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A study of valley-side slope asymmetry based on the application of GIS analysis: Alexander Island, Antarctica

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Abstract: Geographic Information System (GIS) data from southern Alexander Island were used to evaluate valley asymmetry from an area where ground observations had suggested that south facing slopes were steeper than north facing. Using digital elevation modelling (DEM), data were collected from 2° and 10° arcs centred on the four cardinal directions in order to determine average slope angles for a whole nunatak area (Mars Oasis). It was found that south facing slopes were significantly steeper (34°) than the north facing (28°); east and west facing slopes were each 31°. Bedrock in this area is (approximately) horizontally bedded and so valley asymmetry is considered to be due to aspect-influenced periglacial weathering processes.

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Introduction

Observations collected in Viking Valley (Fig. 1) as part of an earlier study (Meiklejohn 1994) had shown that there was distinct valley symmetry, with the south facing slopes being much steeper (58°) than the north facing (30°). Studies of weathering processes and landforms in this same area (Hall 1997a, 1997b) had indicated aspect-constrained weathering processes. The original study by Meiklejohn (1994) was with a very limited sample size and, essentially, dealt with a valley cross section rather than multiple sets of data measurements. Nevertheless, it seemed clear that the asymmetry was not structurally controlled, as the geology consists of horizontally (or nearly horizontally) bedded sedimentary rocks (mainly sandstones and mudstones). Meiklejohn (1994) was able to show that the warming of the north facing valley slope resulted in a much deeper active layer than was measured on the cooler, south facing slope. He argued that the deeper active layer facilitated more extensive weathering and mass movement and that this results in a shallower slope angle when compared to the south facing slope where the active layer thawed later in the summer, froze earlier and was very shallow. The close proximity of the permafrost to the ground surface on southern aspect slopes also helped maintain, by means of bonding the rock material together and increasing the shear strength, the recorded steep slopes (see French 1996, p. 202–203 for a discussion regarding the interaction between permafrost and valley asymmetry).

The aridity of this area suggests that freeze-thaw weathering is spatially and temporally limited to the few locations where water is present, and available data suggest that thermal stress fatigue is likely to play a major role in rock weathering (Hall 1997a, 1997b). Aspect greatly influences weathering within this area (Hall 1997a). Data show that, despite its orientation, the northern aspect exhibits the lowest late summer to early autumn rock temperatures (Hall 1998) but has the highest rock surface temperatures during the summer proper (Hall 1997a). These data (Hall 1997a, 1998) indicate that the influence of aspect at these latitudes is complex and varies with the season. Schmidt hammer rebound values and the sizes of taffoni (Hall 1997a, table 9) indicate that there is substantial weathering on slopes with northern aspects, certainly more than on the eastern and western facing slopes (in that data set information for the southern aspect were missing). Accepting that, in some manner, cryoplanation terraces are the product (in part) of weathering, then the orientation data regarding cryoplanation terraces from this area clearly show the greatest weathering on the north through north-west to western aspects (Hall 1997b, fig. 3) but little or no weathering from east through south to south-west. Meiklejohn (1994, table I) showed the difference between weathering on the north facing slope (greatest) and the south facing slope (least) in Viking Valley and used this, in part, as his explanation for valley asymmetry. Thus, with this evidence of valley asymmetry for Viking Valley and the aspect-constrained effects on weathering for this area, it was decided to test the hypothesis that the whole nunatak complex would show slope asymmetry. The GIS approach offered an ideal method of assessment.

For the Northern Hemisphere valley asymmetry in areas of permafrost frequently exhibits steeper north facing slopes, but with proximity to the pole there is a greater variation in preferred orientation (French 1996). Data from the Antarctic are very sparse and discussion regarding valley asymmetry is rare. French (1996, p. 202) in a discussion regarding valley asymmetry in the Northern Hemisphere, notes that such factors as changes in the inclination of the sun with increasing latitude, direction of snow-bearing winds, impact of active layer thickness, and the role of streams, may all play a role in determining asymmetry orientation. Meiklejohn (1994, fig. 5) also utilised some of these parameters within his model for valley asymmetry development. The GIS analysis presented

