMOTE PREDICTIVE MAP

The overall error of the surficial geology map using the Boost mode in the decision-tree model is 0.03% when compared to the training data. A confusion matrix of the individual accuracies for each surficial geology class is presented in Table 7. The boosted accuracy for the surficial geology map is 99.97%.

The Decision-tree model had difficulty differing between bare soil resulting from recent burns and bedrock signatures in the Landsat imagery. This confusion was expressed in an over prediction of bedrock and bedrock outcrops in burned areas compared to unburned areas in the Plain region of the map sheet (see Figure 1 for outline of Plain and Shield regions). The over prediction of bedrock in these burn regions was confirmed by a limited review of air photographs. The age of the burn areas in the maps sheet ranged from 1965 to 1990 and the Landsat imagery used was from 2001. It was observed that recent burns (1979-1999) caused the model to predict more bedrock and bedrock outcrops than pre-1979 burns (Figure 4).

Table 7. Confusion matrix of accuracy for predictive surficial geology classes (predicted class) compared against training classes (actual class).

	Actual class pixels						
Predicted class pixels	Material class	Lacustrine	Glaciolacustrine	Till veneer	Till	Bedrock	Organic
	Lacustrine	3737					
	Glaciolacustrine		2942	1			
	Till veneer		1	1584			
	Till				20378		1
	Bedrock			2	3	2310	
	Organic				1		1587

