MICROMORPHOLOGY AND MICROFABRICS OF SORTED CIRCLES, FRONT RANGE, COLORADO, U.S.A.

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Abstract

The granulometry, microfabrics and micromorphology of two sorted circles, one on Niwot Ridge, the second adjacent to Arikaree Glacier, are discussed. It is concluded that the Niwot circle is largely inactive, though ice segregation occurs during winter soil freezing. In contrast strong frost sorting, and a convection-like displacement of sediment occurs in the Arikaree circle, with upwelling in the fine grained circle centre, and downward subsidence in the stony borders.

Résumé

La granulométrie, les microtextures et la micromorphologie de deux cercles avec triage, un sur la crête Niwot, l'autre adjacent au glacier Arikaree, sont analysées. L'auteur conclut que le cercle Niwot est essentiellement inactif, malgré la ségrégation de la glace pendant le gel du sol en hiver. Par ailleurs, il se produit un important triage gélival et un déplacement, assimilable à la convection, de sédiments dans le cercle Arikaree, avec soulèvement dans le centre à texture fine du cercle et subsidence vers le bas dans les bordures pierreuses.

Introduction

A wide variety of processes have been cited to explain the formation of periglacial patterned ground. Many features are probably polygenetic (Washburn 1956, 1970), and different mechanisms probably lead to similar patterns (Van Vliet-Lanoë 1988a). The role of frost sorting, (Corte 1960, 1961, 1962) is well known, and clearly influential in the development of sorted patterned ground.

However, the initiation of geometric patterns, such as the sorted circles discussed here, is also associated with displacement of fines and coarser sediments en mass, during and following frost sorting, and Van Vliet Lanoë (1988 a,b) has recently reviewed the main mechanisms which may be responsible for cryoturbation of this kind.

On the basis of field observation and soil micromorphological studies, Van Vliet-Lanoë (1988a,b) and Pissart (1982) argue for the dominance of differential frost heaving as a cause of vertical and lateral sediment displacements within periglacial patterned ground, and consider that density-driven diapiric injection of liquefied sediment during thaw is unlikely, except where groundwater drainage is concentrated. However, Palme and Tveitereid (1977) and Hallet and Prestrud (1986) have recently emphasized the role of thaw-induced convection-like soil displacements in the formation and development of sorted circles, and Harris and Cook (1988) presented evidence for upward injection of fines within sorted circle centres in Jotunheimen, Norway.

This study, of two sorted circles near the Continental Divide in the Colorado Front Range, USA, provides additional evidence concerning cryogenic processes operating within sorted circles, and illustrates the application of detailed small scale studies in assessing the degree of activity of periglacial patterned ground.

The Study Area

Two sorted circle sites were investigated, one on Niwot Ridge, at an elevation of approximately 3600m, the other just to the east of the continental divide, below Arikaree glacier, at an altitude of around 3750 m (Fig. 1). On Niwot Ridge the substrate consists of the weathering products of the underlying metamorphic rocks (Madole 1982), and comprises a silty sand matrix-dominated diamicton (Rissing and Thorn 1985). In Green Lakes Valley a thin till passes laterally into valley side colluvium, but again the substrate comprises a silty sand diamicton.

The climate is mid-latitude continental, with the mean annual temperature at metereological station D1 (3743 m) on Niwot Ridge -3.1 °C (1953-82) and annual precipitation totals ranging from 400 mm to over 1400 mm (Losleben 1983). The tree line is at approximately 3,300 m, and Greenstein (1983) has estimated that the lower limit of continuous permafrost lies at between 3600 m and 3550 m.

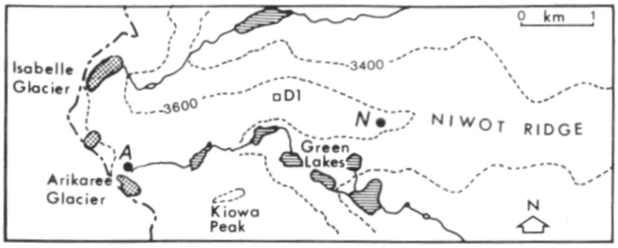

Figure 1. Location map. D1 indicates meteorological station. A: Arikaree site, N: Niwot site

Site Description

At both sites well developed sorted circles formed contiguous patterns, with central area widths 1.5-3.5 m at the Niwot Ridge site (Fig. 2), and 1.5-6 m at Arikaree. One circle at each location was selected for detailed study. The Niwot Ridge circle had a flat fine grained centre of diameter 1.6m, and a raised stony border 2.5-2.8 m wide.

