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Short Communication
Gelifluction and Thixotropy of Maritime Antarctic Soils: Small-Scale Measurements with a Rotational Rheometer

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ABSTRACT

Gelifluction, thixotropy and yield stress were measured from < 5 g soil samples taken from Signy, Alectoria, Greenwich, Wiencke and Livingston islands in the maritime Antarctic using a temperature-controlled rotational rheometer. The small sample size that this method permitted is compatible with sampling from sensitive sample locations. An oscillating 10 Pa shear stress was applied to samples at -0.5 kPa water potential. Two freeze-thaw cycles had temperature ramps from 5°C to -10°C over 2 h, followed by -10°C to 5°C over 2 h and finally at 5°C for 1 h. At freezing onset, the shear modulus, G, dropped to 4–50 per cent of thawed G, with no differences between locations. At thawing onset, G dropped to 8–32 per cent of thawed G, with significant differences between locations ($P < 0.001$). Thixotropy was then measured by applying a 2 kPa oscillating shear stress for 10 min, followed by relaxation at 10 Pa for 2 h. The increased shear stress caused G to drop to less than 8 per cent of the pre-stressed value, with no difference between locations. After 0.1 and 2 h, G was 18–65 per cent and 31–82 per cent of the pre-stressed value, respectively. A shear ramp determined yield stresses ranging from 494–2217 Pa. These findings demonstrate the potential risk of more frequent freeze-thaw cycles or the occurrence of thawed soil to the stability of polar soils. Gelifluction through more frequent freeze-thaw cycles could result in increased slope movement, whereas thixotropy caused by trampling of thawed soils could exacerbate mechanical damage of surface soils. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil; maritime Antarctic; gelifluction; thixotropy; yield stress; rotational rheometer

INTRODUCTION

The maritime Antarctic is one of the most rapidly warming regions on Earth, with mean annual air temperatures along the western Antarctic Peninsula having risen at approximately double the rate of the global mean surface temperature over the past 50–100 years (up to 0.4°C decade^{-1}; Hansen *et al*., 2006; Adams *et al*., 2009). As the climate warms, surface soils of the maritime Antarctic and other polar regions are experiencing longer periods of thaw and an increasing frequency of freeze-thaw cycles (James *et al*., 2013; Smith *et al*., 2012). For Cryosols on King George Island, off the Antarctic Peninsula, Michel *et al*. (2012) recorded about 90 days of thawed soil per annum at 10 cm depth. Diurnal freeze-thaw cycles during summer months can thaw soils to over 40 cm depth (Matsuoka and Moriwaki, 1992), with Matsuoka *et al*. (1990) reporting as many as 50 freeze-thaw cycles per year at 3 cm depth in the Sør Rondane Mountains, Antarctica, and Dennis *et al*. (2013) reporting up to three freeze-thaw cycles per month during the shoulder seasons for soils on Signy Island. Frequent diurnal freeze-thaw cycles mainly affect surficial soils to 5–10 cm depth and can lead to surface velocity of soil movement of 100 cm year^{-1} (Matsuoka, 2001).

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Accentuated movement occurs due to gelifluction, where a mix of liquid and frozen porewater at the onset of freezing or thawing greatly decreases the mechanical strength of soil (Christ *et al*., 2009; Shoop *et al*., 2008). Capillary forces or ice bonding change rapidly and markedly as the temperature of ice nears its melting point, with the associated decline in mechanical strength causing downslope soil movement. Gelifluction lobes and sheets are common features of polar and high-altitude slopes (Bockheim, 2014; Matsuoka, 2001).

Another process affecting the mechanical behaviour of polar soils is dilatency or thixotropy. This process was observed decades ago by pedologists describing the genesis of vesicular or highly consolidated structures in Cryosols (French, 2007). Upon mechanical loading, thixotropic soils lose strength as particles rearrange, but can reform into stronger soils than the pre-thixotropic state, with pore structure more closely packed and sometimes less favourable for biological colonisation (Greenslade *et al*., 2012; Smith *et al*., 2012). Although this process is commonly described for polar soils (Krasnoshchekov, 1999), and in fact exacerbated by field workers as they trample some thawed soils, we have found no published papers that have quantified mechanical changes due to thixotropic processes in polar soils. Given the significance of human physical damage to polar soils (O'Neill *et al*., 2012) and the relevance of soil trampling by polar fauna to ecosystem development (Haussmann *et al*., 2013), a greater understanding of the underlying mechanical processes is long overdue.

Laboratory investigations have quantified mechanical changes to soils at the onset of freezing and thawing using shear (Harris *et al*., 1995), permeability and triaxial testing apparatus (Ishikawa *et al*., 2010). Model slopes have also been tested in the laboratory to control freezing and thawing, and to facilitate accurate monitoring of porewater pressure changes (Harris, 1996; Harris *et al*., 2008). Several papers have upscaled model slope studies of freezing and thawing in the laboratory using a geotechnical centrifuge (Harris *et al*., 2003; Kern-Luetschg and Harris, 2008). The insight gained from these studies is essential to parameterise models of slope movements caused by freeze-thaw cycles in soil (Harris and Smith, 2003; Kirkby, 1995).