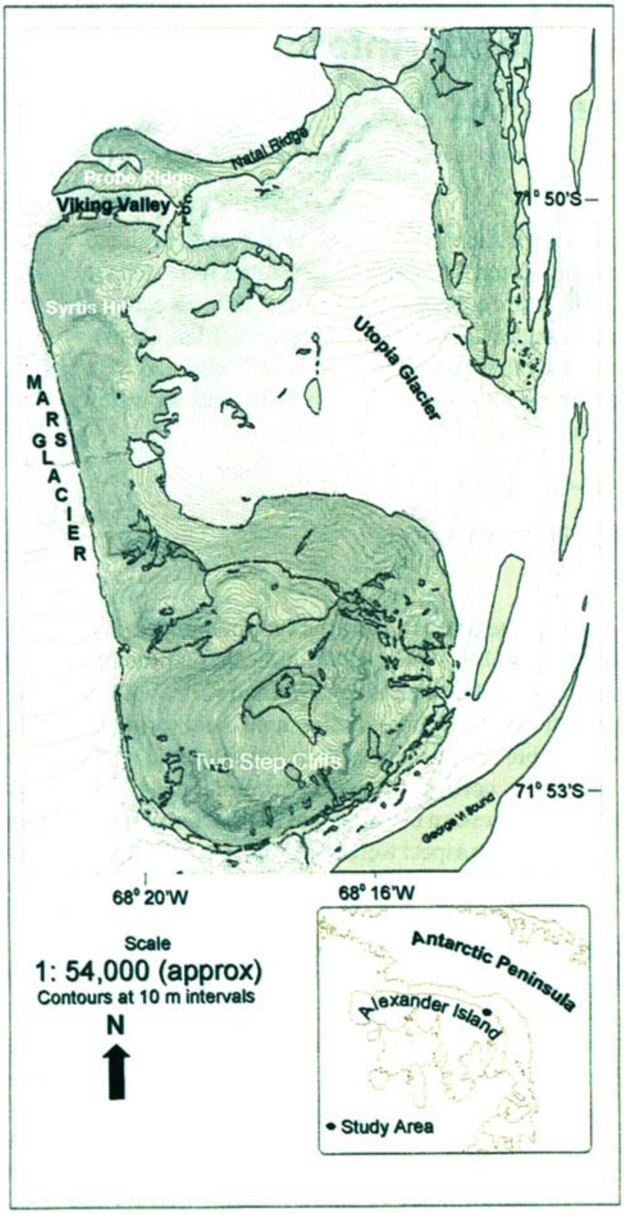

Fig. 1. Location of study area.

here can show the occurrence (or not) of asymmetry but cannot explain it. Fortunately, some of the weathering information available for this area may offer some explanation for the asymmetry observed.

Study area

Measurements were undertaken on the nunatak complex between the Mars Glacier and King George VIth Sound (Fig. 1) at the southern end of Alexander Island (71°54'S, 68°23'W). Formerly covered by ice from the Antarctic Peninsula (Sugden & Clapperton 1978), deglaciation has exposed the higher rock areas and only a few ice remnants remain (e.g. at the head of Viking Valley and on the western side of Two Step, Fig. 1). The area is one of continuous permafrost with very little precipitation and a summer mean air temperature of -2.5°C and a winter mean of -11.5°C (Hall 1997a, 1997b). Geologically the area comprises argillaceous sedimentary rocks, sandstones and mudstones (Taylor *et al.* 1979). The dominant lithology is an arkose sandstone with subspherical, post-compaction siliceous concretions with a ferruginous cement (Thomson 1964, Moncrieff 1989). There are also mudstones, sometimes with lime carbonate nodules, shaly mudstones and orthoquartzitic sandstones; all are near horizontally bedded, with a 7° dip to the north (Fox personal communication 1999). Linearity along the coast is the product of faulting as too is the east–west linearity of the glaciers that cut the coast.

