PREFERENTIAL INCORPORATION OF COARSE SEDIMENT DURING NEEDLE-ICE GROWTH: A PRELIMINARY ANALYSIS

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Abstract

Soils affected by permafrost and periglacial activity commonly exhibit distinctive sorting patterns, either at a macroscopic or microscopic scale, in which coarse material is preferentially lifted towards, or across, the soil surface. Earlier laboratory investigations have indicated no difference between the grain-size distribution of the bulk soil sample and the sediment included within needle-ice crystals. The present study, however, based on laboratory and field data, shows that the included material is significantly coarser than the host material. The results suggest that, during the migration of a freezing front, fine particles are “pushed” ahead of it while “coarse” particles are incorporated within the ice.

Introduction

Ground affected by frost action processes such as needle-ice growth, ice lens formation and frost heave often exhibits distinctive patterns in which sediments may be sorted. Differences in particle characteristics can occur either horizontally across the soil surface or vertically within the soil profile. Features produced by sorting can be macroscopic (e.g., nets, circles, polygons, stripes) or microscopic (comprising small-scale variations in the soil profile). In some instances the net movement of coarse particles to the soil surface has been observed; this causes problems in some agricultural areas during severe winters when stones appear at the soil surface and fence posts are heaved out of the soil (Corte, 1961; Jahn, 1985).

It is generally accepted that needle ice is important in initiating the development of miniature soil patterns. For example, Ballantyne (1996) determined that the differential growth of needle ice was the principal process in the relatively rapid formation of a miniature sorted net in Scotland. Regardless of whether needle ice is a factor causing sediment sorting, it is regarded as a significant factor of soil disturbance on bare slopes and river banks (e.g., Lawler, 1993).

This paper investigates the processes by which growing needle ice may preferentially incorporate sediment that is coarser than the material from which the sediment was lifted, and explores the difference between the results of this study and an earlier study (Meentemeyer and Zippin, 1981). The contribution which this may make to the frost sorting of material and to determining the relative frost susceptibility of soil is also discussed.

Method

This study forms part of a wider investigation into the processes that control the growth of needle ice and the disturbance and transport of sediment by needle-ice crystals. It was conducted primarily in a laboratory, allowing the conditions under which needle ice grows to be closely controlled and monitored. The experimental design and instrumentation used are described in Branson et al. (1996). A limited number of observations of needle-ice growth in natural conditions were also made at river bank and garden sites close to Birmingham, UK.

The apparatus consisted of a split perspex box (50 cm long x 30 cm wide x 40 cm deep), the top two-thirds of which contained the soil sample and the bottom a water bath which ensured that there was a constant supply of water to the soil sample.

A series of experiments used both remoulded samples of soil and undisturbed blocks. The undisturbed blocks were excavated from a river bank where needle ice had been observed. In the perspex box, the stream-facing side of the block (i.e., that which was subject to needle-
ice growth in the field) formed the upper surface of the sample box. In using undisturbed blocks of soil, this series of experiments differs from most other laboratory studies which have used disturbed soil samples which have been sieved and distributed homogeneously in the sample box (e.g., Higashi and Corte, 1971; Meentemeyer and Zippin, 1981; Soons and Greenland, 1970).

Arguments for and against the use of ‘remoulded’ samples have been presented. Freezing and thawing action cause irreversible changes to properties such as the bulk density of the soil, and thus soils will be affected differently by each freeze-thaw cycle (e.g., Polar Research Board, 1984). Thus it may be preferable to use remoulded samples so that a new soil is produced that has not previously been affected by frost action. Experiments would thus commence with soils with similar characteristics. Although this method means that experiments should be reproducible, properties such as compaction and frost-susceptibility may be different to that of the original soil under field conditions. For example, the frost-susceptibility of fine soil may be reduced by remoulding, but similar handling of a coarse sample may increase its frost-susceptibility due to the degradation of particles and manufacture of additional fines. As the current experiments were concerned with the effects that needle-ice growth may have on sediment lifted by the needle-ice crystals, and comparisons are made with natural soil samples, results are presented from an experiment that used an undisturbed block.

