*Edits by Hallet through first section (to line 140)*

*Italicized material from your text.*

13. I’d change “iterative burying and resurfacing” to “cyclic burial and exhumation”

15. delete last word “to”

1 Surface kinematics of periglacial sorted circles using

2 structure-from-motion technology

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10 Abstract

11 Numerical modelling

12 suggests that these features develop from a convection-like circulation of material in the

13 active layer of permafrost. The related cyclic burial and exhumation of material is

14 believed to play an important role in the soil carbon cycle of high latitudes. The connection of

15 sorted circles to permafrost conditions and its changes over time make these ground forms

16 potential paleoclimatic indicators. In this study, we apply for the first time the photogrammetric Structure-

17 from-Motion technology (SfM) to large sets of overlapping terrestrial photos taken in August

18 2007 and 2010 over three sorted circles at Kvadehuksletta, Western Spitsbergen. We retrieve

19 repeat digital elevation models (DEMs) and orthoimages with millimetre-resolution and

20 accuracy. Changes in microrelief over the three years are obtained from DEM-differencing

21 and horizontal displacement fields from tracking features between the orthoimages. In the

22 inner domains of the circles, consisting of fines, surface material moves radially outward with

23 horizontal surface speeds of up to 2 cm a-1. The coarse stones in the interior portion of the peripheral ridges move radially inward at similar rates. A number of substantial

25 deviations from this overall radial symmetry, both in horizontal displacements and in

26 microrelief, shed new light on the potential spatio-temporal evolution of sorted soil circles,

27 and periglacial patterned ground in general.

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31 1 Introduction

32 The term patterned ground describes a range of small-scale (order of 0.1-10m) landforms such as polygons,

33 stripes and circles, found in periglacial environments (Washburn, 1980). Patterned ground

34 develops in frost-susceptible soils due to repeated freezing and thawing.

35 These landforms are considered an excellent geomorphic example of self-organization and

36 emergence in complex systems (e.g. Kessler et al., 2001; Kessler and Werner, 2003). The

37 most prominent forms of this type are found in the active layer of Arctic or Antarctic lowland

38 permafrost, where the permanently frozen subsurface confines water and creates

39 hydrological conditions favorable for ice growth in the overlying layer of seasonal freezing and thawing, the so-called

40 active layer.

41 The most conspicuous type of patterned ground is sorted circles. They consist of a core of

42 fine-grained material, reaching a depth of at least the active layer, surrounded by a

43 much coarser circular border or ridge of open-work fabric that extends 1 to 3 decimeters above

44 the centre surface (Fig. 1). Typical diameters for the fine-grained center are 1-3 m while the

45 coarse elevated border may be 0.5 – 1 m wide. Much smaller forms are also found (e.g.

46 (Matsuoka et al., 2003). The surface material in the center domain shows a radial outward

47 movement on the order of 0.01 m a-1 (Schmertmann and Taylor, 1965; Hallet and Prestrud,

48 1986), and from measuring the tilt of inserted rods similar

49 movement extend to a depth of decimeters (Hallet, 1998). For mass continuity reasons, this suggests that

50 the fine material within the centre follows a displacement pattern similar to a convection cell.

51 This burial – and later resurfacing – of material in patterned ground is an important element

52 within the soil carbon cycle of high latitudes (e.g. Bockheim, 2007; Horwath et al., 2008) as

53 well as soil development (e.g. Bockheim et al., 1998). It also highlights that precise knowledge

54 about patterned ground dynamics has implications far beyond the geomorphic interest in

55 process/form relationships – especially with respect to the effect of warming air and ground

56 temperatures on soil carbon stocks. Moreover, patterned ground is considered a potential

57 paleoclimatic indicator based on the general relation between pattern size and permafrost

58 conditions such as active layer depth (Hallet and Prestrud, 1986).

59 A variety of mechanisms have been suggested for the origin of sorted circles and other

60 patterned-ground landforms (cf. Washburn, 1980), but recent work focusses on differential

61 frost heave (e.g. Peterson, 2008), and its feedback with progressive sorting (e.g. Kessler et al.,

62 2001; Kessler and Werner, 2003). Scientific progress within this field comprises thorough field investigations, laboratory work and theoretical studies (Hallet, 1998), as well as numerical models of the development of unsorted circles (Peterson and Krantz, 2008), and sorted circles and other sorted patterned-ground landforms (Kessler et al.,

66 2001; Kessler and Werner, 2003). According to Kessler and Werner (2003), two main

67 mechanisms determine the development of circles from the starting point of a nearly-uniform stone layer

68 overlying fine-grained soil. First, fine material and stones are transported in opposite directions

69 normal to the freezing front during freeze-thaw cycles, with a lateral component due to the

70 differential freeze-thaw. Second, as stones are thus sorted through time they form elongated

71 regions, which are are progressively squeezed by the fine domains during winter

72 freeze-up, when the rapidly cooling stone domain causes lateral frost heave within the fine

73 domain. The effect of the second mechanism is stone transport along the long axis of the

74 stone domains. Pattern types change in model runs due to increasing slope (causing stripes to

75 develop), decreasing stone concentration (leading to stone labyrinths and stone islands), and

76 increasing lateral confinement (favoring polygonal patterns).