The Arikaree circle had a slightly domed centre of diameter 2.2m, and raised stony border 1.4-3.5 m wide. The excavated circle centres showed evidence for cryoturbation, (Fig. 3), and in both circles organic material extended downwards from the surface in the gravelly interface zone between the stony margins and the fine-grained centres. In the Arikaree circle this formed a distinct pod close to the northern border (Fig. 3). Borders contained many steeply dipping pebbles and boulders, and extended downwards, beyond the base of the excavation. Many of the fine-grained circle centres at Arikaree were subdivided by smaller scale sorted nets, which were defined by narrow gravel borders.

At the Hungry Whistler archaeological site, 3 km to the south of Niwot Ridge, and at about the same altitude, Benedict (1978) observed anthropogenic charcoal fragments at a depth of 43 cm-51 cm in the fine centre of an inactive sorted circle. The charcoal was dated to 5730±130 BP (I–3817) and Benedict concluded that the patterned ground was inactive during human occupation, but was reactivated during the Triple Lakes Stade of Neoglaciation (approx. 5000-3000 BP). On this evidence therefore, it is likely that the sorted circles on Niwot Ridge and in front of Arikaree Glacier have a long history of formation, and have suffered periods of greater and lesser activity.

Experimental Design

The circle centres were trenched, to 0.6 m, the depth of excavation being limited by waterlogging and trench collapse. Oriented undisturbed samples were taken by gently pushing circular cross-section plastic tubes of internal diameter 4.5 cm and depth 3 cm, horizontally into the cleaned trench faces. These were returned to the laboratory, air dried, and impregnated with resin prior to thin sectioning. Thin sections were cut vertically, in the plane of the trench face.

Undisturbed samples were taken at approximately 50 cm intervals across each circle, from depths of 5 cm, 15 cm, 25 cm and 50 cm at the Niwot site, and 5 cm, 10 cm, 20 cm,

Figure 2. Sorted circle, Niwot Ridge site. Scale 50cm.

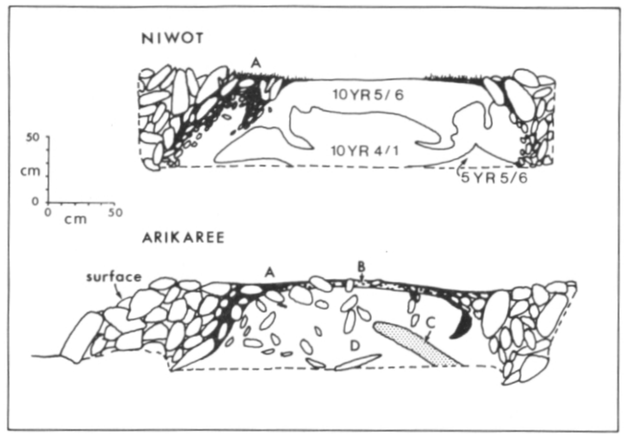

Figure 3. Excavated circles. A: 7.5YR3/2 organic gravelly sand; B: 7.5YR4/4 loose gravelly sand; C: 10YR4/6 sandy silt; D: 10YR4/4 gravelly silty sand.

40 cm and 50 cm at Arikaree, although in places the presence of stones prevented undisturbed sampling, and the nearest area where sampling was possible was then sampled (e.g. sample 50 cm/55 cm, Niwot). Impregnation was also unsuccessful in a few samples. A denser sampling grid , with samples taken from depths of 10 cm, 20 cm, 40 cm, and 60 cm at a horizontal spacing of 25 cm, was used to collect bulk samples for granulometric determinations. Clasts larger than 16 mm intermediate diameter were not included in these samples.