Mechanical testing using these approaches requires kilograms to tonnes of soil, which may conflict with conservation concerns in sensitive polar environments, particularly in Antarctica, where sample collection is regulated by strict environmental protection protocols (http://www.antarctica.ac.uk/apfp/plan/importing-biological-samples.php) and governed by the International Antarctic Treaty. Moreover, larger-scale tests are time-consuming and expensive to conduct, and although they provide vital information about field-scale behaviour, they are not suited to the testing of a large number of locations. Freezing fronts move gradually through these larger soil masses, making it difficult to measure localised impacts on mechanical behaviour at the onset of freezing or thawing.

The primary aim of this study was to examine whether small-scale testing with a temperature-controlled rotational rheometer could provide valuable information on gelifluction, thixotropy and yield stress of polar soils. We investigated a range of surface soils taken from the maritime Antarctic. Less than 5 g of soil were required per test, and so it permitted unplanned mechanical tests of samples collected originally for a biological study (Dennis *et al*., 2012). Stress-dependent loading imparted by the rotational rheometer was highly controlled and the 2 mm thickness of samples decreased thermal gradients imposed by a Peltier stage. There are experimental artefacts induced by such small-scale tests that are described, but the results are valuable for understanding gelifluction and thixotropy processes in polar soils.

MATERIALS AND METHODS

Sampling Locations and Description

Soils were collected from the top 5 cm at Signy, Greenwich, Wiencke, Livingston and Alectoria islands (Figure 1; Table 1). The locations were a subset of a larger sampling programme exploring soil biodiversity in the region (Dennis *et al*., 2012, 2013). We selected areas with varying soil characteristics, ranging from beach sands to orthinogenic soils containing a large proportion of guano from penguins. Greenwich and Wiencke islands are both ornithogenic, with a large incidence of bird activity. The soils are from a weathered rocky outcrop and a raised beach, respectively. Livingston Island soil was observed to be highly thixotropic at the time of sampling, with site 1 containing a large amount of fine material near the surface due to periglacial activity and site 2 containing colluvial deposits from meltwater. Signy Island was also observed to be thixotropic at sampling, with soils derived from shattered rock. Alectoria Island was weathered from a rocky outcrop, containing heavily fractured gneiss and schist, as well as colluvial material. Soil samples were immediately frozen to -20°C and transported by ship to the UK at this temperature.

Mechanical Testing of Soils

Mechanical tests used a Haake MARS parallel plate rotational rheometer (Thermo Scientific, Waltham, MA, USA) with 35 mm diameter profiled stainless steel plates. Attached to the rheometer is a universal temperature controller (Thermo Scientific) that controls the temperature of the lower plate to ± 0.1°C with a Peltier system. The rheometer measures rotational torque and displacement, and vertical displacement, so that stress, strain and dilatency under shear can be calculated. These data can be used to calculate a range of material properties, including viscosity. As past research has challenged the concept of viscous flow in gelifluction (Harris *et al*., 2003), we cautiously limit mechanical characterisation to the interaction between shear stress, τ, and strain, γ, to obtain the shear modulus, G:

$$G = \frac{\tau}{\gamma}. \tag{1}$$

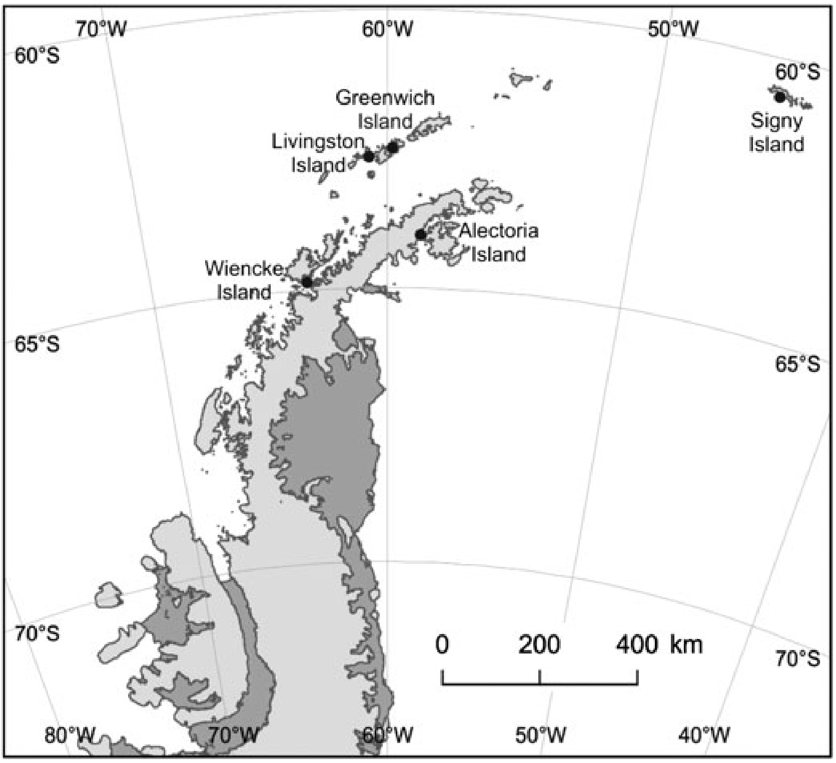

Figure 1 Sampling locations in the Antarctica Peninsula where soil was taken from 0–5 cm depth. The figure was drawn by Peter Fretwell of the British Antarctic Survey. The light shading indicates land and the dark shading indicates ice.

Table 1 Details of the sampling sites in the Antarctic Peninsula and a range of soil properties.

