GEOMORPHOLOGY AND SEDIMENTOLOGY OF UNION GLACIER AREA, ELLSWORTH MOUNTAINS, OCCIDENTAL ANTARCTICA

GEOMORFOLOGIA E SEDIMENTOLOGIA DA ÁREA DA GELEIRA UNION, MONTANHAS ELLSWORTH, ANTÁRTICA OCIDENTAL

Vanessa do Couto Silva Costa

Instituto de Geociências, Universidade Federal Fluminense
Av. Gal. Milton Tavares de Souza, s/n, Niterói, Rio de Janeiro. CEP: 24210-346. Brasil
Email: vanessacosta@id.uff.br

Rosemary Vieira

Instituto de Geociências, Universidade Federal Fluminense
Av. Gal. Milton Tavares de Souza, s/n, Niterói, Rio de Janeiro. CEP: 24210-346. Brasil
Email: rosemaryvieira@id.uff.br

Jefferson Cardia Simões

Instituto de Geociências, Universidade Federal do Rio Grande do Sul
Av. Bento Gonçalves, 9500, Porto Alegre, Rio Grande do Sul. CEP: 91501-970. Brasil
Email: jefferson.simoes@ufrgs.br

Abstract:

The work aims to investigate the geomorphological and sedimentological aspects of Union Glacier area (79°45'00''S; 82°30'00''W), southern sector of Ellsworth Mountains. Geomorphological cartography based on 15 m ASTER (2010) satellite imagery and field works were carried out during the Brazilian expedition (2011/2012) enabled the identification of morainic formations: ice-cored hummock moraines, supraglacial moraines, and recession moraines in the interior of the valleys. With the exception of the latter one, all types of moraines have been developed on the blue-ice areas. The evidence for paleo wet-based glacial conditions is reconstructed from a range of geomorphological record, including exposed abrasion marks, striations and glaciotectonic deformation. This type of deformation is represented by lee sides of oversteepening bedrock promontories which follow the tributaries of glaciers ice flow. Glacial sediments were collected from the moraines for granulometric and morphometric analyses. They show the prevalence of sandy gravel and sand texture, low quantity of fine fractions, and absence of attributes such as striated and faceted clasts, which indicate, on the other side, low-sediment transport capacity from the ice sheet bottom. It is inferred that the moraine debris are originated from local sources. Weathering action and constant katabatic winds are possibly the major agents of transport and alteration of the exposed sediments. The geomorphological features

reveal an ancient thicker ice sheet, and sedimentary characteristics of the morainic formations reveal a latter thinner ice sheet in this sector of Ellsworth Mountains.

Resumo:

O trabalho objetiva examinar as feições geomorfológicas e sedimentológicas de morainas na área da Geleira Union (79°45'00''S; 82°30'00''W), setor sul das montanhas Ellsworth. Trabalhos de campo durante a Expedição Criosfera no verão de 2011/2012 e cartografia com imagem ASTER (2010) possibilitaram identificar formações morâinicas: moraínas com núcleo de gelo, moraínas supraglaciais e moraínas de recessão no interior de vales. Exceto pela última, as demais moraínas se desenvolveram nas áreas de gelo-azul. Evidências de atividade de geleiras de condição termo-basal úmida são reconstruídas a partir de registros geomorfológicos, incluindo marcas de abrasão, estrias, feições *stoss e lee* que seguiam o fluxo de gelo das geleiras tributárias. Amostras de sedimentos glaciais foram coletadas das moraínas e analisadas, revelando o predomínio de textura cascalho arenosa e arenosa, e baixa quantidade de material fino. A ausência de atributos, tais como clastos estriados e facetados indicam, por outro lado, pouca capacidade de transporte de sedimento desde a base do manto de gelo. Ações locais de intemperismo e ventos catabáticos constantes são possivelmente os principais agentes de transporte e alteração dos sedimentos expostos. As características geomorfológicas revelam um manto de gelo mais espesso e as caraterísticas sedimentares das moraínas revelam um manto de gelo menos espesso nessa parte das Montanhas Ellsworth.

1. Introduction

Past fluctuations of the West Antarctic Ice Sheet (WAIS) are of fundamental concern for the possibility of WAIS collapse in the future and a consequent rise in global sea level (HEIN *et al*., 2016). The WAIS volume has undergone fluctuations since the Quaternary, from expansion events, with ice covering local mountains and valleys, to the retraction events with exposure of subglacial topography. Several years of research have produced a large set of geological data constraining Antarctic Ice Sheet history, based on the significant progress of acquisition methods and analysis of terrestrial and marine records of past ice-sheet thickness and extent (RAISED, 2014). Geomorphic/geologic studies can provide evidence of past behavior, e.g. the changes associated with a glacial cycle, which has implications for former basal regimes and the erosive potential of a glacial cycle (SUGDEN *et al*., 2006).

There is evidence for the sensitivity of the WAIS to the climate variations during the last glacial cycle, especially in its peripheral areas. Marine biology studies suggest the disappearance of great part of the ice sheet during interglacials, creating an open seaway between the Pacific and Atlantic sectors (SCHERER *et al*., 1998; BARNES and HILLENBRAND, 2010; STRUGNEL *et al*., 2012). The ice sheet is shrinking in size since the Last Glacial Maximum (LGM) in all sectors, especially in the Pacific-facing sector (FOGWILL *et al*., 2011; JOUGHIN *et al*., 2014; RIGNOT *et al*., 2014). The ice sheet reduction in size and thickness has generated exposed areas with a variety of erosional and depositional forms.

Ellsworth Mountains are located near the modern grounding line zone between the WAIS and Ronne-Filchner Ice Shelf, and exhibit the former levels of past expansion and retreat printed on the landscape (DENTON *et al*., 1992). Outlet glaciers flow around the nunatacks and from the valleys toward the Filchner-Ronne Ice Shelf in Hercules Inlet (RIVERA *et al*., 2014).

Geomorphological evidences in the Ellsworth Mountains suggest that the WAIS was between 450 to 600 m higher during the LGM (ACKERT *et al*., 1999; FOGWILL *et al*., 2011). Bentley *et al*. (2010) show that during this period the ice cover was at least 430 m thicker, and that the WAIS in the Ellsworth Mountains region has decreased its thickness up to 480 m in the past 15 ky. Recent study of Hein *et al*. (2016) suggests the continuous presence of the ice sheet in the southern Ellsworth Mountains uplands for 1.4 Ma, while the sectors near de grounding line have experienced loss of marine-based portions during some interglacials throughout the Pleistocene. A more recent study with analysis of rock samples in the same area reveals that some clasts have been exposed on glacially mounded surfaces for at least 1.4 Ma and perhaps more than 3.5 Ma (SUGDEN *et al*., 2017).

