IN SITU PERMAFROST CREEP, MELVILLE ISLAND, AND IMPLICATIONS FOR GLOBAL CHANGE

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Abstract

In situ measurements of permafrost creep at a number of sites near Rea Point, Eastern Melville Island (latitude 75°22'N; longitude 105°45'W) between 1985 and 1987 indicate rates of deformation between 0.06 to 0.10 cm/yr at a depth of 65 cm. The current mean annual ground temperature (MAGT) is -16.5°C and ground temperatures warmer than -3.0°C occur only in the top 1.0-1.2 m of permafrost and for only 80-100 days per year. If predicted global warming trends were to induce slight thermal changes in the upper 1.0-2.0 m of permafrost at Rea Point greater creep rates might be expected in addition to increased gelifluction and mass wasting in the active layer.

Résumé

Des mesures *in situ* du fluage du pergélisol à plusieurs endroits près de Rea Point dans l'est de l'île Melville (latitude 75°22'N; longitude 105°45'W) effectuées entre 1985 et 1987 indiquent des taux de déformation de 0,06 à 0,10 cm/a à une profondeur de 65 cm. La température annuelle moyenne du sol (TAMS) est actuellement de -16,5°C, et les températures du sol dépassent -3,0°C seulement dans le premier 1 à 1,2 m de pergélisol pendant à peine 80 à 100 jours par an. Si les tendances prévues du réchauffement planétaire devaient entraîner de légères variations thermiques dans le premier 1 à 2 m de pergélisol à Rea Point, il faudrait s'attendre à des taux de fluage plus élevés en plus d'une gélifluxion accélérée et de mouvements de versants plus actifs dans le mollisol.

Introduction

Recent studies suggest that average global temperatures may increase by 2-4°C over the next several decades (e.g. Eybergen and Imeson, 1989; Milko, 1988; Harte and Williams, 1988). This may induce significant temperature increases in frozen ground especially within subarctic areas where permafrost temperatures are relatively high (Goodwin *et al.*, 1984; Osterkamp, 1984). This paper presents field data on rates of permafrost creep in the Canadian High Arctic and uses this information to speculate about the potential deformation which may result in those areas if present global warming scenarios are correct.

Permafrost creep

Permafrost creep results from a variety of time-dependent stresses and strains in ice-rich frozen soil (e.g. Vyalov, 1986). It is dominated by the rheological properties of ice. Glen's flow law suggests that at a temperature of -22°C, the strain rate produced by a given stress is only one-tenth of its value at 0°C, and the strain rate almost doubles from -5°C to 0°C. As the temperature of ice becomes warmer, ice crystal boundaries lose their rigidity (e.g. Hobbs, 1974). The most critical temperature of an ice-rich soil is pressure melting temperature. At this temperature, the ice within the soil provides an absolute minimum resistance to shear stresses (Tsytovich, 1975). The ice becomes ductile and the strength of ductile ice is much less than the strength of brittle ice. Huang *et al.* (1986) found that an exponential relationship exists between increasing temperature and increasing creep of permafrost. This contrasts with the direct near-linear relationship observed earlier by Butkovich (1954). The exponential relationship probably reflects an increase in unfrozen water content (e.g. Smith and Riseborough, 1985; p. 18).

Field studies

Field studies aimed at the measurement of *in situ* frozen soil creep were undertaken between 1985-1987 at Rea Point, Eastern Melville Island, N.W.T. (Figure 1). Some of the results have already been published (e.g. French *et al.*, 1986; Bennett and French, 1988).

A thirteen metre thermistor string, installed in May 1985, has determined the ground temperature profile in the immediate vicinity of Rea Point (Figure 2). The MAGT is -16.5°C and ground temperatures above -5.0°C occur only in the top 1.0 to 1.5 m of the soil. The depth of seasonal thaw (i.e. the active layer thickness) rarely exceeds 30-35 cm except where bedrock is exposed at the surface.