Results

Granulometry

Contoured plots of percent fine gravel (2 mm-16 mm), percent sand (63-200μm), and percent silt + clay (finer than 63 μm) are illustrated in Figures 4 and 5. Clearly the complexity of granulometric variation as identified here is limited by the intensity of sampling of the exposed faces. The Niwot Ridge circle showed > 20 % gravel in samples from 10cm and 20 cm depth, with a small window of lower gravel contents. Sand contents were fairly uniform at around 40 % in an inclined central zone, while silt/clay contents were remarkably uniform at 40-46 % below 20 cm, but slightly lower than this in the near surface zone. Overall the

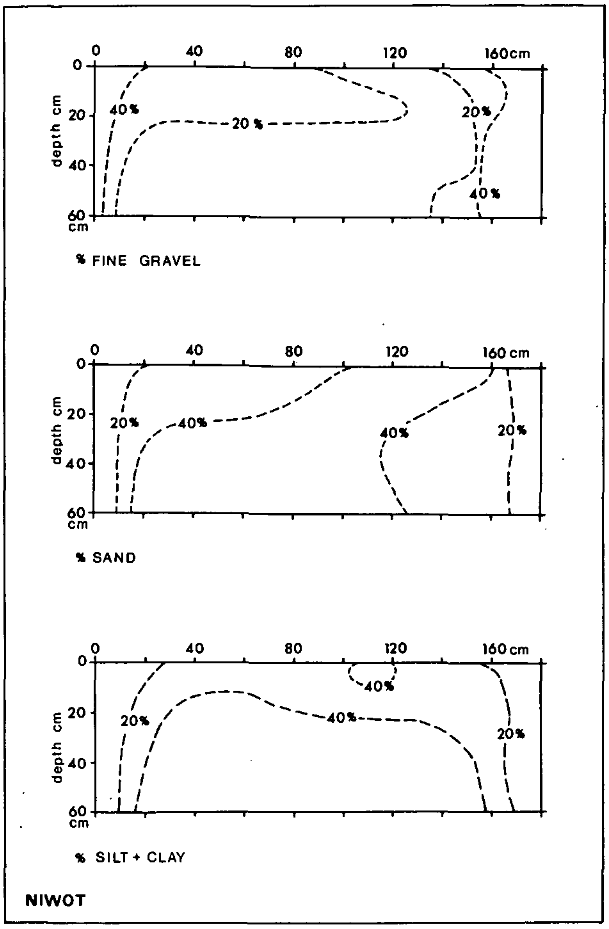

Figure 4. Granulometry of sorted circle, Niwot site. North to right, South to left.

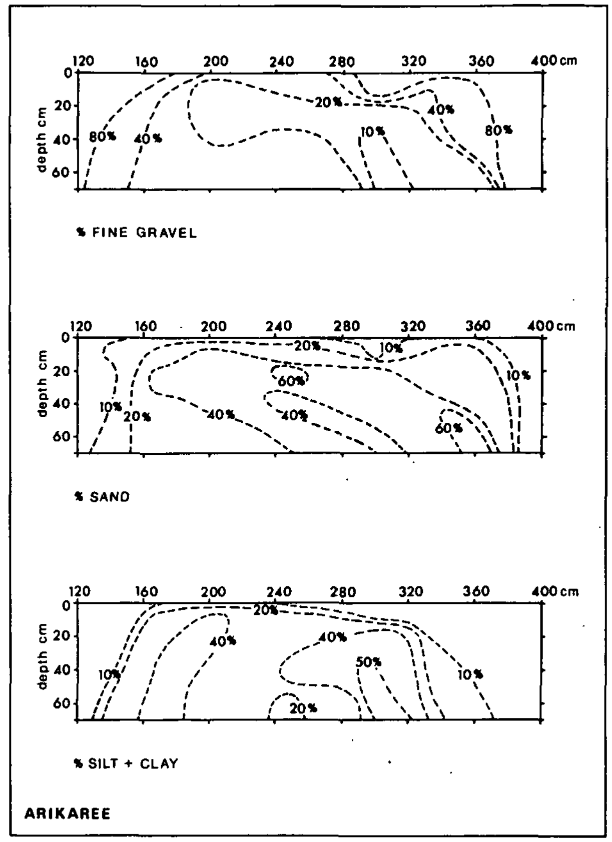

Figure 5. Granulometry of circle centre, Arikaree site.

