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3D Geological Modelling of the Middle Proterozoic stratigraphy, Belcher Islands: Integration of ASTER imagery and SRTM Topography

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ABSTRACT

Regional scale geological maps are still not available for many remote parts of the Earth. All geological maps contain two fundamental pieces of information: a) lithological data: a list of the various rock types present, and b) structural data: geometrical information that describes the spatial relationships of the various rock units. For the purposes of regional scale geological mapping the short wavelength infrared bands of the ASTER satellite are capable of differentiating between some rock units typical of Precambrian terrane (red beds, volcanics and carbonates). Applying edge detection routines to ASTER images provides a lithological map. Integrating this lithological information with topographic contour data provided by the Space Shuttle SRTM mission provides access to structural geometry information. Combining both lithological and geometrical data in a "Common Earth Model" leads a complete geological map compilation. ASTER and SRTM data from over Middle Proterozoic rocks exposed on the Belcher Islands, Hudson Bay, provides an example of this methodology.

INTRODUCTION

The Remote Predictive Mapping (RPM) initiative sponsored by the Geological Survey of Canada is designed to develop and implement an economically viable strategy for upgrading geoscience knowledge in the North via the use of remote sensing and GIS techniques as tools to improve the effectiveness and efficiency of traditional mapping. This submission specifically assesses the potential, and gives some guidelines for use of the ASTER sensor data as a tool for lithological mapping in the Canadian North.

This study is focused on the Belcher Islands, located along the eastern side of Hudson Bay, which represent the southern extension of the circum-Superior geosyncline. This continental margin sequence comprises Middle Paleoproterozoic cyclic shallow and deeper water marine sediments. Sedimentation was interrupted by two sequences of thick tholeiitic continental basalt flows and pyroclastics. This stratigraphic sequence was deformed during Trans-Hudson orogeny to a series of NE-SW trending doubly plunging anticlines and synclines. Original geological mapping of the Belchers at a scale of approximately 1:127K was performed by Jackson (1960). Later a more detailed field mapping program by Ricketts et al. (1982) produced a map with a scale of approximately 1:50K. The Belchers represent an ideal location for testing ideas of remote predictive mapping: the islands are located above the tree-line; vegetation coverage is minimal; and as a consequence of recent glacial scouring there is a high percentage of bare rock outcropping. Individual lithologies such as the two basaltic horizons are resistive to erosion and consequently produce a strong topographic response. Other rock units, for example the red beds and the interbedded carbonates, are associated with diagnostic spectral absorption peaks that might be apparent in an ASTER image (Cudahy 2002).

RATIONALE FOR USE OF ASTER IMAGERY

During any field mapping exercise a geologist is called upon to answer a number of critical questions: Can I identify the rock type present at each outcrop locality? How do I define the position of a contact between adjacent lithological units? Can I establish a pattern of sequential lithologies, or are there cross-cutting relationships that define the relative age between lithological units? Are all the structural data consistent with a single three-dimensional geometrical model that is geologically reasonable? Each of these questions leads to some fundamental concepts that are employed in the construction of all geological maps.

For the field geologist, lithologies are defined on the basis of mineralogy, grain size, and textural variations that are

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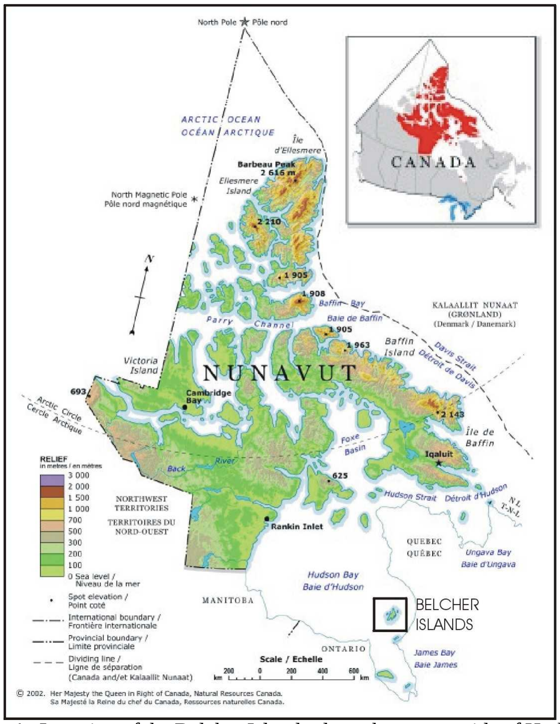

