

## Instruments and Methods

# Cone penetration testing (CPT) in Antarctic firn: an introduction to interpretation

Adrian McCALLUM

*University of the Sunshine Coast, Queensland, Australia  
E-mail: amccallu@usc.edu.au*

**ABSTRACT.** Commercial cone penetration testing (CPT) equipment was adapted to allow penetrative testing in hard polar firn to depths of 10 m. The apparatus is hydraulically driven, rate-controllable and able to penetrate firn with a resistance of 10 MPa. It can be mounted on many types of typical polar vehicles, requiring connection to only hydraulics and 12 V electricity. Data recorded include both cone tip resistance and sleeve friction, a parameter not previously examined through such testing. This paper describes the development and calibration of the equipment and examines factors including snow density, penetration rate and cone size and shape that are shown to affect CPT interpretation. CPT can be used efficiently in polar environments to potentially provide estimates of physical parameters in hard firn to substantial depth.

**KEYWORDS:** glaciological instruments and methods, polar firn, snow, snow mechanics, snow physics

### INTRODUCTION

Investigation of snowpack physical properties has long been of interest to researchers, both for assessing avalanche potential, and for estimating the load-bearing capacity of snow pavements. Abele and Gow (1975) outline three methods of strength assessment, namely surface load tests, sample testing and probing, but only probing provides an in situ means of assessment that is time- and cost-effective.

The Swiss rammsonde, a portable impact penetrometer, has been used since the 1930s to assess snow stratigraphy and the relative resistance of snow layers. However, because of the rate dependency of snow, it is of limited use in establishing empirical or physical relationships; it is also limited in depth. Schaap and Föhn (1987) describe a manually pushed, modified 11.3 mm electric cone penetrometer for investigating alpine snow, but the manual insertion method and restricted capacity limit the usefulness of such a device in hard polar snow. Numerous other instruments have been developed for assessing snow strength and stratigraphy (Bradley, 1968; Dowd and Brown, 1986; Schneebeli and Johnson, 1998; Mackenzie and Payten, 2002); however, they are all limited in depth and capacity, and are not suitable for assessing dense polar snowpacks, where strength in uniaxial compression may approach 3 MPa (Mellor, 1975).

Many factors, including penetrometer size and shape, penetration speed and material behaviour ahead of the penetrometer, affect cone penetration testing (CPT) in soil (Lunne and others, 1997), and many of these factors remain pertinent when attempting to analyse CPT in polar snow. Ice is a rate-dependent material (Schulson and Duval, 2009), so it is probable that during CPT in snow both cone resistance and sleeve friction will vary with rate; penetrative testing (e.g. Fukue, 1977) supports this. Penetrometer size affects measured stress in soils (Whiteley and Dexter, 1981), and Johnson and Schneebeli (1999) modelled size effects in granular materials, so it is probable that both cone size and shape will affect measured stress in snow.

Observation and laboratory testing by Floyer and Jamieson (2006) and LeBaron and others (2012) show that a plug, or compacted zone of broken material, may form ahead of a cone penetrating snow, a process also identified in the indentation of brittle porous rock (Leite and Ferland, 2001). This process requires investigation because such a compacted zone may act, inertly, to transfer the load and affect the depth accuracy of stress measurements. Also, in some soils the cone may 'sense' an approaching layer some 10–20 cone diameters before it reaches the layer (Lunne and others, 1997), supposedly via elastic deformation of the material ahead of the cone, resulting in force transferral, but not fracture of these layers or particles. An understanding of this process is necessary to assess the depth/stress relationship during CPT.

Triaxial testing of low-density snow shows no effect of confining pressure (Scapozza and Bartelt, 2003); however, many other geomaterials (including ice) do display a dependency on confinement (Renshaw and Schulson, 2001), so the effect that overburden may have on cone resistance in mid- to high-density snow warrants investigation; also, does sufficient frictional heating occur during penetration to cause pressure melting, and what effect might this have on test results? how does this friction (never before measured in snow) vary with density, tip resistance, etc.? and what might be extracted from the data?

Cone penetration testing in polar snow, measuring both tip resistance and sleeve friction, has not previously been performed, and there are many questions that need addressing to enable accurate estimation of parameters, such as snow strength, from CPT. This paper introduces the development of robust cone penetration test equipment, suitable for conducting penetrative testing in hard polar snow, and describes some factors that must be considered when interpreting data from such testing. This is the first description of CPT in polar snow, and, thus far, insufficient analysis has occurred to support the scientific value of such testing. However, CPT appears well suited to the rapid



**Fig. 1.** UK11 configured and fitted for CPT. Insets show rigid-link installed and data-collection equipment.

assessment of polar snow for infrastructural site investigation purposes.

## INSTRUMENT DESCRIPTION

Typically, CPT equipment is mounted on a heavy truck or trailer-rig, primarily to ensure that sufficient reaction force can be provided when driving into hard soils. However, any equipment modified for use in Antarctica needs to be relatively lightweight, transportable and modular in nature. To address these needs, a CPT 'box' was manufactured with assistance from Lankelma and Gardline Geosciences (UK).

The 'box' provides a container in which CPT and ancillary equipment can be stored and transported, and in which a CPT operator can stand. A three-point hitch mounting plate of 25 mm thick steel provided a rigid frame upon which hydraulic rams were mounted. This plate (and thus the subsequent 'box' built upon it) attaches to the category-three three-point hitch of a standard agricultural tractor, such as those used by the British Antarctic Survey (BAS). A frame of box tubing was welded to the main structural steel plate, onto which 1.5 mm gauge sheeting was welded. The box (designated UK11 by Lankelma) measuring 1.7 m high  $\times$  1.45 m long  $\times$  1.35 m wide and weighing  $\sim$ 1300 kg when loaded, is shown in Figure 1.

Inside the box is a rack to store 20 rods of 1 m length and a small workbench for data-gathering equipment and a laptop computer; a mounted vice assists in rod attachment and removal. The box is secured by two steel-plate top doors, and a rear door, all of which can be secured closed and padlocked, or latched open while the box is in use. The hardness of the material through which a driven cone can penetrate depends on the reaction force available from the pushing equipment. UK11 weighs only 1300 kg, and because a standard tractor three-point linkage only provides resistance to a downward, not an upward, force, an additional rigid-link was required to provide increased resistance between the base of UK11 and the top hitch of the tractor. During use the rigid-link can be left attached to the tractor, and then unscrewed and 'trailed' between subsequent testing sites. The maximum resistance offered by UK11 with the rigid-link in place is  $\sim$ 40 MPa, equivalent to a 4 t reaction force. The rigid-link is shown in place in Figure 1.

A pair of hydraulic rams with a stroke of 500 mm and bore diameter of 70 mm, capable of a maximum pressure of

**Table 1.** GeoPoint 'Antarctic' cone specifications

<i>General specifications:</i>	
Cone tip section area	1000 mm <sup>2</sup>
Friction sleeve surface	15 000 mm <sup>2</sup>
Total length	280 mm
Weight	2.7 kg
Current source	12 mA
Working temperature	-40 to +60°C
Storage temperature	-40 to +85°C
Connector	Lemo 16 & 18 pins
<i>Tip resistance:</i>	
Range	20 kN
Accuracy	0.25% full scale
Maximum load	150% of range
Cone area ratio	0.74
<i>Sleeve friction:</i>	
Range	3.75 kN
Accuracy	0.25% full scale
Maximum load	150% of range
Sleeve area ratio	1.0 (end area)
<i>Pore pressure:</i>	
Range	1 MPa
Accuracy	0.5% full scale
Maximum load	150% of range
Filter position	u1 & u2
<i>Inclination:</i>	
Range	25° (biaxial)
Accuracy	<2°

21 MPa, were mounted within UK11 (inset Fig. 1). The rams were controlled via a two-way non-friction-controlled lever; hydraulic fluid was provided to the circuit through two external couplings to the tractor's hydraulic circuits. The maximum permissible flow rate was 20 L min<sup>-1</sup>. No visual indication of flow rate was used, but ram penetration rate was indicated on the laptop computer display. Prior to conducting a test the hydraulic flow rate was altered until the desired ram rate was achieved. This rate remained constant throughout a test, except for small amounts of retardation that were observed but not recorded upon penetrating hard ice layers. Driving force is transferred from the rams to the rods by means of a ball-bearing-type clamp that slots into a frame attached to the top of the rams. The clamp can be manipulated to allow rods to be driven downwards but not upwards, or upwards but not downwards (for rod and cone extraction). Maximum capacity of the clamp is 20 t in either direction. Standard 36 mm diameter steel alloy rods, each of length 1 m (provided by A.P. van den Berg), were used to transfer the penetrative force from the hydraulically driven rams to the cone at depth.

