

Geographic factors and geocryological activity in Livingston Island, Antarctic. Preliminary results

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ABSTRACT: The study presents results from the geomorphological mapping of geocryological phenomena on the northwest sector of Hurd Peninsula, Livingston Island, including frost-shattered debris, talus slopes, stone-banked lobes, rockglaciers and patterned ground. Results are integrated in a GIS and compared to data on altitude, slope angle, aspect and calculated summer net radiation. They show a generally poor influence of the studied climate-related variables, a fact that may be related to the particular climatic characteristics of the Maritime Antarctic with positive summer temperatures and rainfall at sea-level, and very high cloudiness that reduces the significance of direct solar radiation. Geocryological evidence supports the presence of permafrost at least in the mid-part of the south slope of Johnsons Ridge and at the Reina Sofia Peak. As suggested by others, very probably permafrost is present even at low altitudes, but geocryological phenomena in the studied sector are inconclusive in that matter.

1 INTRODUCTION

Research on the active layer and permafrost temperatures in Livingston Island has been carried out by the University of Alcalá for several years. The main objective is to study the relationships between the active layer and climate during summer. More recently, a collaboration with the University of Lisbon was established to study the relationships between the results from the previous campaigns and the geomorphological processes. Emphasis is given to permafrost and active layer monitoring and to mapping and monitoring of geocryological phenomena. This report presents the first results from the geomorphological survey of the geocryological forms and deposits, and descriptive statistics of their distribution. The geomorphological map was integrated into a Geographical Information System (GIS) and compared to data on altitude, slope angle, aspect and summer net radiation.

2 THE STUDY AREA

Hurd Peninsula is a mountainous area located at the south coast of Livingston Island, South Shetlands, Antarctic (62°39'S, 60°21'W). The study sector is in the northwestern part of the peninsula and corresponds to the topographic map of the area of the

Spanish Antarctic Station “Juan Carlos I” (SAS). It is an area of 15 km² (33% sea, 40% glacier and 27% ice-free) with altitude ranging from sea-level to 336 m ASL at Johnsons Ridge (Fig. 1). Bedrock is a low-grade metamorphic turbidite sequence (Miers Bluff Formation; Arche et al. 1992).

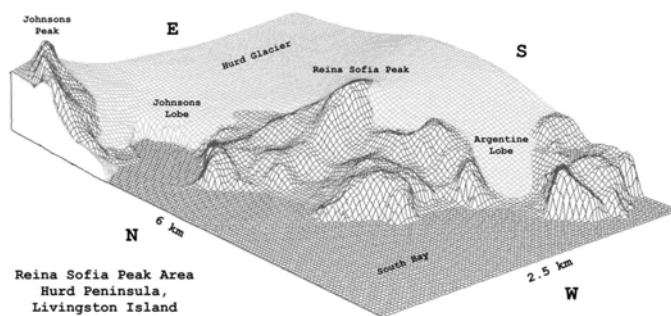


Figure 1. General view of the study area.

Climate at sea-level is cold-oceanic with frequent summer rainfall and moderate annual thermal range. Data from Arctowski Station in King George Island show a mean annual air temperature of ca. -2°C at sea level with mean-monthly values above 0°C from December to March and mean annual precipitation of ca. 500 mm (Department of Antarctic Biology, PAS). According to Serrano & López-Martínez (2000), continuous permafrost occurs in the South