	Signy Island	Greenwich Island	Livingston Island 1	Livingston Island 2	Alectoria Island	Wiencke Island
Latitude (°)	60.72	62.64	62.70	62.70	64.16	65.07
Longitude (°)	45.85	59.95	61.23	61.22	59.14	63.60
Altitude, m	199.00	16.00	75.00	72.00	50.00	5.90
-0.5 kPa water content, g 100 g^{-1}	33.70	33.20	45.10	31.80	30.50	44.80
Carbon, g 100 g^{-1}	0.19	0.85	0.87	0.33	0.36	0.89
Nitrogen, g 100 g^{-1}	0.04	0.11	0.13	0.05	0.09	0.14
Carbon:Nitrogen	5.08	8.01	6.92	6.60	4.01	6.48
Calcium, g 100 g^{-1}	0.00	2.01	6.14	0.10	2.39	27.45
Chloride, g 100 g^{-1}	26.99	58.95	31.46	20.32	35.52	40.95
Electrical conductivity, µS cm^{-1}	24.10	28.50	26.25	19.65	24.10	62.80
pH	7.98	5.76	7.24	6.59	6.36	7.72
Per cent gravel and coarse sand > 400 µm discarded, g 100 g^{-1}	72.8	30.1	23.1	39.3	38.9	29.6
Sieved soil texture, g 100 g^{-1}	89.9	74.4	61.0	83.2	84.9	64.4
Sand (63–400 µm)	7.4	20.1	25.5	14.1	10.2	33.8
Silt (2–63 µm)	2.7	5.5	13.5	2.6	4.9	1.8
Clay (<2 µm)	Algal	None	Moss/	Bare	Moss/	None
Vegetation	mat		lichen		lichen	
Bird guano impact	Low	High	Low	Low	Low	High

Testing with the rotational rheometer and the series of tests described below are illustrated in Figure 2. Mechanical measurements were made on 2 cm^3 of soil at a gap spacing between the rheometer platens of 2 mm. To decrease the effect of particle interlocking during testing, all soil samples were thawed, air-dried, ground gently

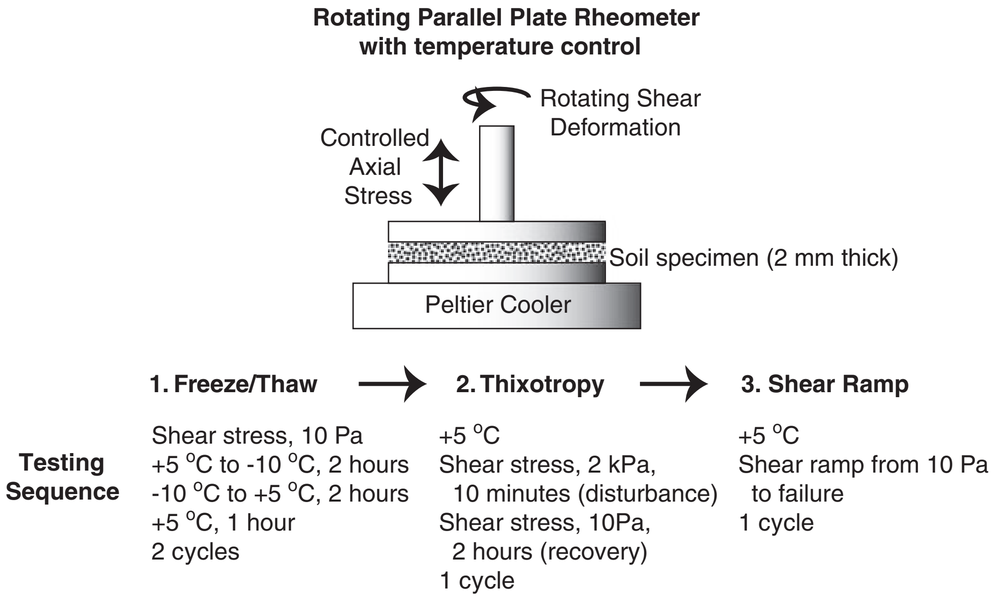

Figure 2 Testing procedure for Antarctic Peninsula soils using a rotational rheometer. Three successive tests were conducted on the same soil sample.

in a mortar and pestle, and then passed through a 400 µm sieve. As such, mechanical behaviour will vary from field conditions, but this needs to be weighed against the benefits of testing small samples in a rotational rheometer. These benefits include the precise control of shear stress and normal load, the ability to freeze and thaw specimens rapidly, and the simultaneous measurements of sample expansion, stress relaxation and temperature of the lower platen. Therefore the approach is useful for exploring gelifluction and thixotropy processes, but larger-scale testing is required to make predictions of field behaviour, particularly in soils dominated by sand and gravel. The sample preparation also disturbs the inherent physical structure of the soil, so further artefacts are created.