Four specially produced 35.6 mm scientific cones from GeoPoint Systems BV were provided by Gardline Geosciences. The cones measure resistance on the cone tip and friction on the cone sleeve. They also have the capacity to measure pore pressure. Although this may be useful for assessing free water within alpine snow, in the dry Antarctic firn tested no pore pressure readings were obtained. The cone with friction sleeve is shown in Figure 2 and cone specifications are listed in Table 1.

Two cones were used during testing, as well as two manufactured flat alloy plates, of diameters 36 and 120 mm, that were occasionally used in place of conical tips for comparative testing.

Both the cone tip and friction sleeve measure the axial resistive force (N) at a rate of 5 Hz; this is then converted to a stress measurement (MPa) within the cone, based on the assumed constant dimensions of the cone tip and the friction sleeve.

A Sick Stegmann wire-draw mechanism and incremental rotary depth encoder attached to the hydraulic rams triggered the recording of cone depth every 5 mm of penetration. Data were recorded using an A.P. van den Berg 'Golog' data recorder, modified to allow recording at this interval. The Golog box was powered via cable connected to the tractor's 12 V system, and connected to a laptop via a RS232/USB connection. Additional input cabling was from the cone and the depth encoder. A standard Panasonic C32 Toughbook laptop computer running A.P. van den Berg's GOnsite (Van den Berg, 2002) Windows-based software was used to manage CPT data acquisition and initial data manipulation.

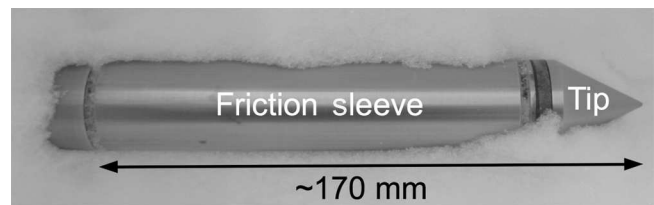
## CALIBRATION

Lunne and others (1997) comprehensively outline the checks and calibrations that should be carried out before performing CPT. The verticality of the CPT box and thrust apparatus was visually verified before the start of each test. This often involved repeated lowering of UK11 to the snow surface in an attempt to achieve a vertical drive axis. However, for more accuracy, a multidirectional spirit level, or similar, should have been used in this assessment. Excessive misalignment was noted if evident. Push rods were inspected for straightness and typically a selected five (out of the twenty rods available) were utilized for the testing. Cone-zero readings were taken at the start and end of each test, and the precision of the measurements obtained was verified through initial spatially confined tests. The cones were new, so cone dimensions were not retarded or deformed in any way, and only limited additional wear was expected during testing in snow and ice; cone end area was similarly unchanged throughout the testing. Seals and pore-water mesh were new, and were replaced as necessary between tests if any excess wear or deterioration was noted. Cones were provided with calibration data, and no additional recalibration was performed in the field. If a cone showed excessive zero-shift, then an alternative (new) cone was used. The cones were calibrated in the cold rooms of the Scott Polar Research Institute (SPRI, Cambridge, UK) prior to deployment, to verify the zero-shift and linearity of the cones over the expected operational temperature range of +5 to  $-20^{\circ}\text{C}$ .

As a result of this testing, all CPT equipment, aside from the Golog box, was equilibrated to ambient temperatures before initial zero values were taken.

## FIELD TESTING

Almost 100 cone penetration tests, typically to 5 m depth, were conducted at various locations within the vicinity of the Halley V Station, Antarctica, over the period 21 January–22 February 2010. The mean temperature at Halley is  $\sim -30^{\circ}\text{C}$ , although summer temperatures sometimes exceed  $0^{\circ}\text{C}$ ; annual snow accumulation is  $\sim 1.2$  m. Tests were conducted at various rates between  $0.16$  and  $55\text{ mm s}^{-1}$ ; the actual rate sometimes varied by  $\pm 1\text{ mm s}^{-1}$  as hardness varied, with the cone retarding or accelerating upon entering



**Fig. 2.** Cone incorporating 35.6 mm diameter tip and 135 mm long cylindrical friction sleeve.

or leaving a harder layer. The mechanical process of conducting each CPT is fairly standard and a set of standard operating procedures (SOPs) outlining this process was produced (these SOPs are not presented here). At a standard sampling rate of  $20\text{ mm s}^{-1}$ , a test to 5 m depth takes  $\sim 5$  min and numerous tests could be conducted in quick succession, tractor movement taking the greatest amount of time. Tests were conducted as weather and operational commitments allowed, and were designed to investigate numerous factors affecting CPT interpretation, including local snow stratigraphy, variation with snow density, effect of penetration rate, effect of confining pressure on tip resistance and sleeve friction, existence of a compacted zone ahead of the cone, effect of compaction and 'sensing' ahead of the cone.

## RESULTS

Selected results are shown to illustrate particular facets of the investigation. Variations of both tip resistance and sleeve friction with snow density are shown in Figure 3. Layers were identified visually, then density was measured gravimetrically in a pit excavated adjacent to the CPT site (snow pit 1).

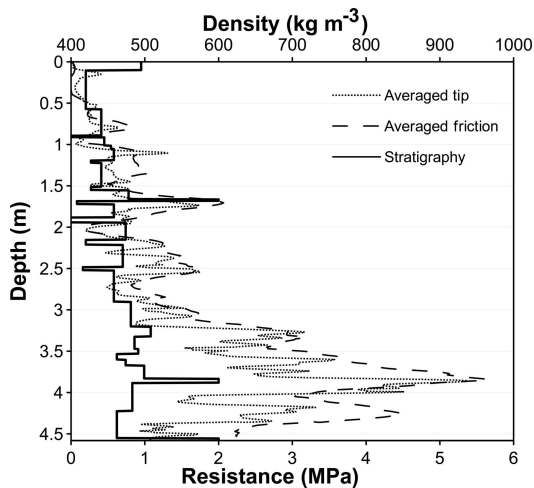
### Effect of penetration rate

Figure 4 shows mean tip resistance (averaged over the entire test depth) for each test vs penetration rate; the solid line is a power-law fit with  $R^2 = 0.97$ . Variation in mean sleeve friction (averaged over test depth) with penetration rate is shown in Figure 5; a possibly erroneous outlying data point at a rate of  $2\text{ mm s}^{-1}$  has been removed. A power-law curve ( $R^2 = 0.94$ ) fits the data well (line of best fit extends to zero, graph is truncated for display). Each data point is the average resistance across the entire test depth ( $\sim 2$  m;  $n \approx 390$ ). Figure 5 almost mirrors Figure 4.

### Effect of penetrometer size

Three tests were conducted to investigate whether altering penetrometer size would result in a change in measured tip resistance. Only one size of cone was available, so these tests compare resistance from different sizes of flat plates (Fig. 6); a cone test is also shown for comparison. To generate comparable resistance values, large-plate data have been normalized by 11, the area of the large plate divided by the area of the small plate. Mean resistance over the entire depth range is plotted as a straight line. From the graph it may appear that large-plate data are not recorded until a depth of 0.14 m; however, inspection of the raw data suggests that fluctuating resistance of  $\sim 5$  to  $10\text{ kPa}$  was measured at this time; whether this is a true representation of resistance at this shallow depth is not known.





