USING TERRESTRIAL LASER SCANNING
FOR DIFFERENTIAL MEASUREMENT OF INTERANNUAL
ROCK GLACIER MOVEMENT IN THE ARGENTINE DRY ANDES

by

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ABSTRACT

Argentina has recently implemented laws to protect glaciers and buried ice in the Andes to improve the sustainability of scarce, long-term water resources. Therefore, all glaciers and buried ice terrains must be located and avoided in any commercial alterations of the landscape. Buried ice in this remote and often dangerous terrain typically is located via the use of remote-sensing techniques. This thesis applies one such technique, Light Detection and Ranging (LiDAR) in the form of Terrestrial Laser Scanning (TLS), to detect rock glacier movement that is indicative of flowing, buried ice not visible in near surface excavations. TLS surveys were completed at two locales, Los Azules and El Altar, in both AD 2013 and AD 2014 on landscapes where buried ice is suspected to have produced the current surface forms. Multiple TLS scans were co-registered with the use of benchmarks, both between scans and between years, which introduced quantifiable positional errors. Digital Elevation Models (DEM) were derived from the point cloud data by standardizing the spacing of the points in the horizontal direction, creating 0.1 m by 0.1 m cells with elevation as the cell value. The DEMs for each year were subtracted from each other to yield a change in elevation. The surface roughness of the rock glaciers (vertical variability within each cell) was empirically determined and evaluated as a threshold for results. Both sites showed sub-decimeter interannual movements, and the direction of their movement is typical of forms with buried ice. The results of the study were validated using independent GPS data showing annual movement rates. Despite the downslope
movement of these rock glaciers, the volume of ice contained within them remains unclear, and further study is required to assess the volume of water contained.
Chapter 1

INTRODUCTION

High concentrations of copper and other precious metals stimulate mineral exploration efforts in the southern Andes. When significant concentrations of extractable minerals are discovered, mining typically proceeds by removing large amounts of surface materials, often disturbing glaciers and other sources of perennial ice in the region (Brenning, 2008; Brenning and Azocar, 2010). Because summer melt of these ice sources may represent a significant portion of the water supplied to surrounding semiarid regions (Azocar and Brenning, 2009; Arenson and Jakob, 2010; Brenning, 2010; Bodin et al., 2010), current laws in Argentina discourage mining operations that adversely affect these sources, and require mining companies to identify and avoid landforms that contain ice.

Much of the ice in the southern Andes is visually obvious as glaciers, which are readily detectable and quantifiable via analysis of airborne and satellite imagery (i.e., North Cascades: Post et al., 1971; Cordillera Blanca: Silvero and Jaquet, 2005; Norway: Paul and Liss, 2009). However, other elements of the frozen water budget, such as permafrost\(^1\) and rock glaciers\(^2\), contain buried ice that is more difficult to quantify because the surface cover blends in with the surrounding terrain. The process is further complicated in that many geomorphic forms may be relicts created by flowing ice that is no longer present. Therefore, a variety of techniques are used to detect the buried ice.
Because of the difficulty in digging into these rugged, rocky terrains, active remote-sensing techniques are often employed to identify buried ice (e.g., shallow seismic surveying and ground penetrating radar). However, these techniques require physically demanding traverses on what is often dangerous terrain. Therefore, other remote-sensing techniques that require less intense human interactions with the landscape are used frequently in detecting surface deformation and movements that are a result of buried, flowing ice (e.g., Differential Interferometric Synthetic Aperture Radar (DINSAR) and Light Detection and Ranging (LiDAR)). The detection of landscape movement using airborne or space-borne DINSAR requires multiple images of a study area with the appropriate sensor/land-surface geometry, with temporal and spatial scales additionally taken into consideration (Wangensteen et al., 2005). The complications of finding such imagery and the intense computational requirements necessary limit the feasibility of this technique.