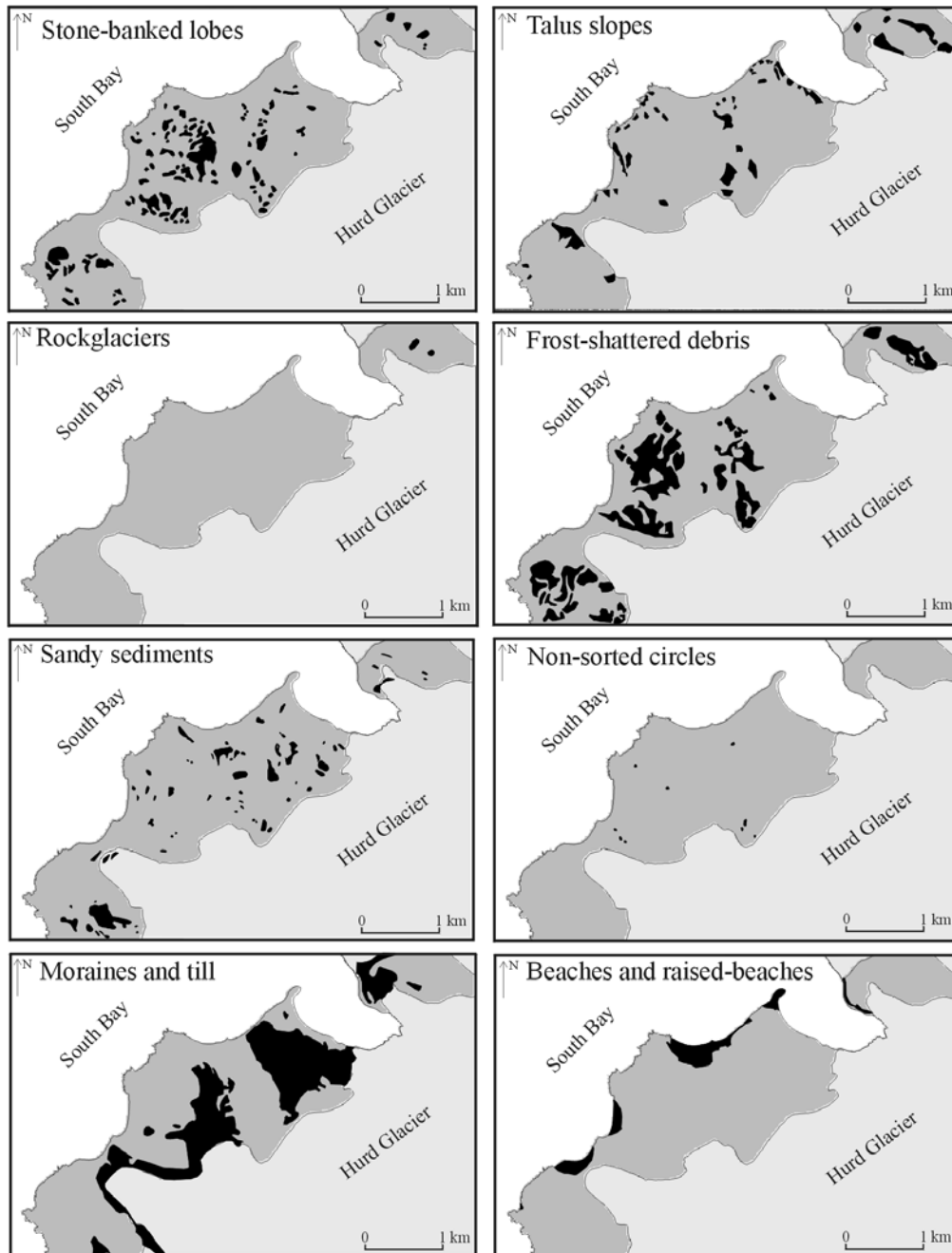


Figure 2. Geomorphological data layers integrated into the Geographical Information System for analysis. The original maps are on the scale 1:5000 with a pixel size of 10 m.

Shetlands above the Holocene raised-beaches (ca. 30 m ASL) and the occurrence of positive average temperatures during the summer results in snowmelt, freeze-thaw cycles and the presence of an active layer.

3 METHODS

In January and February 2000 the geomorphological survey of the northwest Hurd Peninsula was carried out. The topographic map of the SAS area (scale 1:5000, contour equidistance 5 m) was used as background. Special attention was given to periglacial forms and deposits, since these features had so far not been described in detail. Geomorphological publications (Martínez de Pisón et al. 1991, López

Martínez et al. 1992a, López Martínez et al. 1992b, Pallàs et al. 1995, Pallàs 1996) had primarily focused on marine, glacial and tectonic features. The geomorphological map was integrated in a GIS in order to perform statistical analyses. The geomorphological layers are frost-shattered debris, talus slopes, stone-banked solifluction lobes, rockglaciers, patterned ground, moraines and till, sandy sediments, beaches and raised-beaches (Fig. 2). Only the first five of these units are discussed here. All layers contain Boolean values, indicating the presence or absence of each phenomenon.