**Fig. 3.** Mean tip resistance (averaged over the 30.83 mm length of the cone) vs mean, normalized and lag-adjusted (25 mm) sleeve friction (averaged over the 135 mm length of the friction sleeve) superimposed over gravimetric snow density (snow pit 1). Both mean tip resistance and mean friction vary with density.

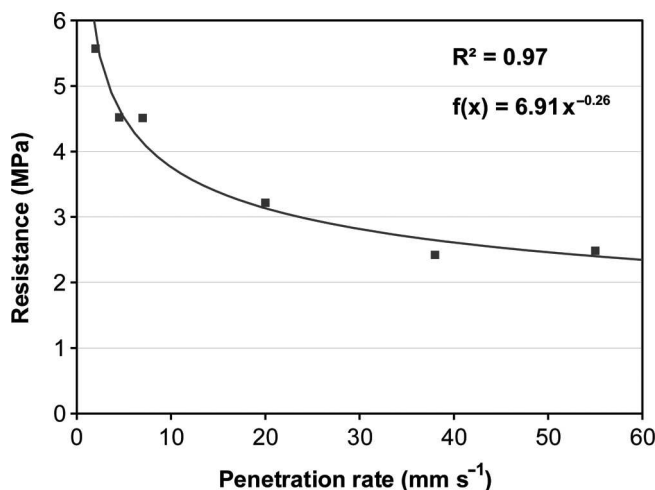
### Effect of cone shape

Kinosita (1964) and Johnson and Schneebeli (1999) have shown that variations in cone shape affect measured resistance values, both in snow and soils. In order to verify this phenomenon, some tests were conducted with a flat plate of identical diameter to the standard 60° cone; no other cone shapes were used. This testing revealed that a flat plate realizes significantly greater resistance than a 60° cone of the same diameter (Fig. 6).

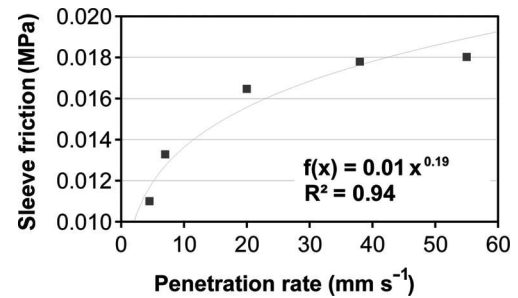
### Effect of confining pressure

To investigate the effect of overburden pressure on tip resistance and sleeve friction, three pairs of tests were conducted in close proximity, with an amount of surface surcharge removed between each pair of tests.

The six tests were conducted at a penetration rate of 25 mm s<sup>-1</sup> to the same absolute depth of 3.0 m (relative to the initial undisturbed surface), but overburden was



**Fig. 4.** Variation of mean cone tip resistance (averaged over entire test depth) with penetration rate; mean values are significantly different ( $p < 0.01$ ).



**Fig. 5.** Variation of mean sleeve friction (averaged over entire test depth) with penetration rate (possibly erroneous point removed); mean values are significantly different ( $p < 0.01$ ).

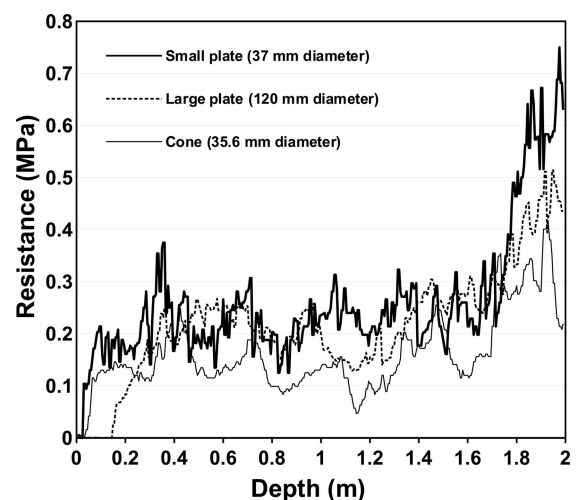
removed by bulldozer after the first and second pair of tests. Comparison was then made between tip resistance and sleeve friction data for the lowest 1 m of each test. Note that experimental technique may have affected these test results, because although no obvious deep fracture or compaction was observed, a bulldozer was used to remove the substantial volume of overburden, with typically two to three passes required each time. This trafficking will have had some impact in compacting and deforming the snow-pack prior to later, supposedly less confined, tests.

Variations in tip resistance for the three pairs of tests are shown in Figure 7, with a line of best fit of gradient  $-0.11 \pm 0.078$ ; each point on the graph is the mean of 195 data points averaged over the test depth.

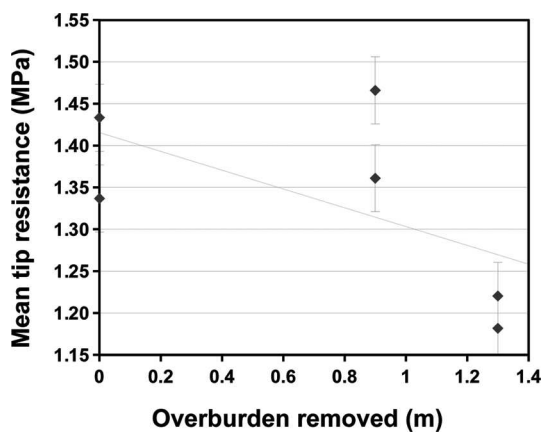
Variations in sleeve friction for the three pairs of tests are shown in Figure 8, with a line of best fit of gradient  $-0.003 \pm 0.0004$ ; each point on the graph is the mean of 195 data points averaged over the test depth.

### Formation of a compacted zone ahead of the cone

Some qualitative assessment was attempted to evaluate whether a compacted zone of fractured snow formed ahead of the advancing cone or plate. No quantitative assessment



**Fig. 6.** Variation in normalized tip resistance between cone and different sizes of plates, showing that normalized resistance decreases as penetrometer size increases. To generate comparable resistance values, large-plate data have been normalized by  $\sim 11$ , the area of the large plate divided by the area of the small plate; mean resistance over the entire depth range is plotted as a straight line.



**Fig. 7.** Inconclusive variation of tip resistance with amount of overburden removed. Each plotted point represents the average over 195 data points. Vertical bars indicate the standard error.

was made; however, both still and video footage of an advancing cone and plate, plus examination of CPT holes post-test were used to assess this phenomenon.

To attempt to observe the physical processes as the cone penetrated the snowpack, a test was conducted at a rate of  $\sim 1 \text{ mm s}^{-1}$ . An incision was made in the snowpack parallel to the cone to enable observation of the cone tip. This enabled the advancing cone to be filmed. Similar work to this has recently been performed in the laboratory (LeBaron and others, 2012).

Although forming such an incision compromised the behaviour of the snow, some observation of what was happening at a granular level was possible. Snow grains appeared to be displaced in a direction largely perpendicular to the advancing cone face before being forced into the sides of the borehole at the cone shoulder. Such behaviour is consistent with work in agricultural soils by Whiteley and Dexter (1981) and the statistical micromechanical model proposed by Johnson (2003). The outcome of this process can be observed in Figure 9, which shows an annulus of compacted material around the perimeter of the bored hole post-test, presumed to be formed by the compaction of snow into the wall at the cone shoulder.

