Terrain Analysis of Taylor Valley, McMurdo Dry Valleys, Antarctica

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Abstract

The surface geology of Taylor Valley records information about the long- and short-term geologic history of the region. It may be possible to extract some of this information using only remote-sensed LiDAR-derived elevation datasets. This study seeks to determine whether a map comprised of soil units created using only elevation data and surface roughness calculations can reproduce previous mapping results based on in-situ observation and soil pedons. We find that within Taylor Valley, till deposit distribution can be well-modelled primarily as a function of elevation, modified by surface roughness.

1. Introduction

The McMurdo Dry Valleys (MDV) are a series of valleys located along the eastern flank of the Transantarctic mountains. Containing 4500 km^2 of exposed bedrock and soils, the MDV are the largest ice-free region of Antarctica. Taylor Valley (TV), located in the central MDV, is one of the larger and most well-studied valleys of the region. Like the rest of the MDV, Taylor Valley is considered a cold desert with a climate characterized by extreme lack of precipitation, low relative humidity, high wind speeds, and freezing temperatures. The landscape of TV consists of bare mountain slopes containing extensive permafrost soils cut by piedmont glaciers, ephemeral streams, and perennially ice-covered lakes. To the East, Taylor valley is plugged by an outlet glacier of the East Antarctic Ice Sheet, and opens to the Ross Sea to the West.

The lack of vascular plants in Taylor Valley means that the distribution of soil properties, permafrost, and ground-ice features within the valley are controlled by geologic processes and not the distribution of biota. Therefore, the surface geology of Taylor Valley preserves information regarding the long-term history of the Antarctic ice sheets and climate, and records short term history of hydraulic and thermokarst geomorphic processes at work in the valley.

Taylor Valley soils have been mapped by Bockheim et al 2008 as distinct till units which are interpreted to record deposition by several successive past glaciation events. A testable hypothesis results from this interpretation: because glaciations cut through and erode older material as they advance, till units should correspond to topography, with older units occupying higher elevations. Additionally, three broad types of permafrost exist in TV: ice-cemented permafrost, dry-frozen permafrost, and ice-cored permafrost. Different permafrost types allow for the formation of different periglacial features such as contraction-crack polygons, water tracks, and ice-cored moraines. These features affect the roughness of the TV surface, and therefore the distribution of surface roughness properties may correspond to soil type.

Based on the assumption that soils of different glacial origins and modern textures can be categorized by elevation and surface roughness, by using elevation data and calculated standard deviation of elevation values for Taylor Valley, this study seeks to create a map composed of seven till units corresponding to the seven till units mapped by Bockheim et al 2008, and to test how well the spatial-extent of calculated units agree with mapped units.

2. Methods

2.1 Data acquisition

Three data sets were utilized to perform this study.

First, a map produced by Bockheim et al 2008, which shows the distribution of glacial deposits in Taylor valley, was captured as a PNG image (Figure 1). The captured image did not originally contain geographic coordinates.

Second, a single tile, x+0300000y-1350000, of the Landsat Image Mosaic of Antarctica (LIMA) covering the extent of the study area was downloaded from http://lima.usgs.gov/. LIMA provides geometrically accurate and high resolution (15 m by 15 m) satellite images of Antarctica (Figure 2). The LIMA tile was useful for georeferencing points on Bockheim maps to recognizable features and for interpreting terrain analyses in Taylor Valley. Metadata for the LIMA tile is available at http://tdds.cr.usgs.gov/metadata/lima/RGBREF/RGBREF_x+0300000y-1350000.htm.

Finally, a high-resolution (1 m by 1 m) digital elevation model (DEM) produced by Fountain et al in 2014 from airborne LiDAR scans was utilized for surface analyses. The LiDAR coverage includes surveys of 8 regions in and around the MDV.

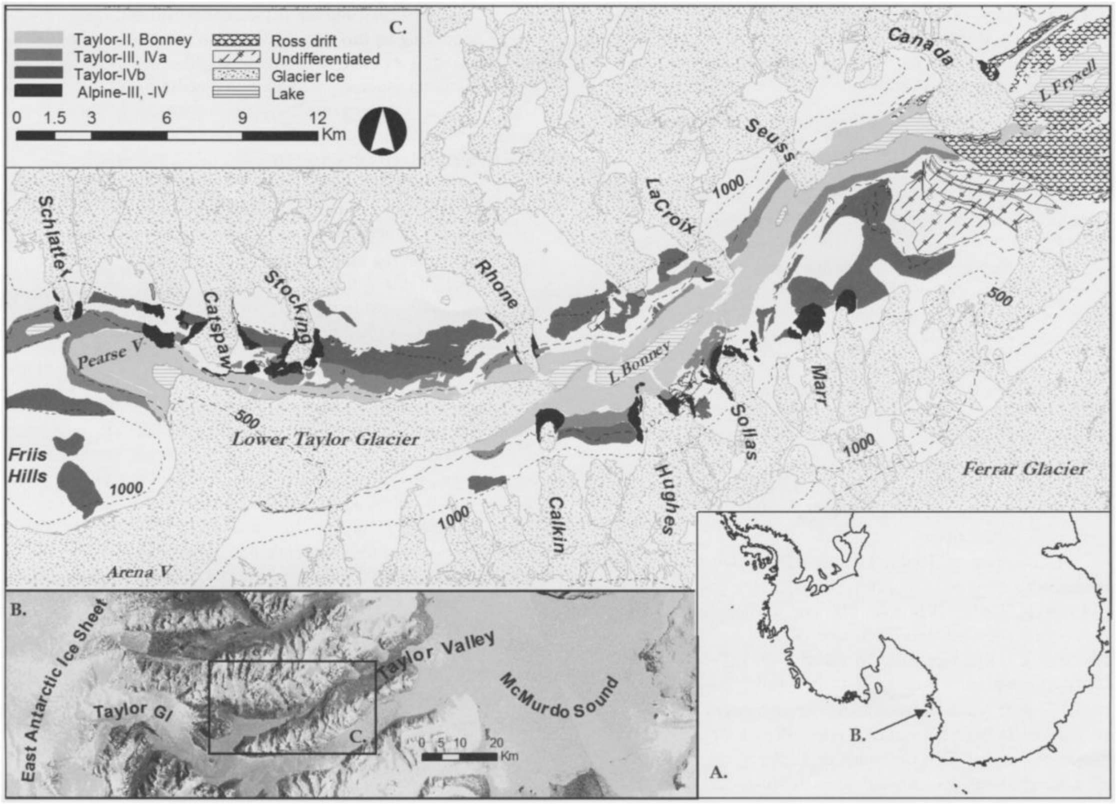


FIGURE 1. Generalized distribution of glacial deposits in Taylor Valley (compiled from Wilch et al., 1993; Hall and Denton, 2000b; Higgins et al., 2000a, 2000b; and unpublished data of Prentice and Bockheim). Colluvial, lacustrine, eolian, Alpine II, and Alpine I deposits are not shown. Blank patches are either the latter, bedrock, or snow.

Figure 1. PDF image of Bockheim et al 2008 used to digitize map units.