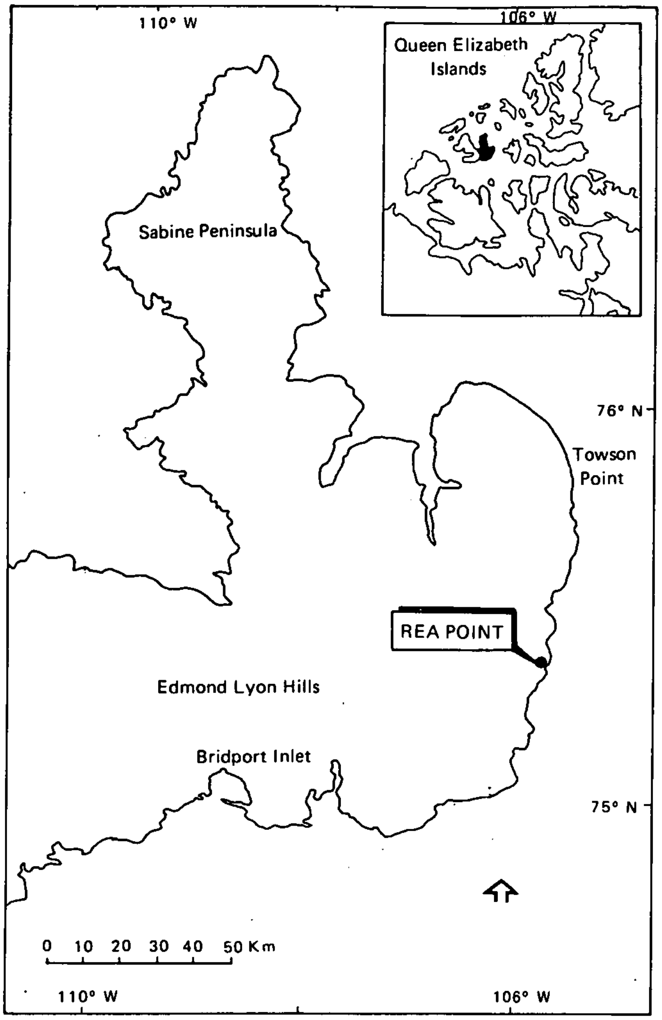

Figure 1. Location of Rea Point, Eastern Melville Island.

Because of the relationships between increasing permafrost temperatures and creep rates, as outlined above, the number of days that soil temperatures are "warm" is an important controlling factor. Soil creep was measured only in soils exceeding -3.0 °C. In this context, soil temperatures at 65 cm depth are warmer than -3.0 °C for approximately 50 to 75 days while at 100 cm depth, this number drops to between 40 and 60. During the entire 2 year period of measurement, temperatures did not exceed -3.0 °C at depths greater than 1.2m.

It is useful to compare these data with those of Savigny and Morgenstern (1986) who measured frozen soil creep in the Mackenzie Valley. At their study site, the mean annual ground temperature was -3.0 °C, and ground temperatures were greater than -3.0 °C throughout much of the permafrost profile. In these warm permafrost soils, the potential for permafrost creep exists for much of the year.

Ten sites on five slopes of different aspect and/or slope angle were instrumented in order to measure frozen soil creep (Figure 4). Each instrumented site consisted of multistring YSI thermistors, 4-tube telescoping heavemeters, and a 3 m long bottom-sealed inclinometer casing designed to accommodate a Terra Technology MP-20 inclinometer