The soil samples were saturated and then dried to -0.5 kPa water potential on a Buchner funnel connected to a hanging water column. Each sample was then placed on the lower plate of the rheometer to approximately 2 mm depth and the upper plate was lowered so that the normal load was 0.1 kPa, which was kept constant during subsequent testing. To minimise evaporation during testing, a layer of glycerine was applied to the exposed edge of the sample with a paint brush and the test area was enclosed with a cover. Samples were then equilibrated to 5°C for 1 h before the application of a sequence of mechanical tests. These tests separated out the effects of freeze-thaw, liquefaction of a thawed specimen and shear failure using the same sample through an automated overnight test:

1. Freeze-thaw: Freezing and thawing were controlled with a Peltier temperature controller, with temperature ramps consisting of 5°C to -10°C over 2 h, followed by -10°C to 5°C over 2 h and finally a constant 5°C for 1 h. Two freeze-thaw cycles were measured. A constant oscillating shear stress of 10 Pa at 0.5 Hz was applied, which is within the linear viscoelastic (LVE) range of all soils tested (i.e. the stress range where all applied stress is recoverable). The testing conditions are similar to those of other studies that have used rotational rheometers to measure the mechanical properties of soils (Barré and Hallett, 2009; Ghezzehei and Or, 2001). Mechanical behaviour was described by the shear modulus at 5°C, G_i, and the lowest point at the onset of freezing, G_f, and thawing, G_t, for each of the two cycles (denoted by the subscripts 1 and 2, respectively). G_f *and* G_t were normalised by dividing by G_i. Expansion during freezing was also recorded and used to calculate strain at freezing, ε_f, and in the thawed sample at 5°C following the two cycles of freezing and thawing, ε_{end}.
2. Thixotropy: After equilibration at 5°C for 1 h during the previous freeze-thaw test, the oscillating shear stress increased to 2 kPa for 10 min, followed by a return to 10 Pa for 2 h. Measurements of shear modulus, G, at the larger stress measured liquefaction, and at 0.1 and 2 h after the stress was removed the short- and long-term recovery of the sample. All G values are normalised against the value measured in the LVE region at 10 Pa before the larger stress was applied.
3. Shear ramp: The oscillating shear stress at 0.5 Hz increased from 10 Pa until failure to measure the shear strength, τ.

Testing of one sample took 8.5 h. The water content of the sample was measured before and after testing by oven drying at 105°C until water loss ceased. Three replicates were measured for each sampling location.

Data were analysed for normal distribution using a Kolmogrov-Smirnov test, with G_f/G_i, G_t/G_i and τ square root transformed. A one-way ANOVA compared means, with $P < 0.05$ indicating a significant difference. Correlation analysis investigated relationships between measured properties of the soils. All data analyses were conducted with IBM SPSS Version 21.

RESULTS

An example of the mechanical response of the soil to cycles of freezing and thawing is shown in Figure 3. The flat period at the beginning of the test is the LVE range at 5°C. At the onset of freezing, a very sharp decline in *G* of one order of magnitude occurred, followed by a rapid increase to *G* values greater than 1 MPa. Thawing resulted again in a sharp decline in *G*, followed by a rapid recovery to about the initial G_i value. On the second cycle of freezing and thawing, a similar trend was observed. Expansion of the sample due to freezing was also observed.

Table 2 summarises all mechanical data of the different sampling locations measured. Between the sampling locations, there was a large difference in G_i measured before the test sequence imposed freeze-thaw or mechanical stresses that may have altered behaviour. The first freeze-thaw cycle increased *G* (i.e. G_1/G_i) for all sampling locations, but the second freeze-thaw cycle had mixed effects on *G* (i.e. G_2/G_i). Both freezing and thawing caused large declines in *G*, but differences between sampling locations were only observed for thawing. Freezing caused expansion up to 0.16 m m^{-1}. Vertical strain at the end of the freeze-thaw cycles varied significantly between soils, with some expanding and others collapsing due to particle rearrangement. Correlation analysis of all data found that calcium concentration (R^2 = 0.636, $P < 0.01$) and latitude (R^2 = 0.611, $P < 0.01$) had negative relationships with G_i, but there was no relationship with other properties.

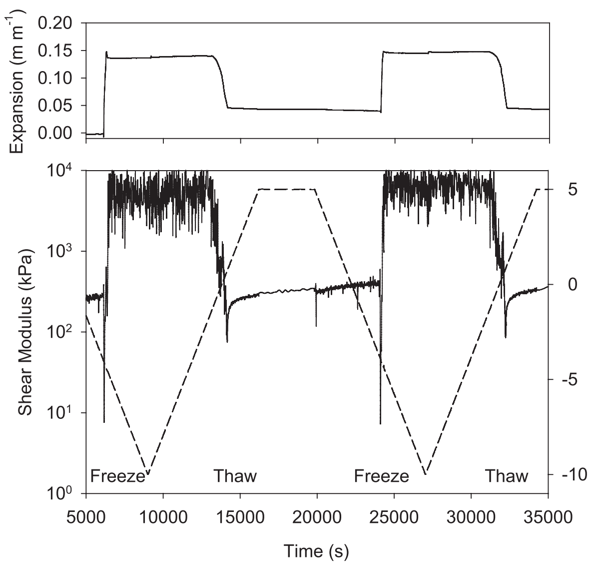

Figure 3 The response of shear modulus, *G*, and vertical expansion undergoing two cycles of freezing and thawing for a soil sampled at Livingston Island 1. Temperature is measured in a Peltier unit that is used to freeze and thaw the sample from its base.

Thixotropy of the same sample illustrated in Figure 3 is shown in Figure 4. *G* declined rapidly upon application of the larger shear stress (2 kPa on Figure 4) and then recovered over time once the stress was removed at about 3500 s. Mechanical loading for 10 min at 2 kPa with an oscillating shear stress caused *G* to decline to less than 10 per cent of the initial value (resistance in Table 2). Whereas soil from Signy Island quickly recovered *G* after 0.1 h of relaxation, soils from the other sampling locations recovered more slowly. After 2 h, soils from Signy and Wiencke islands recovered much further, but soils from other locations remained at less than 35 per cent of the initial *G* value. Yield stress, τ, of the soils after the recovery period to measure thixotropy was generally less than 2 kPa.

