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Rock Weathering Rates on Subantarctic Marion Island

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Abstract

Subantarctic Marion island (46°S) is a shield volcano of basal "gray" lavas and younger "black" lava outflows. Rock weathering rates, as determined by annual mass loss from small clasts (<400 g), was measured over a 3-yr period at 4 sites on the island on an altitudinal transect from the coast toward the interior. Mass loss from gray lava clasts was found to be 0.02% near sea level, increasing to 0.10% yr^{-1} at 730 m a.s.l. Black lava clasts yielded mean losses of up to 0.72% at the sites, although no altitudinal trend in mass loss was evident. In the sea-spray zone, gray and black lava clasts monitored over 1 yr had mean losses of 0.30% and 0.41%, respectively. Weathering rates are marginally inflated by the annual weighing procedure, which has been determined to contribute approximately 0.01% to the measured gray lava clast mass losses, and 0.07% to the black lavas. Since none of the clasts showed visual signs of fracturing or flaking, mass loss appears to be on a granular scale at most, and material removal is probably assisted by rainwash. Extrapolated values suggest that black lava clasts can weather completely within 200 yr and gray lava clasts within approximately 1000 yr at high altitudes. These data have implications for the lifespan of periglacial landforms constituting small clasts, particularly those formed in the early Holocene.

Introduction

The breakdown of bedrock or bedrock-derived residuals to smaller clasts and ultimately to a matrix is a fundamental component in the development of periglacial landforms. It is within these substrates that many of the clastic landforms in the high latitudes of the maritime Antarctic and the peripheral subantarctic islands develop (e.g., Hall, 2002; Boelhouwers et al., 2003). Once landforms such as sorted patterned ground, stone-banked lobes, or openwork screes have formed, the persistence of the landform is a function of the maintenance of the form by the process(es) or driving force(s) and the resistance of the clastic material to complete breakdown through weathering. In studies of relict landforms, the rate of deterioration of clasts must therefore be assumed to be very slow, at least not rapid enough to have significantly affected the properties of the landform since its development. Since few data exist on the rate of rock weathering in such environments, the lifespan of landform components comprising clast-sized or blocky bedrock residuals remains unknown.

To my knowledge, the only long-term data available on rock weathering rates in the subantarctic and maritime antarctic region are from Signy Island (60°S). At this maritime antarctic site, Walton and Hall (1989) monitored weight changes of naturally shaped micaschist and marble clast samples weighing up to 1.6 kg; they measured a maximum mass loss in the order of 0.1% yr^{-1} over 6 yr. Slower rates were obtained for quartz-micaschist samples. Over a 5-yr period, Hall (1990) shows weathering rates for cut tablets of quartz-micaschist and marble (measuring approximately $5 \times 5 \times 2$ cm) to be to be in the order of 2% mass loss 100 yr^{-1} and concludes that the rates of (mechanical) weathering on Signy Island are very slow. This paper presents mass loss data from clasts monitored on subantarctic Marion Island; an island that is characterized by distinct periglacial activity with numerous associated cold-climate landforms constituted of bedrock- or glacially derived clasts (e.g., Sumner et al., 2002; Boelhouwers et al., 2003).

Location

Marion Island is situated in the southern Indian Ocean (46°54′S; 37°45′E, Fig. 1) approximately 2° north of the Antarctic Polar Front. The island is an oval-shaped shield volcano measuring 290 km^2 and rising to 1230 m a.s.l. It consists of older, fine-grained gray basaltic lavas dating from 276,000 B.P. (±30,000), and younger, more porous black lavas and associated red- and black-colored scoria cones that date from 15,000 B.P. (±8000) (McDougal, 1971; Verwoerd, 1971), although a black lava flow occurred in 1980 (Verwoerd et al., 1981). Located in the roaring forties, the island has a hypermaritime climate. Mean maximum and minimum temperatures at sea level are 10.5°C and 5.0°C in summer and 6.0°C and 1.0°C in winter; winds blow most frequently from the northwest with an average velocity of 32 km h^{-1} (Schulze, 1971). Mean annual precipitation is approximately 2000 mm (Smith, 2002). Although the island was glaciated before the black lava outpourings, no glaciers exist today.