The Ellsworth Mountains are an area of high concentration of surface deposits and erosional features, which contains records of the geological, climatic and environmental history. Fogwill *et al*. (2011) recorded blue-ice moraines on Soholt Peaks, Liberty Hills, Independence, Mar-

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ble and Patriot Hills (Heritage Range). Vieira and Simões (2011) and Vieira *et al.* (2012) identified and described, respectively, the glacial geomorphology of Independence and Patriot Hills, and the periglacial features at Patriot Hills, such as rock glacier-like landform, creeping debris--mantled and steep debris-mantled slopes. Nevertheless, the interpretation of many erosional e depositional forms is still a puzzle for the regional glacial history.

The purpose of this work is to investigate the geomorphological and sedimentary aspects through depositional and erosional features in Union Glacier area, southern part of the Ellsworth Mountains, and its morphogenetic environments.

1.1 Regional setting

The Ellsworth Mountains form a NNE–SSW trending mountain range approximately 415 km long, centered at about 79ºS 84ºW (Figure 1); they are divided into two geographically distinct ranges, the Sentinel Range to the north, and the Heritage Range to the south (DENTON *et al.*, 1992). The mountains are located along the northern periphery of the crustal block of the Ellsworth-Whitmore Mountains, which represent part of a displaced terrain once

situated along the paleo-Pacific margin of Gondwana, prior to supercontinent breakup (STOREY, 2005).

Union Glacier (UG) has a total area of 2561 km^2 and length of 86 km, from the ice divide with the Institute Ice Stream down to the grounding line of Constellation Inlet on the Ronne Ice Shelf (RIVERA *et al.*, 2014). The glacier is fed by several glacial valleys, flowing from the interior cirques and accumulation basins between mountains ridges (DENTON *et al.*, 1992) (Figure 1). Union Glacier is characterized by an extensive blue-ice area swept by katabatic winds from the ice sheet and a central moraine line (RIVERA *et al.*, 2010). The maximum ice thickness is 1540 m, with a maximum snow ice boundary layer at 120 m. Ice flow velocity is 20 m/y and shows stability (RIVERA *et al.*, 2014).

In the available climatic series for the region, from 2008 to 2012, the mean daily air temperature was −20.6 °C, with an absolute minimum of −42.7°C (August 2008) and an absolute maximum of 0.5°C (January 2010). Wind speed and direction, between 2008 and 2012, have a mean value of 16.3 knots and a predominant direction from 224°. The maximum wind speed recorded on site was near 60 knots and the predominant wind speeds are higher than 25 knots (RIVERA *et al.*, 2014 - Figure 1).
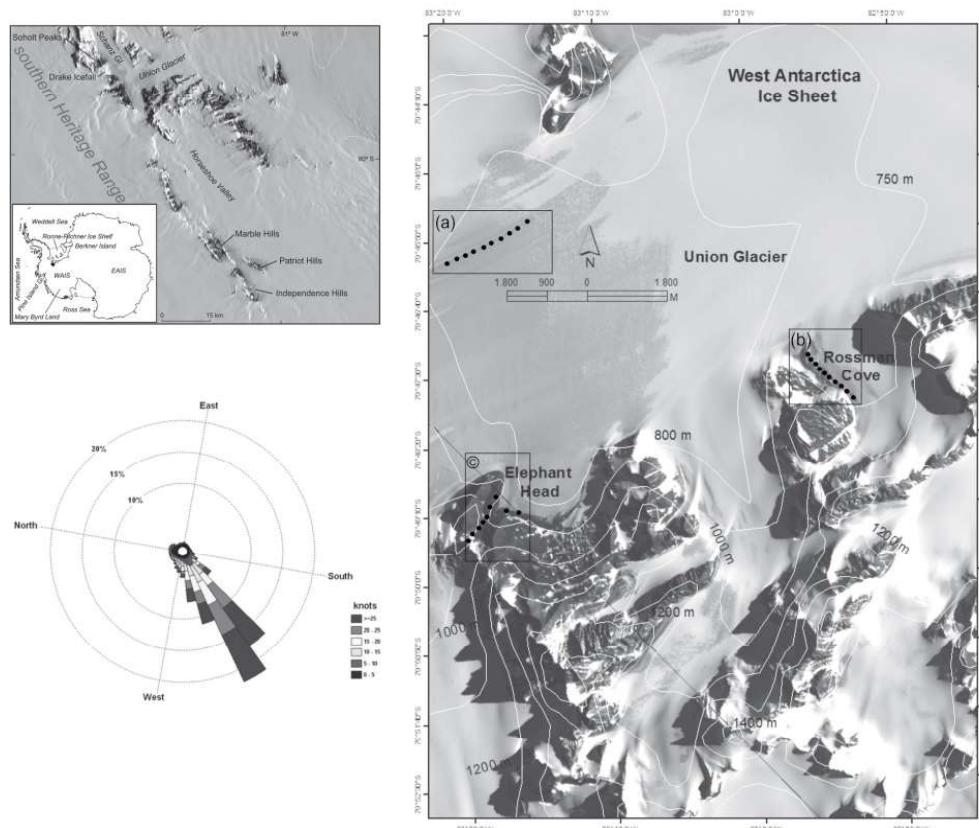

Figure 1 - Union glacier area (sources: ASTER, 2010; FOGWILL et al., 2011). Predominant wind speed and direction for 2008–2012 at the Union Glacier automatic weather station, installed near stake V17 (RIVERA et al., 2014). Sample sites shown in rectangles sets and in black circles: (a) Union glacier; (2) Rossman Cove; (c) Elephant Head.

2. Methods

Identification and classification of moraines as well as observations and measurements of glacial erosional and depositional features, in particular, were performed in 2011-2012 summer season, during the Brazilian Cryosphere Expedition.

Sediments were sampled at: (a) Union Glacier (11 samples); (b) Rossman Cove (10 samples); (c) Elephant Head (9 samples) (Figure 1 and Table 1). 100 g of superficial sediments were collected with a spoon in shallow cavities in order to avoid weathered material, and identified with codes. At each sampling site, control points (GPS coordinates and altitude), photography and observation of the surrounding environment were obtained. For morphometric analysis, 50 clasts were collected with major axis >15 mm from each sample site.

The particle size was determined in the laboratory by dry sieving at phi intervals of -3ϕ to 4ϕ (8 mm to 0,63 mm). Descriptive statistics for particle-size-distribution were obtained using Gradistat, including mean, percentage distributions of gravel, sand and mud and sorting for logarithmic distributions (e.g. FOLK and WARD, 1957). Morphometric analysis of clasts was carried out on 50 clasts with major axis >15 mm in the digital caliper to visually determine the relative size of the three orthogonal axes: *a* (longest), *b* (intermediate) and *c* (shortest).