Platinum resistance thermometers and nylon soil moisture blocks were placed at 1, 3, 5 and 10 cm below the soil surface. Linear vertical displacement transducers (LVDTs) were placed on the soil surface to monitor the growth of the ice crystals from the surface. The electrical output from the thermometers, soil moisture elements and the LVDTs was scanned at 3 s intervals by a datalogger.

The box was placed into a cold chamber and soil surface cooling rate was controlled using a microcomputer which was connected to the thermometer at the soil surface and a heating coil placed above the soil surface.
Prescribed time series of temperature were programmed into the computer which then compared the actual soil surface temperature at a given time with the prescribed temperature in the program. A heating coil above the soil surface was switched on if the actual temperature was below the required temperature (described further in Branson et al., 1996). This method, although quite crude, allowed soil surface temperature to be controlled within +/- 0.2°C. A number of cooling curves with different rates of surface cooling were used.

Prior to the start of a series of experiments, a sample of the soil block was taken for particle-size analysis. Following needle-ice growth, the ice needles and sediment lifted by them were collected and the ice melted. The organic matter was removed from the sediment using hydrogen peroxide and then the sediment was wet-sieved through a 63 μm sieve. The proportion of the sample > 63 μm was wet-sieved through a bank of sieves at 0.5 phi intervals - the coarsest being 2 mm. The fine fraction (< 63 μm) was analysed using the pipette method (e.g., Akroyd, 1969; Head, 1980). This method of analysis was tested for reproducibility by thoroughly mixing a soil sample, dividing it into four equal weight sub-samples and then analysing each sub-sample as described above. No significant difference in grain-size distribution determined for each sub-sample was found.

**Results**

In a number of the laboratory experiments and field observations, sediment was found to have been lifted from the ground surface by the needle-ice crystals. The sediment was lifted in several different forms: either pushed on top of the crystals, forming a soil 'cap' (which could either be frozen or unfrozen) or incorporated within the ice crystals. Sediment was incorporated in two patterns: either as distinct layers of sediment within otherwise clear ice crystals or as particles dispersed throughout the crystals, giving the ice a brown appearance.

Figures 1, 2 and 3 show the grain-size distribution of the parent material. The granulometric composition of material that was included within the needle ice from a
representative laboratory experiment is also shown in Figure 1. The granulometric composition of material from samples of needle ice which grew under natural conditions on the river bank (from which the laboratory sample was taken) is shown in Figure 2. That for samples from a garden nearby is shown in Figure 3. The sediment was principally lifted as distinct layers within the needle-ice crystals and dispersed throughout the ice crystals. Field data were collected to test the possibility that some aspect of the laboratory procedures had influenced the results of the study. Only sediment finer than 2 mm was included in the analysis to ensure comparability with the procedures used by Meentemeyer and Zippin (1981).

The profiles for the three samples are distinct. The incorporated sediment from field site 1 was coarser than the bulk sediment for all particle sizes, while at field site 2 the incorporated sample was coarser than the bulk only for particle sizes less than 0.5 mm (although the difference between the two samples for particles > 0.5 mm is only 0.07 to 0.3%). The profile for the laboratory sample indicates that the incorporated sediment was coarser than the bulk sediment for grain sizes 0.8 to 0.017 mm, and the bulk was coarser than the incorporated material for particles > 0.8 mm and < 0.17 mm (Figure 1). The incorporated and parent materials for each sample were compared statistically using a T-test. For each sample it was concluded that the bulk and incorporated material had significantly different particle-size distributions.

Figure 4 shows a plot of the difference in the percentage finer than of the bulk and incorporated material for each of the soil samples. A positive difference indicates that at that particular grain size the incorporated sample was relatively coarser than the bulk sample, and a negative difference that the bulk sample was coarser than the incorporated sample.