The island surface is characterized by extensive areas of black lava and scoria cones, gray lava moraines and tills from earlier glaciations, and scarps caused by radial faulting on deglaciation (Hall, 1978). Active and relict periglacial landforms exist throughout the island and show distinct trends of increasing size with altitude, a function of deeper frost penetration. These features include sorted patterns within the scoria and black lava residuals; vegetated and stone-banked lobes displaying distinct fabrics; and extensive scree deposits, some of which are vertically and laterally sorted. An altitudinal distribution of relict features has been used in assessing postglacial Holocene environmental conditions on the island (Holness and Boelhouwers, 1998). The presence and persistence of clasts of both rock types is thus fundamental in the development and lifespan of landforms. A 3-yr assessment of mass loss from gray and black clasts was undertaken on the island from April 1997 to April 2000. The study formed part of a broader weathering project that includes an assessment

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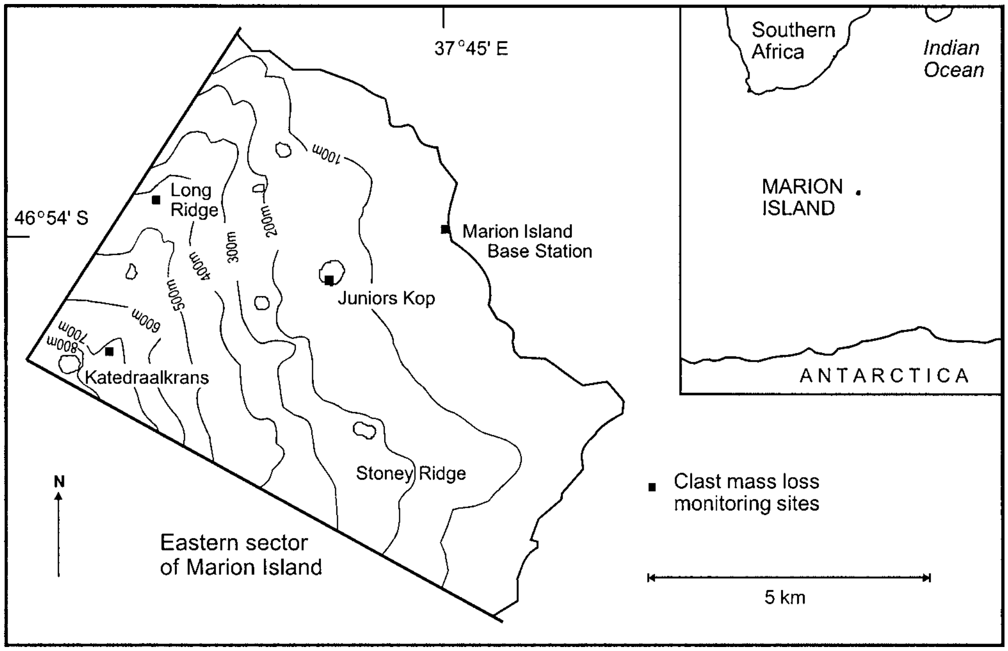

FIGURE 1. Location of the field sites in the eastern sector of the island, where clasts were monitored for mass loss.

of the environmental controls of weathering and the use of weathering characteristics in relative-age dating of landforms (Boelhouwers et al., 2001, 2003; Sumner et al., 2002).

Field Sites and Methodology

Gray and black lava clasts were collected at a site inland from the Meteorological Base Station near the eastern slope of the scoria cone called Juniors Kop (Fig. 1) in April 1997. As is typical for fresh screes on the island, the gray lava clasts were angular with no visible weathering rinds or attached lichen or moss. Gray lavas are fine-grained with a consistently high microporosity but do absorb some free moisture (Table 1). Black lavas, a product of the more recent and gaseous Late Pleistocene and Holocene eruptions, often closely resemble the darker scoria material. Distinctions between the black lava and black scoria are not always obvious in the field, and specific density appears to vary considerably from site to site. For consistency, all black lava samples were collected from one lava flow at the base of Juniors Kop. In comparison to the gray lavas, the black lava samples display a greater porosity and water absorption ability (Table 1). In preparation for long-term field monitoring, all the clasts were oven dried for 24 hr at 105°C, lightly brushed to remove loose particles on the surface, and weighed on a 0.01-g-resolution balance. Size range for the gray lava clasts was ~120 g to 370 g and for the black lava clasts ~100 g to 280 g (Tables 2 and 3).