Roundness (clast size from 2 to 8 mm) was obtained with the aid of a binocular microscope using the descriptive criteria provided by Benn and Ballantine (1994). The estimated roundness classes for each sample was translated into percentages and plotted as frequency distributions. The percentages of very angular (VA) and angular (A) were added to calculate the RA-index. Additionally, shape and roundness were summarized using C_{40} index (% of clasts which axis $c/a \leq 0.4$). RA-index (% of angular and very angular clasts) and RWR-index (% of rounded and well-rounded clasts) were conducted according the method proposed by Benn and Balllantyne (1994), Evans and Benn (2004), and LUKAS *et al.* (2013) in order to distinguish between erosional, transportational and depositional clast histories. We plotted both RA/RWR and C_{40}-index in covariant diagrams to allow a clear distinction between sediments predominantly being passively supraglacially transported and those which have been actively subglacially transported (BENN and BALLANTYNE, 1994; BENNETT *et al.*, 1997; LUKAS *et al.*, 2013). Ternary diagrams (using Triplot) and histograms display clast shape and roundness.

The mapping of geomorphological and glaciological features was based on GPS control-points and ASTER imagery (Advanced Spaceborne Thermal Emission Reflection Radiometer) data. The scenes were acquired on 27/01/2010 with spatial resolution of 15 m data. Morphological features identified in ASTER visible/near-infrared (VNIR) color composite scenes (RGB 321) and verified during field activities were recorded using a portable GPS, with an error of about 3 m. The newly detected morphological features were mapped using ArcGis© software. Geomorphological mapping was elaborated with Polar Stereographic coordinate and WGS84 geodetic reference system.

3. Results and Discussion

3.1.1 Geomorphological features

Figure 2 represents a geomorphological and glaciological map. Well-preserved glacial and periglacial landforms could be identified based on visual interpretation of ASTER images and in field activities, including moraines and micro-scale/meso-scale erosional features (striation and stoss and lee – Figs. 3a-b). Three morainic assemblages were identified: ice-cored hummock moraines, supraglacial moraines, and recession moraines in the interior of the valleys.

Two major erosional features were identified on exposed outcrops at the northeast Rossman Cove Hills side, situated at 40-50 meters above ice surface. Well-defined and preserved potholes, grooves and striations reveal abrasion by glaciers at different periods (Figure 3a-b). Some of them present visible signs of oxidation, with reddish-brown color. These striations are typical of glacial abrasion beneath warm-based ice (SUGDEN *et al.*, 2017). Brightened colored striation can be produced by more recent glacial activity since they were not affected by oxidation.

A stoss and lee feature carved from bedrock (Figure 3c) is the most obvious evidence for the erosive action of overriding ice on the local topography, with smoothly stoss face abraded up ice and plucked down-ice lee face. The top-surface of this outcrop displays extensive subaerial weathering, and no till veneers were found. This landform indicates a past thickest ice sheet covering part of the topography, since the summit of the hill is approximately 200 meters above current ice surface. The feature also indicates an ancient glacier flow toward to UG (Figure 2).

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Table 1: Latitude, longitude, and sampling information for Union Glacier, Rossman Cove and Elephant Head samples.