Light Detection and Ranging (LiDAR) systems provide an active remote-sensing technique that requires little or no interactions with the landscape. Data from these systems provides three-dimensional Cartesian coordinates that can be used to measure surface elevation changes in glaciers and ice sheets (Krabill et al., 2002; Geist and Stotter, 2010; Demuth, 2011), and to detect rock glacier movements (Gutro, 2004). Although the majority of current research uses Airborne Laser Scanning (ALS), Terrestrial Laser Scanning (TLS) technology has proven useful in many recent studies analyzing the differential change of rock and ice features, including rock slides (Prokop and Panholzer, 2009; Oppikofer et al., 2009; Kasperski et al., 2010; Corsini et al., 2013; Abellan et al., 2013), glaciers and debris-covered glacial ice (Kellerer-Pirklbauer et al., 2005; Avian, 2007; Kerr et al., 2009; Neild, 2012), and rock glaciers
Previous work comparing the efficacy of TLS, ALS, and photogrammetry on differential rock slope movement, suggests that TLS offers the most accurate and highest resolution of the three methods, and is well suited for smaller areas (Lato et al., 2014).

This thesis investigates the use of TLS for detecting movement along the termini of two rock glaciers in the Dry Andes, El Altar and Los Azules, which are in areas susceptible to the environmental impacts associated with future mining operations. The data and observations presented in this thesis serve as a part of a larger study conducted at these sites to assess ice volume and annual contribution to the regional water budget. The research presented herein builds upon the wider body of TLS studies of earth materials movement by incorporating more accurate methods of point cloud registration and interannual rectification, while comparing grid models for the assessment of material gains and losses over a one-year period. Furthermore, this study accounts not only for registration and rectification errors, but also considers the influence of surface roughness on the results of differential TLS measurements.
ENDNOTES

1 Permafrost is ground that stays below 0°C for at least two consecutive years, remaining permanently frozen at depth (Benn and Evans, 2010).

2 Rock glaciers are crescentic, lobate features comprised of loose surface materials, interstitial ice, and solid ice that creep downslope. They are formed over time as a) materials from rockfall and weathering accumulate in a periglacial environment, and b) buried snow and/or water infiltrates this rock mass and freezes, creating a permafrost feature. Note that periglacial rock glaciers, comprised of a complex ice/rock mixture, differ from debris-covered glaciers (glacial rock glaciers) in which thick accumulations of sediments cover a bed of predominately ice (Benn and Evans, 2010; Haeberli, 2006).
Chapter 2

STUDY AREA

Our field sites are two rock glaciers in the Dry Andes (Figure 1). The Los Azules rock glacier is located at 31° 04' 00.68" South, 70° 13' 57.59" West, with a minimum elevation of 3643 m and a maximum elevation of 3810 m. The El Altar rock glacier is located at 31° 28' 27.28" South, 70° 28' 25.93" West, with a minimum elevation of 3709 m and a maximum elevation of 3852 m. Source rocks for both rock glaciers are hydrothermally altered andesite and rhyolite. Both rock glaciers are free of vegetation cover; however, vegas\textsuperscript{1} are found near both rock glacier margins. Permanent weather stations with snow gauges, commissioned by mining companies with interests in the area, are located within 4 km of each rock glacier. Data from these stations and imagery available via Google Earth indicates that, in the winter months of 2013, both sites were covered with ca. 1 m of snow.

Physiography of Los Azules Rock Glacier

The Los Azules rock glacier is comprised of several lobes, crescentic forms, and flow-parallel ridges that suggest this feature is likely a complex mixture of several protalus ramparts\textsuperscript{2} and/or smaller rock glaciers (Figures 2 & 3). Ice has been observed in several locations along the form within a few meters of the surface. The entire rock glacier/protalus rampart feature measures approximately 875 m in width and extends about 300 m in length. Field measurements along the southeast terminus indicate that the maximum thickness is 30 m. Rock sources are from a single ridge that trends
northwest to southeast. The lobate forms of this rock glacier indicate that it flows south to southeast from the adjacent ridge, while channelized water flow surfaces at the terminus flowing to the southeast.

**Physiography of El Altar Rock Glacier**

The El Altar rock glacier is approximately 150 m wide and 500 m long lying on an approximately 3 degree slope (Figure 4). Field measurements of vertical thickness along the southeast edge of the rock glacier suggest that it is no greater than 20 m in maximum thickness. The feature is made of up a series of crescentic lobes with several elongated flow-parallel ridges on both its east and west lateral margins. To the northwest, the rock glacier blends into the headwall of the adjacent mountain ridge. The orientation of the rock glacier’s lobate surface forms indicates movement to the southeast. Two different rock types (color and texture) on the surface of the El Altar rock glacier indicate erosion from distinct sources from the adjacent ridges to the north and east. Field observations taken along the southwest margin of 100 clasts found an average diameter of 0.1 m, displaying angular to subangular shapes, suggesting very little abrasion with the surface materials during transport processes. Two pits measuring 5 m in diameter and 4 m in depth were excavated in 2011. Both pits display a coarsening upward sequence with sediments at depth being largely sands, silts, and pebbles. No ice was found in either of these pits or in ca. 10 m long road cuts along the southern and western margins.
ENDNOTES

1 Vegas are small patches of vegetated moorlands found in the valleys of the dry Andes, often fed by glacial and periglacial features (Mendez, 2007).