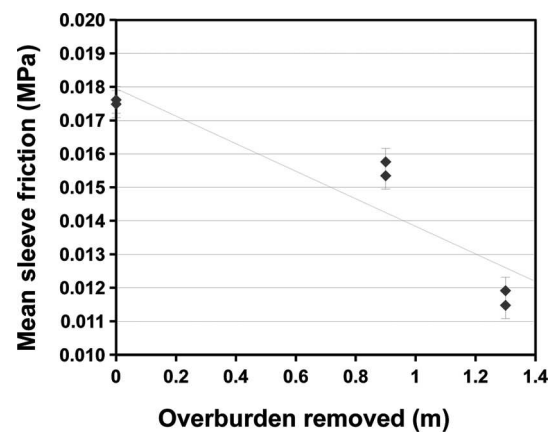
### Pressure melting

Both Federolf and others (2004) and Szabo and Schneebeli (2007) note the rapid, almost immediate, sintering of snow grains immediately after brittle fracture. Some level of pressure melting and re-sintering of fractured bonds was expected as the cone was driven into the snow, possibly sufficient to 'freeze-in' the cone and rods. However, no level of static friction was evident upon retrieval, nor was any free water observed, perhaps suggesting that temperature and snow-moisture conditions were sufficiently cold and dry to limit identifiable pressure melting.

## DISCUSSION

### Variation with density

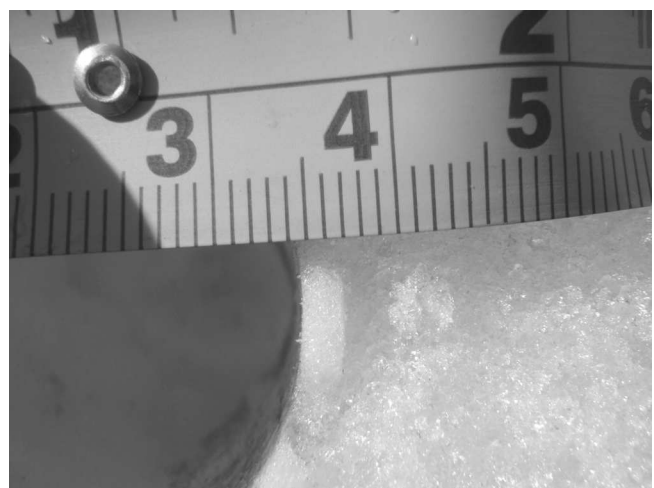
Figure 3 shows good qualitative correlation between tip resistance and density. The resistance trace varies within each layer, owing to the distance required to achieve steady-state resistance, but variations in resistance agree well with density variations. Particularly hard and soft layers are



**Fig. 8.** Significant variation of mean sleeve friction with amount of overburden removed. Each plotted point represents the average over 195 data points. Vertical bars indicate the standard error.

evident, coinciding well with very dense and less dense layers, and both resistance and density are observed to generally increase with depth.

The increase of tip resistance with density is consistent with the positive correlation between ram hardness (obtained via the rammsonde) and density (Gubler, 1975) and is expected. Some resistance variation in snow of the same density is expected because density does not necessarily imply the level of bonding within the snow, whereas measurements made by CPT (or other hardness measurements) will vary with such changes. Although a positive correlation between tip resistance and density is expected, quantifying this relationship from data such as those presented in Figure 3 is difficult, because resistance does not vary in discrete layers (unlike density). Snow microstructural changes and cone size/shape affect the resistance data, but comparison of density and layer-averaged resistance reveals a significant positive correlation of  $>0.6$ . If the gradients of the density and resistance increase with depth are compared (0.0182 vs 0.1485), resistance is seen to vary by almost an order of magnitude more than density. This is consistent with the understanding that snow not only increases in density with



**Fig. 9.** Compacted perimeter ( $\sim 2 \text{ mm}$  thick, tape for scale) observed in cross section of hole post-test, after fractured material ahead of the cone is compacted to the side forming an annulus.

depth, but that increased sintering and strengthening of bonds within the snow also occurs, without necessarily a change in density; extraction of microstructural information by comparing sleeve friction and tip resistance data may be possible. The relationship between friction sleeve data and density is perhaps more complex.

Figure 3 shows that sleeve friction appears to trend with density. The friction trace lags density by perhaps 4–5 cm, especially in the upper 2.5 m, but this lag is not unexpected, and between 2.5 and 4.5 m sleeve friction is seen to qualitatively trend with density. Both friction and density increase with depth, albeit friction (similar to tip resistance) increases at a greater rate. Lag is evident, consistent with the physical dimensions of the friction sleeve (length 135 mm), and the correlation between density and sleeve friction is  $\sim 0.6$  (Pearson correlation significant at the 0.01 level; two-tailed).

Colbeck (1994) noted the decrease in kinetic friction with increasing density, and both Mellor (1964) and Ericksson (1955) note a decrease in friction with grain size. Grain size generally increases with depth during densification (although the increase to a depth of 5 m may only be  $\sim 0.1$  mm; Rick and Albert, 2004), hence some decrease in friction with increased density is implied. This is contrary to observations made using CPT.

The observed increase in sleeve friction with density is assumed to be due to an increased normal force acting upon the friction sleeve, caused by less efficient packing of fractured particles at the cone shoulder as the density of the snow undergoing penetration increases. Such a process would cause greater sleeve friction to be measured in higher-density snow. Testing in pre-drilled holes resulted in friction values five to six times lower than standard friction values ( $p < 0.0001$  for unpaired  $t$  test), suggesting the influence that normal force may have on sleeve friction values. Examination of flat-plate data presented by Abele (1970) also shows that as density increases, penetration resistance increases and penetration distance decreases for the same applied pressure. These observations support the supposition that an increase in density will result in increased friction, not because of grain-size variations but because of the increase in normal force acting on the sleeve.

#### *Effect of grain size*

It is hard to isolate the effect of grain size on cone penetration results, as invariably grain size was observed to vary with density and thus probably with hardness; limited work has been reported on the effect of grain size on penetrometer testing. Floyer and Jamieson (2006) suggest that grain size affects the formation of the compacted zone ahead of a penetrometer in snow. However, because no compacted zone was observed to form ahead of the cone in Antarctic CPT (see annulus formed at side, Fig. 9), grain-size differences do not appear relevant. However, Schweizer (1999) reported that increased grain size tends to shift the brittle/ductile transition towards lower strain rates. Thus, at the same penetration rate, decreased resistance values may be expected in the brittle zone if larger grain sizes are encountered. Also, as grain size generally increases with depth, some level of decreased tip resistance may be expected. Thus, changes in grain size may have some limited effect on measured tip resistance.

Limited literature is available to guide discussion on sleeve friction measurements in snow, because no such testing is known to have previously occurred. However, from

a planar friction perspective, Bowden (1953) considering grain size in snow as a measure of surface roughness suggests that smaller grain size may enable greater packing, resulting in an appreciable increase in effective firm/sleeve contact area. This would mean that sleeve friction measurements may be greater in snow of smaller grain size, all other parameters being equal. This is consistent with the work of Ericksson (1955), who also showed that friction increases with smaller grain size. Thus sleeve friction may also be expected to decrease by some amount with depth as average grain size increases.

Ideally, some measure of these variations could be extracted from the CPT results. However, because of the complicated stratigraphy and other material changes evident within each test, isolation of this phenomenon is not readily achievable. Higher-density snow often has a larger grain size and thus the effect on resistance because of density may tend to override (in the opposite sense) any variation owing to grain size. Controlled laboratory tests in homogeneous blocks of snow, where both grain size and density (as well as microstructure) can be manipulated, would appear necessary to accurately resolve this relation with regard to penetrative testing in snow. Grain size may affect the effective area of the cone.

#### **Effect of penetration rate**

Applying the one-way ANOVA (analysis of variance) test to the variable-rate CPT data in Figure 4 shows that the mean resistance values are not statistically equal ( $F$  statistic  $\sim 150$ ,  $p < 0.001$ ) and the Tukey–Kramer honestly significant difference (HSD) test confirms that all mean resistance values are significantly different from one another ( $p < 0.01$ ). Figure 5 suggests that a rate effect is also apparent when measuring snow friction via a sleeved penetrometer. Application of the one-way ANOVA test to the variable-rate friction data used to generate Figure 5 shows that the mean resistance values are not statistically equal ( $F$  statistic  $\sim 27$ ,  $p < 0.0001$ ), and the HSD test confirms that all mean resistance values are significantly different from one another ( $p < 0.01$ ). This suggests an inverse relationship between tip resistance and sleeve friction at varying penetration rates, although the variation differs by numerous orders of magnitude.