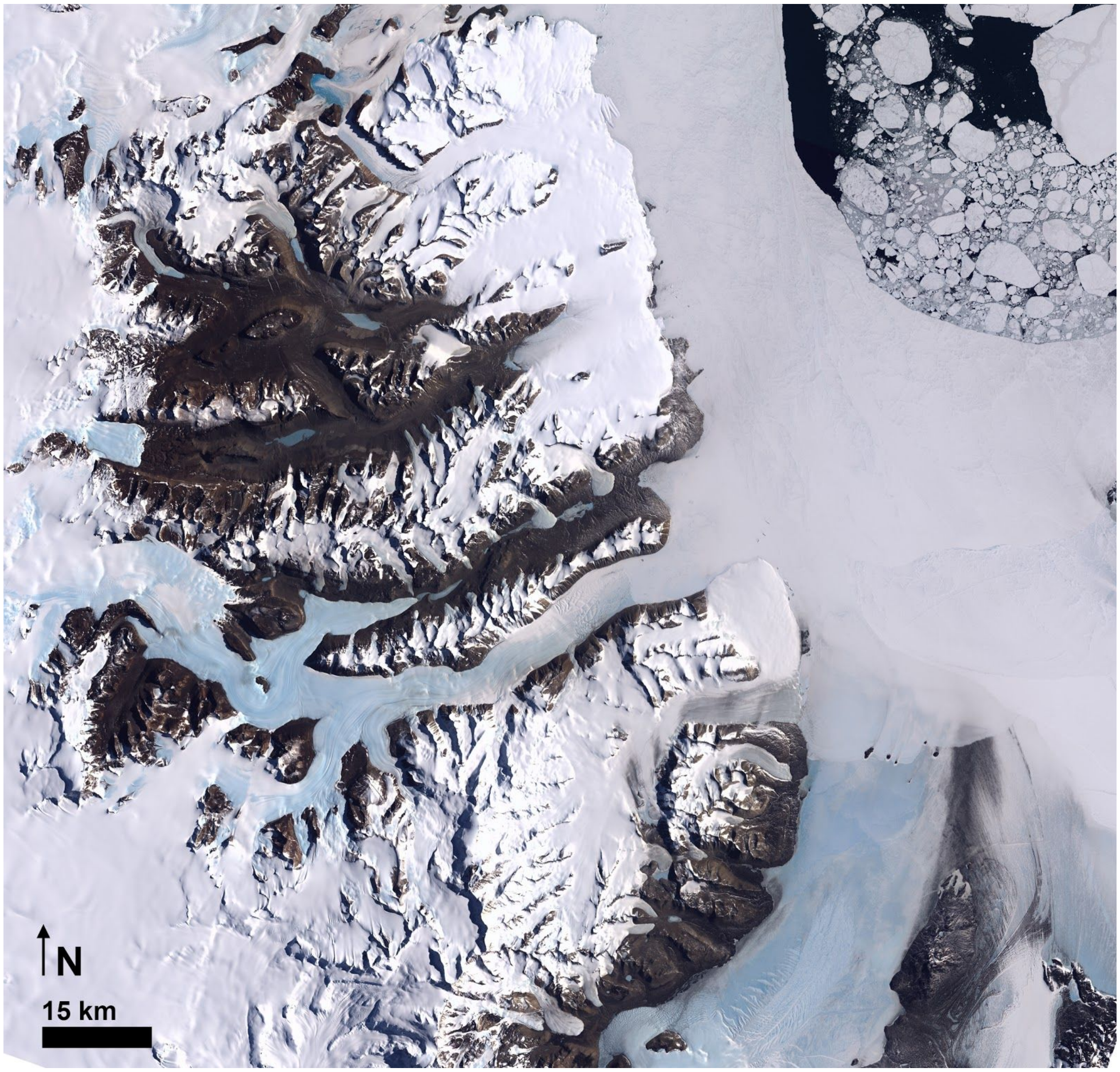


Figure 2. Landsat Image Mosaic of Antarctica (LIMA) tile x+0300000y-1350000 covers the extent of the Central MDV.

2.2 *Digitizing Bockheim 2008 maps*

In order to compare terrain analysis results to previous mapping efforts, Figures produced by Bockheim et al were georeferenced and digitized within Arcmap. To georeference, spatially referenced Landsat mosaics were loaded into ArcMap. The spatial reference for the mosaics is WGS 1984 Arctic Polar Stereographic. Using the tools accessible with the georeferencing toolbar in ArcMap, a total of 6 control points were used to georeference the Bockheim glacial deposit map with respect to the Landsat images with an RMS error of 63.7. The intersections of lake and glacier margins served as easily identifiable point locations for georeferencing. The low-resolution of the PDF map image make more accurate georeferencing difficult. After establishing sufficient control points, the Bockheim figure was rectified and saved as a spatially referenced file (Fig. 3).

A geodatabase was created to store feature data created while digitizing. Two feature classes were created, an outline polygon ("Study Area") to capture the extent of Taylor Valley and a contacts line ("Contacts") to digitize glacial deposit contacts. Domains containing unit names were created and attached to the feature classes (Figure 4). Eight unit names were created to symbolize the eight distinct units mapped by Bockheim et al: "Ross Drift", ”Undifferentiated", ”Taylor-II", ”Taylor-III", ”Taylor-IV", ”Alpine-III", ”Glacier Ice", and ”Lake".

Before converting "Contacts" into polygons representing geologic units, the "Contacts" feature class was checked to ensure it obeyed topography using the Topology Wizard. Contacts were checked for overlaps, dangles, and self-intersection. Point and line errors were corrected using the "Fix Topology Error" tool. Results of error inspection and correction are shown in Figure 5.

Map unit polygons were created from the contour feature class using the "Feature to Polygon Tool". To symbolize and label glacial deposit units, a new text field named "Name" was created for the Glacial Deposits feature class. Names were assigned to the attribute table of each polygon. Map units were symbolized to resemble Bockheim et al 2008. The final steps of map unit digitization are shown in Figure 6.

2.3 Elevation & surface roughness

The original 2014 DEM covers areas beyond the Taylor Valley study area. In order to reduce file size and computation time, the original DEM was cut using the "Extract by Mask" tool to the "Study Area" polygon to produce a clipped DEM file named "2014all_clip" (Figure 7).

Surface roughness ($\mathrm{STD}_{\mathrm{elev}}$) was calculated using "Spatial Analyst Tools" > "Neighborhood" > "Focal Statistics," with a 3 meter by 3 meter moving window to calculate standard deviation of elevation over the entire Taylor Valley DEM (Figure 8). Standard deviation of elevation provides an easily-calculated measure of surface roughness (Grohmann, 2011). Periglacial processes produce small landforms, therefore a small window was chosen in order for local relief (small breaks in slope) to be recorded with high roughness values.

To create a map broken into eight categories based on elevation and roughness, the DEM and $\mathrm{STD}_{\mathrm{elev}}$ files were reclassified into four categories using the "Spatial Analyst" > "Reclass" > "Reclassify" > tool. Category boundaries for each raster file were determined by natural jenks in their respective data histograms. The operation of this tool resulted in layers whose cells contain a value of either 1 (low elevation or low roughness), 2, 3, or 4 (high elevation or high roughness) (Figure 12. A, B).

The reclassified DEM and STD_{elev} layers were then added together using “Spatial Analyst” > “Map Algebra” > “Raster Calculator”. This operation produced a new raster file containing seven categories of value 2 through 8 (Figure 12. C). Low values now correspond to lower, smoother surfaces while higher values correspond to higher, rougher surfaces.

To see whether the spatial distribution of the seven categories based on elevation + roughness values correspond to the spatial distribution of Bockheim’s seven mapped glacial till units, the digitized “Glacial Deposits” polygon feature class layer was reclassified. To accomplish this, first the polygon feature class layer was converted into a shapefile using the “Data Management Tools” > “Generalization” > “Dissolve” tool. Then, so that the unit polygons could eventually be assigned values for map algebra, this shapefile was converted into a raster file using the “Conversion Tools” > “To Raster” > “Feature to Raster” tool. Next, the map units were reclassified using the “Reclassify” tool to new ranks corresponding the categories calculated in the ‘elevation + roughness’ layer. Table 1 shows the conversions used to convert unit *values* in the ‘Glacial Units” raster into new unit *ranks* in the reclassified raster. Conversions were determined by considering each unit’s position in the valley. Down-valley, lower elevation units were assigned lower ranks than up-valley, higher elevation units (Figure 12. D, E).

Table 1. Glacial Deposits Reclassification

Name	*Value*	*Rank*
Ross_Drift	5	2
Undifferentiated	9	3
Taylor_II	6	4
Taylor_III	7	5
Taylor_IV	8	6
Alpine_III	2	7
Lake	4	8
Glacier_Ice	3	8
Older Alpine or non-till	1	8

In order to compare only the soil regions contained in the ‘elevation +roughness’ layer and the ‘reclassified units’ layer, areas corresponding to glacier ice were masked out of both rasters using the “Extract by Mask” tool. Finally, to calculate the difference between the masked ‘elevation + roughness’ and ‘reclassified units’ layers, the absolute value of the difference between the layers was calculated using the “Raster Calculator” tool (Figure 14).

3. Results

3.1 Digitized Bockheim 2008 map

The digitized Bockheim 2008 map is shown in Figure 9. The map delineates seven distinct till units as well as the extent of lakes and glacier ice within Taylor Valley. The PNG image of the map did not provide the resolution necessary to digitize to the full accuracy allowed by the LIMA tile. Even with careful control point selection, the final digitized version of the Bockheim map contained a significant RMS error which can be seen as offsets between digitized contacts and features in the LIMA tile at scales of hundreds of meters in many cases (Figure 10). These discrepancies inevitably cause errors in terrain calculations, however the errors are not significant enough to invalidate regional-scale analyses.