2 A protalus rampart is described as a pile of debris accumulating at the base of a perennial snow patch, often described as developing from fallen rocks rolling or sliding down the snow (Fukui, 2003). Some opposing views describe this feature as caused by permafrost creep and therefore part of a continuum of rock glaciers (Shakesby, 1997).
Chapter 3

METHODS

Terrestrial Laser Scanning

A Trimble GX Advanced Terrestrial Laser Scanner was used to collect point cloud data at the two study sites (Figure 5). This instrument provides data regarding the distance to surfaces in a survey domain by measuring the time of flight of emitted pulses of green light (532 nm) with a factory-tested accuracy of approximately 1.3 mm at a distance of 100 m. The distance measurements are coupled with data regarding the azimuth and zenith of the emitted pulse to place each point in a local Cartesian coordinate system that originates at the instrument. Each data point in the survey domain consists of the three-dimensional coordinates of the first surface reflection along any vector.

To capture points across a landscape, a TLS instrument rotates on its base (around a vertical axis) at user-prescribed increments to scan near- and far-field features. The instrument collects substantially greater numbers of observations from closer features than from the far-field area (i.e., tens of thousands vs. a single, or no observation). The radial pattern of data collection also influences the resolution of the final surface model that will eventually be developed from the data, because the rotational increment chosen will determine the size of the smallest features that can be detected in far-field areas.

The end product of a TLS survey is a detailed, three-dimensional point cloud representative of all reflective surfaces scanned. Each data point minimally has a
coordinate within three-dimensional space (XYZ coordinate), and additionally can contain a laser return-intensity value as well as color information estimated by an on-board camera (RGB values). The raw point cloud model typically requires filtering and data reduction to produce a bare-earth model of the scanned surface. This study did not require filtering for vegetation removal due to the existing bare surface in the Dry Andes study area. However, some manual data reduction was required to eliminate far-field observations of rock walls and areas unrelated to the study domain.

**Fieldwork & Data Collection**

Sites were initially scanned on January 5 through 9, 2013, and rescanned on January 11 through 16, 2014. The local XYZ coordinates as well as return intensity values and true-color approximation were collected for all data in the point clouds. For the Los Azules rock glacier, measurements were taken each year from two separate scan locations south of the feature, facing the snout (Figures 6 & 7). The El Altar rock glacier presented a more complex case due to the horseshoe-shaped nature of the terminus. Seven different scan locations along the terminus were required for complete point cloud coverage (Figures 8 & 9). Several additional scan locations (beyond the seven) and associated additional point cloud coverage at the El Altar site from AD 2013 were not used in final analysis due to inability to replicate coverage the following year. The end product of these surveys was a scan from each TLS position (indicated in Figures 6-9), and focused scans targeting registration benchmarks.

Several temporary benchmarks (0.08 m ceramic spheres provided with the Trimble system) were placed throughout the survey domain to enable multiple scans from a single year to be co-registered in post-processing. The spherical shape of the benchmarks limits registration errors because the mathematically modeled central
point is easy to determine from different scanner locations. Each benchmark was positioned to ensure visibility from different survey stations. The benchmarks were left untouched between scanner relocations, and labeled within the software to match between scans. Because the far-field resolution used for terrain scans is 0.1 m at a distance of 100 m, we performed a separate, focused, high-resolution scans directed precisely towards each sphere to ensure accurate co-registration of scans in post-processing.

To ensure accurate rectification between annual surveys, several permanent benchmarks were used at both study sites. We marked some sphere locations on rocky outcrops adjacent to the scan areas and used these benchmark sites the following year. We additionally drove wooden stakes into the ground at several points, and cemented rebar stakes in other locations, the latter being used for long-term GPS control points. Permanent steel well casings used in drilling operations for monitoring purposes unrelated to our study were also included as benchmarks.