Johnson and Schneebeli (1998, 1999), Schneebeli and Johnson (1998) and Schneebeli and others (1999) have performed extensive investigations into penetration in snow, but do not comment on the effect of penetration rate on tip resistance measured by the snow micro-penetrometer, only stating that ‘constant-velocity penetration ( $1\text{--}40\text{ mm s}^{-1}$ ) avoids the rate-dependence associated with creep deformation’.

Kinosita (1967), in his compression tests on snow, found that once in the brittle zone, stress decreased as speed of compression increased, initially rapidly and then more gradually, almost asymptotically. Gubler (1975) showed that hardness decreased substantially as penetration rate increased (within the brittle zone) during rammsonde tests, and Fukue (1977), in tests on a penetrative blade into snow, identified the ductile/brittle transition zone and also noted a decrease in strength at an increased rate of deformation. These findings are not unexpected and are consistent with the brittle behaviour of snow’s primary constituent, ice. Variations may be expected, owing to the compaction and densification of snow, but if any level of bonded micro-



structure is present within the snow then it is ice bonds that are failing, hence behaviour consistent with ice is expected.

Andersland and Ladanyi (1994) state that frozen soils are much more rate-sensitive than non-frozen soils, and Ladanyi and others (1991) (cited by Lunne and others, 1997; commenting on rate-controlled cone penetration tests in permafrost and ice) suggest that a power-law relationship can be used to express the relationship between penetration resistance,  $q_c$ , and penetration rate,  $\nu$ :

$$q_c = q_0 \left( \frac{\nu}{\nu_0} \right)^{\frac{1}{n}}, \quad (1)$$

where  $n$  is the creep exponent and  $q_0$  and  $\nu_0$  are the coordinates of any selected point on the straight-line plot of  $q_0$  and  $\nu_0$  on a log-log scale. This equation is derived from tests in the ductile zone, but, because rate effects in the brittle zone also appear to follow a power-law relationship (allowing a linear gradient to be established on a log-log plot of rate vs resistance), it can also be applied to the brittle testing described herein (although  $n$  is no longer a 'creep' exponent). This allows estimation of CPT resistance values at various rates within the brittle regime. Buteau and others (2005), in more recent CPT in permafrost, also found a rate dependency (within the ductile range), hence dependence of stress upon rate appears well documented in snow, ice and other frozen geomaterials.

Contrary to these findings, Floyer (2008), investigating penetration of a 12 mm rounded, manually driven penetrometer, 'found no substantial dependence of the force-response on velocity over the velocity range tested' (velocities up to  $120 \text{ cm s}^{-1}$ ), a finding supported by additional work (Floyer and Jamieson, 2010), where again for a round-tipped 12 mm diameter penetrometer in uniform snow, no substantial dependence of the force response on velocity over the velocity range tested was found. Discussions with J. Floyer (27 May 2009) on this matter concluded that rate effects may play a part in some types of snow and with different penetrometer configurations. Additional reasons why Floyer and Jamieson (2010) may have found these results are:

all their tests were at much higher penetration rates (velocities up to  $120 \text{ cm s}^{-1}$  vs my maximum penetration rate of  $\sim 6 \text{ cm s}^{-1}$ ) where the variation in stress with strain rate may be observed to be diminished (see Fig. 4)

actual strain rates may be much higher and therefore also at the far end of the stress/penetration-rate curve (Fig. 4), especially noting the rounded penetrometer, which may be expected to cause greater snow disturbance than a 'sharp' penetrometer in dry snow.

If measured resistance in snow is rate-dependent, as I have shown here, and the rate curve diminishes with strain rate once in the brittle zone (Fig. 4 and work by Schulson, 2001, among others) then it may be that the penetration/strain rates examined by Floyer and Jamieson (2010) are sufficiently high that change in measured resistance may appear insubstantial. This is consistent with the observation by Kinoshita (1967) that at very high rates within the brittle zone the curve asymptotically approached a constant stress. Conversely, my tests (where rate dependence is evident) were conducted at penetration rates (and possibly strain rates) only just within the brittle regime, where greater deterioration in measured resistance with increased strain

rate may be expected. Thus I judge the observed variation of CPT tip resistance with rate to be real.

Figure 5 suggests that sleeve friction may increase (possibly to a limit) with penetration rate. Bowden (1953) observed a marked decrease in friction under sled runners as speed increased (up to  $5 \text{ m s}^{-1}$ ), although a reduced decrease was observed at the speed range of my CPT ( $\sim 1\text{--}50 \text{ mm s}^{-1}$ ). The mechanism at play was assumed to be lubrication by a water film generated via frictional heating. Mellor (1964) states that, in general, friction decreases as sliding rate increases, again typically because of frictional melting and lubrication. No pressure melting or refreezing was evident throughout the CPT, raising the question whether snow dryness and slow penetrative speeds may have contributed to minimal or negligible free water being generated to reduce sleeve friction.

Klein (1947) (cited by Colbeck, 1988) suggests that there are three components to snow friction: solid-to-solid friction, lubricated friction and capillary suction friction, all of which depend on the prevailing snow crystal type, as well as the temperature and liquid-water content of the snow. Solid-to-solid interaction resulting in high friction will occur when the thickness of any generated water film is insufficient to prevent particle contact. If the nature of the snow tested at Halley was dry enough and cold enough to prevent any free water forming at tested penetration speeds, then only solid-to-solid interaction may have occurred.

Bowden (1953) suggests that (for plastic skis) at a temperature of  $-10^\circ\text{C}$ , an increase in friction with rate occurs at speeds below  $\sim 100 \text{ mm s}^{-1}$ . All CPT was conducted below this speed, hence this is the realm of interest. Colbeck (1988), examining Bowden's work, suggests that at sub-freezing temperatures ( $0$  to  $-10^\circ\text{C}$ , my test temperatures), at rates below Bowden's transition rate, a minimum in friction coefficient is observed, such that there is a zone where friction will rise as speed increases. This may explain the shape of the curve generated by my variable-rate friction sleeve measurements (Fig. 5). This behaviour is further supported by Shimbo (1971), who also found that the coefficient of (kinetic) friction increased towards the static value at speeds  $< 0.1 \text{ m s}^{-1}$ .

The discussion thus far has concentrated on penetration rate per se, and has neglected any possible influence that rate may have on normal stress, a major determinant of friction. In all tests conducted, fractured particles are considered to have been forced into the hole wall at the cone shoulder, thus contributing to the ensuing friction measurement. The question is whether there is any difference in the residual hole wall density after completion of a test at different rates. Potentially, a slower test allows greater sintering and compaction of the side-walls to occur, whereas in a faster test perhaps less densification and compaction is possible, resulting in less compaction around the sleeve, increased normal force and greater friction.

Further work is required to assess the factors contributing towards the observed increase in sleeve friction with penetration rate. This increase, although contrary to general behaviour surmised from the literature, appears to be consistent with data obtained from tests at similar temperatures and rates. Limited frictional melting and variable normal forces on the penetrometer friction sleeve may each play their part in the observed variation of sleeve friction with penetration rate.

### Effect of penetrometer size

A size effect is evident from Figure 6: penetrometer resistance decreases as penetrometer size increases. The difference between all tests is statistically significant ( $p < 0.0001$  for two-tailed unpaired  $t$  test). The normalized average percentage decrease in resistance is 16% for a real plate area increase of  $\sim 1100\%$ .

This decrease is qualitatively consistent with work by Johnson (2003), using smaller penetrometers, that showed decreased resistance as penetrometer base area increased (although Johnson showed a greater effect), and is also quantitatively similar to work by Whiteley and Dexter (1981) who, for a similar size increase in area, suggest a resistance decrease of  $\sim 10\%$ ; however, their work was on smaller cone penetrometers with a  $30^\circ$  tip angle, and not on flat plates.

