Lineament Analysis for the McMurdo Dry Valleys region, Antarctica

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ABSTRACT

Light Detecting and Ranging (LiDAR) data were collected for regions spanning approximately 4000 km² in the McMurdo Dry Valleys region of Antarctica. The efficacy of using digital elevation models (DEM}s) derived from these data for geomorphic mapping applications in the Dry Valleys are assessed. Using the ArcGIS Geographic Information Systems (GIS) software suite, we determine optimal image processing techniques to enhance visibility of geologically and geomorphically significant lineaments including faults, dikes, paleoshorelines, and other rifting and glacially induced features. Optimized filters, shadowing parameters, and the determination of positive and negative relief are applied to regions of interest. Results highlight features that can be used to constrain long-term glacial isostatic adjustment and neotectonic processes related to the West Antarctic Rift System (WARS).

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1. Introduction

a. Background

An increased awareness of global climate change coupled with accelerated shrinking of
snow and ice in the polar regions [Rignot and Thomas, 2002] emphasizes the
importance of understanding solid earth and cryosphere interactions at the Earth’s poles. As part
of the International Polar Year (IPY), the Polar Earth Observing Network
(POLENET) project aims to address this issue by increasing the coverage of geophysical
observations, specifically Global Positioning System (GPS) and seismic instruments, in
West Antarctica and Greenland. Complimentary to the present day measurements
acquired through POLENET, Light Detecting and Ranging (LiDAR) data can be used to
determine the longer term crustal deformation history and rift structure of Antarctica (Fig. 1).

![Figure 1: Map of Antarctica showing: Dry Valleys (red star), TAM (blue), and WARS (yellow)](image)

LiDAR data were collected over large regions of the McMurdo Dry Valleys region of
Antarctica (Fig. 1) to calibrate NASA's Ice, Cloud and land Elevation Satellite (ICESat)
altimetry missions. 2-4m resolution Digital Elevation Models (DEMs) derived from these data
can be used for geomorphic applications, giving insight into the tectonics, volcanism, glaciation,
sedimentation, and geomorphic evolution of structures in West Antarctica. Image processing
techniques are applied to LiDAR DEMs to enhance geomorphic features of interest, allowing for
optimal interpretations to be made.

b. Tectonic Setting

The Dry Valleys block--a barren, hyper-arid polar desert ecosystem--is part of the
Transantarctic Mountains, is adjacent to the West Antarctica Rift System (WARS), and
c. Rift Structure and Glacial Isostatic Adjustment

Since the Last Glacial Maximum (LGM, approximately 21,000 years ago), the Earth’s crust has been uplifting, or rebounding, in response to loss in ice mass. This glacial isostatic adjustment, or GIA, is the dominant component of vertical crustal deformation in Antarctica. However, understanding other sources of deformation, including tectonic deformation, mantle upwelling, and sediment loading, are key to completely understanding the stability of the ice sheet.

A major IPY science objective is to address the uncertainty of current ice mass volume change. POLENET efforts will densify the coverage of geophysical instrumentation to measure modern GIA-induced vertical motion and rift-related horizontal strains in West Antarctica. In order to complement this current short-term crustal deformation record resulting from the IPY-POLENET project and to provide a more complete deformational history of West Antarctica, we assess the efficacy of high-resolution DEMs for geomorphic mapping applications in the McMurdo Dry Valleys. As part of this goal, we determine the optimal image processing techniques needed to enhance visibility of lineaments and identify lineament type. Data derived from these features will be used to reconstruct the long-term deformation history and rift structure of the WARS.

2. Methodology

a. Data Acquisition

During the austral summer of 2001-2002, a two-week NASA ATM campaign was conducted, resulting in the collection of dense LiDAR point cloud data [Csatho et. al., 2005]. Point cloud data were processed by NASA and the Ohio State University to produce 20 high-resolution (2-4m) DEM coverages of approximately 4000 km² in the Dry Valleys region of Antarctica (Fig. 3, B). The DEMs are available for download at the USGS Antarctic Resource Center website (http://usarc.usgs.gov/lidar_dlxoad.shtml).
Figure 3: A, 15m resolution Aster image of area at the Dry Valleys; B, Overlain 2m resolution hillshade of the same region. The higher resolution LiDAR data reveal greater structural detail. Black arrow denotes illumination angle of the shaded-relief map.