**Discussion**

The results from the present study contradict the findings of Meentemeyer and Zippin (1981), the only published study that compares the characteristics of the material lifted by needle ice with those of the host material. From their experiments, in which needle ice was grown in a laboratory using remoulded soils as a
growth media, they determined that there was no significant difference between the grain-size distribution of the bulk soil sample and the sediment included within the needle-ice crystals. Thus, they concluded that needle-ice growth does not selectively entrain particular particle sizes.

The difference in the results of the experiments by Meentemeyer and Zippin and the current study may be a result of differences in the experimental design of the two studies. This is discussed below following a review of studies which have investigated the preferential lift of coarse particles by frost action.

**PREFERENTIAL SORTING BY FROST ACTION: A REVIEW**

The frost sorting of material is thought primarily to occur within particles in the centimetre size range. Van Vliet-Lané (1985) described a process by which coarse material becomes uplifted from the surrounding soil (based on the work of Kaplar, 1965), in which ice nucleation and segregation occur first at the base of the stone and then push the stone up through the soil matrix. This initial growth of ice beneath the stone depletes the local water supply and thus it is less likely that further ice segregation will occur in the vicinity of the stone. This process is thought to occur principally where the thermal conductivity of the stone is greater, and its porosity lower, than that of the surrounding soil matrix (Van Vliet-Lané, 1985).

Washburn (1979) suggested that the upfreezing of stones can occur by either one of two processes: frost push or frost pull. The former process is similar to that described above - ice forms beneath coarser material and forces it up. During frost pull, the freezing boundary descends to the top of the particle, and the frozen sediment adheres to it. The stone is then lifted by heave of the freezing layer during the period taken for the freezing boundary to descend from top to bottom of the stone.

Results from an earlier series of laboratory experiments by Corte (1961, 1962a, 1962b, 1963, 1965, 1966), subsequently confirmed by Rowell and Dillon (1972), which used sediment particles in a water column that was frozen at different rates, indicate that coarser particles are preferentially incorporated into ice during freezing. These experiments show that fine particles

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*Figure 4. Percentage by which included sediment is coarser than the parent material.*

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<td>% by which incorporated material is coarser than host material</td>
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<td></td>
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<tr>
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<td>Field 1</td>
<td>Field 2</td>
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migrate ahead of the freezing line, whilst coarser particles are trapped in the ice. Particles become incorporated into the frozen layer when they cannot maintain a water film between them and the ice interface. Whether a particle is incorporated is thus dependent on its size, shape and density (Corte, 1962a, 1962b); larger particles require a greater volume of water in their thin films, and this may become depleted if there is limited moisture availability or surface temperatures are very low. Different size particles will become incorporated therefore at different freezing rates. Rowell and Dillon (1972) analysed the data from Corte's (1962b) experiments and determined that particles of 0.2 mm diameter were pushed ahead of the freezing front at freezing rates of less than 2 mm hr\(^{-1}\) per hour, while particles with a diameter of 10 µm moved at freezing rates of less than 1 cm hr\(^{-1}\). The latter figures were of the same magnitude as those from Rowell and Dillon's own experiments which showed that particles 5-10 µm, and occasionally down to 0.1 µm became frozen at freezing rates of 1 cm hr\(^{-1}\). The experiments also indicated that clay particles became aggregated during the freezing process (Rowell and Dillon, 1972).

Hallet (1990) described a similar process by which fine particles are rejected from ice lenses within soils when the freezing front propagates upwards towards the soil surface (rather than downwards when needle-ice growth ceases). He suggests that, during the propagation of the freezing front, small non-buoyant particles within the soil water are rejected from the freezing water. The size of “small” particles is not defined, although as suggested by Corte, the relative size of the particles that are rejected from, or incorporated into, the ice is probably related to moisture and temperature conditions. This rejection process is less effective for “larger” particles because the distance that the water must travel (a function of particle circumference) is increased, and thus they are preferentially frozen into the ice when the water in their thin adhered films is not replaced.