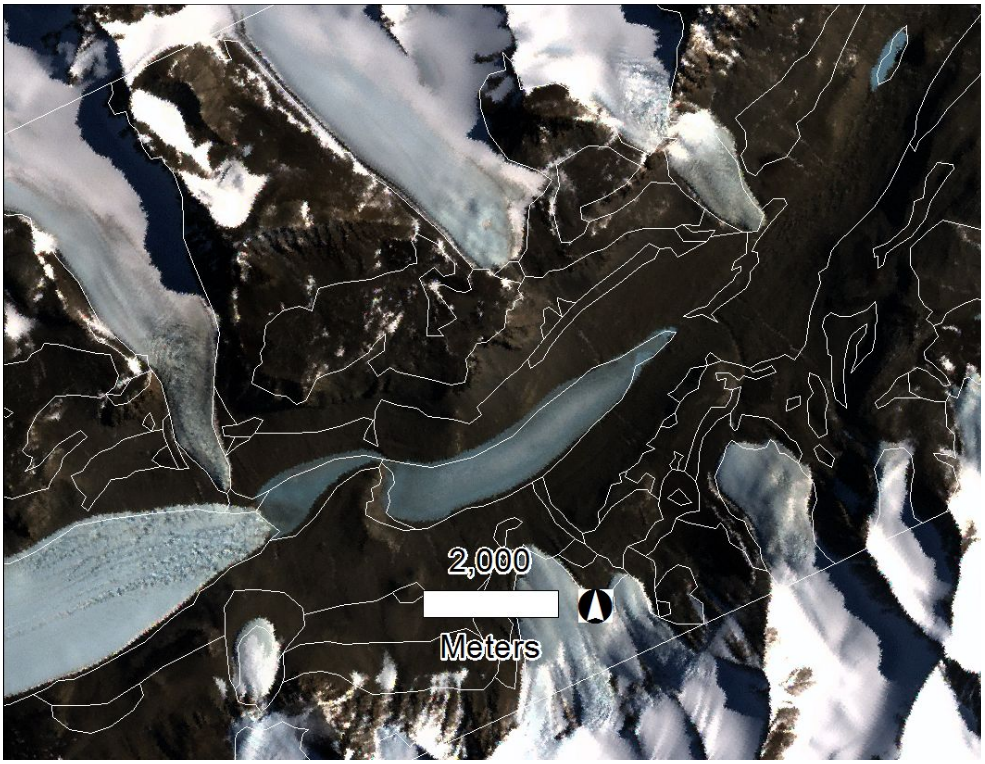


Figure 10. Examples of offset geologic contacts (red ellipse) between Lake Bonney and Taylor-II till in the western reach of Taylor valley.

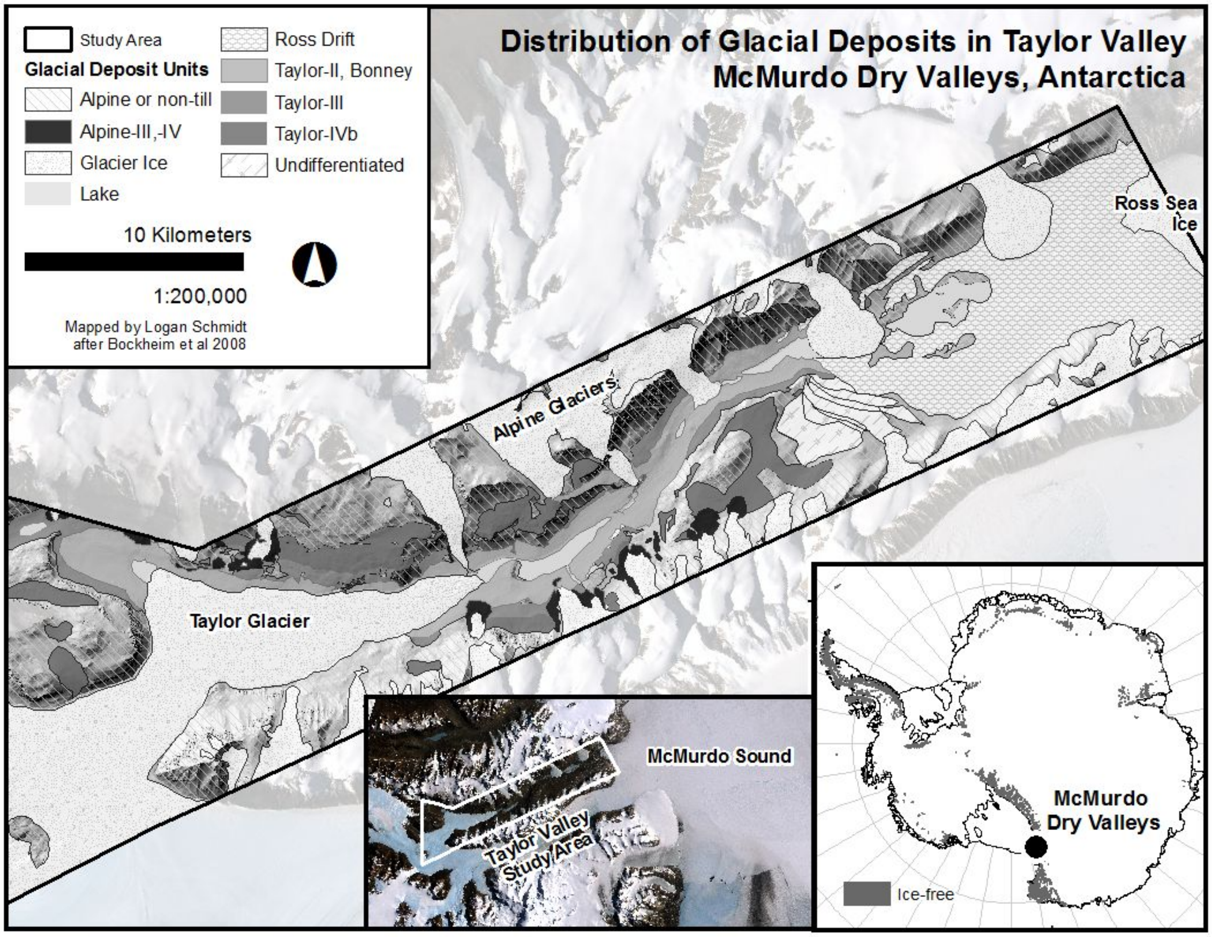


Figure 9. Digitized map of glacial deposits and landscape features in Taylor Valley compiled from Bockheim et al 2008 superposed over LIMA tile of the Central MDV and projected to the WGS 1984 USGS Transantarctic Mountains coordinate system. Besides glacier and lake ice, the map categorizes seven distinct till units. Taylor Valley has experienced three kinds of glaciations in the past ~2 billion years: the eastward advance of Taylor Glacier, the north/south advance of alpine glaciers, and the westward advance of the grounded Ross Sea Shelf. Each advance deposits a distinct layer of till resulting in the mosaic of units seen above. With minimal fluvial or biotic activity in the valley, these till units remain largely undisturbed and thus should correspond to elevation. Cryoturbation and periglacial processes acting differentially across the valley according to the presence of ground ice and climatic variations may result in surface textures diagnostic of certain tills.

3.2 Terrain roughness

The results of STD_{elev} calculations are shown in Figure 11. The fine resolution of the DEM allowed for the capture of local-scale differences in terrain elevation. With this calculation, valley walls and glacier margins exhibit the highest roughness values. There is significant spatial variability in STD_{elev} across till units. Down-valley till units appear to be less rough than up-valley till units. The elevation information contained in the DEM shown in Figure 11 B seems to correlate well with unit contacts. Additionally, it appears that some correlation between Bockheim 2008 geologic contacts and roughness values may also exist.