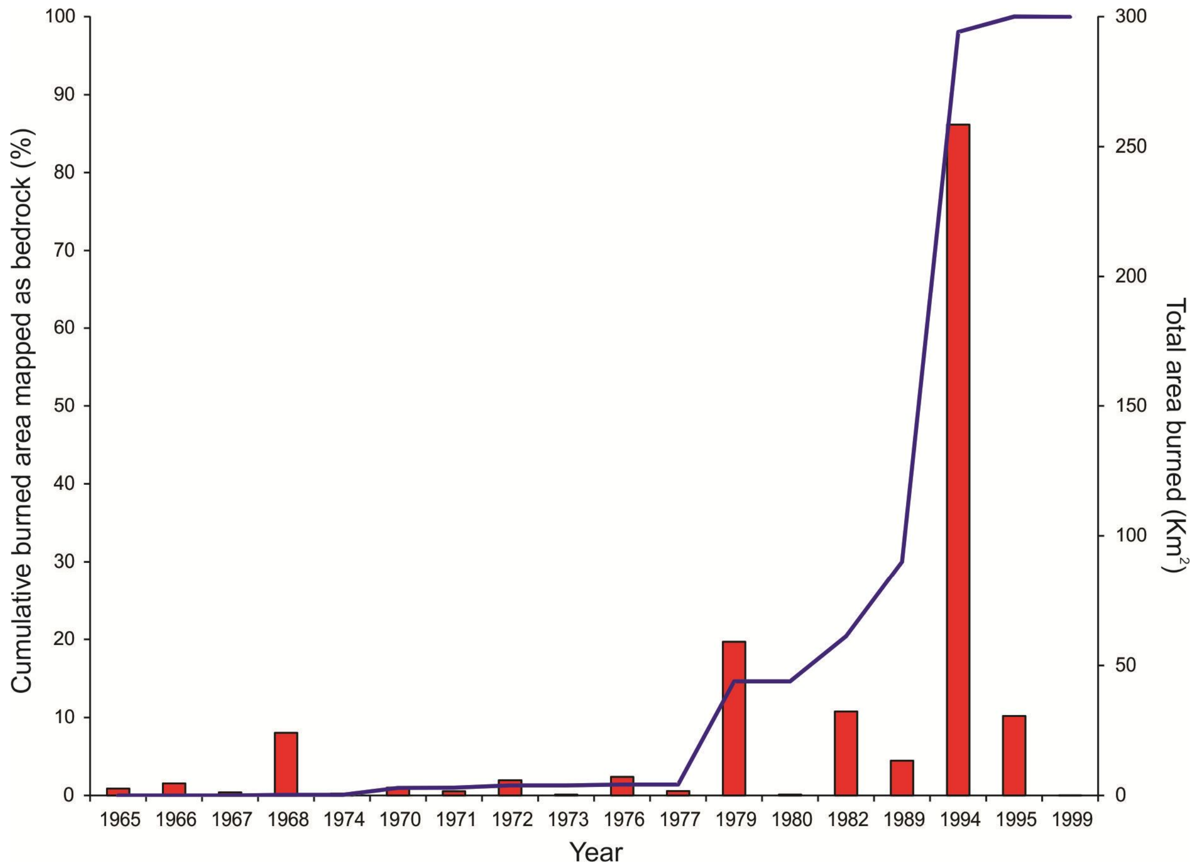

Figure 4. Compares the cumulative burned area in the Plain region mapped as bedrock (y-1 axis) and total area in the plain region that was burned each year. This data indicated that the model is more influenced by post-1979 burns than by pre-1979 burns in prediction of bedrock in the Plain region of map sheet 85-N.

The bedrock occurrences predicted within regions burned between 1979 and 1999 were deleted from the final surficial geology map and replaced by surrounding surficial geology units. In areas burned prior to 1979 the predicted bedrock occurrences were not altered.

Table 8 presents the percent coverage of each surficial material within mapsheet NTS 85-N. Surficial geology with the largest coverage includes: undifferentiated till (48%), glaciolacustrine (22%) and till veneer (15%), bedrock terrain (6%) not including bedrock outcrops (bedrock terrain >15,300m^2). The majority of bedrock terrain and bedrock outcrops are located in the Shield portion of the Marian River map sheet.

Table 8. Coverage of surficial geology expressed as the number of pixels and the percent area of land for NTS 85-N.

Surficial material	Surface area (km^2)	Percent area (%)
Organic	488.1	5.81
Lacustrine	168.4	2.00
Glaciolacustrine	1900.5	22.6
Till veneer	1293.4	15.4
Till undifferentiated	4041.2	48.1
Bedrock	513.4	6.1

A total of 34,322 individual bedrock outcrops were predicted for the 85-N map sheet with 1131 outcrops in the Plains region and 33,191outcrops in the Shield region. The derived predictive surficial geology map for NTS 85-N is presented Figure 5 and in Appendix A. Glaciofluvial point features (drumlinoids, eskers and moraines) and sediment deposits from limited air photo interpretation from Craig (1965) were added to the final version of the RPM map.

In addition to preparing a RPM map of 85-N, a RPM map of the north half of 85-K was also produced and contains the same surficial geology units as 85-N. The production of this map was driven by the need to have surficial geological knowledge of the region for route planning purposes of the Government of the Northwest Territories. The production of the north half of 85-K used the training areas from 85-N and thus is only a primary surficial geology map. More detailed work needs to be done including developing local training regions and field surveys to properly map the surficial geology of the region. The raw model output of 85-N and the north half of 85-K is presented as a geo-referenced tiff file in the data section of this openfile.