77 The model of Kessler and Werner (2003) can be considered an hypothesis for the main

78 mechanisms involved in patterned-ground formation. It provides specific predictions about

79 the dynamics of central and border domains. Whereas existing empirical data of sorted circle

80 dynamics consist only of sparse point measurements (e.g. Hallet and Prestrud, 1986; Hallet,

81 1998), measurements of the three-dimensional surface displacement fields and microtopography are

82 feasible today – even over short timescales. Such data would be considerably better suited to test these

83 predictions that the sparse data currently available. Orther questions also arise: 1) if and how the dynamics of the circles might be influenced

84 by changes in the underlying frozen ground, such as changes in its thermal properties and

85 structure, and related impacts on the ground hydrology? How representative are the existing sparse data ? A comprehensive benchmark of

86 present-day dynamics would aid research on this subject, which is linked to the potential

87 importance of cryoturbation and differential frost heave in the global carbon cycle.

88 Ultimately, better understanding of the processes involved in the dynamics of patterned

89 ground and their changes over time would facilitate their use as indicator for present and past

90 environmental conditions in cold regions. Our objective is thus to test a methodology for

91 deriving the 3D surface kinematics of sorted circles, and to analyze our initial data with

92 respect to predictions from conceptual and numerical models.

93 To quantify the surface kinematics of selected sorted circles we apply the Structure-from-

94 Motion (SfM) technology to a multi-temporal set of terrestrial images to derive vertical and

95 horizontal components of change over time. SfM combines well-established photogrammetric

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principles, in particular bundle adjustment and image matching, with modern computational methods to arrive at a powerful and user-friendly software environment that is able to extract a three-dimensional model from a set of images, which then forms the base for a range of further products, among them digital elevation models (DEMs) and orthoimages. The SfM technology has already proved to be very powerful for a large range of geoscientific applications, such as geological and glaciological studies, coastal erosion, river morphology, volcanic activity, or landsliding (e.g. Girod, 2012; James and Robson, 2012; Westoby et al., 2012; Fonstad et

al., 2013).

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2 Method

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2.1 Study site and data collection

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For our study we selected a series of three adjacent sorted circles at Kvadehuksletta, Brøggerhalvøya, Western Spitsbergen (Fig. 1). The sorted circles at Kvadehuksletta are among the best- developed of their kind on Earth, as far as we known, and comparably easy to access 10 km to the southeast from the Ny-Ålesund research station, and with the Geopol hut in close vicinity. As a result these circles have been subject to a number of earlier investigations (Hallet and Prestrud, 1986; Anderson, 1988; Hallet et al., 1988; Etzelmuller and Sollid, 1991; Hallet, 1998; Putkonen, 1998) (see also Introduction), and a detailed geomorphological map

is also available (Tolgensbakk and Sollid, 1987).

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Kvadehuksletta is a wide strandflat, covered with beach deposits of Holocene and older age. Our study site is situated above the late glacial marine limit. The overall elevation of the circles studied is around 82 to 83 m asl. Bedrock in the area consists of dolomite, and most of the beach-ridge stones are of local origin. Due to weathering of the dolomite and subsequent eluviation, a frost-susceptible silty fine-grained soil has developed (Etzelmuller and Sollid, 1991), which facilitates the development of sorted circles. Large areas between the beach ridges are covered by such sorted circles, grading in some areas towards sorted polygons and, more irregular sorted forms as well as stripes on slopes (Tolgensbakk and Sollid, 1987). The fine inner domains of the circles often have a variable cover of vegetation, mainly dominated by cryptogamic crust, that gives the inner circle a dark appearance, but sometimes also with higher plants such as sedges and salix. The vegetation tends to be densest close to stone borders, and shows evidence of the surface movement pattern. Salix is found in some stone domains that are generally unvegetated. Climatic data are available from Ny-Ålesund, where mean

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annual air temperature is -6.3 °C and mean annual precipitation is 385 mm for the normal period 1961-1990. Recent warming in the Arctic areas suggests that these values may no longer be fully representative (Isaksen et al., 2007a; Isaksen et al., 2007b), and in Fig. 2 the mean monthly anomaly from the normal, calculated for the period 1991 – 2010, provides a more realistic picture of the present climatic situation at the site. The anomaly is most pronounced in winter. Fig 2 also displays air temperatures during the study period and melting season degree day sums, and near surface temperatures

1999 – 2010 (7 day running mean) from the 15 m deep Jansonhaugen borehole near Longyearbyen (K. Isaksen, personal communication 2013). The recent warming causes warmer ground and deeper active layer at the Janssonhaugen site, and this is presumably also the case at Kvadehuksletta. Apart from the unusual warm winter of 2005-

2006, (Isaksen et al. 2007a), no extreme events likely to influence our measurements, are

recorded in these data.