Figure 1: Location of the Belcher Islands along the eastern side of Hudson Bay. Rocks exposed on the Belchers represent a continuation of the Circum Superior geo-synclinal rocks that were deformed during the Trans-Hudson Orogeny (Schmidt 1980).

visible to the human eye. Most rocks, whether they are of igneous,metamorphic, or sedimentary origin are an intimate mixture of a number of mineral phases. Mineral deposits by definition represent a localised anomalous concentration of a mineral, or suite of mineral phases. ASTER data sets contain 3 bands in the visible and near infrared (VNIR) and 6 bands of information in the short wave infrared (SWIR). Therefore through careful selection of specific band ratios it is possible to accentuate the signal of specific rock types, for example carbonates, and clastics. Inclusion of more band information in the SWIR portion of the spectrum means that if information from all bands is included in the analysis one should expect better resolution of lithologies than is achievable with Landsat. Conversely ASTER imagery does not provide enough band information to diagnostically discriminate more than just a limited number of specific minerals.

The line on a map that demarcates the boundary, or contact, between two adjacent lithologies represents the location where the field geologist believes a significant change in lithology occurs. For the remote sensor the same problem is more commonly addressed by the question of defining some threshold, which will be used to separate one unit defined by spectral response at one level from another unit having a spectral response at a different level. The number of lithological contacts within any given area cannot be totally isolated from other criteria such as mapping scale. When mapping on a regional scale it is only possible to recognize these major subdivisions, while on a local scale one can map many different lithologies within some of the Formations. For the remote sensor this factor is limited by the spatial resolution of the available imagery. ASTER is capable of higher spatial resolution than Landsat in the VNIR portion of the electromagnetic spectrum.

The locus of any boundary across a geological map is defined by the interplay between two three dimensional surfaces, one representing the geological contact and the other the topographic surface. This relationship is more fully articulated in the commonly applied strike line method of geological structure analysis. Further it provides an excellent input for a GIS approach to geological mapping by identifying all crossover points where a geological contact defined by ASTER imagery intersects with topographic contours defined by SRTM imagery.

A fault plane, when present, impacts on the morphology of both the topographic surface and the geological contact surfaces. On the topographic surface a fault may be represented by a lineament related to a zone of increased erosion. In most instances, adjacent geological contacts should exhibit similar magnitude of displacement. If this were not observed the geologist would interpret this in terms of syn-depositional faulting. Folds present an interesting challenge to the spectral geologist. To the field geologist following the rock unit around the nose of a fold, they are the same lithologic unit. The spectral response of any lithologic unit as seen by any remote sensor is mediated by the interaction between the incoming sun's rays, the morphology of the exposed outcrop surface and the look direction of the sensor package. The spectral response from the north dipping limb of a lithological unit may be quite different from that observed over the south dipping limb of the same lithologic unit. It is a challenge for the spectral geologist to properly correlate these two spectral responses.

DATA PROCESSING

ASTER Data

This study is based on ASTER L1B scene ASTL1B 0109291641550311290018. Prior to proceeding with any interpretation of the ASTER imagery a number data correction routines need to be applied. First, it is necessary to apply a atmospheric correction to transform the raw data from DN (Digital Number) to apparent reflectance. A number of possible methods are available (i.e. IARR, FLAASH, Acorn). Water of Hudson Bay forms a large portion of the scene. Characteristically this would be associated with near zero pixels. Inclusion of these pixels in any statistical based analytical routine could significantly bias the output. To alleviate this problem all water pixels were masked. Effects of band cross talk were minimised (ERSDAC 2003).

SRTM Topography

Space Shuttle derived topography over the Belcher Islands serves to accentuate the close association between topographic response and weathering. SRTM data for Canada is available with a minimum spatial resolution of 90m. Hence, the topographic signal is not capable of detecting lithological boundaries to the same precision as the ASTER imagery.

However, the topographic data around the nose of each the plunging fold provides critical information for discriminating between synclinal and anticlinal folds. Information from the fold limbs is incapable of providing any younging information.

RESULTS

ASTER

When processed differently a number of interpretive images can be generated from the VNIR and SWIR band data. Simple band combinations in a RGB image are effective to outlining basic content of data (Figure 2). The spatial resolution of SWIR bands is twice that of the VNIR bands. Hence images created from the SWIR data do not appear as crisp as the VNIR images. Relative Band Depth (RBD) images are excellent for targeting diagnostic mineral features. The assumption of these approaches is that the concentration of broad mineral classes is associated with the preferential absorption of signal in specific wavelength bands.