**Data Registration and Rectification**

Scan Registration

For same-year scans at a given study area, the XYZ locations of the individual ceramic spheres were used to provide a registration framework for multiple point clouds. The location of a single sphere within an individual scan was matched to the same sphere location in a different scan at the same site. This was performed multiple times for many spheres within each scene, to reduce error in three-dimensional placement. A root mean square error (RMSE) of the distance between these coordinate pairs was calculated to assess error in fit. This value represented the difference
between a predicted location and the observed location for each sphere. In this study, we used the highest registration RMSE value calculated for each site and refer to this error as the registration error.

In rare instances, we encountered errors in registering adjacent scenes, due to accidental sphere movement, TLS station movement, or both. For example, small, millimeter-scale movement of the TLS instrument caused either by the settling of the tripod or heavy winds may yield meter-scale far-field errors. In these cases, individual points in the scene were matched manually. Non-sphere benchmarks, such as survey stakes and monitoring-well casings, aided the manual matching process. Point pairs were matched until the RMSE was minimized and visual analysis indicated each scan was angularly consistent.

The end products of scan registration were the following six scenes: 1) Los Azules, AD 2013; 2) Los Azules, AD 2014; 3) El Altar East, AD 2013; 4) El Altar East, AD 2014; 5) El Altar West, AD 2013; and 6) El Altar West, AD 2014.

Interannual Rectification

To compare scenes between years, point clouds were aligned with respect to the positions of permanent markers (survey stakes and well casings) in the scans. As the purpose of the study is to assess interannual differential movement, it was important to ensure that rectification errors were, ideally, much smaller than the possible amount of rock glacier movement. Misalignment of point clouds would incorrectly suggest movement over the course of a year. As with scan registration, errors of interannual rectifications were quantified and minimized using RMSEs, and the geometry of the overlain, interannual clouds was visually verified. In this study, we used the highest rectification RMSE calculated for each site and refer to this as the
rectification error. Once the rectification was completed, data points outside the bounds of the rock glaciers as well as areas with poor interannual scan overlap were trimmed from the point clouds.

**Surface Model Development**

A Digital Elevation Model (DEM) can be derived from point cloud data by standardizing the spacing of the points in the horizontal (XY) direction to create a grid (raster) data model. A grid of a given cell size is created on the XY plane of the point cloud. The elevation value of each cell can correspond to the minimum, maximum, or average value in the Z direction, as determined by the model creator, as a single-point representation of the distribution of original point cloud elevation values that reside within the XY plane of a given cell. This type of standardized surface model is useful for traditional raster analysis methods, including differential change detection, while also providing a result comparable to other remotely sensed data available for the study area (i.e., digital orthophotos and other high-resolution satellite imagery).

The six rectified scenes were converted from point clouds to DEMs using the aforementioned method. Each DEM contains 0.1 m by 0.1 m cells, a grid spacing chosen for its appropriateness in the terrain (i.e., predominantly cobble- and boulder-sized clasts on the surface) that also takes into account computational feasibility. All areas within the site intended for differential movement analysis had between $10^0$ and $10^3$ points per cell. Each cell contains the minimum Z value of the points within its XY bounds to ensure that the model represents the bare surface.
Surface Roughness Calculation

Many cells in the DEMs contain a high density ($10^3$) of points, but due to the roughness of the terrain, some cells display a relative scarcity of data, leading to uncertainty in the scanner’s detection of the lowest elevation that exists for every cell. Differences in surface coverage and density between interannual scans can be caused by differences in station location and scan resolution, contributing to the variability of the maximum and minimum elevation values within a given cell. The likelihood of capturing the lowest elevation of the terrain in a given cell is proportional to the number of scan points in that cell. Therefore, when ca. $10^1$ points are returned in a given cell area, it is unclear how much of the true elevation profile of this extremely rough and rocky landscape has been recorded. To avoid misrepresenting differential movement where we simply have only scanned a high and a low elevation of the same surface in subsequent years, we calculate the average surface roughness of the landform to provide an estimate of error that accounts for possible missing elevation data in some cells.