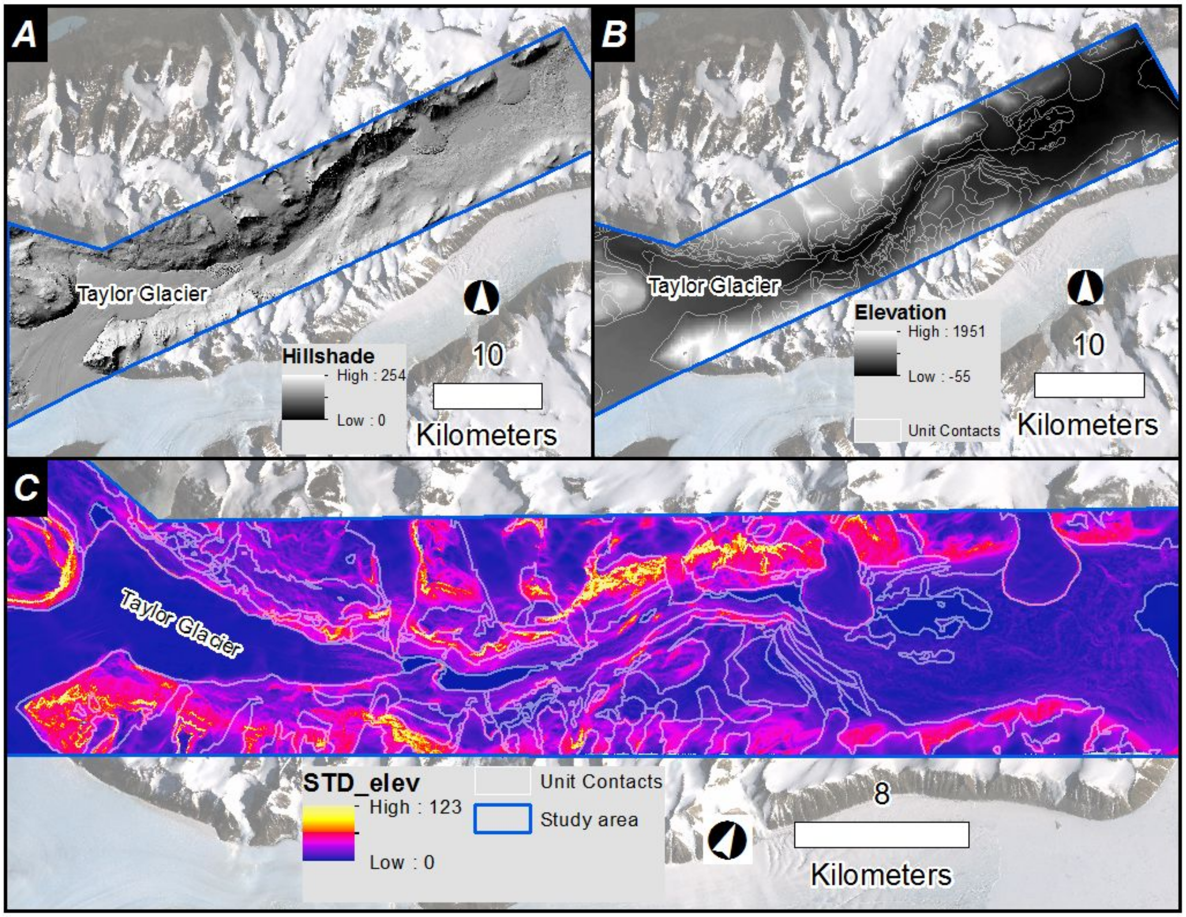


Figure 11. Elevation and elevation-derived data within Taylor Valley overlaid upon LIMA tile of the Central MDV and projected to the WGS 1984 USGS Transantarctic Mountains coordinate system. (A) DEM-Derived Hillshade depicting regional-scale geomorphology of the valley. (B) Digital elevation model of Taylor Valley with superposed geologic unit contacts. (C) Standard deviation of elevation (STD_{elev}) calculated using a 3 m by 3 m window with superposed unit contacts. Brighter colors indicate a higher roughness value.

3.3 Surface elevation and roughness as a proxy for surface geology

By reclassifying the DEM elevation values and surface roughness values into 4 ranks, and adding the results together, a new map containing elevation and roughness information parsed into seven ranks was obtained (Figure 12. A, B, C). To test whether the seven calculated units correspond meaningfully to the seven till deposits mapped by Bockheim 2008, the digitized till units were similarly reclassified into seven ranks according to their position in the valley (Figure 12. D, E). After masking out glacier and lake ice, by subtracting the two rasters and taking the absolute value of their difference, a final comparison map quantifying how closely the proxy units agree with the mapped units is obtained (Figure 12. F). Higher values correspond to greater differences. Values can be considered a measure of error in the proxy map's ability to predict till units. Table 2. shows error statistics for individual till units. Some units are better predicted by the surface calculations (Ross Drift) than others (Alpine-III). Variation of difference within the units remains fairly constant across all units. There does not seem to be a correlation between higher average error and higher variation of error within units (Figure 13).

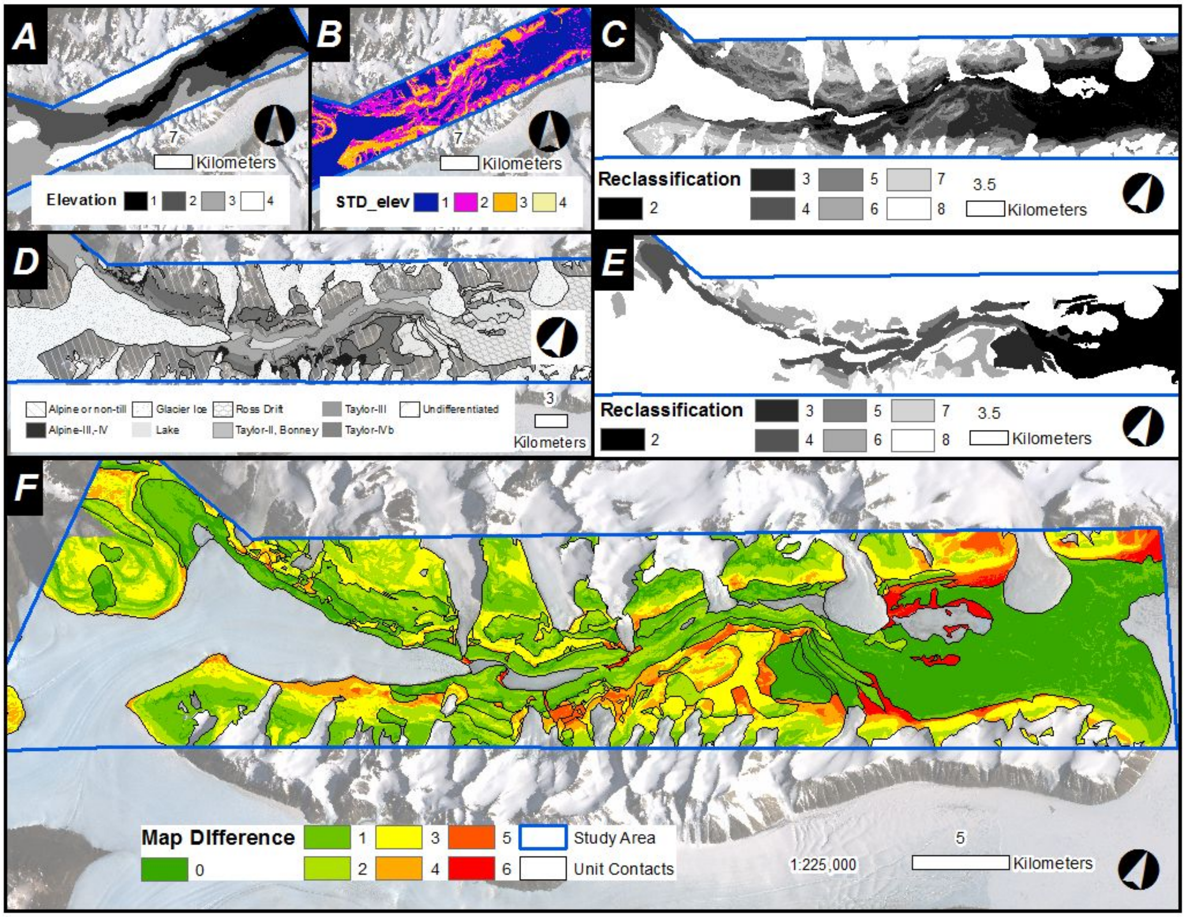


Figure 12. Maps used to determine the accuracy of using elevation and surface roughness as a proxy for till units. (A) DEM raster model and (B) STD_{elev} raster model of Taylor Valley, each reclassified to 4 values. (C) Proxy surface geology map of Taylor Valley derived from the sum of *(A)* and *(B)* with glacier ice masked out. The resulting seven values contain elevation and roughness information and are intended to work as a proxy for Bockheim till units. (D) Geologic units after Bockheim et al 2008. (E) Geologic units reclassified to seven map values corresponding to each unit's position in the valley with glacial ice masked out. (F) Difference map of *(C)* and *(E)* calculated by taking the absolute value of the difference of the two rasters. Green corresponds to agreement between maps while red corresponds to large differences. Black lines are geologic contacts as in *(D)*. All maps are projected to the WGS 1984 USGS Transantarctic Mountains coordinate system

Table 2. Statistics for difference values contained in each glacial till unit

	Min	Max	Mean	Std
Ross Sea Drift	0.00	6.00	0.28	0.65
Undifferentiated	0.00	6.00	0.30	0.48
Taylor-II	0.00	6.00	0.93	0.65
Taylor-III	0.00	5.00	0.96	0.72
Taylor-IV	0.00	6.00	1.64	0.92
Alpine-III	0.00	6.00	2.99	0.82
Old Alpine or Non-till	0.00	6.00	2.73	1.36