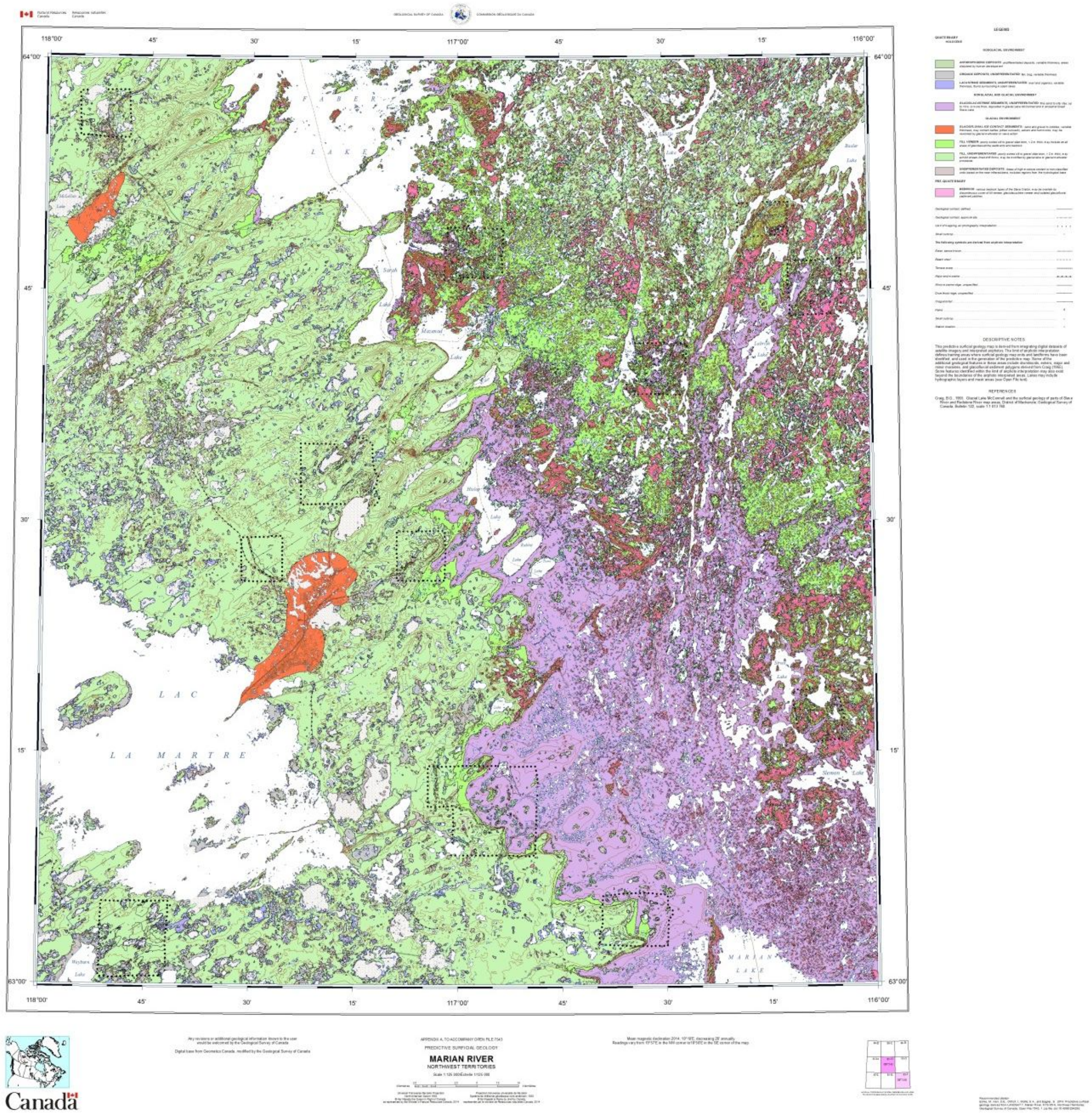

Figure 5. Remote predictive surficial geology map for Marian River NTS 85-N based on LANDSAT, fire history and elevation data. Map scale at 1:125 000.

DIGITAL DATA

The raw model output of 85-N and north half of 85-K is included in this open file as a geo-referenced tiff file. The generalized surficial geology data and topographic features are presented in both Shapefiles and geodatabases. The geo-referenced data files include the predictive surficial geology and the airphoto interpreted training data. Appendix A provides a printable map of the predictive surficial geology for 85-N (map scale 1: 125 000). Bedrock outcrops consisting of < 17 pixels were convert to a point feature prior to the generalization process. These features are included in the geodatabase and displayed as “x” in Appendix A.

DISCLAIMER

Her Majesty the Queen in right of Canada, as represented by the Minister of Natural Resources ("Canada"), does not warrant or guarantee the accuracy or completeness of the information ("Data") on this map and does not assume any responsibility or liability with respect to any damage or loss arising from the use or interpretation of the Data.

The Data on this map are intended to convey regional trends and should be used as a guide only. The Data should not be used for design or construction at any specific location, nor are the Data to be used as a replacement for the types of site-specific geotechnical investigations.

CONCLUSIONS

This report presents a predictive surficial geology map for the Marian River map sheet NTS 85-N and a preliminary surficial geology model of the Rae map sheet NTS 85-K. These datasets have been generated using a RPM approach in order to provide a first order assessment of surficial geology. This preliminary information is required to assess terrain risks to northern infrastructure and to guide mineral exploration and future mapping within the Slave, Bear-Slave and Interior Platform geological provinces.

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APPENDIX A

Predictive surficial geology map for Marian River, NTS 85-N. A printable version of this surficial geology map is also provided in this Open File as a digital pdf (map scale 1:125 000).