Marshall (2005) notes that the size effect is greatest when penetrometer size is  $< 40$  times grain size (average observed in my snow pits was 0.7 mm) and this may explain why the differences observed were not as great as those suggested by Johnson (2003); flat plates used in testing were of diameters  $\sim 36$  and  $\sim 120$  mm.

Cone size can also affect the rate at which local material is strained at the head of the cone, causing variations in resistance at constant rates of penetration. Ladanyi (1982), exploring the link between probe size, strain rate and tip resistance in frozen geomaterials, derived Eqn (2) to relate representative strain rate,  $\dot{\epsilon}_{\text{rep}}$ , failure strain in uniaxial compression,  $\epsilon_f$ , penetration rate,  $\dot{p}$ , and penetrometer diameter,  $d$ ,

$$\dot{\epsilon}_{\text{rep}} = 6\epsilon_f \frac{\dot{p}}{d}, \quad (2)$$

and then used Eqn (3) to relate strain rates to tip resistance:

$$q_{c1} = q_{c2} \left( \frac{\dot{\epsilon}_{c1}}{\dot{\epsilon}_{c2}} \right)^{\frac{1}{n}}, \quad (3)$$

where  $q_{c1}$  is tip resistance for penetrometer one,  $q_{c2}$  is tip resistance for penetrometer two,  $\dot{\epsilon}_{c1}$  is strain rate for penetrometer one,  $\dot{\epsilon}_{c2}$  is strain rate for penetrometer two and  $n$  is the creep exponent obtained from the slope of  $q_c$  vs strain rate in a log–log plot. ( $n \approx 3$  for ice at low strain rates, but may be  $\sim 10$ – $20$  at higher strain rates.)

Applying these equations to the flat-plate data (diameters  $\sim 36$  and  $\sim 120$  mm) reveals that for  $n = 10.3$  (derived from strength of ice vs strain rate; Petrovich, 2003), a reduction in resistance owing to plate size of 14% is predicted. This agrees very well with the observed average decrease of 16%. A size effect is evident in assessing strength of snow with a penetrometer, and further techniques must be explored to enable consistent comparison between datasets from penetrometers of different size.

### Effect of cone shape

Resistances are substantially greater in the flat-plate test (statistically significant with  $p < 0.0001$  via unpaired  $t$  test); the difference in average resistance (to 5 m depth) is  $\sim 188\%$ , although the difference at discrete depths sometimes rises to  $> 200\%$ . This is quantitatively consistent with modelled data presented by Johnson (2003), who suggested an increase in resistance of two to three times as cone angle increases from  $60^\circ$  towards  $90^\circ$ . It is also consistent with the qualitative supposition (Johnson, 2003) that as the tip angle approaches that of a flat plate (a  $180^\circ$  cone), the increased dimension normal to penetration and the formation of a compacted

zone moving ahead of the penetrometer increase the number of snow microstructural elements mobilized and markedly increase resistance to penetration. Gill (1968), in work in soil, found similarly that the measured resistance increased as cone angle increased, primarily as a function of the cone angle. Nowatzki and Karafiath (1972), also working with soils, found that at higher relative densities, where less packing is observed, change in cone angle had a greater effect on cone resistance.

Application of Kinoshita's (1967) equation relating cone angle to penetration resistance in the brittle zone,

$$F = 7\vartheta^{1.67} \rho^3 Z^2, \quad (4)$$

where  $F$  is force in kgf,  $\vartheta$  is the vertical angle of the cone ( $^\circ$ ),  $\rho$  is snow density ( $\text{kg m}^{-3}$ ) and  $Z$  is distance of the cone apex under the snow surface (cm), suggests that variation between the two shapes in snow of density  $450 \text{ kg m}^{-3}$  may be  $\sim 600\%$ . This is far greater than observed. This discrepancy may exist because Kinoshita's work essentially involved shallow penetration, in which the cone did not penetrate beneath the surface, and substantial ejection of overburden upon cone entry was incorporated, and Kinoshita's maximum rates of penetration ( $0.55 \text{ mm s}^{-1}$ ) were only just within the brittle zone ( $> \sim 0.16 \text{ mm s}^{-1}$ , as defined by Gaméda and others, 1996), where changes in rate result in greater stress variation.

Because compacted material will form on any flat plate, altering the shape towards conical, it is surmised that the difference in resistance between any flat plate and conical test will diminish with depth. Figure 10 shows the 100-point running mean for the ratio of tip resistance from a flat-plate test to tip resistance from a standard cone test vs depth.

Although the mean ratio still exhibits large variability owing to stratigraphy, the linear trend line suggests a decrease in this ratio with depth. This suggests that the flat plate may become more 'cone-like' as a test progresses. Further testing is necessary to verify this behaviour, yet it appears intuitively feasible. The shape of the cone has a marked effect on the physical interaction of the penetrometer with the medium, with resultant effects on measured resistance values, and must be considered when attempting to compare or interpret penetrative tests.

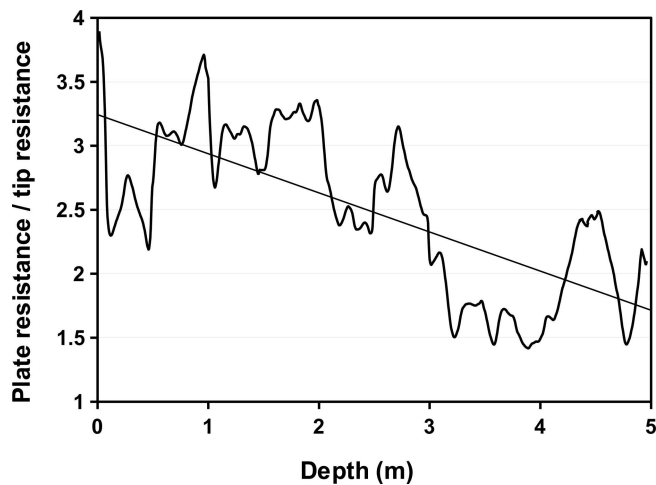
### Effect of confining pressure

Variations in mean tip resistances at different overburden pressures are not consistently statistically different, so it is unwise to draw firm conclusions about the effect of overburden pressure on cone tip resistance.

The rationale for a possible increase in resistance as confining pressure is increased is that crack initiation (required for brittle failure) is restricted and greater resistances are achieved (Renshaw and Schulson, 2001). Within shallow snow the variation in confining stress is very small compared with tip resistances, hence an insignificant or unclear trend, as evident, is not unexpected. Also, and importantly, in porous (lower-density) snow this effect will be significantly reduced as, regardless of the confining pressure, sufficient pore space exists to ameliorate this effect, enabling unhindered fracture and compaction, regardless of the applied amount of confining pressure, whereas as porosity reduces (and density approaches that of ice) the effects of confinement may increase.

Hence, although confining pressure may have some impact upon the tip resistance proffered by polar snow, the





**Fig. 10.** Ratio of flat-plate resistance to cone resistance generally decreases with depth, consistent with the formation of a conical mass of compacted snow on the flat plate as the test progresses.

variation is complicated by the density and nature of the material, and analysis of the data is inconclusive.

It is possible that an increase in overburden stress may have a greater impact on sleeve friction (within a post-fractured granular medium) than on tip resistance (where normal stress may have less effect, owing to a bonded matrix pre-fracture). Figure 8 shows sleeve friction decreasing as overburden pressure is reduced; a  $\sim 40\%$  reduction is observed after the removal of 2 m of overburden. This suggests that overburden and resultant vertical stress may affect the normal stress on the friction sleeve and thus the measured friction (in snow of the same density and microstructure). This is consistent with the evolution of friction at depth under varying overburden pressure (McClung and Schaerer, 1993) and is consistent with expectations. However, Colbeck (1988) (commenting on an observation by Perla and Glenne, 1981) claims that for pressures typically exerted by skiers (1–5 kPa) there appears to be negligible variation in friction with increased load, a consequence of the true contact area being proportional to the load.