| Sample ID	Latitude	Longitude	Altitude (m.a.s.l)	Silt (%)	Sand (%)	Gravel (%)
Union Glacier						
UG-MO-01	79° 45' 51.8''S	83° 14' 55.0''W	762	0,8	14,1	85,2
UG-MO-02	79° 45' 59.1''S	83° 15' 09.2''W	756	0,1	16,9	83,0
UG-MO-03	79° 45' 66.6''S	83° 15' 89.5''W	759	0,1	31,9	68,0
UG-MO-04	79° 45' 73.7'S	83° 16' 68.0''W	767	0	10,9	89,1
UG-MO-05	79° 45' 81.0''S	83° 17' 58.5''W	767	2,4	10,4	87,2
UG-MO-06	79° 45' 86.1''S	83° 18' 22.0''W	762	0,1	23,7	76,3
UG-MO-07	79° 45' 91.7''S	83° 18' 98.9''W	753	3,1	4,1	92,9
UG-MO-08	79° 45' 97.5''S	83° 19' 81.8''W	766	0	13,5	86,5
UG-MO-09	79° 46' 03.5''S	83° 20' 72.8''W	772	2,8	21,5	75,7
UG-MO-010	79° 46' 08.8''S	83° 21' 57.2''W	776	0	12,8	87,1
Rossman Cove						
Beach-MO-01	79° 47' 89.2''S	82° 53' 36.9''W	747	0	24,2	75,8
Beach-MO-02	79° 47' 84.9''S	82° 53' 53.6''W	763	0	27,6	72,4
Beach-MO-03	79° 47' 80.8''S	82° 53' 74.7''W	766	0,1	18,7	81,2
Beach-MO-04	79° 47' 75.7''S	82° 54' 01.1''W	761	0,1	23,0	76,9
Beach-MO-05	79° 47' 71.7''S	82° 54' 29.2''W	766	0,4	26,3	73,3
Beach-MO-06	79° 47' 68.6''S	82° 54' 58.4''W	752	0,1	18,5	81,4
Beach-MO-07	79° 47' 60.9''S	82° 54' 85.0''W	741	0,1	14,9	85,0
Beach-MO-08	79° 47' 56.2''S	82° 55' 09.6''W	738	0,3	24,1	75,7
Beach-MO-09	79° 47' 50.3''S	82° 55' 39.7''W	738	0	11,6	88,3
Beach-MO-10	79° 47' 43.9''S	82° 55' 71.1''W	726	0,1	19,7	80,2
Elephant Head						
EHV-01	79° 49' 29.8''S	83° 20' 42.6''W	810	0,1	39,6	60,3
EHV-02	79° 49' 23.8''S	83° 18' 92.8''W	739	0,1	52,5	47,4
EHV-03	79° 49' 13.1''S	83° 18' 42.5''W	691	0,0	41,8	58,2
EHV-04	79° 49' 28.9''S	83° 20' 02.0''W	818	0,4	29,5	70,1
EHV-05	79° 49' 22.9''S	83° 19' 07.7''W	741	0,1	48,9	51,0
EHV-06	79° 49' 03.2''S	83° 18' 03.2''W	700	0,2	38,6	61,2
EH-MO-01	79° 49' 11.1''S	83° 16' 10.7''W	718	0,5	10,9	88,6
EH-MO-02	79° 49' 01.2''S	83° 12'25.4''W	737	0,2	13,0	86,9
EH-MO-03	79° 49' 05.4''S	83° 12' 39.6''W	782	0,5	14,0	85,5
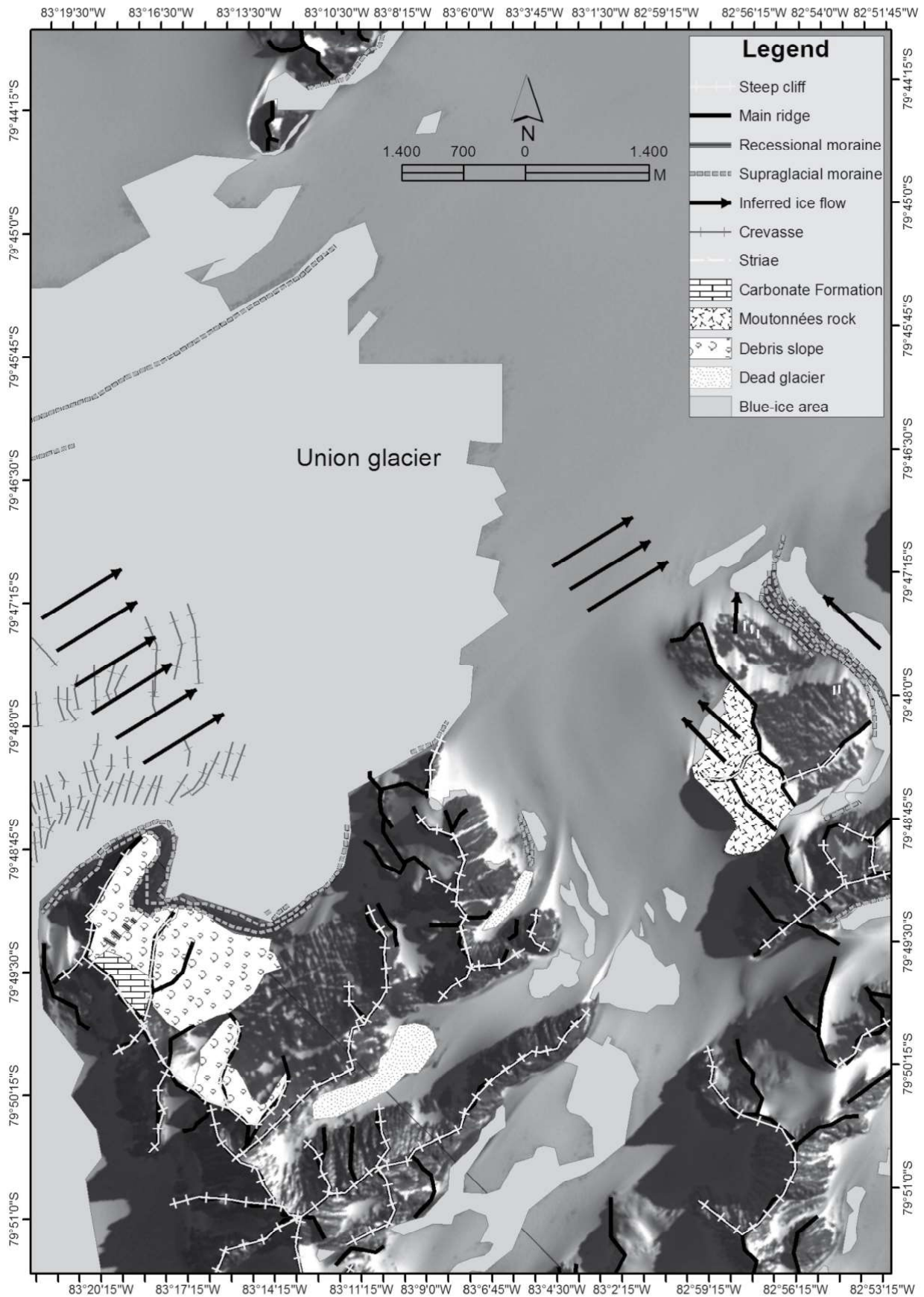
Figure 2 - Geomorphological and glaciological map (with background image Aster color composite 321 acquired on 27/01/2010). Glacier flow is inferred by the geomorphological features and Rivera et al. (2014).
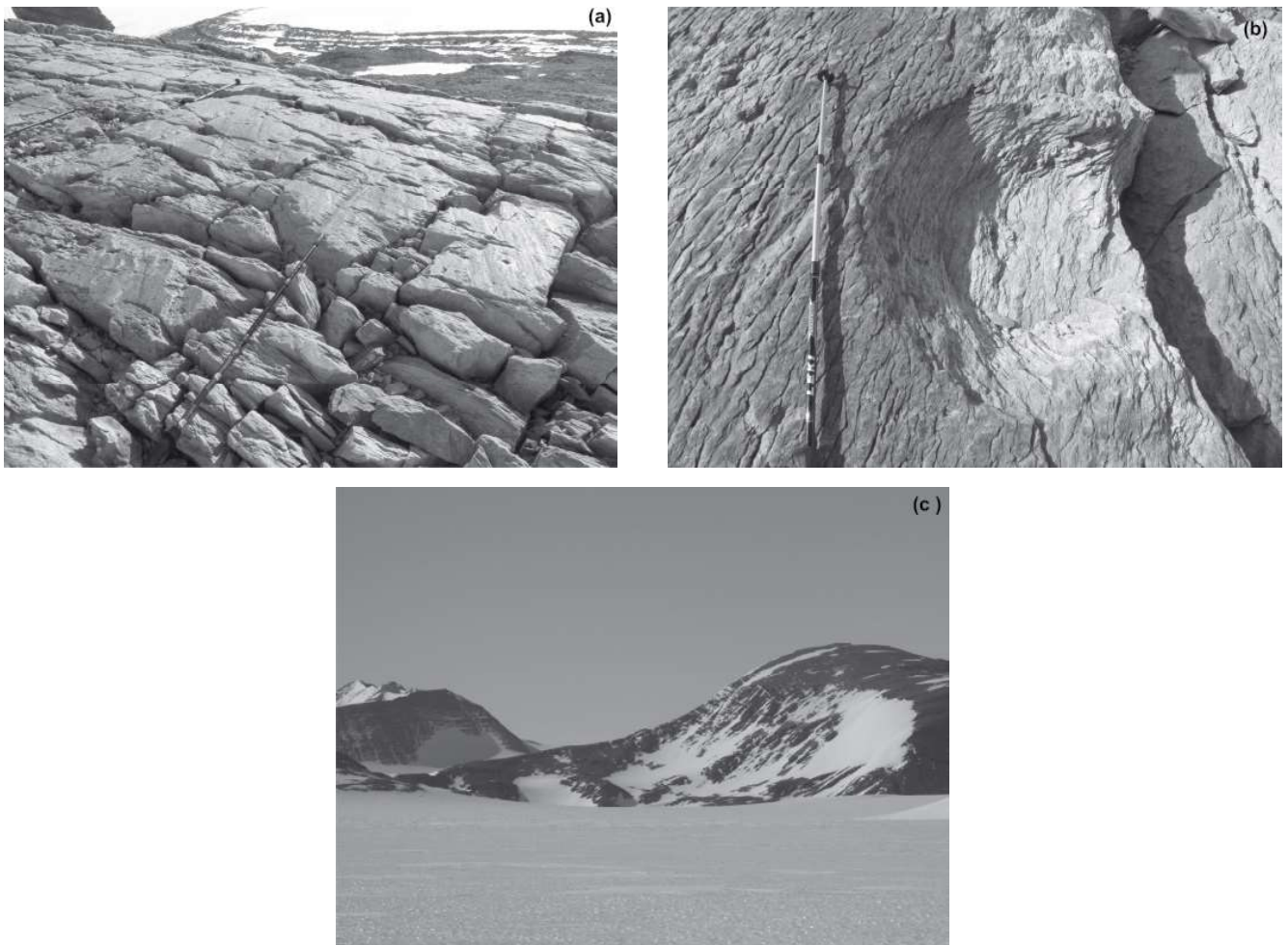
Figure 3 - (a) Striations on Rossman Cove bedrocks; (b) potholes on Rossman Cove bedrocks; (c) Stoss and lee feature in Rossman Cove area. The summit of the hill is approximately 200 meters above current ice surface.