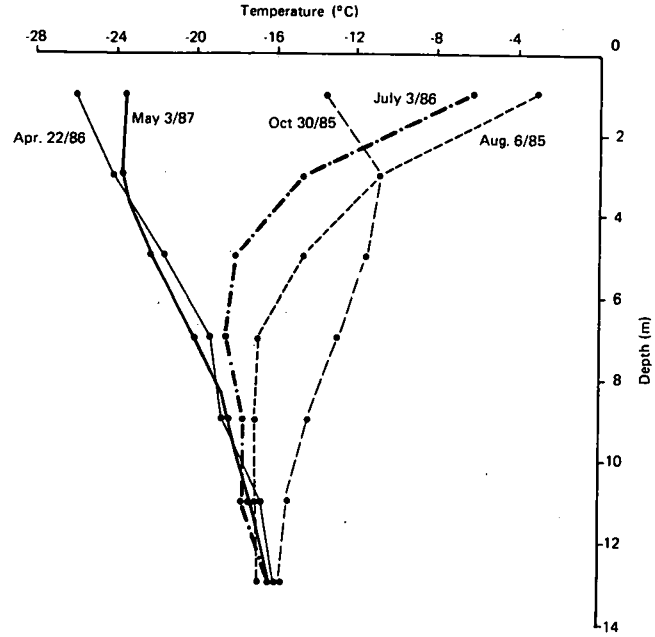

Figure 2. Ground temperature conditions at Rea Point between August 1985 and May 1987.

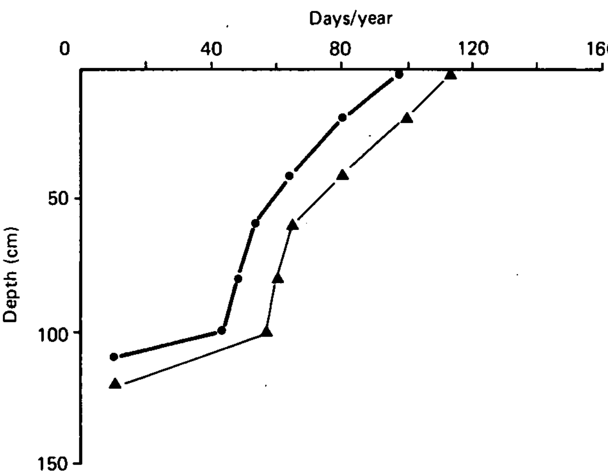

Figure 3. Maximum and minimum numbers of days with soil temperatures greater than -3.0 °C (all study sites).

torpedo. The inclinometer system was designed to detect changes in the downslope configuration of slope soils to 0.0003 cm over a 30 cm vertical distance. Accuracy of the system, however, as measured in field tests is demonstrated by maximum variability of 0.0061 cm for repeated readings at a single point over a 25 °C temperature range. Results are well within the resolution of the system.

Drilling was undertaken in May 1985 using a seismic drill mounted on a FN60 Nodwell. The plastic inclinometer casing (O.D. 70.9 mm) was surrounded by a slurry of grout mixed *in situ* and damped in place by a long thin metal rod. Reference measurements were made on August 6, 1985, with follow-up measurements taken three times a year during the following two years.

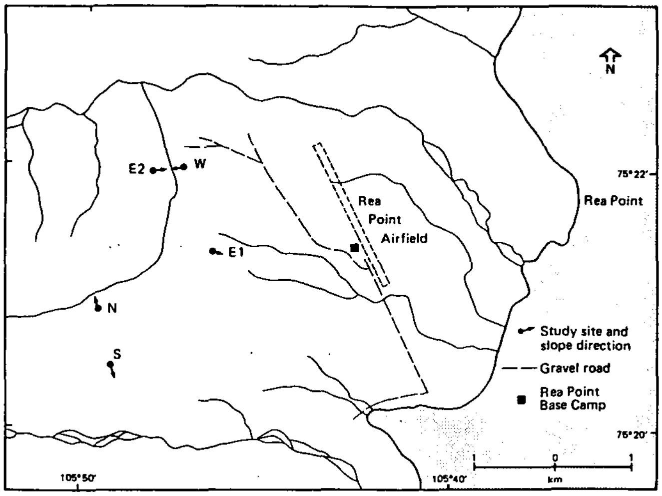

Figure 4. Location of the five study slopes.

RATES OF CREEP

Annual creep rates were calculated by determining the deformation of the casing between August 6, 1985 and August 1, 1987 and dividing by two. Annual maximum rates range from 0.3 cm yr^{-1} at 35 cm depth to 0.1 cm yr^{-1} at 65 cm depth (Bennett and French, 1988). However, average annual rates are less and range from 0.11 cm yr^{-1} at 35 cm to 0.04 cm yr^{-1} at 65 cm depth (Table 1). Since the deformations measured at the 35 cm depth may have incorporated some gelifluction occurring at the base of the active layer, we place greatest reliance upon data measured at the 65 cm depth.