A digital elevation model (dem) with a pixel size of 10 x 10 m (Ramos 1997) derived from the topographic map mentioned above was used to produce derivative layers (slope and aspect). The net radiation model for the summer campaign of 1996 (cf. a

description of the methodology by Ramos 1997) was also used. This layer, documented by incoming and outgoing long and short-wave radiation measurements at two sites has limitations but offers valuable information on the distribution of net radiation. This is particularly significant, since the contribution of diffuse radiation is important, a detail not incorporated in the GIS-based potential solar radiation models. The mentioned layers are used as geographical variables in the analysis. Aspect and altitude are assumed to reflect climatic control and slope the influence of gravity on the geomorphological processes. Summer net radiation, altitude and aspect should relate to the active layer thickness. No other spatially accurate climate data exists for the study area.

The classified layers of the geographical variables were crossed with the geocryological layers, in order to calculate frequency distributions. Weighed data (in percentage) refer to the ratio between the area of a geocryological variable in a given class of a geographical variable, and the total ice-free area of the latter. The results may distinguish, for example, between a class of net radiation which occupies a small area and shows a small number of pixels of a given phenomenon (large weighed value but small total area frequency), and a class with a very large area, that includes a large number of pixels of the same phenomenon (small weighed value but large total area frequency). In such cases, the former could show to be more significant, since it bears a higher probability of occurrence of the phenomenon.

4 RESULTS

4.1 *Frost-shattered debris*

Areas mapped as frost-shattered debris (Fig. 2) comprise the terrain covered by angular debris, excluding talus slopes which form a different data layer. The thickness of the debris mantle was not estimated.

Angular debris covers about 21% of the ice-free terrain. Clast size is closely related to the lithology of the Miers Bluff Formation. Greywacke and fine sandstone result in larger clasts. Shale layers produce smaller, frequently matrix-supported clasts. The frost-shattered area does not overlap the mapped moraine and till areas, in which sub-rounded to sub-angular clasts dominate. The sectors presenting frost-shattered debris are usually those which first suffered deglaciation and where former glacial debris (or bedrock) is shattered into angular fragments.

Within the frost-shattered debris area, 88% shows slope angles below 30° (Table 1). With respect to the

altitudinal zonation, 59% of the area lies between 75 and 125 m ASL, with each of the other altitude classes showing values below 8%. Nevertheless, the weighed values show a large dispersion with high values occurring also between 175 and 275 m ASL. This indicates an indistinct control by altitude. If geomorphological controls are looked for, the altitudes showing a small area of frost-shattered debris (e.g. 0-50, 125-175 and above 275 m) are generally free-faces or talus slopes.

The control of aspect is vague. The minima between E and S seem to be an artefact related to the limited area with such aspects, as the weighed data indicates (32% of the area facing south is covered by frost-shattered debris). It is interesting to note that the weighed values tend to decrease in NE and N aspects. Concerning summer net radiation, a significant concentration in a particular class cannot be noted.

4.2 *Talus*

Talus slopes occupy ca. 6% of the ice-free area. Their preferential location is below large free-faces where rockfall activity is intense (coastal cliffs and other steep slopes). The significance of coastal cliff locations is evident in the altitudinal analysis which shows that 58% of the talus area is below 75 m ASL (Table 1). The rest is scattered in the other altitude classes. Weighed values show a less clear distribution, with several peaks related to the altitudes where steepest slopes occur. 66% of the talus shows gradients from 25 to 50°. The weighed values show that the significance of talus is greater for slopes steeper than 35°. Concerning aspect, two maxima are observed: 23% of the talus faces NE and 58% faces SW to NW with values below 7% in the other classes. Weighed values show a somewhat similar distribution. Summer net radiation does not seem to present a large control when considering the total areas but the weighed values suggest a significance for the areas receiving between 200 and 300 MJ/m².

4.3 *Stone-banked solifluction lobes*

Stone-banked lobes (SBL) are widespread and form in frost-shattered debris or till. In some places, lobes coalesce into sheets. Frontal heights of lobes are generally around 0.5 m but can reach over 2 m. These values suggest that they are related to annual freeze-thaw cycles (Matsuoka, 2001) and probably involve most of the active layer, since permafrost was found by the authors at 0.5 to 1 m depth in boreholes at 275 m ASL in the Reina Sofia Peak (Ramos & Vieira 2003). Although SBL are not necessarily indicators of permafrost, features of the

Table 1. Geocryological phenomena and their spatial significance in northwest Hurd Peninsula (A%, Percent area; W%, Weighed area per total area occupied by each class in the study sector).