Methodology

Using existing British Antarctic Survey (1998) digital contour information for the Mars Oasis area of southern Alexander Island a digital elevation model (DEM) in the format of a TIN (Triangulated Irregular Network) was constructed in Arc/Info^R. The 10 m proximal tolerance TIN was then converted into a polygon coverage that included aspect, slope and surface area values (Fig. 2a). This polygon coverage was built to exclude all areas covered by ice and snow as snow and ice slopes may differ significantly from those of the bedrock beneath, leaving only exposed rock polygons. This 'rock' data set was used to crop the initial aspect and slope DEM to generate a new coverage. From this new layer north, south, east and west information on slope angle was extracted in ArcEdit^R (Fig. 2b). Topology was created from individual 'packets' of information for each of the aspects. Using the surface area of each TIN triangle as a weighting factor each slope and aspect value has equal significance and thus the values are independent measures of slope. Initially, aspects were constrained to +/- 1° of the cardinal orientation (e.g. between 179° and 181° for the south orientation). Although this approach produced a substantial data set (e.g. 831 north aspect slope values) it was felt that the 2° constraint was too narrow as it did not facilitate continuity down a complete slope as, in many instances, there was more than a 2° orientation distribution on a single slope. The data analysis was thus re-run for a +/- 5° arc and, although this produced significantly more data (e.g. 3659 north slope values), it provided a more realistic assessment of slopes (Table I). For each of the cardinal directions, the two packets of information (aspect and slope for both the 2°and the 10° arcs) were exported to a database where a statistical analysis was performed using one-way ANOVA (with aspect as the independent variable, slope as the dependent, and the whole being weighted as a function of slope with surface area). It would have been possible, but time consuming, to run regressions for all aspects but this was not done for two reasons. First, the size of the data sets that would have resulted. Second, the original focus was the comparison of only north and south slopes as these were the