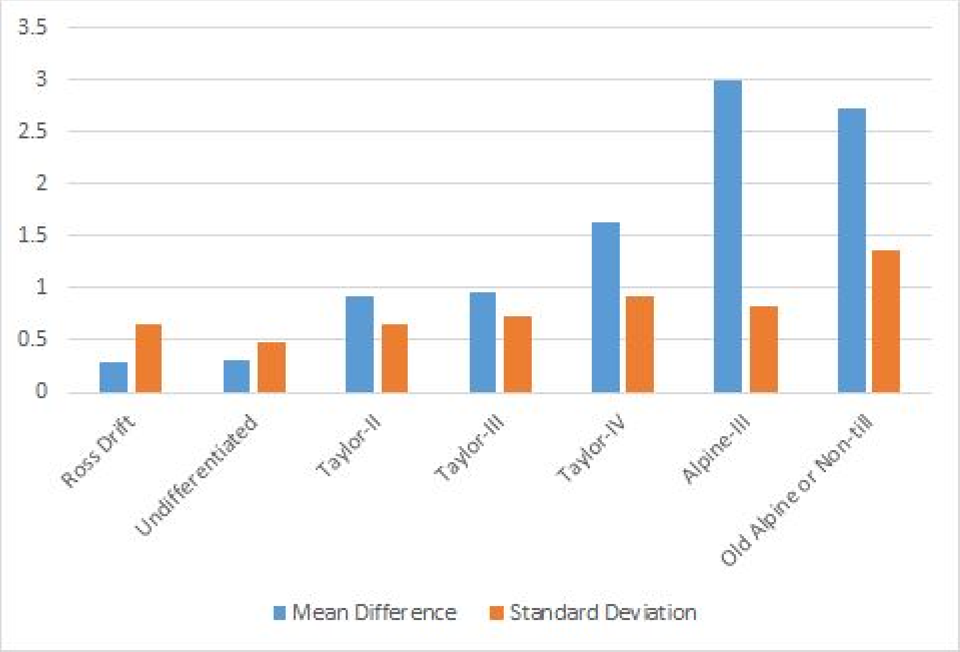


Figure 13. Histogram showing the mean and standard deviation of difference values calculated for individual till polygon boundaries.

4. Discussion

Can the spatial extent of Bockheim's mapped glacial deposit units be independently predicted using only DEM-derived elevation data? The results achieved by this study suggests that even rudimentary analyses can produce promising results. Bockheim 2008 classified soils based on relative age, texture, structure, and salt-content. With elevation data and a roughness calculation based on a single parameter, the proxy map produced units which correlated surprisingly well with Bockheim's. Of the seven till units examined, three were predicted with a mean error of less than 1 (Figure 13). Even the least-well predicted unit, Alpine-III, was still calculated with an error of 3, which is better than 50% accuracy (3.5/7).

If the results of this study are taken to meaningful, they indicate that the distribution of till units in Taylor Valley is largely controlled by elevation. This result is reasonable for till units deposited by subsequent glaciation events. Without significant fluvial activity or biotic disturbance, there are few landscape processes within Taylor Valley capable of performing geomorphic work to displace sediments from where they are initially deposited besides cross-cutting glaciation events. Indeed, the DEM on it's own correlates well with the mapped units.

Intriguingly, performing a surface roughness calculation improved the proxy map. Surface roughness may be capturing the geomorphic results of cryoturbation and periglacial processes, which may produce diagnostic landforms differentially across the valley and and across till units. It is perhaps possible that the textural differences between tills used by Bockenheim to categorize till units might also be expressed at the local-relief scale and captured by the roughness calculation. If this is the case, then it makes sense that differences in surface roughness would correspond to mapped till units. Of course, it is just as possible that the STD_{elev} calculation is actually capturing the locations of slopes within the valley, which would correspond to till boundaries, but for the same reason that elevation does. In this case, the roughness calculation is providing little additional information.

The proxy map works best for the largest and lowest elevation units, and seems to be less accurate for predicting the extent of higher elevation units. This pattern may be caused by over-calculated roughness values on steep slopes combined with the accumulation of errors introduced by inaccurately digitizing the more irregular geologic contacts which exist on the valley walls. It is reasonable to expect that the predictive power of the proxy map decreases with increasing surface complexity.

5. Conclusions and Future work

As a region which has been subjected to intense glaciation and whose geomorphology is sensitive to small changes in landscape properties (climate, hydrology, topography), study of the surface geology of the MDV allows for profound insights into the long-term and short-term geologic history experienced by these rocky oases. This study suggests that even relatively simple surface analyses using high-resolution remote-sensing have significant potential for parsing the evolution of MDV landscapes. With elevation data and surface roughness calculations, this study was able to recreate the spatial extent of till units mapped based on age, texture, and the presence of ice and salt to considerable effect.

This study was limited by time and disk-space. With more of each, other surface roughness calculations might have been employed. STD_{slope} might provide more meaningful results by ignoring the effects of steep slopes. Methods similar to those utilized by this study could be tested in other nearby valleys.

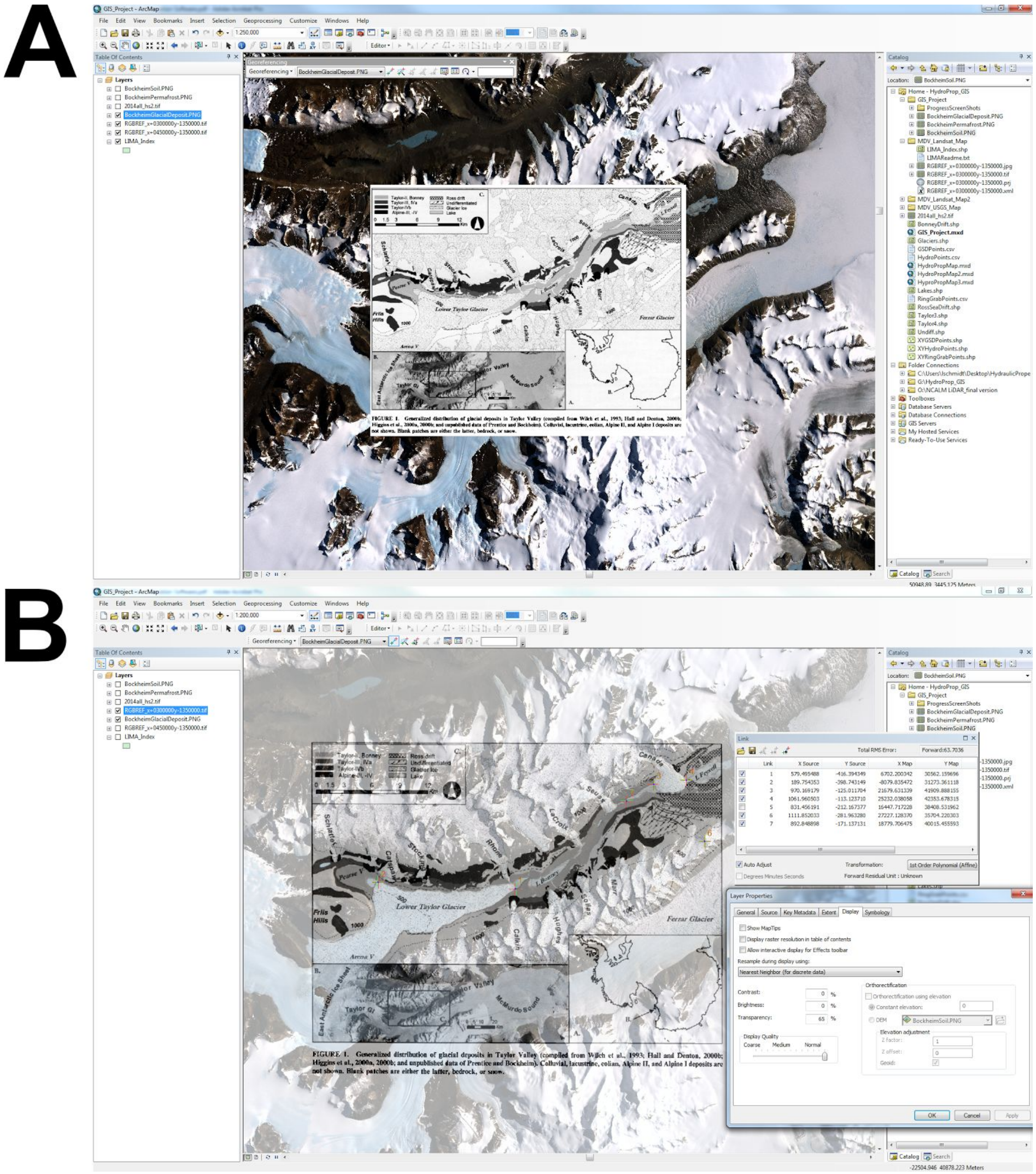
With more sophisticated and directed terrain analyses, it is possible that an algorithm could be developed which has the capability to swiftly map any part of the Dry Valleys which contains sufficiently high-resolution LiDAR data with minimal user input. With remote-sensed data alone, much might be discovered about the most remote and inhospitable continent on Earth - from thousands of miles away.