Livingston Island 1 and Wiencke Island soils had the greatest combined silt and clay contents, and the greatest water contents at testing following equilibration to -0.5 kPa water potential. Whilst these soils had much smaller *G* compared to the other soils that had fewer fine particles, Alectoria Island soil displayed similar rheological behaviour despite a coarser texture and smaller water content at testing. There was no correlation between particle size and mechanical measurements.

DISCUSSION

Very large drops in shear modulus occurred under the freeze-thaw and thixotropy tests for soils sampled from various locations in the maritime Antarctic. At the onset of freezing or thawing, the largest drop lasted for only a brief instant, with conditions returning to pre-thaw or pre-freeze ones within tens of seconds. This temperature-dependent rapid drop in soil mechanical behaviour has been investigated in controlled triaxial (Ishikawa *et al*., 2010) and larger-scale laboratory tests (Harris *et al*., 1993), but our study provides a new understanding of localised changes in the micromechanical behaviour of soil at the onset of freezing and thawing, with results obtained using a range of Antarctic soils. At the onset of thawing, we found that many of these soils lose about 80 per cent of their shear modulus compared to that of the previous thawed state. For the short period of time when shear modulus is so small, the thawing soils will be far more susceptible to movement on slopes or to particle rearrangement due to overburden soil pressures or under frost heave.

Thixotropy caused even greater loss in shear modulus on thawing, with mechanical damage through processes such as trampling potentially decreasing shear modulus by > 90 per cent and slow recovery over time. Surprisingly, few studies have quantified the physical impacts of trampling on Antarctic soils. Tejedo *et al*. (2009) measured a 50 per cent increase in soil bulk density and an 800 per cent

Table 2 Freeze-thaw, thixotropy and yield stress, τ, of soils sampled from different locations in the Antarctic Peninsula.

	Signy Island		Greenwich Island		Livingston Island 1		Livingston Island 2		Alectoria Island		Wiencke Island		P	LSD
Freeze-thaw	135	±4938	124	±8705	30	±24 652	120	±41	17	±12	33	±10	0.030	40730
G_i, Pa	816		557		498		766	639	493	256	518	762		
G_1/G_i	2.31	±0.65	1.26	±0.41	14.54	±4.90	1.60	±0.19	11.70	±6.34	2.47	±0.78	0.047	4.67
G_2/G_i	0.65	±0.45	0.41	±0.62	4.90	±4.25	0.19	±0.61	6.34	±9.03	0.78	±0.72	0.065	5.80
G_{f1}/G_i	0.32	±0.10	0.21	±0.06	0.15	±0.07	0.04	±0.01	0.40	±0.18	0.50	±0.14	0.108	0.16
G_{t1}/G_1	0.26	±0.02	0.32	±0.04	0.08	±0.02	0.25	±0.02	0.16	±0.04	0.24	±0.01	0.001	0.04
G_{f2}/G_1	0.23	±0.05	0.26	±0.03	0.20	±0.08	0.19	±0.13	0.30	±0.14	0.42	±0.09	0.454	0.12
G_{t2}/G_2	0.32	±0.03	0.22	±0.03	0.11	±0.02	0.21	±0.01	0.23	±0.02	0.26	±0.02	0.001	0.03
ε_{f1}, m m^{-1}	0.062	±0.007	0.131	±0.005	0.047	±0.008	0.156	±0.009	0.064	±0.005	0.088	±0.007	0.001	0.010
ε_{f2}, m m^{-1}	0.062	±0.004	0.124	±0.020	0.077	±0.006	0.121	±0.011	0.060	±0.004	0.094	±0.006	0.002	0.015
ε_{end}, m m^{-1}	0.007	±0.004	0.027	±0.013	-0.079	±0.042	0.103	±0.048	-0.038	±0.019	-0.003	±0.036	0.025	0.044
Thixotropy														
Resistance, G_R/G_2	0.05	±0.01	0.04	±0.01	0.04	±0.03	0.05	±0.00	0.03	±0.00	0.08	±0.03	0.552	0.02
Short recovery (0.1 h), G_S/G_2	0.65	±0.06	0.19	±0.06	0.25	±0.20	0.28	±0.04	0.18	±0.02	0.19	±0.09	0.035	0.14
Long recovery (2 h), G_L/G_2	0.82	±0.14	0.31	±0.05	0.34	±0.22	0.55	±0.05	0.32	±0.02	0.71	±0.20	0.088	0.19
Shear ramp τ, Pa	2217	±424	811	±118	1202	±1156	1078	±627	494	±54	1185	±696	0.545	896

Note: G is the shear modulus with the subscripts referring to: i, initial condition; 1, after the first freeze-thaw cycle; 2, after the second freeze-thaw cycle; f, smallest value at the onset of freezing; t, smallest value at the onset of thawing; R, resistance to an oscillating stress of 2 kPa; and S and L, short- and long-term recovery following removal of this stress. ε is the vertical strain; and ε_{end} is strain in the thawed sample at 5°C following the two cycles of freezing and thawing. The mean ± standard error is shown with P determined with ANOVA and the least-significant difference, LSD, with a post-hoc Games-Howell test.