Studies by Pérez (e.g., 1991), Hastentrath (1977) and Ballantyne (1996) have concentrated on the sorting of coarse material by needle ice, and have concluded that recurrent needle ice lifts stones on or near the soil surface, which then migrate into surface indentations by creep and rolling when the crystals melt. This process of sorting is related to needle-ice ablation rather than formation and consequently is not applicable to the preferential lift of sediment during needle-ice growth.

**Preferential Incorporation of Coarse Particles During Needle-Ice Growth**

To explain why coarser sediment may be preferentially incorporated into needle-ice crystals it is important to understand the processes by which particles may become incorporated during freezing. Results from this study show that sediment is lifted by needle ice when there is an imbalance in the heat and water fluxes to/from the freezing front. This can occur when moisture supply is restricted or there is over-rapid heat loss from the ground surface. This imbalance causes the freezing front, which is required to be stable to maintain needle-ice growth, to descend. Sediment is then frozen within the ice (Branson et al., 1996). The descent of the freezing front seems to occur at different spatial and temporal scales, and depending on the scale involved, results in the formation of either multi-tiered needle ice, needle-ice crystals with sediment dispersed throughout the crystal, or frozen soil caps.

Sediment becomes incorporated within needle ice as a result of the migration of the freezing front. It is probably this migration process, similar to that described by Corte (1961, 1962a, 1962b) and Hallet (1990), which caused the preferential incorporation of coarser sediment into the ice. When the freezing front descends into the soil profile, the coarser particles are more likely to become frozen in situ; the reduction in the rate of moisture flow to the freezing front which causes needle-ice growth to cease means that the moisture film around the “coarser” particles is depleted. The fine particles then be “pushed” ahead of the migrating freezing front (although some fines may be “attached” to the coarser particles and thus are also incorporated into the ice). If ice segregation then recommences, the in situ frozen (relatively coarser) material is incorporated between two layers of needle ice. Thus it is expected that sediment layers or dispersed particles within the ice crystals or lifted as a frozen soil cap, can have a higher fraction of coarser particles than the soil from which it originated. The critical size of the “coarse” and “fine” sediment is dependent on the rate of freezing which in turn is affected by soil moisture content and soil surface temperature.

**Influence of Soil Moisture on Sediment Incorporation**

The plots of the difference between the bulk and needle-ice entrained material (Figure 4) show that there is a variation in the texture of the different soil samples, particularly between the field samples and the laboratory sample. Part of the difference between samples is caused by natural variations in the parent sediment, and thus the particle sizes available to be lifted and/or entrained. It is suggested, however, that soil moisture availability, and its influence on freezing rate, is also significant.

Temperature and soil moisture data were not available for the field sites and the rate of freezing during
the growth of the needle ice cannot therefore be determined. At the river bank site (grain-size distribution, Figure 2), however, where soil moisture supply was unlimited, it is likely that the freezing rate was not sufficiently rapid to incorporate the smaller particles, and thus the % coarser of the included sediment is greater than the % coarser of the bulk sample throughout the profile. Similarly, the needle ice at field site 2 grew shortly after a period of heavy rain, and thus moisture was probably not limited.