6. References

Bockheim, J.G., Prentice, M.L., McLeod, M., 2008. Distribution of glacial deposits, soils, and permafrost in Taylor Valley, Antarctica. Arctic, Antarctic, and Alpine Research 40, 279–286. doi:10.1657/1523-0430(06-057)

Grohmann, Carlos Henrique, Mike J. Smith, and Claudio Riccomini. "Multiscale analysis of topographic surface roughness in the Midland Valley, Scotland." *IEEE Transactions on Geoscience and Remote Sensing* 49.4 (2011): 1200-1213.

7. Methods Figures



Link

Total RMS Error: Forward:63.7036

	Link	X Source	Y Source	X Map	Y Map
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☑	2	189.754353	-398.743149	-8079.835472	31273.361118
☑	3	970.169179	-125.011704	21679.631339	41909.888155
☑	4	1061.960503	-113.123710	25232.038058	42353.678315
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☑	7	892.848898	-171.137131	18779.706475	40015.455593

☑ Auto Adjust
Transformation: 1st Order Polynomial (Affine)
☐ Degrees Minutes Seconds
Forward Residual Unit : Unknown

Layer Properties

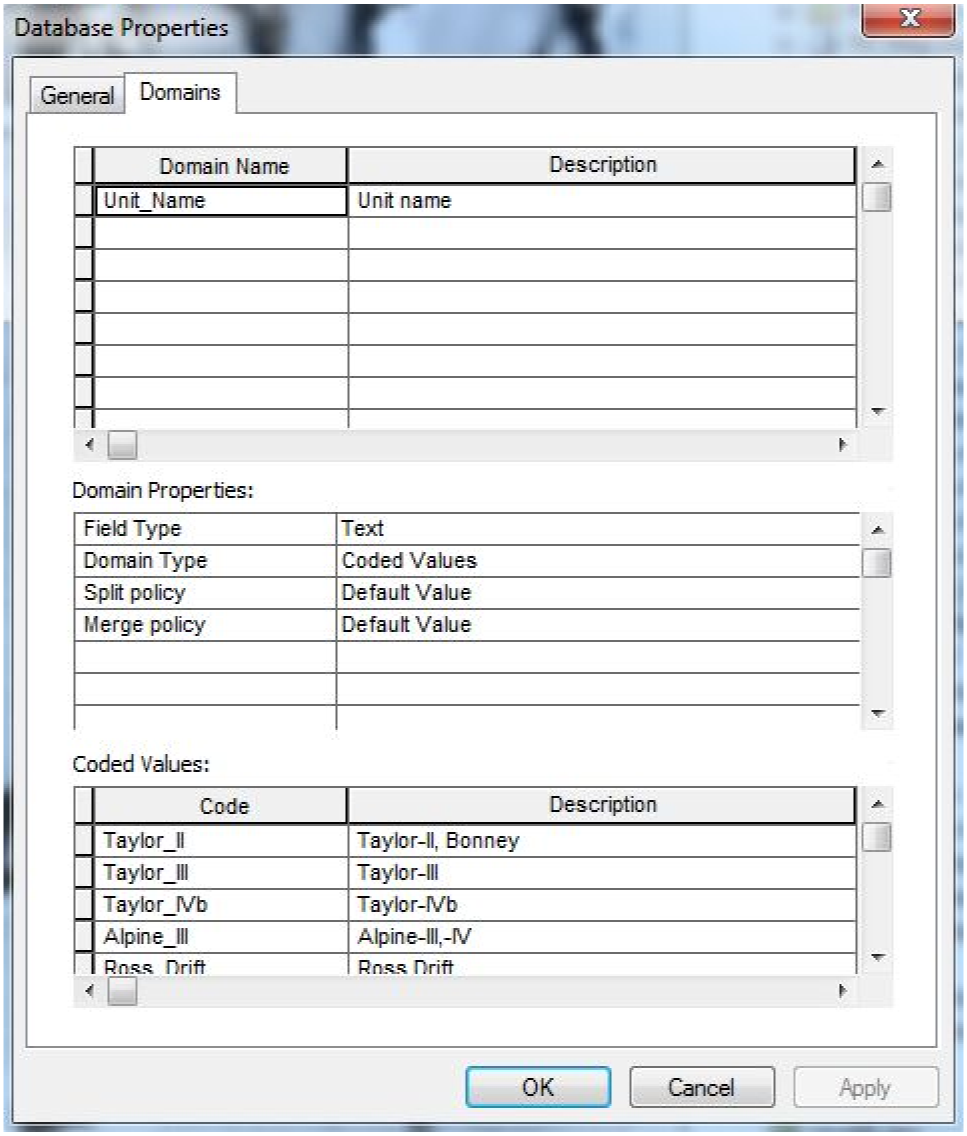
General | Source | Key Metadata | Extent | Display | Symbology

☐ Show MapTips
☐ Display raster resolution in table of contents
☐ Allow interactive display for Effects toolbar
Resample during display using: Nearest Neighbor (for discrete data)
Contrast: 0 %
Brightness: 0 %
Transparency: 65 %
Display Quality: Coarse Medium Normal
Orthorectification
☐ Orthorectification using elevation
● Constant elevation: 0
○ DEM BockheimSoil.PNG
Elevation adjustment
Z factor: 1
Z offset: 0
Geoid: ☑

OK | Cancel | Apply

-22504.946 40878.223 Meters

Figure 3. Georeferencing Bockheim 2008 glacial deposits map PNG image using a LIMA tile of the McMurdo Dry Valleys. **(A)** Unreferenced PNG image overlaying LIMA tile x+0300000y-1350000. **(B)** Control points and links table used to georeference map image. 6 control points with an RMS error of 63.7 were used. The Georefferenced map was rectified using Nearest Neighbor.



Domain Name	Description
Unit_Name	Unit name

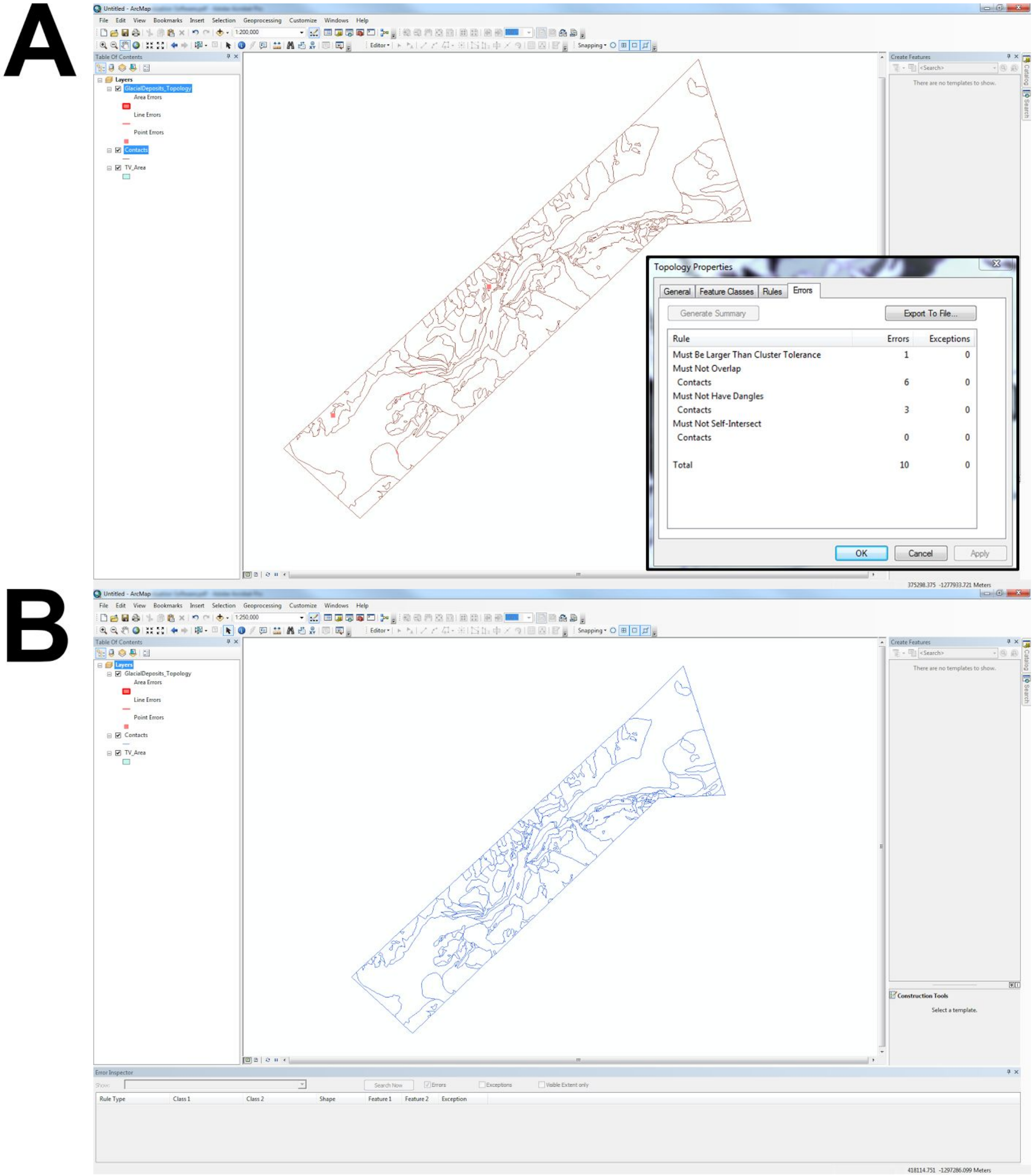
Domain Properties:

Field Type	Text
Domain Type	Coded Values
Split policy	Default Value
Merge policy	Default Value

Coded Values:

Code	Description
Taylor_II	Taylor-II, Bonney
Taylor_III	Taylor-III
Taylor_IVb	Taylor-IVb
Alpine_III	Alpine-III,-IV
Ross Drift	Ross Drift

Figure 4. Creation of a 'Unit_Name' domain to contain codes for naming glacial deposits.



Rule	Errors	Exceptions
Must Be Larger Than Cluster Tolerance	1	0
Must Not Overlap		
Contacts	6	0
Must Not Have Dangles		
Contacts	3	0
Must Not Self-Intersect		
Contacts	0	0
Total	10	0

Figure 5. Topology errors (A) and corrected topology (B) for digitized unit contacts.

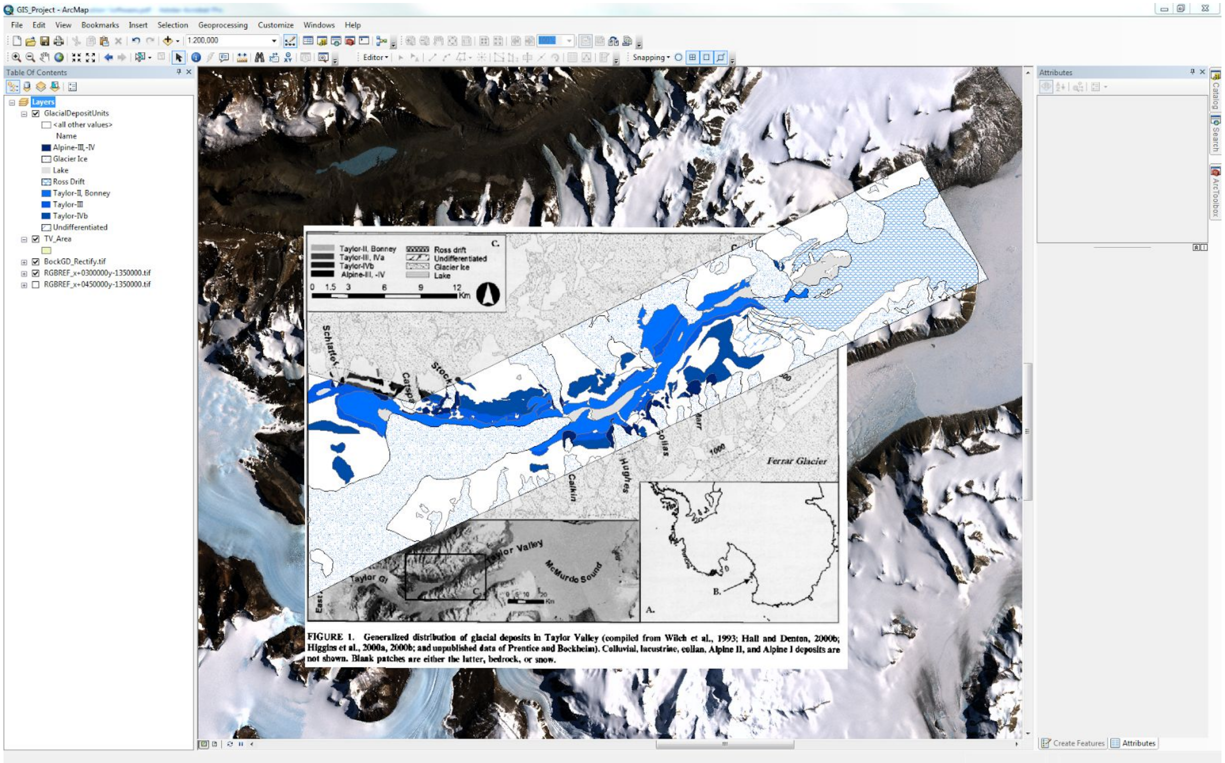


FIGURE 1. Generalized distribution of glacial deposits in Taylor Valley (compiled from Wilch et al., 1993; Hall and Denton, 2000b; Higgins et al., 2000a, 2000b; and unpublished data of Prentice and Bockheim). Colluvial, lacustrine, eolian, Alpine II, and Alpine I deposits are not shown. Blank patches are either the latter, bedrock, or snow.

Figure 6. Digitized glacial deposit, lake, and glacier polygons overlaid atop a georeferenced image of a map by Bockheim et al 2008 and a LIMA tile of Taylor Valley. Units were tentatively symbolized in blue for clarity.