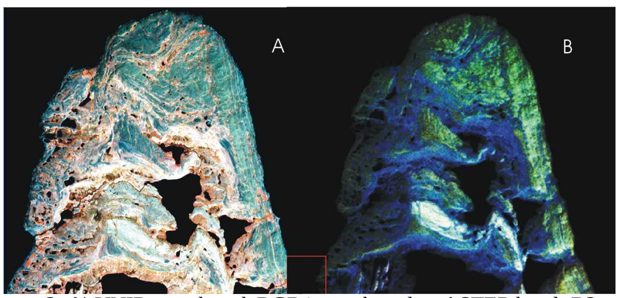

Figure 2: A) VNIR wavelength RGB image based on ASTER bands B3, B2, B1. B) SWIR wavelength RGB image based on ASTER bands B9, B6, B4.

The full dimensionality of the ASTER data set can be utilized through the use of a Principal Component based approach termed Minimum Noise Fraction (MNF) (Kruse and Boardman 2002). When applied to hyperspectral data sets with greater than 100 bands of data the MNF procedure results in a series of "spectral endmembers". Commonly the next processing step is to determine what fractions of these "endmembers" should be used to reconstruct / approximate the spectral signal of a specific geological entity. This type of approach assumes that geological features can be classified through mixing of a limited number of mineral classes. Processing a nine band ASTER data set produced 7 endmembers. In this case mixing of endmember fractions is not appropriate. By assuming a lithology based mapping approach each endmember is believed to correspond to an individual geological unit.

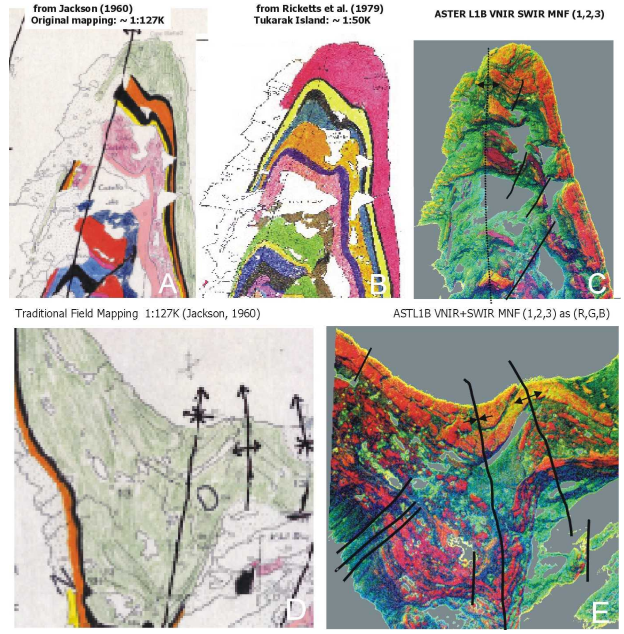

Figure 3: Two examples comparing field geological maps and RGB images based on MNF "endmembers" 1, 2, 3 computed from ASTER data. Geological maps are interpretive, since they do not specifically address the distribution of any overburden. Both examples show increased detail provided by the ASTER imagery.
A) Jackson (1960), B) Ricketts et al. (1982), C) ASTER,
D) Jackson (1960), E) ASTER.

As demonstrated by the two examples provided in Figure 3A and 3B, the MNF images have detected most of the lithological boundaries identified in the field mapping surveys. A more complete analysis is required to determine if the MNF image has not identified any previously described geological unit. The next stage in this process would be to develop a spectral classification of individual rock units and to test if similar spectral signals correspond to different silicate lithologies. The end-product of this would be a spectral based lithology only map of the Belcher Islands

SRTM Topography

Space Shuttle derived topography over the Belcher Islands serves to accentuate the close association between topographic response and weathering. SRTM data for Canada is available with a minimum spatial resolution of 90m. Hence, the topographic signal is not capable of detecting lithological boundaries to the same precision as the ASTER imagery. However, the topographic data around the nose of each the plunging fold provides critical information for discriminating between synclinal and anticlinal folds.