Areas of 100 m$^2$ on the terminal margins of both study areas were selected as a sample for surface roughness calculations. Each sample was selected from a single scan location, and from a single year of collection, in order to eliminate the need to account for registration errors and rectification errors. Two 0.1 m grid models were created from each sample, one using the maximum value for each cell, and the second using the minimum elevation value for each cell. The cell values in the two grids were subtracted from one another, resulting in a vertical deviation for each cell. The RMSEs calculated using these deviations are considered to be a proxy for the surface roughness.
Digital Elevation Model Comparison and Assessing Error

The standardized DEMs created from the point cloud data allow for the assessment of differential movement of each landform via direct cell-to-cell comparison (Bauer, 2003). Interannual comparisons were made by subtracting values of the AD 2013 DEM from the corresponding cell values in the AD 2014 DEM. This yielded a deviation in elevation value for each cell, representing change that occurred during the year, notwithstanding error.

For each site, a cumulative error was calculated from the sum of the errors associated with registration, rectification, and the surface roughness value. Interannual elevation deviation values below (for positive elevation change) and above (for negative elevation change) this cumulative error were determined to be beyond the threshold of detectable change with our methods and were excluded in the final analysis of differential movement (detected surface change).
ENDNOTES

1 The data were collected with Trimble’s Pointscape software, which serves as the software interface to the instrument. Point clouds were registered with Trimble’s RealWorks Survey, which allows for semi-automated sphere identification and selection. RealWorks Survey also computes the RMSE for the sphere locations, which aids in quantifying the errors associated with the registration and rectification processed. The open-source program CloudCompare was used for creating gridded DEMs from the registered point clouds. Comparisons of these digital elevation models were made in ESRI ArcMap using raster algebra.
Chapter 4

RESULTS

Los Azules

The AD 2013 and AD 2014 surveys for the Los Azules rock glacier yielded 6,045,923 and 2,837,756 data points, respectively. Analysis of the TLS data indicates the majority of interannual movement results in elevation changes that are within the 12.9 cm of cumulative error (Table 1 and Figure 10). A frequency histogram depicting the elevation change observed (Figure 11) indicates that changes beyond the error threshold occur in 2.3% of the rock glacier’s area (Table 2).

After subtracting positional and model errors/limitations on the Los Azules rock glacier, the average displacement for those cells within the model that display elevation change is 0.1 cm (Table 2 and Figure 12). However, this average incorporates both gains (positive) and losses (negative) and therefore does not fully represent change in either direction. A frequency histogram depicting only change detected beyond the error range shows that a slight majority of the changes are negative (Figure 13). The percentage of the total area with detected elevation gain, 0.9%, was slightly smaller than the percentage of total area with a detected elevation loss, 1.4%, despite the fact that the average detected elevation gain, 5.5 cm, was larger than the average detected elevation loss, 3.4 cm (Table 2).
**El Altar East**

The AD 2013 and AD 2014 surveys at the El Altar rock glacier’s eastern section yielded 4,670,309 and 2,652,990 data points, respectively. Analysis of the TLS data indicates the majority of interannual movement results in elevation changes that are within the 11.6 cm of cumulative error (Table 1 and Figure 14). A frequency histogram depicting the elevation change observed indicates that changes beyond the error threshold occur in 4.2% of the rock glacier’s area (Figure 15).

A model depicting elevation changes of the El Altar rock glacier’s eastern margin, after subtracting positional and model errors/limitations (Figure 16), shows an average displacement of 2.0 cm for those cells that display elevation change (Table 2). However, this average incorporates both gains (positive) and losses (negative) and therefore does not fully represent change in either direction. A frequency histogram depicting only change detected beyond the error range shows that a slight majority of the changes are positive (Figure 17). The percentage of the total area with detected elevation gain, 2.4%, was slightly larger than the percentage of total area with a detected elevation loss, 1.8% (Table 2). The average detected elevation gain, 7.7 cm, was larger than the average detected elevation loss, 5.8 cm (Table 2). On the extreme end of both negative and positive elevation change values, there are large displacements representing known excavation sites that are influencing these averages.

**El Altar West**

The AD 2013 and AD 2014 surveys at the El Altar rock glacier’s western section yielded 3,505,964 and 1,903,095 data points, respectively. Analysis of the TLS data indicates the majority of interannual movement results in elevation changes that are within the 9.4 cm cumulative error (Table 1 and Figure 18). A frequency
A model depicting elevation changes of the El Altar rock glacier’s western margin after subtracting positional and model errors/limitations (Figure 20) shows an average displacement of 3.0 cm for those cells that display elevation change (Table 2). However, this average incorporates both gains (positive) and losses (negative) and therefore does not fully represent change in either direction. A frequency histogram depicting only change detected beyond the error range shows a majority of elevation changes are positive (Figure 21). The percentage of the total area with detected elevation gain, 13.8%, was much greater than the percentage of total area with a detected elevation loss, 0.9%, despite the fact that the average detected elevation gain, 3.5 cm, was smaller than the average detected elevation loss, 5.6 cm (Table 2).