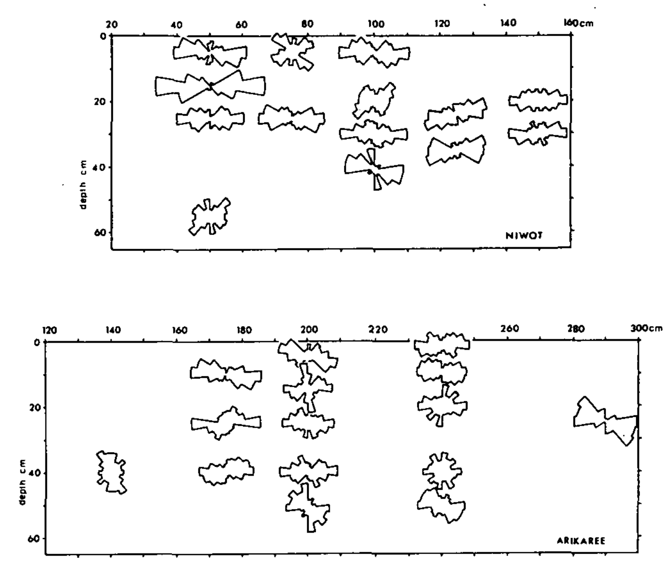

Figure 6. Microfabrics from excavated circle centres.

centre of this circle showed slight coarsening towards the surface, but very rapid coarsening into gravel at the margins.

The second excavated circle (Arikaree), showed a more complex granulometric pattern in its fine grained centre. Gravel content was above 20 %, except in an inclined tongue of gravel-deficient, but silt and sand-rich sediment extending up from the base of the excavation on the northern side (Fig. 5). This tongue was observed in the field (Fig. 3). A steeply inclined silt-rich zone was also present on the southern side. The surface layer showed high gravel contents.

MICROFABRICS

The orientations of 100 elongate sand grains, (100 µm–2000 µm intermediate diameter), as exposed in thin section, were recorded for each slide, using a low powered petrological microscope. In addition, the orientations of elongate granule-sized clasts (2 mm - 4 mm intermediate diameter) were recorded by means of direct measurements over a light table. The data are presented as rose diagrams (Figs. 6 and 7).

In the Niwot circle, microfabrics were dominantly horizontal, though the deepest sample (50 cm/55 cm) showed a multimodal distribution. Granule-sized clasts showed multimodal fabrics, though often with a significant sub-horizontal component.

The microfabrics from Arikaree were dominantly horizontal in the upper 15 cm of soil, but below this many thin sections showed multimodal fabrics, reflecting zones of

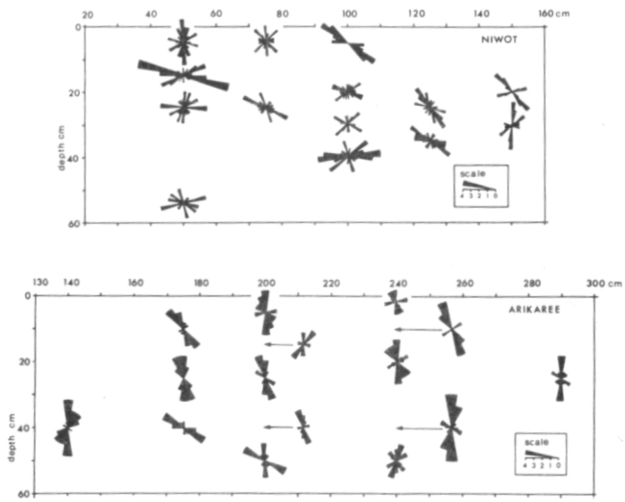

Figure 7. Dips of elongate granules, as seen in thin section.

varying grain inclination within individual slides. Patterns of birefringence indicated that silt flakes were often aligned parallel to the sand grain fabrics. The granule-sized grains present in the Arikaree thin sections were consistently steeply inclined or vertical, in contrast to those from the Niwot Ridge circle (Fig. 7). In samples from the upper 15 cm of the Arikaree circle therefore, granule grains were aligned transverse to the fabric of the sand grains and matrix, but in deeper samples, sand grains tended to be aligned parallel to adjacent steeply dipping granules (Figs. 8b, and 8c).

MICROMORPHOLOGY

Thin sections showed a dense silt and fine sand matrix surrounding angular to subrounded medium to coarse sand grains, and occasional larger gravel-sized clasts (Fig. 8a). Smooth walled bubble-like vesicular pores were common in both Niwot and Arikaree thin sections, with vesicle diameters up to 1800 µm (Fig. 8a). Rather diffuse sub-horizontal silt-rich patches, lenses and streaks were common in the Niwot samples, up to 1200 µm thick and 10mm wide (Fig. 8a). These were draped across dense sandy layers, and were often associated with coatings of silt on the upper surfaces of sand grains.