In general, creep rates at Rea Point are much less than the average 0.25 to 0.3 cm yr^{-1} rates reported by Savigny and Morgenstern (1986, p. 513, 514) in the relatively warm permafrost of the Mackenzie Valley.

Greatest downslope creep at Rea Point is measured in summer and autumn. This may be demonstrated by dividing the total creep at 65 cm depth into six discrete time periods (Figure 5a). Such creep occurs almost certainly because permafrost temperatures are warmest at this time. The exponential relationship between soil temperature and soil creep (Figure 5b) is best illustrated by east slope data at 35 cm depth. However, these are limited and must be viewed with caution because gelifluction may also be involved. A more convincing exponential relationship may be shown for west slope data at 65 cm depth. Unfortunately, data from other sites at 65 cm depth (see table 1) are insufficient to infer similar relationships and it is highly probable that other factors such as average ice content and/or slope angle are also important.

In summary, our data suggest that creep decreases with depth and ceases at depths 100 cm below the ground surface. Some of our data suggest that one of the primary controls over this pattern is temperature. The hypothesis that the temperature-creep relationship is independent of depth may be strengthened perhaps, by the results of Savigny and Morgenstern (1986, p. 513) who measured creep in "warm" ice-rich sediments at depths exceeding 30 m. At Rea Point, measurable permafrost creep is generally limited to ice-rich soils at temperatures exceeding -3.0°C. Under today's climate, this condition is met only by material within 50 to 75 cm of the permafrost table.

Discussion

Although we stress the temperature control over permafrost creep in this paper, the link between ice content and temperature, as far as creep is concerned, is also fundamental. In this respect, we examined the relationship between ice content and depth in an earlier paper (French *et al.*, 1986). In general, the soils are ice-rich both at 1) the permafrost table (the upper 50 cm of permafrost) and 2) the boundary between weathered and unweathered bedrock. This boundary

Table 1. Average annual rates of *in situ* frozen soil creep for the period August 1985—August 1987 together with information regarding soil thermal conditions.

Study Site	Net Downslope Frozen Soil Creep (cm/yr) 35cm	65cm	95cm	Ambient Soil Temperature	Maximum Snow Cover	Active Layer Depth	Depth to -5°C Isotherm
W1	0.30	0.10	0.00	-2.7	15-25	25	121
W2	N/A	0.06	0.00	-1.3	10	40	157
W3	N/A	0.10	0.00	-0.8	0-5	53	171
W4	0.09	0.00	0.00	-1.6	0.5	29	144
N	0.16	0.10	0.00	-1.9	5	30	130
S	0.09	0.00	0.00	-1.4	5-10	35	183
E1-1	N/A	0.00	0.00	-1.0	25-30	41	145
E1-2	0.00	0.00	0.00	-1.9	5-10	28	135
E2-1	0.10	0.03	0.00	-0.9	30-40	30	162
E2-2	0.03	0.00	0.00	-1.6	20-40	29	150