Validation of TLS Movements via RTK GPS Derived Surface Velocities

Elevation changes detected via interannual DEM analysis were compared with independent GPS data collected from permanently attached stakes on both rock glaciers (data originally presented in Meglioli, 2014a and 2014b). Repeated GPS measurements were collected over the course of several years with millimeter-accurate Real Time Kinetic (RTK) instrumentation. The rate of change of these coordinates constitutes a surface velocity measurement.

The rate and vector of surface movement of the stakes were calculated using a three-year record of GPS measurements (change in northing, easting, and elevation) by averaging to an annual rate and direction. At the Los Azules rock glacier, the GPS rod closest to the scanned area, MAW5, was destroyed (Figure 22). The second closest rod, MAW1, is significantly upslope from the scanned area. The velocity established
at this point is 2.6 cm per year in a generally southward direction. For the El Altar rock glacier’s eastern section, the closest rod is M007 with a rate of 3.2 cm per year in a southeast direction (Figure 23). For the El Altar rock glacier’s western section, the closest rod is M011 with a rate of 6.4 cm per year in a generally southward direction. These rates represent three-dimensional movement, and therefore do not directly compare with the results from our methods, which show the averages of elevation changes within the cell models. However, the GPS rates provide a proxy for the value of the movements observed within a single year (i.e., sub-decimeter).
Chapter 5

DISCUSSION

The results of this thesis indicate that TLS surveys can be used to develop decimeter scale models to detect elevation changes along the termini of rock glaciers in the study area. Although many readily available techniques provide comparable or better spatial coverage (i.e., interferometry), it is often difficult to collect specific imagery for areas of interest at appropriate times. GPS and traditional survey methods produce substantial insights regarding rates of movement at specific intervals, but fail to capture any of the details regarding the nature of the movement over the breadth of the rock glacier.

The results of this study are dependent on the survey design and limiting the errors inherent to instrumentation and data processing. Effective measurement distances for the purpose of differential analysis are often less than the maximum stated limits of a given instrument; therefore, far-field measurements must be anticipated and reduced in survey design (O’Neal, 2014). The surrounding terrain and accessibility of optimal scanner locations can exacerbate line-of-sight issues, which are manifested as areal gaps in the scanned data at each site. In addition, maintaining minimal spacing between neighboring benchmarks, either temporary or permanent is important in limiting instrument inaccuracies at distance. The distance between neighboring permanent external control points around the margin of the glacier was approximately 50 m, with temporary benchmarks at closer intervals. When we coupled the error of these field controls with the surface elements of the rock glacier itself, we
were able to identify elevation changes that exceeded cumulative error thresholds. Attempting to evaluate rock glaciers without substantial survey control points away from the feature itself can complicate the detection of differential elevation change (Goshorn-Maroney, 2013).

The elevation change behavior detected at the two sites is typical of rock glacier advance mechanisms. Active rock glaciers grow continuously along the long-axis in a downslope direction (Kääb and Reichmuth, 2005). Material in the upper layers is carried over the underlying layers downslope and deposited at the terminus, while sliding conditions can move the mass forward as well (Haeberli et al., 1998). The resulting movement behavior is largely dependent on the vertical profile and associated horizontal velocities of the individual rock glacier.

The Los Azules rock glacier shows little change during the study period, which is consistent with the few centimeters of movement shown in the GPS data at a site slightly upslope from the scanned area. Most of the elevation changes can be visually described as minor slope failures. Despite the site remaining relatively undisturbed throughout the year, there is evidence in the data of guanaco trails and road grading that would account for some of this already minimal movement (trails manifested as occluded east-west lines in Figure 12 and elevation gains possibly caused by road grading are seen in southern portion of the same figure). In addition, despite far-field data reduction, there may be some change falsly detected at the Los Azules rock glacier due to variability in instrument returns at distance (seen in the eastern portion of the scanned area in Figure 12). Elevation loss at the terminus was detected by the TLS; however, some of the corresponding downslope elevation gain was not beyond the threshold of the cumulative error. The elevation change detected at the terminus in
the form of slope failures can be interpreted as processes consistent with the mechanisms of active rock glacier advance.