In the Arikaree samples sub-horizontal banded or lenticular structures of dense silt were observed only in the upper 15 cm of soil (Fig. 8b), and were conspicuously absent in deeper samples. Below 15 cm matrix birefringence, sand grain alignment and the alignment of granule-sized grains were often parallel, and frequently steep. Sharply defined textural boundaries between silt-rich and sand-rich zones were also observed in some thin sections, the silt zones displaying a streaky pattern parallel to the textural boundaries (Fig. 8c). Distinct flow structures, consisting of "bow waves" and streamlined tails were observed in the matrix surrounding many larger grains (Fig.8d).

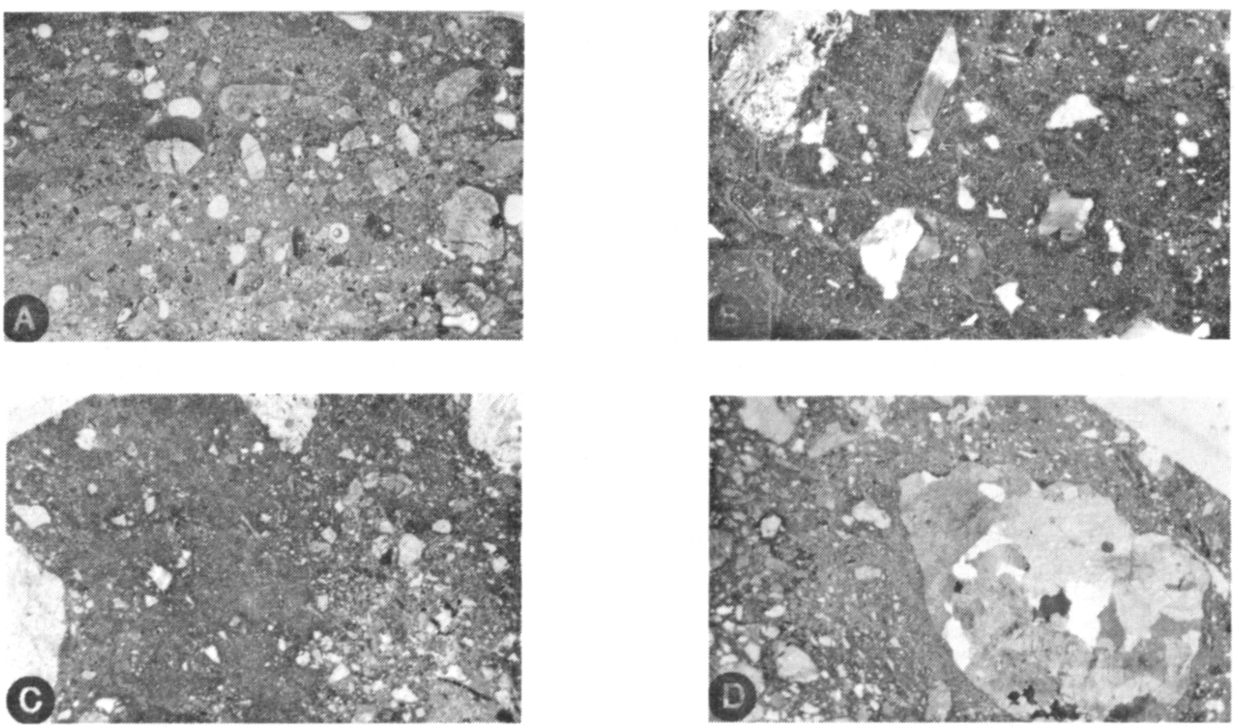

Figure 8. (a) Sample 50/15 Niwot. Silt cappings over sand grains, vesicles (white) and top left, diffuse lenticular structures associated with ice lensing. Frame length 20mm, plane light. (b) Sample 240/10 Arikaree. Steeply inclined sand grains aligned perpendicular to cryogenic platy structure. Frame length 10mm, partly crossed polarisers. (c) Sample 240/40 Arikaree. Boundary between a vertical silt- rich zone (left) and sand zone (right). The silt-rich zone extended 300mm vertically across the thin section. Frame length 20mm, partly crossed polarisers. (d) Sample 290/25 Arikaree. Flow 'tail' around a granule-sized clast. Frame length 20mm, plane light.