Depositional features were fairly found in Rossman Cove, Elephant Head Valley and Union Glacier, and are represented by supraglacial/ice-cored moraine. Ice-cored hummocky moraines were observed at the margin of UG, at Mount Dolence. With the exception of Elephant Head Valley, all investigated moraines have developed on the blue-ice areas, and massive ice was recorded below the debris cover.

Ice-cored moraines emerge on the current ice-sheet at the northeast side of Rossman Cove, central part of UG and at Elephant Head Valley, at southern margin of UG. In Rossman Cove, the arcuate moraines are characterized by continuous ridges with narrow bands of debris-rich ice extending more than 2 km northeastward as a tail, indicating flow structures. The ridges are mainly 1-6 m of amplitude (Figs. 2 and 4).

Extensive high ice-cored moraine develops at the marginal flank of UG, against the Elephant Head Val-

ley side, and fore wall of the Mount Dolence bedrock ridges, on the blue-ice ablation zone (Figure 5a). The moraine is high, over 7 m, with a predominance of gravel and boulders. The ice-cored moraine becomes thicker toward the interior of the Elephant Head valley, which could be evidence for glacial flow toward this margin, periglacial processes with slope activities, or a past thick ice sheet (Figure 5b).

A long and narrow moraine of approximately 2.35 km develops in the center of UG, but the height does not exceed 1 m (Figure 6). The sediment is a mix of grain sizes, ranging from sand and gravel to boulders. The genesis of these moraines implicates different processes, but their location on the blue-ice area submits them to the inherent environmental conditions, such as the sublimation and erosion processes produced by the constant action of katabatic winds from the polar plateau, and, in addition, the complex spatial and temporal patterns of ice flow.

Figure 4 - Rossman Cove supraglacial moraine, with length of 2 km, approximately.

(a)

(b)

Figure 5 - (a) Elephant Head supraglacial moraine and blue-ice area, view from mount Dolence area; (b) Elephant Head supraglacial moraine and blue-ice area, view from the interior of the valley.

Figure 6 - Union Glacier moraine. Hyde glacier in the back.

3.2 Sedimentological aspects: grain-size and clast shape analyses

Sediment sampling at Union Glacier and Rossman Cove was carried out during occasional melting events, when subsurface material could be accessed. In UG samples particle size distribution presents small variations, but still distinct. The grain size analysis shows that the sediment consists of more than 68% gravel to sand (Table 1). Sand comprises 4-31% of the sediments. The content of silt and finer material does not exceed 3.1% and the average was only 1%. As the region is subjected to strong winds, the concentration of gravel predominates on the surface. Therefore, the results indicate well-sorted sediments, and only two of them are poorly sorted. The histograms show the low proportion of very angular and angular clasts; clasts are predominantly sub-angular and sub-rounded (Figure 7). No striated or faceted clasts were observed.

The texture of the samples of Rossman Cove su-

praglacial moraines is composed by at least 72% gravel and 21-27% sand (Table 1). Samples are divided into sandy gravel and sandy fine gravel. The content of silt and finer material does not exceed 0.4% and the average was only 0.1%. The region is also subject to the action of strong winds, so the concentration of gravel also predominates on the surface. The samples are moderately to well-sorted, with the exception of Sample 5. Modifications by wind abrasion and transport of finer particle size material may explain the higher percentage of rounded clasts on the surface (Figure 8).

Particle size analysis of recessional and supra-glacial moraine at Elephant Head Valley shows the predominance of sandy gravel and sand textures (Table 1). The sand content ranges from 11 to 52%, the highest sand content of all sampled sites. The valley is partially wind-protected and there is considerable debris supply from slopes, which may explain the increased presence of sands and poor selection of sediments.
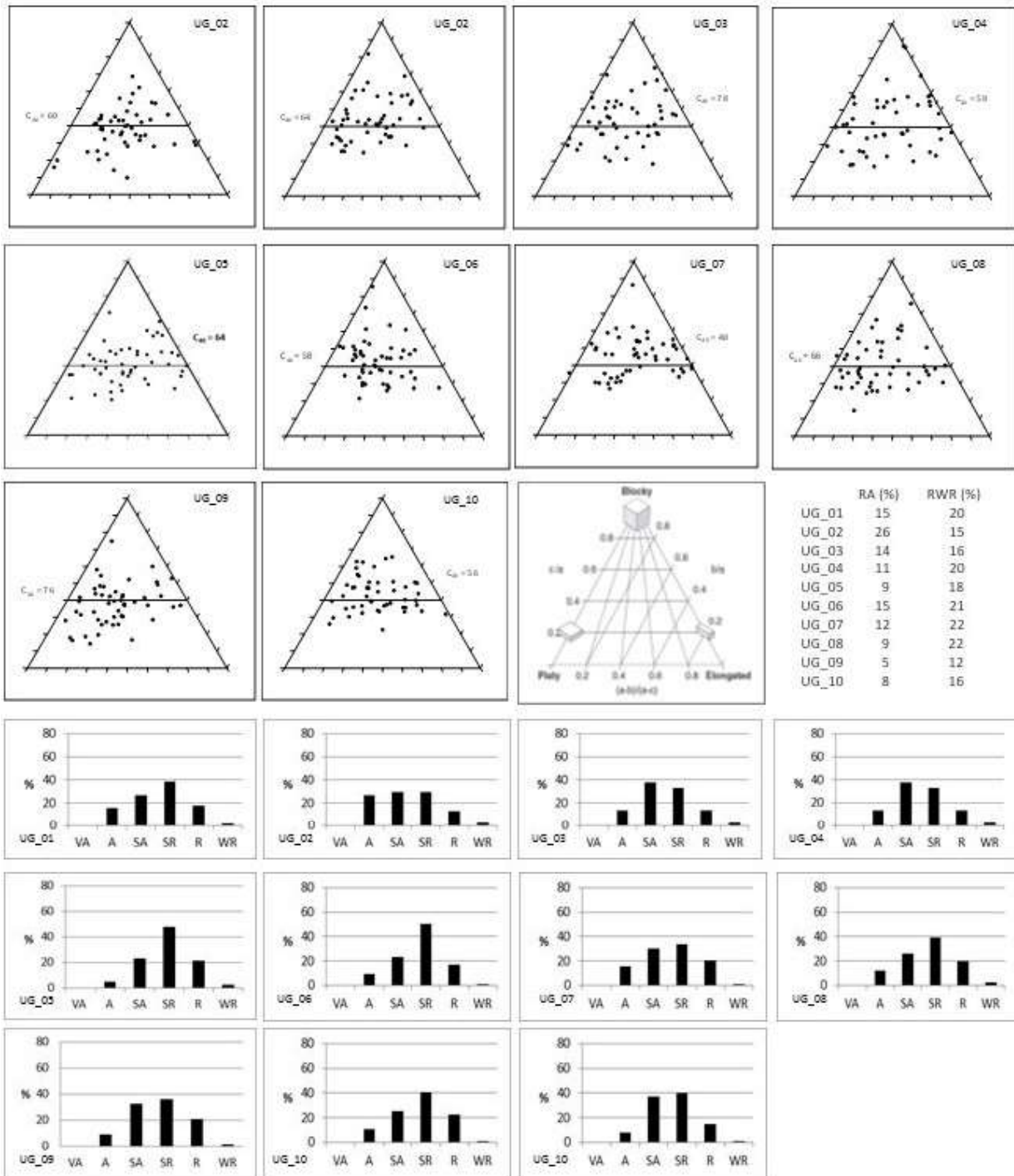
Figure 7 - Union Glacier: (a) ternary diagrams (form); (b) roundness histograms. RA (% angular and very angular clasts); RWR (% rounded and well-rounded clasts).