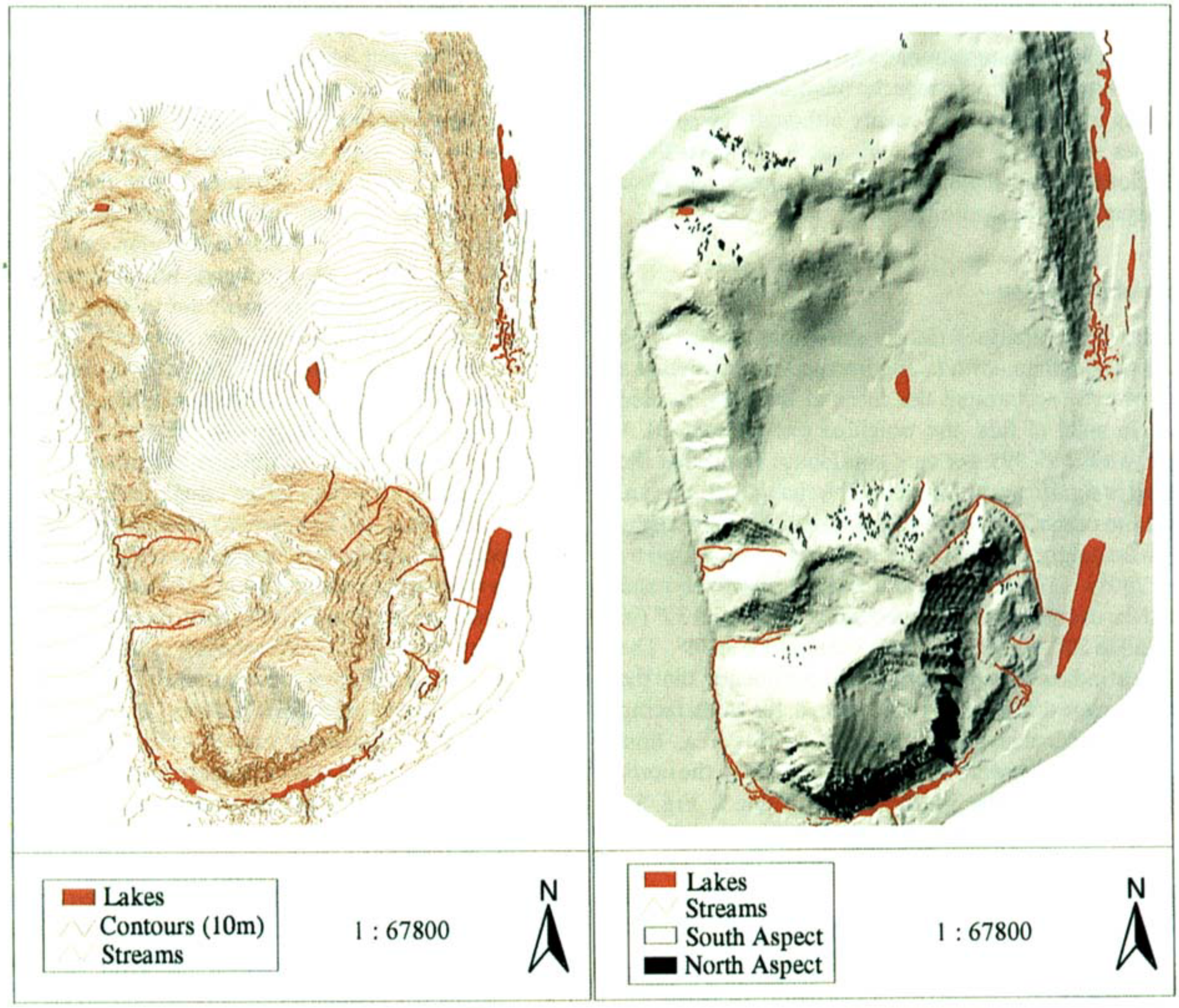

Fig. 2. **a.** Slope map based on contour information. **b.** Example of the south and north aspect slope segments extracted by ArcEdit that were used in the statistical analysis.

aspects for which field observations were available. Whilst obviously valuable in the longer term to undertake a more comprehensive evaluation, it was felt that, at this stage, it was solely the original field observation that should be tested.

In the derivation of the contours for the Mars Oasis map, digitized index contours were at 200 m spacing but with a substantial number of height measurements between and throughout the index contours (Fox personal communication 1999). Thus, the overall map accuracy is better than 200 m and the overall inaccuracy of the generated non-index contours is minor since most of the significant and drastic changes in elevation are accounted for in the original sampling. Further, the underlying error of the auto-correlated non-index contours is uniform throughout the area, affecting all aspects equally. Thus, all the values we derive are related in all planes in direct correlation to the index contours and other measured height variables. In addition, the use of TIN drastically reduces the error since the values are not calculated on the two linear values between the index contours. Whilst our significance value is probably on the high side, this was the best DEM generating method for this type of analysis. In the final analysis, the DEM approach is fraught with inaccuracy based upon the derivation of the original data and so the resulting slope values are not necessarily "accurate" in the sense that field measurements would derive the exact same angles (although neither is it impossible). Rather, the derived values

Table I. Summary of slope angle (and number of observations) for the cardinal aspects as a function of the 2° or 10° arc of data acquisition.

Aspect	+/-1° arc Slope angle	*n*	+/- 5° arc Slope angle	*n*
north	30°	831	28°	3659
south	34°	631	34°	2164
east	32°	4332	31°	13101
west	30°	1325	31°	4039

are accurate within the accuracy of the original data and the manner in which those were obtained. The argument is made that the approach used here minimizes the inherent inaccuracies such that in terms of bedrock slope the relationship of north to south slopes is a reflection of reality although the specific slope values should be viewed with caution. With these considerations in mind, it is argued that the following analysis of slope asymmetry has validity.

Results and discussion

The results of the analyses clearly show that south facing slopes are steeper than north facing irrespective of whether a ± 1° arc or ± 5° arc around the cardinal direction is used (Fig. 3). In spite of this, the weighted one-way ANOVA indicated, with a 99.999 per cent confidence level, that the data sets were significantly different. The change to a ± 5° arc increased the number of north facing slope observations by 340% (interestingly the south, east and west all increased by just over 200% – 243%, 202% and 204% respectively) and decreased the overall northern aspect slope angle from 30° (in the ± 1° arc) to 28°, but left the south facing slope at 34°. The ANOVA test indicated, with even greater confidence, that the two data sets were different and that, indeed, the south facing slopes were steeper than the north facing for this area. East and west facing slopes were both steeper (31°) than the north facing but less than the south facing (Table I, Fig. 3). Statistically, the east and west aspects are significantly different from those of both north and south. Thus, with a high statistical confidence (99.999%) GIS slope data indicate southern aspects are steeper than the eastern or western, and that, in turn, these are steeper than the northern.

There seems to be clear evidence in support of aspect-related slope asymmetry from this area. The hypothesis of Meiklejohn (1994) that south facing slopes are steeper than north facing is substantiated. This information does not, though, offer any explanation for the cause. Fortunately, the horizontal, or near horizontal, nature of the rocks in this area coupled with the limited suite of lithologies negates any structural or lithological explanation. French (1996, p. 183), states that, for slope evolution in periglacial regions, it is necessary to take into account "...(a) the regional and microclimates, (b) the lithology, and (c) the dominant weathering process". Within this region both climate and structure/lithology can be considered uniform so that the asymmetrical effects are probably due to microclimate and its effect upon weathering and slope processes. This being an area of continuous permafrost, aspect will certainly play an important role in determining the thickness of the active layer; the north facing slope being warmer would have the deeper active layer. As weathering and mass movement are constrained to the active layer it then follows that greater weathering and mass movement can be expected on the north facing slopes. Temperature differences between north and south facing slopes were significant (see table I of Meiklejohn 1994), with the ground surface mean for the north facing being 21.9°C and that for the south 7.1°C. Weathering indicators (e.g. Schmidt hammer rebound values) substantiate the notion of increased weathering on the north facing slopes. Thus, there appears to be evidence regarding aspect-constrained effects on temperatures, active layer thickness and weathering rates that shows a distinct difference between north and south facing slopes.