	Frost-shattered debris		Talus slopes		Stone-banked Lobes		Rockglaciers		Non-sorted circles		
	A %	W%	A%	W%	A%	W%	A%	W%	A%	W%	
SLOPE (°)	<5	6.3	14.6	0.6	0.4	2.0	2.2	0.0	0.0	0.9	-
	5-10	16.2	23.8	2.2	0.9	13.2	9.4	1.6	0.0	0.2	-
	10-15	17.7	23.9	5.0	1.8	20.2	13.2	13.1	0.2	0.1	-
	15-20	18.9	26.9	6.9	2.6	20.7	14.3	13.1	0.2	0.0	-
	20-25	14.8	25.7	8.4	3.9	16.2	13.6	19.7	0.4	0.0	-
	25-30	14.2	24.0	16.4	7.3	15.7	12.8	27.9	0.5	0.0	-
	30-35	5.9	20.3	11.1	10.1	6.3	10.5	13.1	0.5	0.1	-
	35-40	4.2	12.7	18.3	14.8	4.0	6.0	6.6	0.2	0.1	-
	40-45	1.2	7.1	9.2	14.7	1.1	3.2	4.9	0.3	0.0	-
	45-50	0.3	1.9	11.0	22.0	0.3	1.2	0.0	0.0	0.0	-
>50	0.2	1.2	10.9	14.8	0.2	0.7	0.0	0.0	0.0	-	
ALTITUDE (m ASL)	<50	4.3	3.6	40.7	10.2	7.0	2.8	0.0	0.0	0.0	-
	50-75	8.3	11.9	16.9	7.2	14.8	10.3	0.0	0.0	0.1	-
	75-100	22.7	28.6	4.0	1.5	30.3	18.4	0.0	0.0	0.0	-
	100-125	36.7	38.7	4.2	1.3	28.4	14.5	0.0	0.0	0.4	-
	125-150	7.2	15.3	3.8	2.4	6.9	7.1	0.0	0.0	0.0	-
	150-175	3.3	12.4	8.7	9.6	2.8	5.0	23.0	0.9	0.0	-
	175-200	6.4	32.5	6.2	9.4	3.8	9.2	47.5	2.6	0.0	-
	200-225	3.5	40.2	1.3	4.6	1.5	8.3	29.5	3.7	0.0	-
	225-250	2.8	29.0	5.5	16.9	1.7	8.6	0.0	0.0	0.0	-
	250-275	4.8	34.6	5.3	11.5	2.9	10.2	0.0	0.0	2.2	-
>275	0.1	0.5	3.5	8.5	0.0	0.0	0.0	0.0	0.0	-	
ASPECT	N	8.6	16.0	7.0	3.7	10.9	9.9	0.0	-	0.2	-
	NE	16.1	18.5	23.1	7.6	24.9	13.9	0.0	-	0.1	-
	E	7.8	20.1	2.3	1.7	9.4	11.8	0.0	-	0.1	-
	SE	3.3	23.8	0.1	0.3	2.0	7.1	0.0	-	0.6	-
	S	9.3	32.5	5.8	5.8	6.6	11.0	1.1	-	0.4	-
	SW	18.7	25.3	26.8	10.4	14.0	9.2	1.0	-	0.1	-
	W	13.4	19.7	20.3	8.5	9.6	6.9	0.1	-	0.1	-
	NW	18.1	20.7	11.2	3.7	16.7	9.2	0.0	-	0.1	-
Flat	4.7	15.6	3.3	3.1	5.8	9.4	0.0	-	0.2	-	
SUMMER NET RADIATION (MJ/m ²)	<200	0.0	0.9	1.0	7.1	0.0	0.4	0.0	0.0	0.0	0.0
	200-225	0.1	1.5	5.4	21.6	0.1	0.8	0.0	0.0	0.0	0.0
	225-250	1.4	9.0	9.8	18.1	1.1	3.4	8.2	0.6	0.0	0.0
	250-275	0.6	7.2	4.3	13.5	0.5	2.6	4.9	0.6	0.0	0.0
	275-300	2.8	13.1	11.2	14.8	2.0	4.5	9.8	0.5	0.0	0.0
	300-325	10.3	27.0	11.3	8.3	9.5	12.1	44.3	1.3	0.0	0.0
	325-350	7.4	24.9	8.6	8.1	7.2	11.7	6.6	0.2	2.5	0.1
	350-375	15.7	27.9	6.0	3.0	11.9	10.3	19.7	0.4	2.5	0.0
	375-400	15.4	19.6	5.6	2.0	11.5	7.1	6.6	0.1	37.5	0.3
	400-425	16.6	18.5	4.0	1.3	11.8	6.4	0.0	0.0	50.0	0.4
	425-450	14.5	18.7	8.5	3.0	23.2	14.5	0.0	0.0	7.5	0.1
	450-475	9.8	17.9	18.4	9.3	16.7	14.7	0.0	0.0	0.0	0.0
475-500	3.2	25.0	2.4	5.3	3.3	12.2	0.0	0.0	0.0	0.0	
>500	2.1	17.1	3.5	8.2	1.2	4.9	0.0	0.0	0.0	0.0	