The supraglacial moraine is located at the margin of UG, next to the blue-ice area, with continuous local wind action, and it was the site with collected smaller number of samples, due to the high concentration of boulders and massive subsurface ice. The moraine rises between 5 and 8 meters above the present ice surface.

The percentage of samples of sandy gravel is greater than 85%, followed by sands (10 to 14%). Fine material is unexpressive. The prevalence of sub-angular and sub-rounded clasts may reveal that the action of wind in this area is intense (Figure 9).

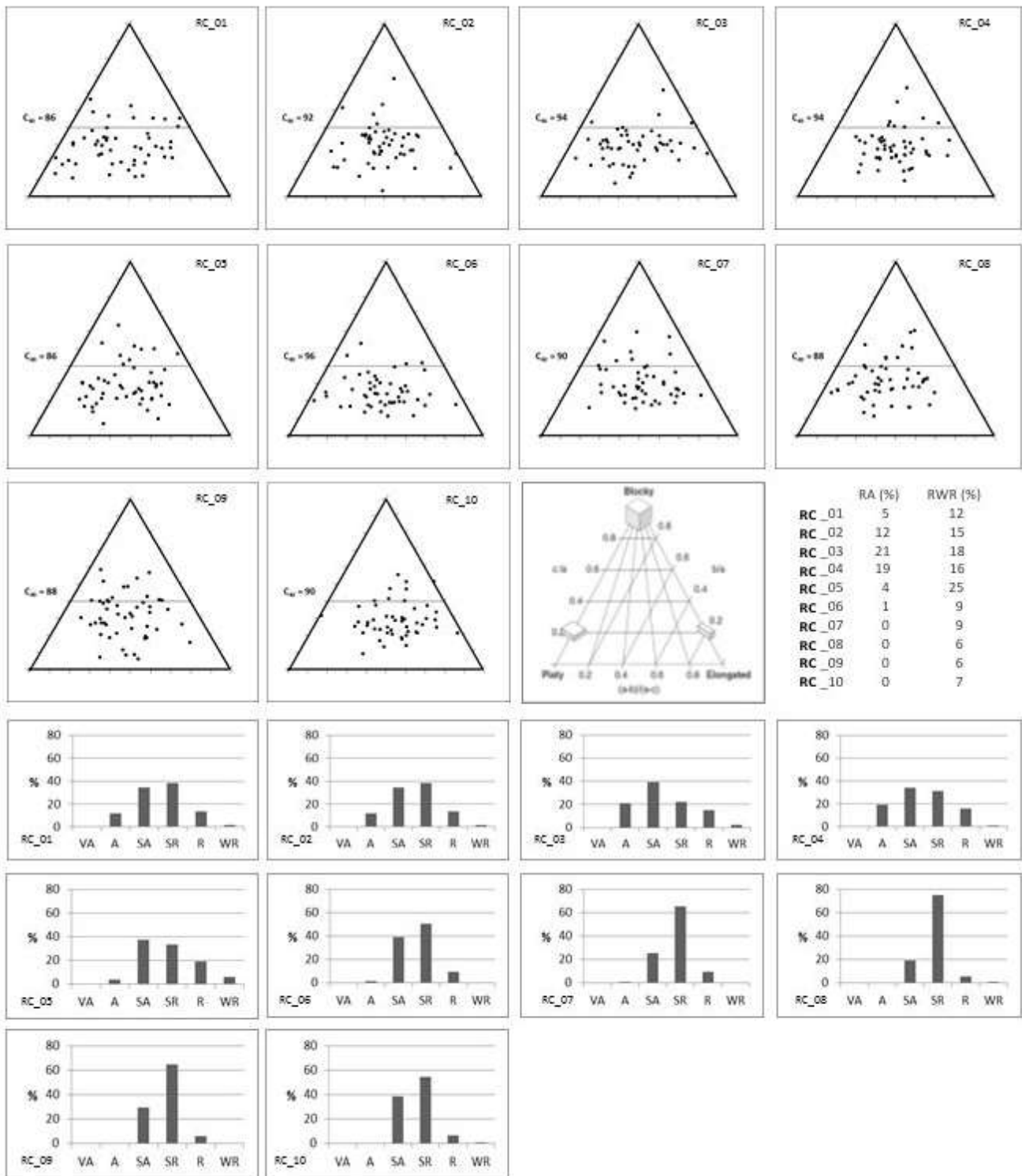*Rev. Bras. Geomorfol. (Online), São Paulo, v.18, n.3, (Jul-Set) p.579-594, 2017*

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Figure 8 - Rossman Cove: (a) ternary diagrams (form); (b) roundness histograms. RA (% angular and very angular clasts); RWR (% rounded and well-rounded clasts).

Therefore, we interpret the supraglacial debris in this sector as originating mainly from surrounding slopes, which have supraglacially entrained, transported and accumulated in this area, as also observed in Dronning Maund Land (HÄTTESTRAND and JOHANSE, 2005) and in Marie Byrd Land (SUGDEN *et al.*, 2005).

All the samples ($\geq$ 15mm) show a predominance of high C_{40} index that indicates discs and slabs shapes.