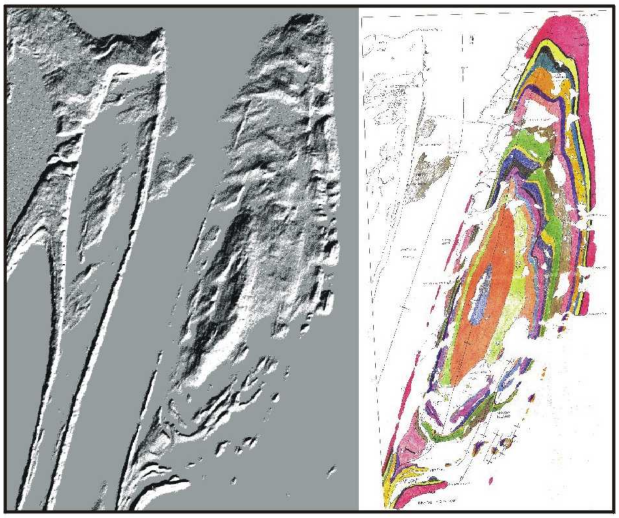

Figure 4: Comparison of SRTM topographic image of the Belcher Islands with the geological map of the area as reported by Ricketts et al., (1982). Each of the two volcanic horizons forms distinctive topographic rises; they are more resistive to erosion. The geometry of the topography at the fold closures provides diagnostic evidence regarding fold geometry. The closure on the western island is a concave surface indicating a syncline. While the equivalent closure on the more easterly island is a convex surface corresponding to an anticline.

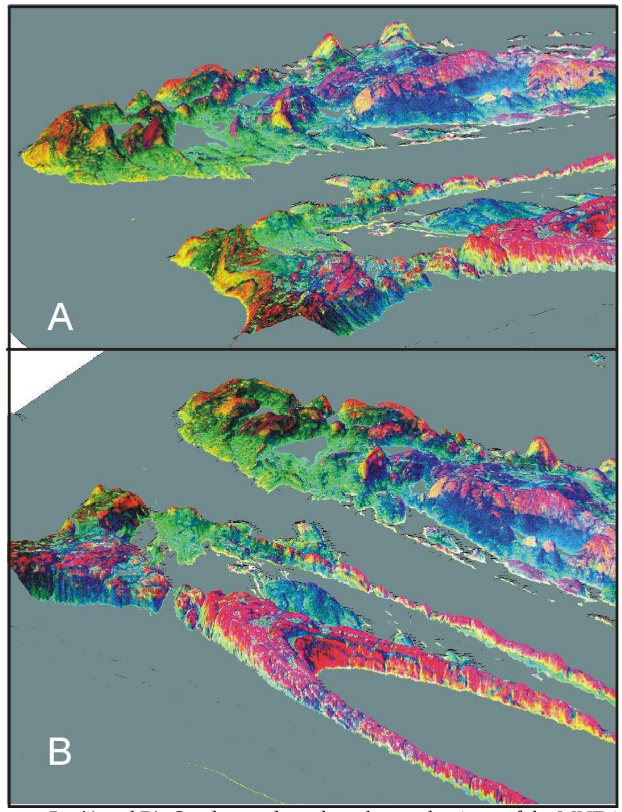

Figure 5: A) and B): Southeasterly and northeasterly views of the MNF 1, 2, 3 image orthorectified to the SRTM topographic surface. Note the relationship between cap rock units and topographic ridges, co-incidence of topography variations with lithological variations at fold noses.

ASTER + SRTM Integration

Draping the MNF 1,2,3 image over the SRTM topography serves to accentuate the close relationship between these two independently acquired images. There are many examples of the geology tracing across the topography just as one might expect in a typical field setting (Figure 5). The geometry of the fold closures are completely compatible with spectrally derived lithological variations.

It is possible to use the relationship bedding dip and topographic contours in a GIS approach to deriving tectonic (geometrical) information to complement the lithology based map produced by ASTER data. The use of an edge-detection routine would define the bounding surfaces of individual rock units. Converting the topographic surface imagery to a series of contours provides another set of line segments. Intersection points between lines defining geological contacts the contour lines provide a series of control points from which one can derive geometrical information. Two approaches are possible. First, local dip and strike estimates can be calculated from any three consecutive intersection points using a simple three-point solution method. Second, matching points having common elevation/contact estimates provides dip and strike information. Practical limitations on geometrical information are imposed by the limited spatial resolution of the ASTER imagery, and the limited elevation resolution of the SRTM data.

CONCLUSIONS

ASTER data can be successfully used to produce regional scale maps (1:50K) of lithological variations in Canada's northern terrains. Through the application of band ratios, relative band depths, and full-dimensional MNF transform procedures it is possible to differentiate most of the major rock types present on the Belcher Islands. Orthorectifying the ASTER imagery to a topographic surface defined by the Space Shuttle SRTM mission provides access to the geometrical aspects of a geological map. Integrating the lithological and geometrical data into a "Common Earth Model" provides a complete geological map. Fundamental limitations of this approach are imposed by the spatial resolution of the imagery sources, and by the spectral similarity of some rock units when their discrimination is based on information from a limited number of wavelength bands.

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