observed type develop frequently in the warm permafrost zone (Matsuoka 2001). They are good indicators of geocryological dynamics near the ground surface.

SBL occupy 10% of the study area, 25% of it on till and the rest on frost-shattered debris. Their altitudinal distribution ranges from sea-level to the upper slopes of the Reina Sofia Peak and Johnsons ridge. Nevertheless, 74% of the area is located between 50 and 125 m ASL (Table 1). This is because most of the sloping areas are located in that altitudinal range. However, if this data is weighed by the hypsometric curve of the ice-free terrain, the

distribution is more scattered. The maximum frequency is in the range of 75-100 m and a plateau is visible at 175-275 m ASL. This relates to the altitudinal range of the sloping and flatter areas. The relative minimum at 150-175 m is connected to erosional platforms. 41% of the SBL are located in slopes between 10-20° and 86% between 5 and 30°. The weighed data shows a similar distribution but high slope angles gain importance.

Aspect does not show any pronounced influence on SBL distribution. The concentration from NE to SW is an artefact associated to the higher frequency of slopes with those aspects (see weighed

data). The net radiation model shows that 92% of the SBL occur in the range of 300–475 MJ/m². This is also supported by the weighed data which, however, shows slightly higher values.

4.4 *Rockglaciers*

Rockglaciers are the most visible expression of the presence of mountain permafrost (King et al. 1992, King & Åkerman 1993). Protalus rockglaciers are found at the south slope of Johnsons Ridge. They are small features. Two main bodies are considered here, but a more detailed field survey will allow a better mapping of the existing features. Other rockglaciers are known in Livingston Island outside the study sector (Serrano & López-Martínez 2000).

Rockglaciers occupy 0.2% of the ice-free area. They occur between 150 and 225 m ASL and show chiefly S and SW aspect (Table 1). 85% of the rockglacier area is in 10° to 35° slopes, with sectors from 5 to 10° and 35 to 45°. The net radiation model shows that the rockglacier area experienced 225 to 400 MJ/m², with an area of 71% from 300 to 375 MJ/m².

4.5 *Non-sorted circles*

Patterned ground is the most frequent periglacial phenomenon in the South Shetlands (Serrano & López Martínez 1998). However, in the study sector it is restricted to few sites. This is probably due to the steep nature of the terrain. In addition to miniature nets and stripes that were not mapped, non-sorted circles appear in some flat sites and occupy about 0.1% of the ice-free area. The altitudes of non-sorted circles are closely related to the levels of the erosional surfaces. It is, however, significant that the area with stone circles at each altitude class, weighed by the total area of that same class, increases with altitude (Table 1). A wide range of net radiation values was obtained. This data should be used with care, since the small spatial significance of the features may increase the effect of intrinsic dem errors. For indicative purposes, the net radiation was 375 to 400 MJ/m² during the summer of 1996 in 88% of the stone circle areas.