The results in this study indicate accretion along the El Altar rock glacier terminus at a rate of approximately 3.5 cm (derived from average detected elevation gain for the El Altar rock glacier’s western section). Although the extent of elevation change is only over 14.7% of the rock glacier’s area, the distribution of this change is spatially along the entire western margin. Material movement appears to be largely creep-driven, with additional small slope failures across the breadth of the outer margin. This is consistent with the rate and direction of movement detected from GPS data at this location during the study period.

Both rock glaciers intersect elevations of observed perennial ice near adjacent headwalls, suggesting that these features may be part of a continuous, debris-protected, flowing bed of ice. It remains unclear as to whether these landforms are relict of past cold climates that are losing volumetric ice over time, or if annual snowpack is melted and refrozen at depth into the rock glaciers. Despite these uncertainties, this study provides valuable first insights as part of an ongoing investigation of the rates of rock glacier movement in this poorly studied region. Our work contributes to a better understanding of the long term growth and decay of these landforms, and thus their contributions to the regional water supply.
Figure 1  Map displaying the locations of the survey areas (white dots). The shaded relief base map was derived from the GTOPO 30 DEM. The inset map shows the location of the study region in the context of South America.
Figure 2  Los Azules rock glacier, as viewed from the southwest.
Figure 3  Southeastern terminus of Los Azules rock glacier
Figure 4  El Altar rock glacier, as viewed from an adjacent ridge to the southeast, looking at the terminus.
Figure 5  Photo showing the setup of the terrestrial laser scanner (TLS) at the El Altar site. The unit is atop a tripod facing the eastern side of the rock glacier.
Figure 6  Aerial image of the Los Azules rock glacier displaying the TLS survey locations (black dots) and the extent of the AD 2013 point cloud (orange dots with light to dark representing the intensity of the returned signal).
Figure 7  Aerial image of the Los Azules rock glacier displaying the TLS survey locations (black dots) and the extent of the AD 2014 point cloud (orange dots with light to dark representing the intensity of the returned signal).
Figure 8  Aerial image of the El Altar rock glacier displaying the TLS survey locations (black dots) and the extent of the AD 2013 point cloud (orange dots with light to dark representing the intensity of the returned signal).
Figure 9  Aerial image of the El Altar rock glacier displaying the TLS survey locations (black dots) and the extent of the AD 2014 point cloud (orange dots with light to dark representing the intensity of the returned signal).
Figure 10  Aerial image of the Los Azules rock glacier with an overlay of the AD 2013 to AD 2014 differential LIDAR data. Scaled from <-24 cm to >24 cm, areas that show gain are represented by positive values (blue) and areas that show loss are represented by negative values (red).
Figure 11  Histogram displaying the frequency of movement observed in each of the 0.1 m by 0.1 m elevation model cells along on the western margin of the Los Azules rock glacier (see Figure 10). Positive values represent gain and negative values represent loss.
Figure 12  Aerial image of the Los Azules rock glacier displaying areas where the amount of movement detected exceeds the positional errors (instrument, registration, and rectification) and the surface roughness. Areas that gained material from AD 2013 to AD 2014 are shown in blue and areas that lost material are in red.
Figure 13  Histogram displaying the frequency of change observed in each of the 0.1 m by 0.1 m elevation model cells along on the southwestern margin of Los Azules rock glacier after accounting for both positional error and surface roughness (see Figure 12). Positive values represent gain and negative values represent loss.
Figure 14  Aerial image of the El Altar rock glacier with an overlay of the east side AD 2013 to AD 2014 differential LIDAR data. Scaled from $<-24$ cm to $>24$ cm, areas that show gain are represented by positive values (blue) and areas that show loss are represented by negative values (red).
Figure 15  Histogram displaying the frequency of change observed in each of the
0.1 m by 0.1 m elevation model cells along on the eastern margin of El
Altar rock glacier (see Figure 14). Positive values represent gain and
negative values represent loss.
Figure 16  Aerial image of the El Altar rock glacier (east side) displaying areas where the amount of movement detected exceeds the positional errors (instrument, registration, and rectification) and the surface roughness. Areas that gained material from AD 2013 to AD 2014 are shown in blue and areas that lost material are in red.
Figure 17  Histogram displaying the frequency of change observed in each of the 0.1 m by 0.1 m elevation model cells along on the eastern margin of El Altar rock glacier after accounting for both positional error and surface roughness (see Figure 16). Positive values represent gain and negative values represent loss.
Figure 18  Aerial image of the El Altar rock glacier with an overlay of the west side AD 2013 to AD 2014 differential LIDAR data. Scaled from < -24 cm to >24 cm, areas that show gain are represented by positive values (blue) and areas that show loss are represented by negative values (red).
Figure 19  Histogram displaying the frequency of change observed in each of the 0.1 m by 0.1 m elevation model cells along on the western margin of El Altar rock glacier (see Figure 18). Positive values represent gain and negative values represent loss.
Figure 20  Aerial image of the El Altar rock glacier (west side) displaying areas where the amount of movement detected exceeds the positional errors (instrument, registration, and rectification) and the surface roughness. Areas that gained material from AD 2013 to AD 2014 are shown in blue and areas that lost material are in red.
Figure 21  Histogram displaying the frequency of change observed in each of the 0.1 m by 0.1 m elevation model cells along the western margin of El Altar rock glacier after accounting for both positional error and surface roughness (see Figure 20). Positive values represent gain and negative values represent loss.
Figure 22  GPS study locations on Los Azules rock glacier. The pink circles and associated identification codes represent individual measurement rods (figure derived from Meglioli, 2014b).
Figure 23  GPS study locations on El Altar rock glacier. The red circles and associated identification codes represent individual measurement rods (figure derived from Meglioli, 2014a).
### Table 1  Summary of TLS data analysis