TABLE 1

Rock physical properties (Cooke, 1979) of a sample set of the clasts used for monitoring of mass loss

Rock type		Porosity (%)	Micro-porosity (%)	Water absorption (%)	Saturation coefficient
Gray lava	mean	6.01	91.84	3.63	0.61
(n = 10)	std. dev.	0.92	3.49	0.64	0.10
Black lava	mean	17.86	61.67	7.65	0.47
(n = 10)	std. dev.	6.89	8.32	0.34	0.13

Four field locations on the eastern side of the island were selected for long-term monitoring of clast mass loss: the Meteorological Base Station at the coast (15 m a.s.l.), a lava vent on the western slope of Juniors Kop (250 m a.s.l.), Long Ridge (450 m a.s.l.) and the eastern extreme of Katedraalkrans (730 m a.s.l.) (Fig. 1). Three black lava and 3 gray lava clasts were placed on an exposed horizontal bedrock surface at the Meteorological Base Station. At each of the inland locations, 3 gray and 3 black lava clasts were placed on an exposed bedrock surface.

The clasts were withdrawn from the field during each April of 1998, 1999, and 2000. They were oven dried and weighed, and the same samples were returned to their respective locations. Although caution was taken to prevent mass loss during the procedure (each clast was individually wrapped for transportation to and from sites), some mass loss could be expected. This experimental error was estimated by subjecting a set of 3 other gray and 3 black lava clasts to the procedure of wrapping, transportation, and oven drying on two test runs. The first test used Juniors Kop–return as the destination, and the second test run used Long Ridge–return.

For comparison with the coastal zone, additional clasts of gray and black lava were placed at the summit of a sea cliff near the island Meteorological Station in April 1999. The site was chosen where clasts should experience some sea spray during high seas but no direct wash. These clasts were reweighed in April 2000.

Results

An estimation of the experimental error induced by the transportation and weighing procedure is shown in Table 4. Over the two test runs, the gray lava clasts showed mass loss of up to 0.02% of the dry mass, averaging 0.01%. Black lava clasts proved more susceptible to the experimental procedure, and the highest individual mass loss recorded was 0.12%, with an average of 0.07% for the 3 clasts (Table 4). The smallest clasts in both sets of rock types gave the highest experimentally induced mass loss averaged for both tests, although that trend was not evident in the first test alone.

Mass loss for the clasts over the monitoring period is shown in Tables 2 and 3. Annual loss from individual clasts can vary considerably

TABLE 2

Annual mass loss from gray lava clasts between April 1997 and April 2000 (unless otherwise indicated)

Location	Initial mass (g) 1997	Mass loss (% original dry mass) 1998	1999	2000	Annual mean mass loss (%)	Annual mean mass loss of samples (%)
Meteorological Station (15 m a.s.l.)	161.17	0.01	0.02	No data	0.01	0.02
	236.11	0.00	0.04	No data	0.02	
	308.15	0.03	0.03	No data	0.03	
Juniors Kop (250 m a.s.l.)	125.50	0.09	0.05	0.06	0.07	0.05
	284.07	0.10	0.00	0.06	0.05	
	289.37	0.07	0.01	0.02	0.04	
Long Ridge (450 m a.s.l.)	170.16	0.04	0.07	0.05	0.06	0.09
	209.13	0.12	0.11	0.03	0.09	
	274.88	0.13	0.13	0.08	0.12	
Katedraalkrans Ridge (730 m a.s.l.)	149.88	0.15	0.11	0.11	0.13	0.10
	209.23	0.11	0.07	0.10	0.09	
	368.70	0.13	0.10	0.04	0.09	
Coastal (spray zone)	(Monitored 1999–2000)		155.92g	0.75	0.75	0.30
			218.03g	0.14	0.14	
			292.76g	0.02	0.02	

from year to year, although at no stage were clasts found to have fractured completely or to have lost large fragments of material. In general, the values are marginally higher in the first year, ending April 1998, but no trend or stabilization of values can be noted thereafter.