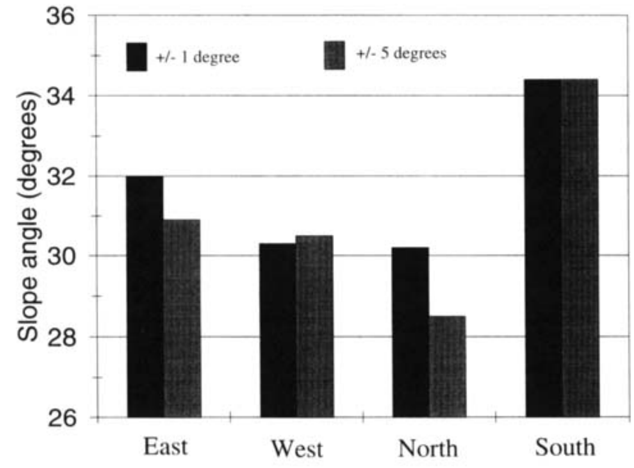

Fig. 3. To show the slope angle differences for the four cardinal directions as indicated by both +/- 1° and +/- 5° arcs of data capture.

The majority of periglacial texts consider the weathering attribute associated with valley asymmetry to be that of freeze-thaw weathering, but recently suggestions have been made that this may be an over simplification (e.g. see French 1996, p. 183). The whole concept that freeze-thaw is the ubiquitous and sole weathering process in cold regions is being questioned (e.g. Hall 1995) and this is particularly appropriate here owing to the general aridity of the area. Available information (Hall 1997a) indicates that snowfall is very limited and that the availability of water is highly restricted, both spatially and temporally. If moisture is not present breakdown by the freeze-thaw mechanism is impossible. Hall (1997b, p. 185) argues that in these higher latitudes protective shading is detrimental to geomorphic activity (weathering, transport, water availability, etc.) and so the greatest amount of change takes place on the sunnier north facing slopes. Certainly, weathering data (e.g. taffoni occurrence and size, and Schmidt hammer rebound values) indicate greatest weathering on the northern and western exposures (Hall 1997a), which can also explain the aspect-specific orientation of cryoplanation terraces (Hall 1997b). Rock temperature data (Meiklejohn 1994, Hall 1997a, 1997b) show that thermal stress fatigue and thermal shock are the most likely factors in weathering within this area, and "...the western and northern exposures experienced a far greater range..." and that "...the rate of change of temperature was far greater on the western and northern aspects..." (Hall 1997b, p. 186). Thus, the insolation factor that affects the thickness of the active layer will, even in the absence of moisture, contribute to enhanced weathering on the north facing slopes. However, water is not totally absent but rather is spatially and/or temporally constrained such that it is on the warmer slopes that it will more readily be in the liquid form and thus able to enhance both weathering and transport. The combination of a deeper active layer and the enhanced transport this can facilitate, together with the increased weathering, can explain the gentler north facing slopes.

Table II. Data from Base Esperanza (63°24'S, 56°59'W, 13 m a.s.l.) to show the total irradiation (in kWH m^{-2}) of a horizontal plane compared to that of both northern and southern tilted planes (albedo = 0.25) of 90°, 45°, 30° and for the mean slope (28°and 34° for north and south respectively) angles found in the GIS analysis.