Discussion

The Niwot Ridge sorted circle showed a relatively uniform granulometry across its fine grained centre, the results being similar to those of Rissing and Thorn (1985), who sampled a smaller sorted circle on Niwot Ridge in a vertical profile, to a depth of 40 cm. The uniformity of sediment, with just a slight coarsening in the upper 20cm, suggests that frost sorting, responsible for circle development, has reached an advanced stage, so that much of the gravel-sized and coarser clastic material is already concentrated in the circle borders.

In contrast, the excavated circle from the higher Arikaree site showed a more complex pattern of granulometric variation, with much higher gravel contents. The steeply inclined zones of silt- and sand-rich soil within this circle centre resemble the granulometric patterns reported by Harris and Cook (1988) from excavated sorted circles in Jotunheimen, Norway. These authors suggested that upward displacement of sediment within the circle centres was responsible for such tongues, and a similar explanation is proposed here for the Arikaree circle. The continuation of the gravel- and organic-rich surface layer of the circle centre into the adjacent stony borders suggests radial movement at the surface (Benedict 1987 and Hallet et al. 1988), and subsequent downward subsidence within the borders. The marked thickening of the surface gravel-rich layer 80 cm from the northern border may indicate initiation of secondary circle development within the primary circle centre, as observed in some adjacent circles at the Arikaree site.

Benedict (1969) and Fahey (1975) demonstrated steep microfabrics near the surface of nonsorted patterned ground in Niwot Ridge, and concluded that vertical soil displacements due to frost action were responsible. Warburton (1985) argued that thaw-induced microfabrics are more likely to be preserved in undisturbed soil samples, since sampling always follows the last thaw event. Thaw-consolidation might produce sub-horizontal grains, though vertical frost-heaved grains may retain their orientations (see for instance Fox and Protz 1981). Diapiric injection of fluidised soil from near the base of the active layer would however, give steeply inclined microfabrics (Harris and Cook 1988).

The dominantly horizontal pattern of microfabrics in the Niwot Ridge circle suggests vertical compaction of the soil, either due to ice-lens growth during freezing, or consolidation during thawing. The cryogenic micromorphology of this circle centre reflects ice segregation processes during freezing, with some translocation of finer material and fabric collapse to form vesicles during thaw (Harris 1983, Harris and Ellis 1980, Van Vliet-Lanoë et al. 1984).

Microfabrics in the upper 10 cm-20 cm of soil at the Arikaree circle resemble those from Niwot Ridge, but at greater depths more pronounced vertical or inclined sand grain dips occur, with flow structures around larger clasts and steeply inclined sharply defined boundaries between silt-rich and sand-rich zones. Granule-sized clasts are almost exclusively steeply inclined or vertical at all depths, suggesting strong frost sorting.

Van Vliet-Lanoë (1988a) has illustrated cryoturbation in which silt was injected into sand. The injected silt contained well preserved microscopic traces of ice lenses, which bent downwards close to the silt/sand interface. This clearly relates to ice segregation during the freezing phase, and Van Vliet-Lanoë concluded that injection resulted from freezing-induced stresses. In contrast, cryogenically-induced microstructures are absent at Arikaree below 20cm depth. It appears that they are largely destroyed during thawing by thixotropic behaviour of the soil. Small-scale density controlled diapiric injection of fines apparently takes place during thaw, producing the textural zonation observed here.

The upward displacement of fines in the Arikaree circle centre apparently forms part of a convection-like circulation within the sorted circle. Benedict (1978) at the nearby Hungry Whistler site detected evidence for such circulatory movement within similar sorted circles. Stone tools and flakes, together with charcoal had suffered lateral movement on the surface from the circle centres into the coarser borders, and many were carried down into the borders, to a maximum depth of 51cm.

Conclusion

The sorted circle from 3600 m on Niwot Ridge appears to be largely inactive under present day conditions, though it suffers ice segregation and frost heaving in winter. It is likely that permafrost is absent. In contrast, the sorted circle at 3750m, below Arikaree Glacier, shows evidence of strong frost sorting of clasts coarser than sand size, and upward intrusion of fines into the circle centre from depth, with a counterbalancing downward sinking of the stony borders. From the evidence presented here, it appears that thaw consolidation of the upper few decimetres of the fine-grained circle centre produces a higher density, lower permeability layer which blankets the lower soil as it subsequently thaws. High water contents at depth (possibly reinforced by melting of ice-rich soil immediately above the permafrost table), causes thixotropic soil behaviour as consolidation takes place, and with an unstable density configuration, upward intrusion of fines from depth.

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