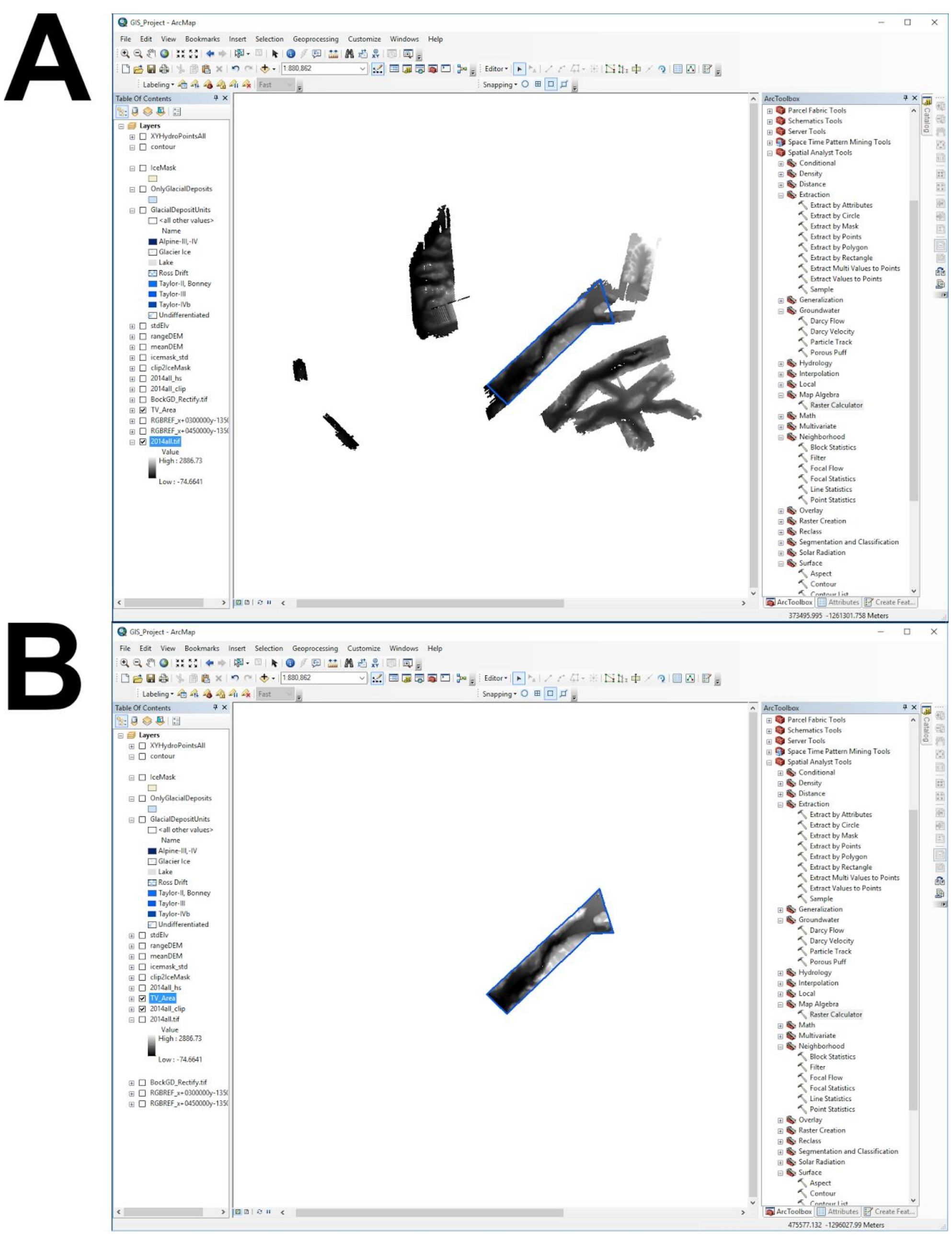
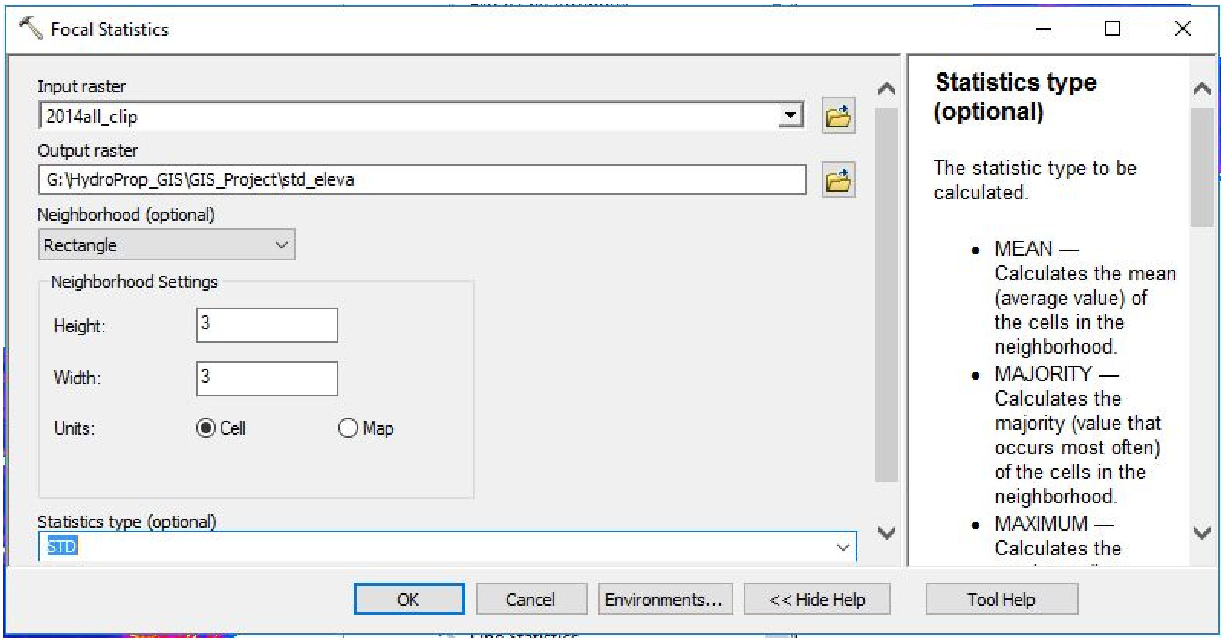


Figure 7. Extent of original (A) and clipped (B) 2014 DEM layer. Blue polygon outlines extent of study area and was used as the clipping mask.



Focal Statistics

Input raster

2014all_clip

Output raster

G:\HydroProp_GIS\GIS_Project\std_eleva

Neighborhood (optional)

Rectangle

Neighborhood Settings

Height: 3

Width: 3

Units: ● Cell ○ Map

Statistics type (optional)

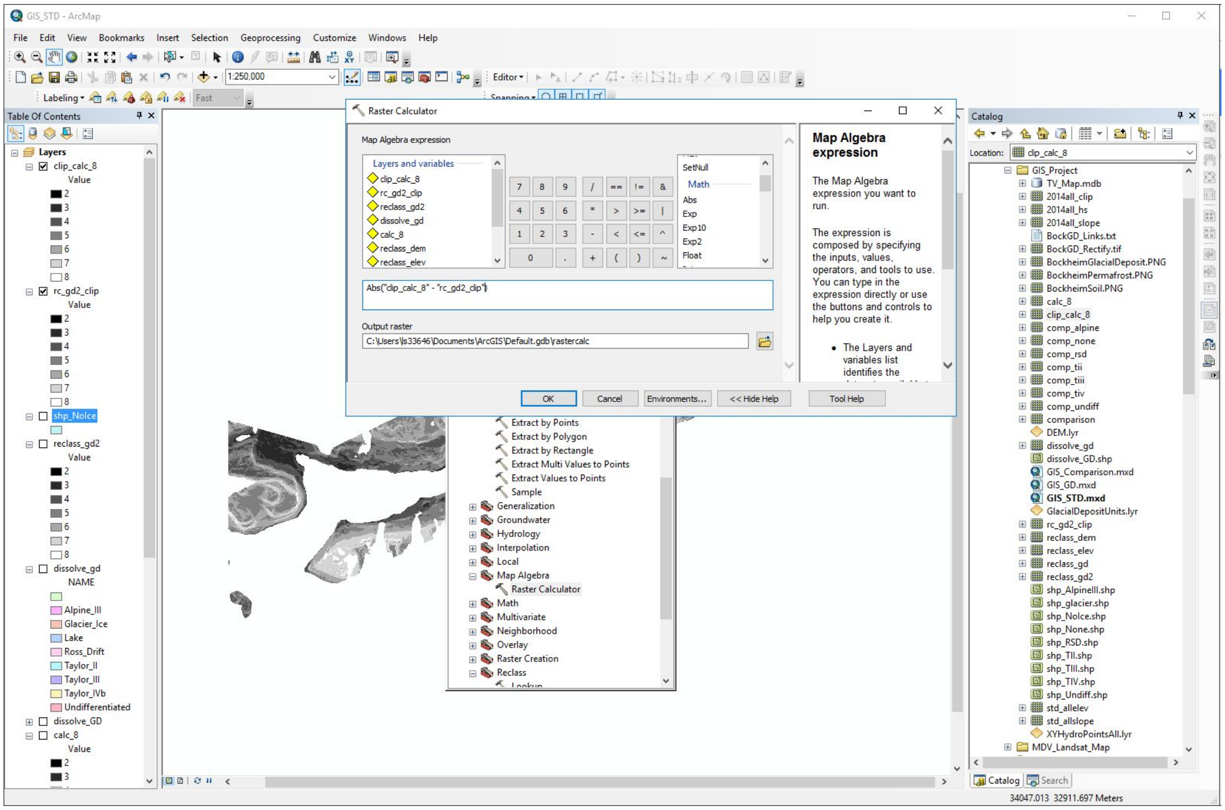
STD

Statistics type (optional)

The statistic type to be calculated.

- MEAN — Calculates the mean (average value) of the cells in the neighborhood.
- MAJORITY — Calculates the majority (value that occurs most often) of the cells in the neighborhood.
- MAXIMUM — Calculates the

Figure 8. Inputs used to calculate standard deviation of elevation (STD_{elev}) raster from digital elevation model raster. A 3 m by 3 m window was chosen to capture changes in local features.



Map Algebra expression

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Abs("clip_calc_8" - "rc_gd2_clip")
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Output raster: C:\Users\ls33646\Documents\ArcGIS\Default.gdb\rastercalc

Map Algebra expression

The Map Algebra expression you want to run.

The expression is composed by specifying the inputs, values, operators, and tools to use. You can type in the expression directly or use the buttons and controls to help you create it.

- The Layers and variables list identifies the

Figure 14. Raster Calculator operation to derive a quantitative comparison between the spatial distribution of elevation + roughness and glacial deposit units. The absolute value of the difference allows higher values in the new raster to correspond to greater differences between the input rasters.