An overall trend of greater mass loss with altitude was apparent for the gray lavas, with an increase from 0.02% near sea level (only marginally greater than the experimentally induced mass loss) to 0.10% at the highest-altitude site. In contrast, the black lava samples showed no obvious trend of annual mass loss with altitude. With the exception of the Long Ridge data (average of 0.44% yr^{-1}), mass loss overall appeared fairly consistent at approximately 0.7% yr^{-1}. These measured values for black lava clasts were an order of magnitude greater than the annual experimentally induced mass loss (Table 4). Although both the gray and black lava sets at each location incorporate different-sized clasts, no trend of increasing or decreasing loss with size (i.e., mass) is apparent within the range used.

Mass loss for coastal samples over the 1-yr period is shown in Tables 2 and 3. More samples than those indicated on the tables were placed for monitoring at the site in 1999; however, the station personnel reported particularly high seas and wave action during the year, and some clasts were lost. Mass losses proved highly variable between individual clasts, probably due to attrition by wash or direct erosion by sea spray. Mean gray lava mass loss of the coastal samples was an order of magnitude greater than that of the base station samples, which lay beyond the spray zone. Mass loss for the two black lava clasts was marginally lower than that of the 5 base samples, but within the same order of magnitude.

Discussion

During the monitoring period, the samples showed a measurable annual mass loss that was roughly an order of magnitude greater than that induced by the annual weighing procedure. Over the 3-yr monitoring period, the slightly higher overall values found after the first year can be attributed to the sample stabilization after emplacement as clasts adjusted to their different environmental surroundings. Even though results may be marginally inflated initially, the overall mass loss is considered a reasonably accurate representation of field deterioration rates of exposed clasts under the prevailing environmental conditions.

Results obtained for the coastal samples provided rates from a different weathering regime due to exposure to sea spray and the natural addition of salts. Clasts can also experience some attrition due to

TABLE 3

Annual mass loss from black lava clasts between April 1997 and April 2000 (unless otherwise indicated)

Location	Initial mass (g) 1997	Mass loss (% original dry mass) 1998	1999	2000	Annual mean mass loss (%)	Annual mean mass loss of samples (%)
Meteorological Station (15 m a.s.l.)	99.52	0.72	1.00	No data	0.86	0.71
	124.60	0.35	0.10	No data	0.22	
	252.40	1.03	No data	No data	1.03	
Juniors Kop (250 m a.s.l.)	188.65	1.07	0.29	0.45	0.60	0.72
	194.34	1.47	0.70	0.60	0.93	
	236.41	1.22	0.36	0.29	0.62	
Long Ridge (450 m a.s.l.)	98.52	0.60	1.16	No data	0.88	0.44
	158.37	0.37	0.12	0.19	0.23	
	238.21	0.21	0.17	0.22	0.20	
Katedraalkrans (730 m a.s.l.)	135.89	0.88	1.69	1.06	1.21	0.67
	179.46	0.43	0.28	0.32	0.35	
	279.48	0.41	0.45	0.50	0.45	
Coastal (spray zone)	(Monitored 1999–2000)		240.02	0.44	0.44	0.41
			271.85	0.38	0.38	

TABLE 4

Tests to determine the experimental contribution to mass loss of the annual transportation, drying and weighing procedure (see text)

Rock type	Initial mass (g)	Mass loss (%) Test 1	Mass loss (%) Test 2	Mean mass loss (%)
Gray lava	111.29	0.00	0.02	0.01
	277.39	0.01	0.01	
	373.86	0.00	0.01	
Black lava	93.60	0.09	0.12	0.07
	164.29	0.07	0.02	
	211.16	0.09	0.02	

direct impact of spray or occasional wash during very high seas. Although the effect of enhanced salt weathering and wetting and drying cannot be discarded as a controlling factor, the higher mean mass loss found for the gray lava clasts in comparison to the inland sites probably reflects attrition or direct erosion by water. With only 2 black lava samples retrieved, results cannot be taken as truly representative, but mass loss is in the order of magnitude of the inland sites. Due to the short duration of exposure, these data can only be considered a first approximation of weathering rates on the coastal periphery.