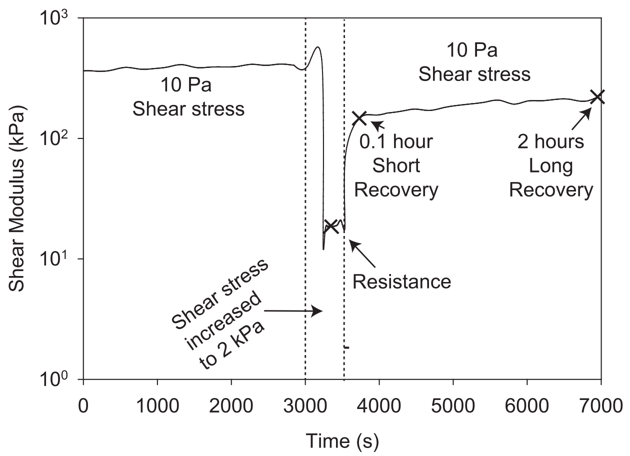

Figure 4 The response of shear modulus, G, of a thawed soil sampled at Livingston Island 1 to a 10 min oscillating shear stress of 2 kPa. Thixotropy is described by the change in G upon loading with the higher shear stress and its recovery 0.1 h and 2 h after the shear stress is removed.

increase in resistance to compression (measured with a penetrometer) following about 1000 human footsteps on Antarctic soils in the Byers Peninsula. Over a 5 year recovery period, resistance to compression, recovered from 600 kPa to 100 kPa, and so the soils showed a large amount of resilience to damage. In our approach, the equivalent of 300 disturbances was imposed through cyclic loading with a 2 kPa shear stress. All of the soils had a very poor resistance to this stress level, which is much smaller than the stress from a human footprint (50–60 kPa), with recovery varying considerably between different soils. There is a need for wider measurements of physical disturbance and recovery of Antarctic soils, as Tejedo *et al.*'s (2009) results could be site-specific. Moreover, field measurements could be compared to our laboratory test to evaluate its effectiveness.

Few trends were found between the mechanical behaviour of the different soils and other soil properties. This was most surprising for texture, particularly given that soil from Livingston Island 1 contained a much greater proportion of clay-sized particles than any other soil, but had similar behaviour to that of the coarser-textured soil from Alectoria Island. Soil texture, albeit over a fairly narrow textural range, was found not to influence solifluction observed in the field for a study in northern Sweden (Ridefelt *et al.*, 2011). Several recent soil surveys on the Antarctic Peninsula described by Guglielmin and Vieira (2014) and another survey on the Fildes Peninsula and Ardley Island (Michel *et al.*, 2014) found large differences in parent material and biological inputs that create great diversity in soil properties. This is reflected in the large differences between many of the soil properties that we found (Table 1) and could affect the texture impact on mechanical behaviour. Our results, and the soil survey research conducted by others, suggest that the potential impact of increasing frequency of freeze-thaw cycles on gelifluction may require site-specific testing. Local environmental factors, particularly altitude, have been found in the field to have a larger impact on the extent of observed gelifluction features. For instance, Michel *et al*. (2014) found virtually no gelifluction at sea level but > 10 per cent land area coverage above 100 m asl due to the greater occurrence of periglacial processes.

Whilst the rotational rheometer approach presented has the advantage of controlled micromechanical testing and the use of small sample masses, the small specimen thickness necessitates sieving and increases the risk of experimental artefacts from particle interlocking or sample heterogeneity (Barré and Hallett, 2009). Moreover, porewater migration due to freezing or thawing fronts (Harris *et al*., 1995) and the resultant impact on the hydrological behaviour of the soil (Ishikawa *et al*., 2010) were not possible to study. In this study, soils were tested near to saturation at -0.5 kPa, but future research could explore a range of water potentials, as done in rotational rheometer measurements of agricultural soils (Ghezzehei and Or, 2001) and pure clays (Barré and Hallett, 2009). The small-scale measurements also need to be verified against traditional shear and triaxial testing approaches.

There is scope to use the rotational rheometer to gain greater insight into the fundamental processes that control the mechanical behaviour of soils under cycles of freezing and thawing. Chemical properties of the soil solution that are known to affect mechanical behaviour, such as salinity (Holthusen *et al*., 2010), pH and dissolved organic matter (Tarchitzky and Chen, 2002), could be manipulated in the small sample sizes tested. It would be interesting to explore the effect of these solutes (Kelleners, 2013) and soil pore sizes on freezing point depression in relation to soil mechanical behaviour under freezing and thawing. Sampling could also be targeted to investigate soils of contrasting parent material and a broader range of textures, potentially based on previous soil survey exercises on the Antarctic Peninsula (Guglielmin and Vieira, 2014; Michel *et al*., 2014) or other regions where periglacial processes occur.

CONCLUSIONS

With a commercial, temperature-controlled rotational rheometer, the gelifluction, thixotropy and yield stress of small soil masses from different locations in the maritime Antarctic could be tested. Compared to other testing approaches, this method is more compatible with conservation concerns in polar regions, where only a limited mass of soil may be removed. The narrow thickness of the test specimen allows for a more rapid heat transfer than is possible in larger specimens, and so the micromechanics of freezing and thawing porewater on bulk soil behaviour can be explored more closely. Nevertheless, the small sample size has greater potential to create experimental artefacts, which requires further exploration.