	Horizontal	N90°	S90°	N45°	S45°	N30°	S30°	N28°	S34°
Jan	144	101	65	146	93	151	114	151	109
Feb	106	91	44	121	57	121	73	121	68
March	77	96	30	109	37	103	39	102	38
April	39	90	14	85	17	74	17	72	17
May	19	135	4	107	4	82	4	78	4
June	10	300	-1	220	-4	159	-5	150	-4
July	14	210	1	158	-1	117	-1	111	-1
Aug	33	128	9	111	10	90	10	87	10
Sept	66	111	23	116	27	104	28	102	28
Oct	112	114	42	142	53	139	67	138	60
Nov	139	104	60	147	83	151	106	151	100
Dec	154	103	72	153	105	159	126	159	121
Year	915	1582	362	1616	483	1451	580	1423	551

The impact of radiation receipts upon the slopes has been qualitatively considered but little has been done to evaluate the quantitative impact, the study of Davidson (1992) being one significant exception. As Meiklejohn's model (1994, fig. 5) and theory (e.g. Fench 1996) suggest, the role of radiation upon ground/rock temperatures can be a significant factor. What is rarely considered is the impact of radiation upon slopes of different angles. The angle which depends upon the time of year (and hence the declination of the sun), can greatly affect solar heating. Bolsenga (1964, p. 1) states "Quantitative information on global radiation is needed in many types of studies including those pertaining to the distribution, accretion, and ablation of ice and snow, the thawing of soils...." and provides tables for daily sums of global radiation for cloudless skies. As invaluable as these are, they still do not facilitate evaluation of different slope aspects, angles and albedos – the very factors needed in slope studies. MeteoNorm™ is a computer programme that allows for the calculation of radiation receipt (global, diffuse and direct) for slopes of any aspect, angle and albedo for non-polar sites. Although it is not possible to run the calculations for Mars Oasis, data from Base Esperanza (63°24'S, 56°59'W, 13 m a.s.l.), the nearest Antarctic station available in MeteoNorm™, does provide information germane to the arguments presented here. Calculations were run to derive irradiation (in kWh m^{-2}) for a horizontal surface and north and south facing slopes of 90°, 45°, 30° and for the mean values (28° and 34° respectively) derived from the DEM analysis (Table II). These show some results that might not have been arrived at intuitively, but which may impact on valley asymmetry. The data for the horizontal surface show the expected pattern, with highest values from the October to March, spring to autumn period, and lowest values during the winter. The slope data are significantly different, with the north facing slope receiving the highest radiation receipt in midwinter on the 90° and 45° slopes – the time when the slopes are nearly normal to the declination of the sun. The 30° slope shows two peaks, one in winter when the sun's rays are nearly normal to the surface and one in summer when, although the sun's angle is much steeper, the radiation input is high. The 28° slope has a winter peak but the highest values are in summer. Conversely, the south facing slopes have low to negative radiation receipts in winter and higher, but still low when compared to the north facing slopes, values in summer. The principle shown by these Base Esperanza data, is that there is a highly significant radiation receipt differential between the northern and southern slopes that should, further influenced by slope angle, greatly impact slope processes. With the availability of moisture, and certainly the propensity for snow melt is higher on the north facing slope, so (following the arguments of Davidson 1992) the north facing slopes should experience more freeze-thaw and wet-dry weathering; the data of Hall (1997a) would suggest that thermal stress fatigue should also be a major factor. Thus, the radiation data indicate that the north facing slopes will be geomorphologically far more active than the south facing slopes, and that the slope asymmetry model of Meiklejohn (1994) appears to be substantiated. The importance of radiation receipt upon slope processes, and the impact that slope angle, aspect and albedo has upon these, is in need of much more quantitative evaluation.

Conclusions

The GIS approach to the evaluation of valley asymmetry provides, where data are available, a very efficient and powerful diagnostic tool. Certainly it facilitates acquisition of far larger data sets than would be possible by non-computer based approaches. The results from Mars Oasis clearly demonstrate that there is aspect-related slope asymmetry, with steeper south facing slopes, that is not the result of structural or lithologic factors. The general aridity of this area mitigates against the ubiquitous action of freeze-thaw weathering but it can occur in spatially-constrained areas where water is available; north facing slopes would be those most likely to experience snow melt where snow is available. Field information suggests that weathering by thermal stress fatigue/shock should also be considered and that this, too, would be most effective on north facing slopes. The impact of solar radiation on the slopes, and the variability of this through the year, is potentially a major factor and more information on this is required. The weathering, coupled with the aspect influence on active layer thickness, helps explain the greater breakdown and debris mobility on north facing slopes and hence the lower angle. The occurrence of a number of weathering related landforms (taffoni and cryoplanation terraces) in this area substantiates this hypothesis. Thus, despite the errors that can be produced from the original DEM data, it appears that there truly is valley asymmetry in this region and that it can be explained by aspect-constrained process differentiation.

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