None of the clasts were completely fractured during the monitoring period. This suggests that clast mass loss on the inland sites operates up to a granular scale, as supported by the measured reduction in angularity with duration of exposure (Sumner et al., 2002). Annual fluctuations in mass loss from clasts may be a function of nonlinear loss of surface material, as noted particularly for the deviations from the mean in the second and third years of data. Rainwash may play a significant role in dislodging surface material from clasts. Although the trend shows that altitude is important in determining the rate of mass loss of the gray lavas, the actual mechanism(s) of rock weathering cannot be determined from these data. Environmental conditions on the island, including rock temperature and rock moisture, are presented elsewhere (Boelhouwers et al., 2003), and verifying weathering mechanisms will probably require further detailed investigation under controlled environmental conditions.

Weathering rates of the higher-altitude Marion Island gray lava samples are similar to findings by Walton and Hall (1989) and Hall (1990) from Signy Island in the maritime Antarctic. A mass loss of 0.1% yr^{-1} found for naturally shaped clasts on Signy Island by Walton and Hall (1989) compares favorably with the measured values of 0.09 and 0.10% mass loss on Long Ridge (450 m a.s.l.) and Katedraalkrans (730 m a.s.l.). At low altitude, weathering rates for Marion Island gray lava mass loss are slower, while rates for black lava mass loss are higher overall. By measuring mass loss from freshly cut blocks of Signy Island lithologies, Hall (1990) extrapolated deterioration rates to a mass loss in the order of 2% 100 yr^{-1}—assuming a linear progression of deterioration of samples. On this basis, extrapolation of Marion Island measured rates gives a rate of breakdown of up to 10% 100 yr^{-1} for the gray lava clasts (depending on the site altitude), and a value that can exceed 70% 100 yr^{-1} for black lava clasts.

Although extrapolated values must be viewed with caution, the rate of breakdown for black lava clasts is ostensibly high enough for clasts in this size range ($<\sim$300 g) to have deteriorated to less than half their size within 100 yr and to have weathered completely within 200 yr. Gray lava clasts in the size range monitored ($<\sim$400 g) may be completely weathered in 1000 yr at high altitude. Rates assessed under current environmental conditions can be expected to differ under other climatic conditions. On the basis of temperature alone, the data suggest that during depressed temperature conditions the rates of mass loss for gray lavas would increase at lower altitudes, while black lava rates should remain fairly constant. These data have implications for the persistence of active and inactive sorted ground comprising clastic residuals, depending on the age of the forms (which may date back to the termination of the Late Pleistocene glaciation). Since larger clasts have a smaller surface-to-mass ratio, it is possible that landforms constituting larger clasts than those measured here have a proportionally longer lifespan. Over time, the size range distribution would then be affected, with smaller clasts weathering away more rapidly. Notwithstanding the practical difficulties, mass loss over a greater range of rock sizes requires further testing in the field if rates are to be directly applicable to landforms with larger clast sizes.

Conclusion

Weathering rates of basaltic gray lava clasts increase from 0.02% near sea level to 0.10% yr^{-1} at 730 m a.s.l. and are comparable with clast deterioration rates on Signy Island (Walton and Hall, 1989; Hall, 1990). In contrast, measured black lava weathering rates can exceed 0.70% yr^{-1} and appear unaffected by altitude. Mode of weathering cannot be derived from the data, although altitude appears to be an important controlling factor in the weathering of gray lava clasts. Weathering of the clasts over the monitoring period occurred on a granular or smaller scale, with the removal of weathered material probably assisted by rainwash.

Assuming a linear weathering rate with time, extrapolation of weathering rates (e.g., Hall, 1990) suggests that small black lava clasts may be completely weathered within less than 200 yr on the island. This rate appears to be independent of temperature conditions, as is evident in the similar results obtained from different altitudes. Gray lava clasts weather at a slower rate, and at high altitude where gray lava clast rates are greatest, extrapolations imply a clast longevity of approximately 1000 yr. Gray lava weathering rates are slower at lower altitudes but can be expected to have been faster during depressed temperature conditions, when colder conditions such as those found now at high altitude would have prevailed at lower altitudes (e.g., Holness and Boelhouwers, 1998). Mass loss data imply a limited lifespan for smaller clasts. Thus, the longevity of clastic landforms, particularly in studies where relict landforms are used in paleoenvironmental reconstruction, needs to be considered further.

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