Both freezing and thawing caused large drops in shear modulus, with differences in behaviour between the sampled locations only observed for thawing. All soils were therefore highly thixotropic, with recovery rates following the removal of the increased shear stress varying significantly between sampling locations. These results are significant for current and projected warming trends in the Antarctic Peninsula. Increased frequency of freeze-thaw cycles could exacerbate slope movement through gelifluction, whereas a greater duration of thawed soil could increase thixotropy caused by trampling, leading to mechanical damage to surface soils.

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REFERENCES

Adams B, Arthern R, Atkinson A, Barbante C, Bargagli R, Bergstrom D, Bertler N, Bindschadler R, Bockheim JG, Boutron C, Bromwich D, Chown S, Comiso J, Convey P, Cook A, di Prisco G, Fahrback E, Fastook J, Forcarda J, Gili J-M, Gugliemin M, Gutt J, Hellmer H, Hennion F, Heywood K, Hodgson D, Holland D, Hong S, Huiskes A, Isla E, Jacobs S, Jones A, Lenton A, Marshall G, Mayewski P, Meredith M, Metzl N, Monaghan A, Naveira-Garabato A, Newsham K, Orejas C, Peck L, Portner H-O, Rintoul S, Robinson S, Roscoe H, Rossi S, Scambos T, Shanklin J, Smetacek V, Speer K, Stevens MI, Summerhayes C, Trathan P, Turner J, van der Veen K, Vaughan D, Verde C, Webb D, Wiencke C, Woodworth P, Worby T, Worland R, Yamanouchi T. 2009. The instrumental period. In *Antarctic Climate Change and the Environment*. Turner J, Bindschadler R, Convey P, di Prisco G, Fahrbach E, Gutt J, Hodgson D, Mayewski P, Summerhayes C (eds). Scientific Committee on Antarctic Research: Cambridge, UK; 183–298.

Barré P, Hallett PD. 2009. Rheological stabilization of wet soils by model root and fungal exudates depends on clay mineralogy. *European Journal of Soil Science* **60**: 525–538. DOI:10.1111/j.1365-2389.2009.01151.x.

Bockheim JG. 2014. Distribution, properties and origin of viscous-flow features in the McMurdo Dry Valleys, Antarctica. *Geomorphology* **204**: 114–122. DOI:10.1016/j.geomorph.2013.07.032.

Christ M, Kim YC, Park JB. 2009. The influence of temperature and cycles on acoustic and mechanical properties of frozen soils. *KSCE Journal of Civil Engineering* **13**: 153–159. DOI:10.1007/s12205-009-0153-1.

Dennis PG, Rushton SP, Newsham KK, Lauducina VA, Ord VJ, Daniell TJ, O'Donnell AG, Hopkins DW. 2012. Soil fungal community composition does not alter along a latitudinal gradient through the maritime and sub-Antarctic. *Fungal*

Ecology **5**: 403–408. DOI:10.1016/j.funeco.2011.12.002.

Dennis PG, Newsham KK, Rushton SP, Ord VJ, O'Donnell AG, Hopkins DW. 2013. Warming constrains bacterial community responses to nutrient inputs in a southern, but not northern, maritime Antarctic soil. *Soil Biology and Biochemistry* **57**: 248–255. DOI:10.1016/j.soilbio.2012.07.009.

French HM. 2007. *The Periglacial Environment*, Third edition. John Wiley and Sons, Inc: Chichester.

Ghezzehei TA, Or D. 2001. Rheological properties of wet soils and clays under steady and oscillatory stresses. *Soil Science Society of America Journal* **65**: 624–637. DOI:10.2136/sssaj2001.653624x.

Greenslade P, Potapov M, Russell D, Convey P. 2012. Global Collembola on Deception Island. *Journal of Insect Science* **12**: 16. DOI:10.1673/031.012.11101.

Guglielmin M, Vieira G. 2014. Permafrost and periglacial research in Antarctica: New results and perspectives. *Geomorphology* **225**: 1–3. DOI:10.1016/j.geomorph.2014.04.005.

Hansen J, Sato M, Ruedy R, Low K, Lea DW, Medina E. 2006. Global temperature change. *Proceedings of the National Academy of Sciences* **103**: 14288–14293. DOI:10.1073/pnas.0606291103..

Harris C. 1996. Physical modelling of periglacial solifluction: Review and future strategy. *Permafrost and Periglacial Processes* **7**: 349–360. DOI:10.1002/ppp235>3.0.co;2-o.

Harris C, Smith JS. 2003. Modelling gelifluction processes: the significance of frost heave and slope gradient. In *Proceedings of the 8th International Conference on Permafrost, Zurich*, Phillips M, Springman SM, Arenson LU (eds). Balkema: Lisse, The Netherlands; 355–360.

Harris C, Gallop M, Coutard JP. 1993. Physical modeling of gelifluction and frost creep - some results of a large-scale laboratory experiment. *Earth Surface Processes and Landforms* **18**: 383–398. DOI:10.1002/esp.3290180502.

Harris C, Davies MCR, Coutard JP. 1995. Laboratory simulation of periglacial solifluction: Significance of porewater pressures, moisture contents and undrained shear strengths during soil thawing. *Permafrost and Periglacial Processes* **6**: 293–311. DOI:10.1002/ppp.3430060403.