The diagrams in Figure 10 show the covariant plot and analyses how two aspects of the clasts (shape and roundness) may vary with the origin and history of the transportation of glacial deposits (EVANS and BENN, 2004). The most sampled sites data showed little consistency, therefore not revealing the effective action of glacial transport on sediments form, which means short distance of transportation by the glacier or lack of meltwater subglacial activity. In this sense, it may be inferred that debris have been accumulated on the ice sheet surface rather than being transported away by the glacier. The morainic deposits, with the exception of sub-rounded clasts, have no significant signs of subglacial meltwater transport, such as fines and striated clast (HÄTTESTRANS and JOHANSEN, 2005; SUGDEN *et al*., 2005). In addition, there is no actual evidence for basally derived material brought to the surface by upward flow as observed in Patriot and Independence Hills (VIEIRA and SIMÕES, 2011; FOGWILL *et al*., 2011; HEIN *et al*., 2016). Finally, initial mineralogical analyses reveal local lithology as sediment provenance.
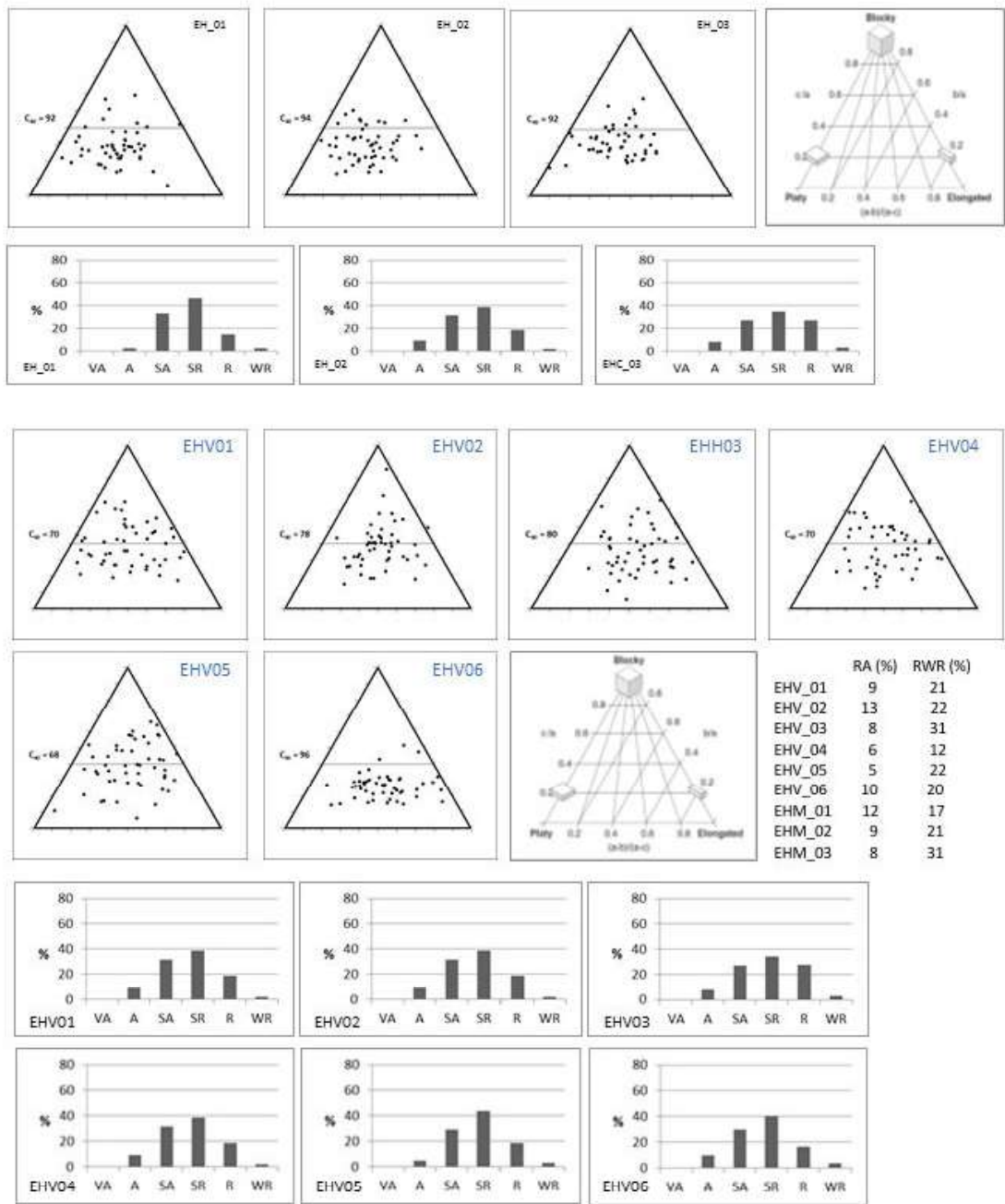

Figure 9 - Elephant Head: (a) ternary diagrams (form); (b) roundness histograms. RA (% angular and very angular clasts); RWR (% rounded and well-rounded clasts).
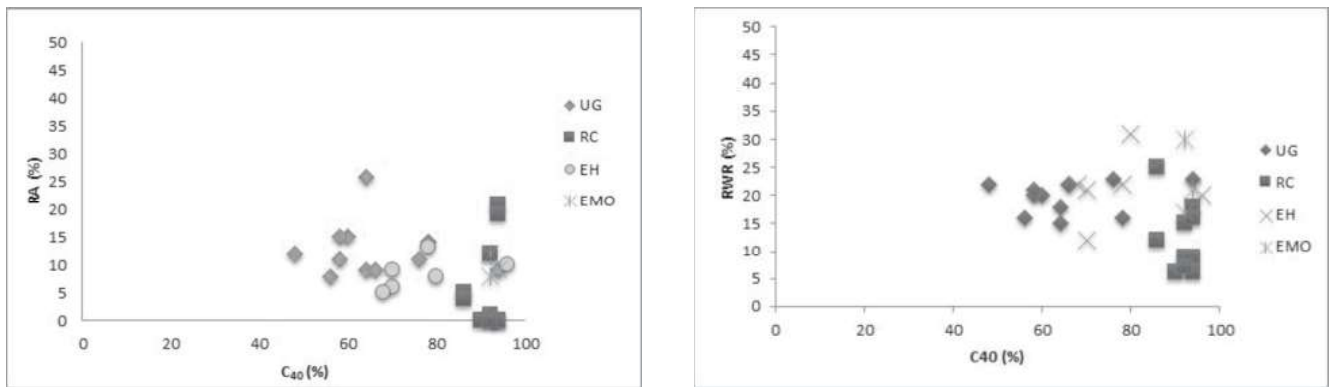
Figure 10 - Covariant plots of sediment samples: C40 (% of clasts which axis c / a ≤ 0.4), RA (% of angular and very angular clasts) and RWR (% rounded and well-rounded clasts). Each symbol represents one sample with 50 clasts: UG (Union Glacier); RC (Rossman Cove); EH (Elephant Head); EMO (Elephant Head Supraglacial Moraine).