4.6 *Other evidence of geocryological activity*

In the fronto-lateral moraine of the Argentine Lobe (Hurd Glacier) active-layer detachment slides were observed. They are a few square meters and concern the inner slope of the moraine. The slip surface is in the bottom of the active layer and mas-

sive ice is visible, indicating that the moraine is ice-cored.

In the south slope of Johnsons Ridge, debris-flows occurred. The deposits that suggest a track over the glacier larger than 100 m, were observed at Johnsons Lobe (Hurd Glacier). Research on the photographic archive of the SAS allowed the identification of the time of occurrence of the main event, which was between 9 and 17 December 1999.

5 DISCUSSION

Considering the Holocene deglaciation of the Peninsula (Pallàs 1996), the widespread character of frost-shattered debris indicates that freeze-thaw cycles may have played a major morphogenic role. Only the more recently deglaciated areas show little evidence of frost shattering. The absence of a clear control of the studied geographical variables may be related to the lack of lithostructural information and to the microscale controls still hard to integrate in the GIS. It is also possible that integrated effects from combinations of factors may outweigh each individual one.

The collected data suggests that the location of talus slopes is linked to pre-existing topographic conditions, more than to any other climate related factor.

Stone-banked lobes are frequent and form in slopes where enough debris is available. No direct control by aspect has been identified. However, the relatively high values of summer net radiation suggest deep thaw. In comparison, the area with rockglaciers shows lower net radiation values, a fact in agreement with their different geocryological characteristics. An important control on rockglaciers seems to be the high frost-shattering activity from the free-faces of Johnsons Ridge. The dominating south and southwest aspects of the slope where they form show good conditions for ground cooling during winter and lower summer radiation inputs. However, the study area is small and the rockglacier sector shows little spatial representativity for an accurate assessment of the factors.

Non-sorted circles form in wind-exposed terrain where snow cover is scarce during winter. The increased spatial significance of sorted-circles with altitude shows the control of air temperatures and wind.

It is important to note that significant factors were not taken in account in the present approach; they include melt water and ground moisture (abundant during the summer and playing a major role on the ground mass and energy transfers),

snow cover, thickness of the deposits, detailed lithology, age of deglaciation and of the mapped features.

6 CONCLUSIONS AND PERSPECTIVES FOR THE FUTURE

The first results of the study of the influence of the geographical factors on the geocryological phenomena of Hurd Peninsula indicate that aspect, altitude and summer net radiation, at least separately, exert small influence in the distribution of frost-shattered debris and talus slopes, which are widespread. Rockglaciers are found in areas with smaller values of summer net radiation but other factors are needed simultaneously for them to occur (e.g. debris supply). In areas with stone-banked lobes, summer net radiation is generally higher, a fact that controls the development of a thicker active layer. Non-sorted circles exist in wind-exposed terrain, particularly in summit areas. The generally poor correlation of most of the phenomena with aspect is an important fact, which may be related to the effect of diffuse radiation in the net radiation.

The geocryological phenomena indicate the presence of permafrost at least in the mid-part of the south slope of Johnsons Ridge. Excavations in Reina Sofía Peak also show its presence and the same is indicated by borehole temperatures (Ramos & Vieira 2003). As suggested by Serrano & López-Martínez (2000), permafrost is very probably present even at low altitude but the geocryological phenomena in the studied sector are inconclusive in this matter.

The data used here will be analysed in the future with other statistical methods (e.g. analysis of variance, discriminant analysis and logistical regression) to assess possible relationships not detected by this preliminary descriptive approach. In order to obtain a larger diversity of processes and of control factors, the study area will be enlarged to the entire Hurd Peninsula. The integration of the geomorphic data with temperature observations from boreholes and meteorological stations, and physical modelling will be continued within this research framework.

7 ACKNOWLEDGEMENTS

This research is part of the project RADIANTAR-2001 (ANT1998/0571) funded by the CICYT. Vieira was supported by Fundação Calouste Gulbenkian and Fundação para a Ciência e a

Tecnologia - FACC. This author thanks the PNIA, Teracom, Optimização and the Photographic Archive - CEG. The authors thank Prof. Wilfried Haeberli and Dr. Jan Boelhouwers for the constructive comments which very much contributed to improve the original version of the paper, and an anonymous reviewer for helpful comments.

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