Harris C, Davies MCR, Rea BR. 2003. Gelifluction: Viscous flow or plastic creep? *Earth Surface Processes and Landforms* **28**: 1289–1301. DOI:10.1002/esp.543.

Harris C, Kern-Luetschg M, Murton J, Font M, Davies M, Smith F. 2008. Solifluction Processes on Permafrost and Non-permafrost Slopes: Results of a Large-scale Laboratory Simulation. *Permafrost and Periglacial Processes* **19**: 359–378. DOI:10.1002/ppp.630.

Haussmann NS, Rudolph EM, Kalwij JM, McIntyre T. 2013. Fur seal populations facilitate establishment of exotic vascular plants. *Biological Conservation* **162**: 33–40. DOI:10.1016/j.biocon.2013.03.024.

Holthusen D, Peth S, Horn R. 2010. Impact of potassium concentration and matric potential on soil stability derived from rheological parameters. *Soil and Tillage Research* **111**: 75–85. DOI:10.1016/j.sti11.2010.08.002.

Ishikawa T, Tokoro T, Ito K, Miura S. 2010. Testing methods for hydro-mechanical characteristics of unsaturated soils subjected to one-dimensional freeze-thaw action. *Soils and Foundations* **50**: 431–440. DOI:10.3208/sandf.50.431.

James M, Lewkowicz AG, Smith SL, Miceli CM. 2013. Multi-decadal degradation and persistence of permafrost in the Alaska Highway corridor, northwest Canada. *Environmental Research Letters* **8**: 10. DOI:10.1088/1748-9326/8/4/045013.

Kelleners TJ. 2013. Coupled Water Flow and Heat Transport in Seasonally Frozen Soils with Snow Accumulation. *Vadose Zone Journal* **12**: 11. DOI:10.2136/vzj2012.0162.

Kern-Luetschg M, Harris C. 2008. Centrifuge Modelling of Solifluction Processes: Displacement Profiles Associated with One-sided and Two-sided Active Layer Freezing. *Permafrost and Periglacial Processes* **19**: 379–392. DOI:10.1002/ppp.633.

Kirkby MJ. 1995. A model for variations in gelifluction rates with temperature and topography: Implications for global change. *Geografiska Annaler Series a-Physical Geography* **77A**: 269–278. DOI:10.2307/521336.

Krasnoshchekov YN. 1999. Microelements in cryozems of Northern Taiga in the Yenisei River basin, Central Siberia. *Eurasian Soil Science* **32**: 1297–1304.

Matsuoka N. 2001. Solifluction rates, processes and landforms: a global review. *Earth-Science Reviews* **55**: 107–134. DOI:10.1016/s0012-8252(01)00057-5.

Matsuoka N, Moriwaki K. 1992. Frost heave and creep in the sor rondane mountains, antarctica. *Arctic and Alpine Research* **24**: 271–280. DOI:10.2307/1551282.

Matsuoka N, Moriwaki K, Iwata S, Hirakawa K. 1990. Ground temperature regimes and their relationship to periglacial processes in the Sør Rondane Mountains, East Antarctica. *Proceedings of the NIPR Symposium on Antarctic Geosciences* **4**: 55–66.

Michel RFM, Schaefer C, Poelking EL, Simas FNB, Fernandes EI, Bockheim JG. 2012. Active layer temperature in two Cryosols from King George Island, Maritime Antarctica. *Geomorphology* **155**: 12–19. DOI:10.1016/j.geomorph.2011.12.013.

Michel RFM, Schaefer C, Lopez-Martinez J, Simas FNB, Haus NW, Serrano E, Bockheim JG. 2014. Soils and landforms from Fildes Peninsula and Ardley Island, Maritime Antarctica. *Geomorphology* **225**: 76–86. DOI:10.1016/j.geomorph.2014.03.041.

O'Neill TA, Balks MR, Lopez-Martinez J, McWhirter JL. 2012. A method for assessing the physical recovery of Antarctic desert pavements following human-induced disturbances: A case study in the Ross Sea region of Antarctica. *Journal of Environmental Management* **112**: 415–428. DOI:10.1016/j.jenvman.2012.08.008.

Ridefelt H, Boelhouwers J, Etzelmuller B. 2011. Local variations of solifluction activity and environment in the Abisko Mountains, Northern Sweden. *Earth Surface Processes and Landforms* **36**: 2042–2053. DOI:10.1002/esp.2225.

Shoop S, Affleck R, Haehnel R, Janoo V. 2008. Mechanical behavior modeling of thaw-weakened soil. *Cold Regions Science and Technology* **52**: 191–206. DOI:10.1016/j.coldregions.2007.04.023.

Smith TE, Wall DH, Hogg ID, Adams BJ, Nielsen UN, Virginia RA. 2012. Thawing permafrost alters nematode populations and soil habitat characteristics in an Antarctic polar desert ecosystem. *Pedobiologia* **55**: 75–81. DOI:10.1016/j.pedobi.2011.11.001.

Tarchitzky J, Chen Y. 2002. Rheology of sodium-montmorillonite suspensions: Effects of humic substances and pH. *Soil Science Society of America Journal* **66**: 406–412. DOI:10.2136/sssaj2002.4060.

Tejedo P, Justel A, Benayas J, Rico E, Convey P, Quesada A. 2009. Soil trampling in an Antarctic Specially Protected Area: tools to assess levels of human impact. *Antarctic Science* **21**: 229–236. DOI:10.1017/S0954102009001795.