Evidence for erosive action is clearly exposed in Rossman Cove area, with a 200 m high leeside escarpment, glacial striations and potholes on convex surfaces at the east side of the hill, more than 50 m above the present ice surface (Figs. 2 and 3a-3c). The thicker ice sheet and, consequently warm-based ice, may be the agent of these processes. Nonetheless, Atkins *et al*. (2002) and Hambrey and Fitzsimons (2010) show that cold-based glaciers, whose bed temperature is below the melting point, may cause considerable geomorphological action, not only the erosion of rocks but also the deposition of sediment, supplanting the conventional assumption that basal processes are ineffective in cold glaciers, therefore incapable of basal activity and have little or minimal influence on the landscape (PATERSON, 1994). The geomorphological and sedimentological analyses provide conditions to infer that cold-based glaciers could neither erode sufficiently to change the landscape nor transport existing sedimentary material to create the morainic assemblages, eg. HEIN *et al*. (2016) and SUGDEN *et al*. (2017).

On the other side, sedimentological characteristics of the moraines cannot confirm the warm-based condition. Considering the sediment texture, sand predominates and fine sediments are quite rare. These textures recorded may be the result of (re)working of preexisting sediments, but without major changes due to absence of continuous meltwater flow. Although thaw is not entirely absent in the area, despite the very low temperatures, it is not efficient enough to modify the sedimentary material. The sublimation of ice beneath the debris cover is also slow, due to extensive bolder cover surface. The modification of morainic material in the study area is most likely to be the result of wind and weathering actions.

Assuming no other changes in regional climate and in the preservation of landforms and sediments at the scale of hundreds of thousands of years (HEIN *et al*., 2016), changes in these arid environments by slope activity and water flow are limited (HAMBREY and FITZSIMONS, 2010), except at Elephant Head Valley. The current slope activity observed in Elephant Head Valley may be the result of the combination of wind action and solifluction, as observed in other areas in the interior of Antarctica, such as in Patriot Hills (VIEIRA and SIMÕES, 2011; VIEIRA *et al*., 2012) and in Northern Victory Land (FRENCH and GUGLIELMIN, 1999).

Considering the likely source of supraglacial moraines debris, generally it is assumed that the material is brought to the ice surface by shear bands within the glacier, formed in areas of compressive ice flow (HAMBREY and GLASSER, 2003), as observed in Patriot Hills, approximately 70 km south of UG area, (FOGWILL *et al*., 2011; HEIN *et al*., 2016). Debris brought in surface ice is accumulated as ablation till, when the adjacent ice sublimates. Evidence for such shear bands includes the presence of sediment in subvertical bands in sections through the ice (CASSIDY *et al*., 1992), and signals of subglacial debris transport, containing fine, sub-rounded and striated clasts (EVANS and O'COFAIGH, 2003). However, these evidences are not present in supraglacial moraines in the study area, with the exception of finer-grained sub-rounded clasts, which may be related to the local processes, such as the constant action of katabatic winds.

The supraglacial moraine observed in Elephant Head blue-ice area (Figs. 5a-b) may be interpreted as a recording of the thinning processes of the ice sheet at UG

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region. The ice thickness change is related to exposition of the steep slopes, which started to contribute with debris to the surrounded areas. The thick debris cover cuts off ablation and creates a protected moraine-covered ice standing above the bare glacier surface (FOGWILL *et al.*, 2011). The morainic slopes observed in Figure 5b are likely the result of intense input of debris from the steep slopes to the interior of the valley and to the blue-ice area.

Similar process could be applied to the supraglacial Rossman Cove moraines, where moraines have developed next to the hills. However the sequence of moraine crests and the northeast direction of the tail, argues for influence of the main glacier flow, the UG, on the structure of deposit, represented by the debris accumulation and deformation of the moraine (Figs. 2 and 4). The medial moraine developed at the narrowest section of the UG also reflects the glacier flows, but, in this case, it is inferred that the debris accumulated in downslope areas, as at the base of the slopes, are displaced by the tributary glaciers (Figure 6). Further studies about ice flow in the vicinity of the moraines are necessary to elucidate the process.

In Hein *et al.* (2016) study, where geomorphic and cosmogenic nuclide data of Patriot and Marble Hills were consistent with an ice sheet that thickened and thinned in response to Quaternary glacial-interglacial cycles, there was no evidence to suggest a change in glaciological conditions that would accompany the loss of the entire ice sheet and the build-up of individual mountain glaciers in this part of Ellsworth Mountains. In addition, in a warming scenario of the interglacial periods of the Quaternary, with the deglaciation of the WAIS, the increased temperature and accumulation would provide favorable conditions for the formation of warm-based glaciers (JAMIESON *et al.*, 2010). Nevertheless, study of Sugden *et al.* (2017) in the same area shows glacier erosion older than 3.4 Ma, and suggests that the landforms indicate the presence of warm-based ice and meltwater, which may be related to mid-Miocene ~ 14 million years ago.

The sedimentary and geomorphological characteristics of the morainic deposits suggest a persistent glaciation with effective erosive action on the local relief, but it is inferred that the morainic formation processes correspond to a further deglaciation period. Definitive interpretation of the morainic deposits is still problematic because there are no dating records of the sediments and boulders in the area.

Subsequent analyses of mineralogical provenance of sediments and direction of glacier flow are important to identify the genesis of the material and may say whether or not there was participation of subglacial material. Comparisons can be made with the studies of Hein *et al.* (2016) and Sugden *et al.* (2017) in neighbor areas, and with similar studies in other areas in Antarctica.

Conclusions

Glacial deposits and erosional features preserved in UG ice-free area offer notable inference for the ice fluctuation in this part of Ellsworth Mountains. The geomorphology and sedimentology of the UG area show current erosional and depositional features, which have been created under a thicker overriding ice that covered the area in the past, and in a posterior phase of deglaciation and ice sheet thinning. It is interpreted that the erosional features were shaped by the warm-base conditions, as result of the thicker ice sheet, and the supraglacial moraines are relict features of a latter period of ice thinning in the region. Such features can be used in the reconstruction of ancient surface elevations, extensions of ice and age of the blue-ice areas.

This study leads to initial conclusion that typical indicators of subglacial transport are absent in the area of UG. The large amount of sandy gravel and sand, the low quantity of fine fractions and the absence of striated and faceted clasts indicate distinct agents and processes. The local weathering activity on the slopes and the persistent katabatic winds possibly are the major agents of alteration and transport of the exposed sediments, respectively, which support the existence of the ice sheet for a long period of time.

The geomorphological records point to ancient wet-based thermal conditions reconstructed from a range of landforms, including exposed abrasion marks and glaciotectonic deformation. The latter is represented by lee sides of oversteepening bedrock which follow the ice flow of tributary glaciers, with the stoss part relatively intact whereas the distal part is more impacted by fracturing and quarrying. We infer that the past convergent flow of the thick ice through the valleys has accelerated the ice flow, and has promoted frictional heating and basal activity. The processes of erosion by cold-based ice seem to play a limited role in landscape change in the Union Glacier area.

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