This may be the case on the surface of natural alpine snow; however, during penetration it is assumed that processed, rearranged, compacted and densified snow beside the friction sleeve is of a largely uniform nature, such that any increase in normal pressure will result in an increase in friction upon the sleeve. Also, pressure upon the friction sleeve is estimated to be an order of magnitude greater than the values considered by Colbeck (1988). Although my tests were probably affected to some extent by the testing method, some decrease in observed sleeve friction owing to decreased overburden pressure (and thus normal force upon the sleeve) is apparent.

### Formation of a compacted zone ahead of the cone

Observations described herein suggest that no compacted zone formed ahead of the advancing cone, and Figure 9 suggests that fractured material was pushed normal to the cone and forced into the hole walls at the cone shoulder. The hardness of this annulus of compacted snow rose from 'finger' to 'pencil' post-CPT. Similar observations were made in an attempt to identify the formation of a compacted zone ahead of an advancing flat plate. Figure 11 shows a cone of



**Fig. 11.** Low-angle conical plug routinely observed on a flat plate post-test. The flat plate has a diameter of 36 mm.

compacted snow, routinely observed on the face of the flat plate upon completion of a test.

Cross sections of the hole formed during CPT were not examined after any flat-plate tests, so the existence or otherwise of a compacted perimeter is not known; however, it is surmised that after initial formation of a conical plug on the end of the flat plate, the snow then behaves in a similar manner during penetration, being forced to the sides at the cone shoulder although deformation, destruction and reforming of the conical plug ahead of the flat plate are likely to occur as the penetration process continues, especially through layers of varying hardness.

Discussion with J. Floyer (27 May 2009) clarified that the formation of a compacted zone ahead of a penetrating object in snow is likely to depend upon the size and shape of the indenter, the nature of the snow and probably also the penetration rate. During CPT, the combination of a relatively thin, smooth, sharp penetrometer tip and extremely dry snow appears to have resulted in an immeasurable or negligible compacted zone ahead of the penetrometer, with all fractured particles forced normal to the penetrometer face and thence compacted into the sides at the cone shoulder. The compaction of fractured material into the sides of the hole at the cone shoulder appears to be the dominant displacement mechanism occurring ahead of the  $60^\circ$  steel cone in the dry snow tested, and is consistent with Kinoshita (1964), who described the packing of broken ice grains into the compressed region beside or under the cone; snow was preferentially displaced to the side as cone angle decreased.

When a flat plate was used, a compacted zone of snow (approaching the density of ice) was formed on the plate during testing. Although the snow in question was again very dry and likely not conducive to bonding, it is surmised that fracture, compaction and then pressure melting of particles occurs ahead of the flat plate. The depression of the melting point of ice varies between  $\sim 0.08$  and  $\sim 0.1 \text{ KMPa}^{-1}$  (depending on the saturation state of the air; Hooke, 2005), and pressures during flat-plate penetration approached 10 MPa, suggesting that a  $1^\circ\text{C}$  depression of the ice melting point may be possible. (Note also that actual pressures on the plate face may exceed those recorded, owing to the limitations of the CPT data-acquisition system.) Snow temperatures were not routinely recorded during CPT,

but outside air temperatures occasionally reached  $>0^{\circ}\text{C}$ , hence the existence of some pressure melting ahead of the flat plate cannot be discounted. It is surmised that this conical zone formed after a certain distance and probably deformed throughout the test, growing in size, yet also probably deflecting additional particles (because of its conical shape) as penetration continued. The formation of a similar 'body' is reported by Gill (1968) in his work on agricultural soils. He notes that 'the compaction and adhesion of soil to blunt rigid bodies ... results in the formation of soil bodies'; when the tool is blunt a clear and distinct soil body forms on the body of an advancing penetrometer.

The formation of compacted material on a penetrating flat plate appears possible and is consistent with observations in other geomaterials. During penetration with a  $60^{\circ}$  cone in dry polar snow it appears that fractured material is displaced preferentially to the sides and no compacted zone is formed ahead of the cone. The compaction or densification of the snow alongside the cone also has obvious implications for the friction measurement obtained via the friction sleeve.

### Pressure melting

Floyer (2008) cautions against stopping during penetrometer pushes, because fractured snow could re-bond, resulting in force spikes (not related to actual snow hardness) upon recommencement of a push. Melting and re-sintering was expected, yet none was visibly or aurally evident while conducting CPT, nor does examination of CPT data suggest any freezing-in occurred. In one test, the cone was left stationary in situ for  $\sim 1$  hour to conduct a dissipation test (a test typically conducted during CPT to measure pressure/resistance changes while the cone is held stationary). No 'spike' in resistance (suggesting stiction or adhesion between cone/rods and snow) was observed upon resumption of the test. This may be because of the limited data sampling of the equipment used, or may be evidence of a lack of pressure melting.

A simple quantitative assessment of this phenomenon can be obtained by consideration of melting point depression, as discussed above. Cone tip resistance values were typically  $<10\text{ MPa}$ , hence at snow temperatures of  $\sim -10^{\circ}\text{C}$  it is extremely improbable that melting occurred. This is substantiated by Barnes and others (1971), who found that when brass slid on ice (at maximum applied pressure of  $\sim 1\text{ MPa}$ ) no melting occurred at speeds  $<100\text{ mm s}^{-1}$  at a temperature of  $-12^{\circ}\text{C}$ . The increase in pressure required to generate melting during penetration does not appear likely with the testing conditions discussed herein.

### CONCLUSION

Support from BAS, Lankelma and Gardline Geosciences enabled the development of innovative CPT equipment that can be mounted onto the three-point hitch of a standard tractor, and be used to perform CPT to depths of  $>5\text{ m}$  in polar snowpacks. The box and associated CPT equipment proved secure, robust and versatile and was very well suited to the envisaged task. CPT enabled the collection of both tip resistance and not previously recorded sleeve friction data, offering insight into many phenomena pertaining to the assessment of the stratigraphy, hardness and strength of polar snow. This paper provides an introduction to phenomena that should be considered when attempting to interpret CPT

in polar snow. CPT appears very well suited to the rapid assessment of polar snow for infrastructural site investigation purposes and, with further testing, analysis and equipment refinement, CPT could prove a valuable scientific tool for rapid in situ assessment of polar snow.

### ACKNOWLEDGEMENTS

This research was made possible by the generous assistance of Lankelma and Gardline Geosciences and the British Antarctic Survey and Halley Research Station. This paper was considerably improved by the suggestions of three anonymous reviewers; their time and effort is appreciated.