b. Image Enhancement Techniques

Remote sensing techniques, such as LiDAR, are useful for mapping features from complex terrains in isolated and extreme environments such as the TAM [Krabill et. al., 2002]. Using the ArcGIS Geographic Information Systems (GIS) software suite, image manipulation techniques were applied to LiDAR-derived DEMs from the McMurdo Dry Valleys region of Antarctica to highlight lineaments. Lineaments are topographic, tonal, and geomorphic features, including faults, dikes, fractures, folds, ridges, and bedding. In addition, curvilinear features including paleoshorelines, deltas, and features of glacial origin are also of interest. Given a particular DEM, digital processing techniques can be applied such that specific linear and curvilinear features are enhanced. Digitization of visible structures allows for more quantitative interpretations to be made, and aids in the comparison of observed structure orientation to already established models of an area. In general, viewing remote sensing data (LiDAR DEMs) in a GIS allows the analyst to resolve the significance and coupling of otherwise disparate pieces of geophysical data.

1.) Artificial Hillshades

Artificially illuminated shaded-relief DEMs are referred to as hillshades. Depending on the illumination azimuth chosen, features are either enhanced or muted in a hillshade. In general, features parallel to the illumination angle are obscured while features oriented roughly perpendicular are highlighted. All 20 DEM coverages were systematically illuminated in increments of 45 degrees, starting with true north. These initial hillshades will be used to identify
target regions for further processing by identifying areas with key features of interest. Close attention was given to any visible paleoshorelines, faults, dikes, and glacial features. When reliably dated, paleoshorelines provide crustal tilting rates since the last LGM, while faults and dikes provide constraints on the rift structure of West Antarctica. Glacial features may also provide insight into ice extent since the last glacial maximum.

2.) FILTERING, CROSS CORRELATION, AND RELIEF ANALYSIS
High-pass and low-pass filters applied to the DEMs enhance the visibility of potentially significant features. A high-pass filter serves to enhance sharp edges while a low-pass filter smoothes the data (Fig. 4). Artificially illuminating high-pass and low-pass filtered DEMs produce shaded-relief images that highlight features not visible or poorly constrained in a regular unfiltered hillshade.

Cross correlation is another technique that can be used to aid the identification of topographic structures, specifically positive relief features such as dikes. A rudimentary cross correlation is achieved by multiplying filtered DEMs illuminated at opposing angles. Cell by cell raster multiplication of filtered hillshades amplifies overlapping shadows cast by positive relief structures. Negative relief structures are correspondingly muted (Fig. 5).

Relief analysis is the differentiation of negative relief structures from positive relief structures. This technique is especially useful in a GIS setting as layers for positive and negative
relief features can be turned on and off, easing the identification of trends (if any) present for either type of classifications.

3.) Digitization and Rose Diagrams
Digitization is the process of converting information from one format to another, using a trace method. For this study, relevant lineaments were identified and digitized, meaning each lineament was digitally traced and recorded in a data layer. After digitization, relevant information was then attributed to each digitized feature (i.e. azimuth). The parameters and techniques used to highlight lineaments were also recorded for future reference. Digitization allows the analyst to focus solely on the lineament layer and any spatial trends, and also allows for statistical information, such as azimuth and relief, to be derived. Rose diagrams (polar histograms) summarize azimuthal trends for an area, and are useful for comparison of lineament trends between sub-regions.

Figure 5: A and B, Filtered, hillshaded images in opposing illumination angles; C, Image resulting from multiplication of A and B (cell-by-cell raster multiplication). Blue arrows show lineaments, black arrows show noise.

3. Results
a. Sub-region Analysis
As any single DEM coverage may have sub-regions with lineaments of varying orientation, these sub-regions therefore require different processing parameters for optimum enhancement. Table 1 is a sample description of the various parameters necessary to achieve the best lineament enhancements for the sub-regions present. Division into sub-regions is important since not all areas are optimally highlighted by the same hillshade parameters.

b. Optimal image enhancement techniques
For each of the 20 sites in the McMurdo Dry Valleys, we produced 8 different hillshades with artificial illumination from azimuths 45 degrees apart for a total of 160 different images. The filtering and cross-correlation methods were tested mostly on the Denton Hills DEM. This area was chosen because of the amount of structures visible and the existence of prior literature