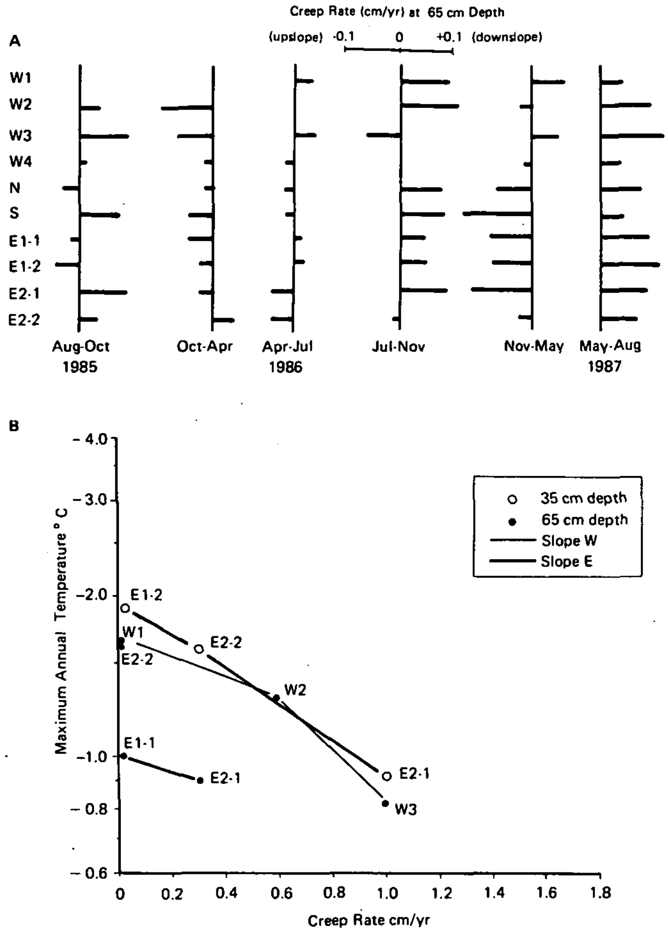

Figure 5. Variability of creep rates: A) Diagram showing upslope and downslope creep rates at 65 cm depth for six discrete time periods; B) Diagram showing creep rates at 35 and 65 cm depth in relation to maximum annual ground temperatures (log scale) on east and west-facing slopes. Straight lines represent possible exponential relationships between creep rate and temperature.

ranges from approximately 1.5 m deep near ridge crests to 2 m deep at the base of slopes. Because permafrost creep will be greatest in soils which are ice-rich two zones of permafrost creep may be identified; one at the permafrost table and one at the boundary between weathered and unweathered bedrock.

Global change implications

If predicted global warming trends were to lead to a 2-4 °C increase in MAAT in the High Arctic, it is reasonable to assume that this might translate into a 1-3 °C increase in the MAGT. At Rea Point, this would result in an increase in active layer thickness to about 60-80 cm and temperatures greater than -3.0 °C would extend to depths of about 2-3 m. Under such conditions, not only might gelifluction and other mass movements in the active layer increase, but also the amount, and depth of occurrence, of permafrost creep would increase substantially. Although the magnitude of permafrost creep would not reach that recorded by Savigny and Morgenstern (1986) from "warm" permafrost in the Mackenzie Valley, the increase would be sufficient to necessitate the reexamination of many engineering design and construction techniques in the High Arctic.

The creep data measured in our studies, and those by Savigny and Morgenstern (1986), also prompt speculation as to the magnitude of deformation which might occur when ice-rich permafrost ultimately degrades. While this is more relevant to subarctic conditions under present global change scenarios, a Pleistocene analogue may be found in the presence of non-diastrophic structures such as valley bulges, cambers and gulls (e.g. Hollingsworth *et al.*, 1944; Kellaway, 1972; Horswill and Horton, 1976) which exist in temperate latitudes today. They are best developed in Jurassic and Cretaceous sediments which contain thick, often overconsolidated, argillaceous sequences.

Possible mechanisms suggested for the development of these structures include lateral movement due to stress relief, vertical loading due to overlying ice, and downslope creep of frozen soils. Our field measurements indicate that the latter is not merely a theoretical consideration, especially given the long periods of time during the Pleistocene when "warm" permafrost conditions would have prevailed. Moreover, high pore pressures, developed temporarily from the melting of icy beds at depth, might have magnified creep rates even further.

Conclusions

In situ measurements of permafrost creep at a number of sites near Rea Point, Eastern Melville Island between 1985 and 1987 indicate that rates of permafrost creep are partially temperature dependent. Rates of deformation of between 0.06 to 0.1 cm yr^{-1} at a depth of 65 cm were measured. If predicted global warming trends were to induce slight thermal changes in the upper 2.5 metres of permafrost at Rea Point, higher annual rates of creep might be expected. Warmer permafrost temperatures would (a) increase the depth to which measurable creep occurs and, (b) extend the number of days per year during which creep occurs.

Acknowledgements

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