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# Water, heat and solute dynamics of a mud boil, Spitsbergen

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**Abstract**

Mud boils, a form of non-sorted circles, cover the ground surface in many periglacial landscapes. The vegetation-covered trough acts as an effective buffer to the downward movement of water and chemicals, while the bare center experiences larger fluxes of heat and mass. Since dissolved ions affect the electric conductivity of the soil solution, measurements of the bulk soil electric conductivity offer potential for estimating solute concentration. Since 1998, bulk soil electric conductivity has been measured automatically and hourly using 32 time domain reflectometry probes over an approximately 1 m diameter mud boil close to Ny Ålesund, Spitsbergen. Soil water electric conductivity was calculated from bulk soil electric conductivity using volumetric soil water content and a calibration parameter. The seasonal and spatial behaviour of water, temperature and solute concentration within two profiles of this mud boil were analyzed. Concentrations of estimated soil water electric conductivity were highest during the summer period when the active layer was thawed. Thermodynamic equilibrium modelling of the soil solution during freezing suggests that precipitation of dissolved species leads to the observed decrease in electric conductivity. There is a pronounced vertical solute concentration gradient in both profiles, while there is little evidence for horizontal solute concentration gradients beneath the mudboil.


*Keywords:* Permafrost; Freezing; Geophysical methods; Electric conductivity; Solute dynamics; Patterned ground

## 1. Introduction

Analysis of the phenomenology and dynamic processes of patterned ground yields information on past and present climate and environmental conditions (Washburn, 1979; Romanovskii, 1996). The objective of this study is to characterize (seasonally and spatially) the water and solute dynamics of this heterogeneous system using soil solution sampling, high temporal resolution measurements of bulk soil electric conductivity and

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thermodynamic equilibrium modelling of solution chemistry. This, in turn, adds insight to the mechanical dynamic of the mud boil, and to the discussions on the origin and formation of these periglacial features.

Furthermore, these findings contribute directly to the European Science Foundation project on 'Sedimentary Source-to-Sink-fluxes in Cold Environments'. An understanding of climate processes and their control on mass transfer processes, such as subsurface behaviour of solutes in a mudboil, aids in the understanding of mass export of cold drainage baisins.

## 2. Theories of mud boil formation

Mud boils are symmetric surface features in periglacial environments that have puzzled and fascinated researchers since at least 1900. Early observations and theories of the origin of patterned ground were the beginning of exciting research. Washburn (1956) summarized and discussed postulations of 19 separate mechanisms of formation for non-sorted circles in particular. These ideas are still central in today's discussions of patterned ground formation.

Mud boils (also known as frost boils, frost scars, mud circles and mud hummocks), classified as non-sorted circles, are found in areas where the ground is subject to seasonal freezing and thawing. They are characterized by a bare, usually doming round mineral soil center, surrounded by vegetation. Some of the mechanisms postulated for their formation are: the sorting of soil materials based on grain size; convection cell like cryoturbation; diapir formation or upwellings of lower soil horizons under pressure (Washburn, 1956). A review of the main mechanisms involved in cryoturbations was presented by Van Vliet-Lanoë (1991) based upon field measurements and micromorphological data. She concluded that "differential frost heaving appears to be the main mechanism of cryoturbation" (pp. 123) and that the presence of organics enhances differential frost heaving. Kessler et al. (2001) modelled sorted circle formation (with barren finer grained circle centers surrounded by stones) from two layers distinct in particle size using a purely mechanical model. The freezing front pushed soil to more compressible soil regions, accumulating in soil plugs that reach to the surface. During thawing, consolidation occurred vertically. The circle was maintained at the surface by the circulation of the stone and fine material domains, upward in the circle center and downward at the edges. Walker et al. (2004) presented horizontal soil profiles across a mud boil. Nutrient concentrations (available potassium, phosphor, nitrogen) and water content declined from the margins toward the center, a trend which they attributed to more 'mechanical' activity towards the center of the boil.

### 2.1. Study site

The Bayelva catchment is located about 3 km from Ny-Ålesund, Spitsbergen (78°55′N, 11°E) in the forefield of the Brøggerbreen glacier (Fig. 1A, B). In this region, continuous permafrost underlies coastal areas to depths of about 100 m and mountainous areas to depths greater than 500 m. The North Atlantic Current warms this area to mean monthly air temperatures around −13 °C in January and 5 °C in July, respectively and provides about 400 mm annual precipitation mostly as snow between September and May. Our study site is located at about 25 m above mean sea level, on top of a small hill covered with unsorted circles (Fig. 1C). It is not clear if the mud boils on this hill are currently being degraded (for example, by gelifluction) or maintained by active cryoturbation. Vegetation encroaching from the sides into the mud boil's center – though the centers are still doming – is an indicator for slow mass displacement and semi-active behaviour. While other patterned ground phenomena (such as sorted circles and stripes) are found in the vicinity of the hill, these mud boils are only present on Leirhaugen hill. The mud boils were or are formed under local conditions favourable for mud boil formation after the last glacial period.

Leirhaugen hill is mainly composed of rock, but partly covered by a mixture of sediments: glacial till, finer glacio-fluvial sediments and clay formed by the last glacial advance (Tolgensbakk, personal communication). The gray color of the sediments suggests that the material was deposited by the Kongsfjorden glacier and not the adjacent Brøggerbreen glacier, which deposits redder material. Marine sedimentation could also have contributed since the hill is located below the marine limit (about 38 m).

## 3. Methods

We instrumented one of these non-sorted circles (Fig. 1D) in August 1998 to automatically monitor hourly temperature and volumetric liquid water content ($\theta$). Altogether 32 time domain reflectometry (TDR) probes and 32 temperature probes were installed over the 1 × 1 m profile. The position of the TDR probes is shown in Fig. 2. The TDR and temperature data set considered in this study is limited to 1999, the year in which suction lysimeter data were collected. During installation, soil samples were taken for the analysis of physical parameters. The texture and composition of 25