In the laboratory sample it is unclear, however, why the incorporated sediment was dominated by a finer fraction than that of the bulk material at grain sizes < 0.017 mm. During the laboratory experiments, in which ice containing layers of sediment were formed, the moisture and soil surface temperature conditions were manipulated in an attempt to cause sediment incorporation (moisture supply was limited and surface cooling rate increased). This caused the freezing rate to increase until it was too rapid to sustain ice segregation (and an associated stable freezing front), and consequently the freezing front migrated into the soil profile and sediment incorporation occurred. Given the limitations in soil moisture it is probable that the freezing rates were higher than those which occurred in the field. Typically, freezing rates in the laboratory were between c. 4 and 14 mm hr⁻¹ (this was determined indirectly from the thickness of the sediment layer produced and the profile of heave at the soil surface). These rates are of the same order of magnitude at which Rowell and Dillon (1972) observed that particles less than 0.01 mm were incorporated into the ice lenses. This can explain why relatively more finer particles below 0.017 mm were incorporated into the laboratory samples than the field samples (25% of incorporated sediment was finer than 0.017 mm in the laboratory compared to 18% and 20% in field samples 1 and 2 respectively). It does not explain, however, why the incorporated material of the laboratory sample was finer than the bulk, since, if the freezing rates increase and finer sediment was incorporated, there should be minimal difference between the bulk and incorporated sample. This is an area which requires further laboratory testing, with a variety of soils and controlled freezing rates. In particular, micromorphological analysis of frozen soil profiles could be used to analyse the patterns of particle size in relation to the freezing front.

**Sediment Lifted in an Unfrozen Soil Cap**

When soil is lifted as an unfrozen soil cap, ice nucleation occurs below the soil surface at a distance determined by the availability of moisture, ice segregation commences immediately, and thus the position of the freezing front relative to the ground surface remains stationary (as long as there is a sufficient flow of moisture to the freezing front). Thus there is no “pushing” of fines down the soil profile. This could influence the relative grain size of the incorporated soil in one of two ways:

1. If the soil has been affected by needle-ice growth on a number of occasions, then the soil surface may be covered with loose, relatively coarser particles that were lifted towards the soil surface by the previous events. Thus the soil cap will contain particles that are relatively coarser than the bulk soil.

2. Alternatively, if the surface material has been removed by a process such as slope wash or aeolian erosion prior to needle-ice growth, then the material lifted will have a similar grain-size distribution to that of the host soil.

Meentemeyer and Zippin (1981) did not state how the material was lifted in their experiments (i.e., as layers or as a soil cap), but as the soil sample was progressively depleted in moisture over the series of experiments it is likely that the sediment was lifted as an unfrozen soil cap. Thus, as the soil had been remoulded prior to the experiments, the sediment lifted would have a similar texture to the parent sample as described in situation (2) above. This could explain why the results of the current experiment, in which the sediment was lifted by a process which involved the migration of the freezing front, produced different results to those of Meentemeyer and Zippin.

**Implications of Preferential Incorporation**

This study has only analysed sediment less than 2 mm diameter, and differences in grain-size composition between the bulk and included material were only evident for all samples at grain sizes less than approx 0.5 mm. This suggests that the geomorphic implications of the process in this case are not likely to be very evident. Nevertheless, a concentration of coarser particles at the soil surface may affect the future frost-susceptibility of the soil. This is similar to the process described by Ballantyne (1996), whereby the lift and drop of stones by needle-ice melt increases the textural contrasts between the coarse borders and fine cells of frost nets. Patterns initiated by this process could then be developed by other processes such as differential frost heave and the growth of ice lenses within fine soil. For sediment incorporated within needle ice the differences in particle size will be of a smaller magnitude.

**Conclusion**

This preliminary analysis of sediment from a small number of observations has shown that particles lifted by needle ice are generally coarser than the soil from which they are lifted. It is considered unlikely that the processes controlling the preferential inclusion of coars-
er particles observed in this study are related to the processes which form patterned ground. Nevertheless, preferential uplift may cause small-scale variations in grain-size distribution through the soil profile, with coarser particles being “pushed” up the profile. In this study preferential incorporation was thought to occur by fine particles being “pushed” down the soil profile in front of a migrating front, unlike the coarse particles which become frozen. Further investigations should focus upon the critical freezing rate thresholds at which particles of different sizes are entrained within the needle ice.

References