<table>
<thead>
<tr>
<th>Location</th>
<th>Survey Date</th>
<th>Number of Points</th>
<th>Number of Survey Stations</th>
<th>Registration Error (cm)</th>
<th>Rectification Error (cm)</th>
<th>Total Positional Error (cm)</th>
<th>Surface Roughness (cm)</th>
<th>Combined Total Positional Error and Surface Roughness (cm)</th>
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<tr>
<td>Los Azules</td>
<td>January 9, 2013</td>
<td>6,946,923</td>
<td>2</td>
<td>0.3</td>
<td>0.8</td>
<td>1.3</td>
<td>11.6</td>
<td>12.5</td>
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<tr>
<td></td>
<td>January 11, 2014</td>
<td>2,837,766</td>
<td>2</td>
<td>0.6</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>El Altar (East)</td>
<td>January 6, 2013</td>
<td>4,670,369</td>
<td>3</td>
<td>1.3</td>
<td>2.1</td>
<td>3.4</td>
<td>8.2</td>
<td>11.6</td>
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<tr>
<td></td>
<td>January 15 to 16, 2014</td>
<td>2,652,980</td>
<td>4</td>
<td>0.9</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>El Altar (West)</td>
<td>January 6, 2013</td>
<td>3,505,964</td>
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<td>0.6</td>
<td>1.1</td>
<td>2.0</td>
<td>7.4</td>
<td>9.4</td>
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<tr>
<td></td>
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<td>4</td>
<td>0.9</td>
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Table 2  Differential model results

<table>
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<tr>
<th>Location</th>
<th>Points Analyzed in Differential Model</th>
<th>Detected Surface Change (Percent of Total Area)</th>
<th>Average Displacement (cm)</th>
<th>Detected Gain (Percent of Total Area)</th>
<th>Average Detected Gain (cm)</th>
<th>Detected Loss (Percent of Total Area)</th>
<th>Average Detected Loss (cm)</th>
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<tbody>
<tr>
<td>Los Azules</td>
<td>293.489</td>
<td>2.3%</td>
<td>+0.1</td>
<td>0.9%</td>
<td>5.5</td>
<td>1.4%</td>
<td>3.4</td>
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<tr>
<td>El Altar (East)</td>
<td>204.542</td>
<td>4.2%</td>
<td>+2.0</td>
<td>2.4%</td>
<td>7.7</td>
<td>1.8%</td>
<td>5.8</td>
</tr>
<tr>
<td>El Altar (West)</td>
<td>265.422</td>
<td>14.7%</td>
<td>+3.0</td>
<td>13.8%</td>
<td>3.5</td>
<td>0.9%</td>
<td>5.6</td>
</tr>
</tbody>
</table>
REFERENCES