### REFERENCES

- Abele G (1970) Deformation of snow under rigid plates at a constant rate of penetration. *CRREL Res. Rep.* 273
- Abele G and Gow AJ (1975) Compressibility characteristics of undisturbed snow. *CRREL Res. Rep.* 336
- Andersland OB and Ladanyi B (1994) *Introduction to frozen ground engineering*. Chapman & Hall, New York
- Barnes P, Tabor D and Walker JCF (1971) The friction and creep of polycrystalline ice. *Proc. R. Soc. London, Ser. A*, **324**(1557), 127–155
- Bowden FP (1953) Friction on snow and ice. *Proc. R. Soc. London, Ser. A*, **217**(1131), 462–478 (doi: 8-0-471-15893-6)
- Bradley CC (1968) The resistograph and the compressive strength of snow. *J. Glaciol.*, **7**(51), 499–506
- Buteau S, Fortier R and Allard M (2005) Rate-controlled cone penetration tests in permafrost. *Can. Geotech. J.*, **42**(1), 184–197 (doi: 10.1139/t04-093)
- Colbeck SC (1988) The kinetic friction of snow. *J. Glaciol.*, **34**(116), 78–86
- Colbeck SC (1994) A review of the friction of snow skis. *J. Sports Sci.*, **12**(3), 285–295 (doi: 10.1080/02640419408732174)
- Dowd T and Brown RL (1986) A new instrument for determining strength profiles in snow cover. *J. Glaciol.*, **32**(111), 299–301
- Ericksson R (1955) Friction of runners on snow and ice. *SIPRE Transl.* 44.
- Federolf P and 7 others (2004) Mechanical properties of snow during rapid impact. In Bartelt P, Adams E, Christen M, Sack R and Sato A eds. *Snow Engineering V: Proceedings of the 5th International Conference on Snow Engineering, 5–8 July 2004, Davos, Switzerland*. Taylor and Francis, London, 209–214
- Floyer JA (2008) Layer detection and snowpack stratigraphy characterisation from digital penetrometer signals. (PhD thesis, University of Calgary)
- Floyer J and Jamieson B (2006) Empirical analysis of snow deformation below penetrometer tips. In Gleason JA ed. *Proceedings of the International Snow Science Workshop, 1–6 October 2006, Telluride, CO*. International Snow Science Workshops, Telluride, CO, 555–561
- Floyer JA and Jamieson JB (2010) Rate-effect experiments on round-tipped penetrometer insertion into uniform snow. *J. Glaciol.*, **56**(198), 664–672 (doi: 10.3189/002214310793146322)
- Fukue M (1977) Mechanical performance of snow under loading. (PhD thesis, McGill University)
- Gaméda S, Vigneault C and Raghavan GSV (1996) Snow behaviour under compaction for the production of ice. *Energy*, **21**(1), 15–20 (doi: 10.1016/0360-5442(95)00081-X)
- Gill WR (1968) Influence of compaction hardening of soil on penetration resistance. *Trans. Am. Soc. Agric. Eng.*, **11**, 741–745
- Gubler HU (1975) On the Rammsonde hardness equation. *IAHS Publ.* 114 (Symposium at Grindelwald 1974 – *Snow Mechanics*), 110–121
- Hooke RLeB (2005) *Principles of glacier mechanics*, 2nd edn. Cambridge University Press, Cambridge

- Johnson JB (2003) A statistical micromechanical theory of cone penetration in granular materials. *ERDC/CRREL Tech. Rep.* 03-3
- Johnson JB and Schneebeli M (1998) Snow strength penetrometer. United States Patent 5831161
- Johnson JB and Schneebeli M (1999) Characterizing the microstructural and micromechanical properties of snow. *Cold Reg. Sci. Technol.*, **30**(1–3), 91–100 (doi: 10.1016/S0165-232X(99)00013-0)
- Kinosita S (1964) Intrusion of a rigid cone into snow. *Low Temp. Sci., Ser. A*, **23**, 17–37 [in Japanese with English summary]
- Kinosita S (1967) Compression of snow at constant speed. In Oura H ed. *Physics of snow and ice*. Institute of Low Temperature Science, Hokkaido University, Sapporo, 911–927
- Klein GJ (1947) *The snow characteristics of aircraft skis*. (Aeronautical Report AR-2) Division of Mechanical Engineering, National Research Council, Ottawa, Ont.
- Ladanyi B (1982) Determination of geotechnical parameters of frozen soils by means of the cone penetration test. In Verruijt A, Beringer FL and de Leeuw EH eds. *Proceedings of the Second European Symposium on Penetration Testing, Amsterdam, 24–27 May 1982*. AA Balkema, Rotterdam, 671–678
- Ladanyi B, Lunne T and Winsor WD (1991) Experience with the performance of load-controlled cone penetration tests in permafrost and ice. In *Proceedings of the 44th Canadian Geotechnical Conference, 29 September–2 October 1991, Calgary, Alberta, Canada*. (C-CORE Publication 91-23) Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, St John's, Newf.
- LeBaron AM, Miller DA and Van Herwijnen A (2012) Axisymmetric measurements of extended deformation around the snow micropenetrometer tip. In *Proceedings of the International Snow Science Workshop, 16–21 September 2012, Anchorage, Alaska*. International Snow Science Workshops. <http://arc.lib.montana.edu/snow-science/item/1710>
- Leite MH and Ferland F (2001) Determination of unconfined compressive strength and Young's modulus of porous materials by indentation tests. *Eng. Geol.*, **59**(3–4), 267–280 (doi: 10.1016/S0013-7952(00)00081-8)
- Lunne T, Powell JJM and Robertson PK (1997) *Cone penetration testing in geotechnical practice*. Blackie Academic and Professional, London
- Mackenzie R and Payten W (2002) A portable, variable-speed penetrometer for snow pit evaluation. In Stevens JR ed. *Proceedings of the International Snow Science Workshop, 29 September–4 October 2002, Penticton, British Columbia*. Snow Avalanche Programs, British Columbia Ministry of Transportation, Victoria, B.C., 294–300
- Marshall H-P (2005) Snowpack spatial variability: towards understanding its effect on remote sensing measurements and snow slope stability. (PhD thesis, University of Washington)
- McClung DM and Schaerer PA (1993) *The avalanche handbook*. The Mountaineers, Seattle, WA
- Mellor M (1964) Properties of snow. *CRREL Monogr.* III-A1.
- Mellor M (1975) A review of basic snow mechanics. *IAHS Publ.* 114 (Symposium at Grindelwald 1974 – *Snow Mechanics*), 251–291
- Nowatzki EA and Karafiath LL (1972) *The effect of cone angle on penetration resistance*. (Highway Research Record 405) Highway Research Board, Washington, DC, 51–59
- Perla R and Glenne B (1981) Skiing. In Gray DM and Male DH eds. *Handbook of snow: principles, processes, management and use*. Pergamon Press, Toronto, Ont., 709–740
- Petrovich JJ (2003) Mechanical properties of ice and snow. *J. Mater. Sci.*, **38**(1), 1–6 (doi: 10.1023/A:1021134128038)
- Renshaw CE and Schulson EM (2001) Universal behaviour in compressive failure of brittle materials. *Nature*, **412**(6850), 897–900 (doi: 10.1038/35091045)
- Rick U and Albert M (2004) Microstructure of West Antarctic firn and its effect on air permeability. *CRREL Tech. Rep.* TR-04-16
- Scapozza C and Bartelt P (2003) The influence of temperature on the small-strain viscous deformation mechanics of snow: a comparison with polycrystalline ice. *Ann. Glaciol.*, **37**, 90–96 (doi: 10.3189/172756403781815410)
- Schaap LHJ and Föhn PMB (1987) Cone penetration testing in snow. *Can. Geotech. J.*, **24**(3), 335–341 (doi: 10.1139/t87-044)
- Schneebeli M and Johnson JB (1998) A constant-speed penetrometer for high-resolution snow stratigraphy. *Ann. Glaciol.*, **26**, 107–111
- Schneebeli M, Pielmeier C and Johnson JB (1999) Measuring snow microstructure and hardness using a high resolution penetrometer. *Cold Reg. Sci. Technol.*, **30**(1–3), 101–114 (doi: 10.1016/S0165-232X(99)00030-0)
- Schulson EM (2001) Brittle failure of ice. *Eng. Fract. Mech.*, **68**(17–18), 1839–1887 (doi: 10.1016/S0013-7944(01)00037-6)
- Schulson EM and Duval P (2009) *Creep and fracture of ice*. Cambridge University Press, Cambridge
- Schweizer J (1999) Review of dry snow slab avalanche release. *Cold Reg. Sci. Technol.*, **30**(1–3), 43–57 (doi: 10.1016/S0165-232X(99)00025-7)
- Shimbo M (1971) Friction on snow of ski soles unwaxed and waxed. In Kinoshita K ed. *Scientific study of skiing in Japan*. Hitachi, Tokyo, 99–112 [in Japanese]
- Szabo D and Schneebeli M (2007) Subsecond sintering of ice. *Appl. Phys. Lett.*, **90**(15), 151916 (doi: 10.1063/1.2721391)
- Van den Berg AP (2002) *GOnsite software v1.2*. AP van den Berg, Heerenveen
- Whiteley GM and Dexter AR (1981) The dependence of soil penetrometer pressure on penetrometer size. *J. Agr. Eng. Res.*, **26**(6), 467–476 (doi: 10.1016/0021-8634(81)90080-9)

MS received 15 November 2012 and accepted in revised form 23 October 2013