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on the area [Wilson and Csatho, 2007]. Table 1 summarizes the hillshade parameters useful in extracting lineaments. We also rank from 1 to 5 (1 = poor, 5 = great) the visibility and number of lineaments present for a structurally complex ridge in Denton Hills. A sum of the two individual ranks, or composite rank, is computed to ease the identification of areas with abundant lineaments and the optimized parameters needed to view them.

c. Digitization

We digitized a prominent ridge of the Denton Hills region and computed the dominant azimuth and approximate length for the most visible lineaments present (Fig. 6, Top). Using the Generic Mapping Tools (GMT) software suite, a symmetric rose diagram of our primary Denton Hills ridge was generated using azimuth and length data. The data were partitioned into 5-degree bins and plotted twice, once with the lengths of the lineaments taken into account (serving as a weighted polar histogram) and once with just uniform lineament lengths (Fig. 6, Bottom). Bedding features were avoided in the rose diagram analysis. Two dominant trends (NE-SW and NW-SE) emerge, with approximately 90-degree separation between the main axes.

4. Discussion

a. Optimal image enhancement techniques

The geology of a particular area dictates the orientation, type, and age of the structures being identified. Linear structures (faults, dikes, etc) are best highlighted by artificial illumination from an azimuth perpendicular to that of the structure. This shadowing effect produces a contrast such that, when high pass filtered, structures not already highlighted are revealed. For illumination angles oblique to structures, hillshade analysis was a successful method for all lineament types.

Filtering and cross correlation were successful with positive relief structures such as dikes (ex. Denton Hills region). Noise was also accentuated by the cross-correlation technique, allowing the analyst to distinguish genuine lineaments from data quality artifacts. In general, many parameters are available to produce the highest quality contrast including: illumination angle, color palette, and relief. As with hillshade analysis, relief analysis was successful for all lineament types. Less prominent lineaments, specifically faults, typically require a more in depth analysis than high relief, more prominent lineaments such as dikes.

b. Future Work

Although results from this work drew from and are applicable to all the DEMs analyzed, the bulk of the methods were tested on primarily one region: a Denton Hills ridge. We would like to digitize and produce rose diagrams for additional areas of the Dry Valleys. These diagrams, coupled with relief analysis and rock ages, have the potential to elucidate the neotectonic stress regime and rift architecture imposed by the WARS.

Paleoshorelines (ancient beach lines) exist at several locations in and around the Dry Valleys. These shorelines have the potential to constrain long-term GIA rates that would also complement current, short-term, deformation rates being carried out by IPY-POLENET efforts. A more accurate assessment of GIA can be aided by higher resolution imagery of paleoshorelines. Since the sampling rate of raw LiDAR point cloud data is not uniform, it is possible to produce higher resolution DEMs extracted from those areas with higher density point...
data. These new DEMs, in turn, could form the basis for a more accurate estimation of long-term vertical crustal deformation induced by GIA.

Figure 6: Top, Denton Hills DEM with digitized lineaments outlined in yellow; Bottom Left, Symmetric polar histogram of azimuths in 5-degree bins, uncorrected for lineament lengths; Bottom Right, Same as in left, with bins weighted according to lineament lengths.
c. Conclusions

Dense LiDAR data were used to derive high-resolution DEMs of 20 sites at the McMurdo Dry Valleys in Antarctica. These DEMs were analyzed to assess their efficacy for geomorphic applications and to determine optimal image processing techniques to highlight pertinent structural lineaments. Hillshade and relief analysis are successful techniques that can be applied to all types of lineaments. Filtering and cross-correlation techniques are strongest when used to identify positive relief structures. Analyzing LiDAR-derived DEMs in a GIS setting has clear potential for assessing the significance of lineaments. In the Dry Valleys, these enhanced lineaments can be used to interpret rift architecture, long-term glacial isostatic adjustment and neotectonic processes.
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Table 1: Sample summary of optimal processing parameters for the Denton Hills, Arena, and Odell regions, McMurdo Dry Valleys. For azimuths, true north begins at 0° and proceeds in a clockwise manner. Altitude is the elevation angle in degrees where 0° denotes the horizon, and 90° is directly above the region. Features are ranked based on the visibility and number of features from 1 to 5 (1 = poor, 5 = great). A composite rank (sum of the two individual ranks) eases the identification of areas with abundant lineaments and describes the general parameters necessary for maximum visibility. When applicable, certain DEMs are separated into sub-regions.
REFERENCES


