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Unchanged surface morphology in debris-covered glaciers and rock glaciers in Tröllaskagi peninsula (northern Iceland)

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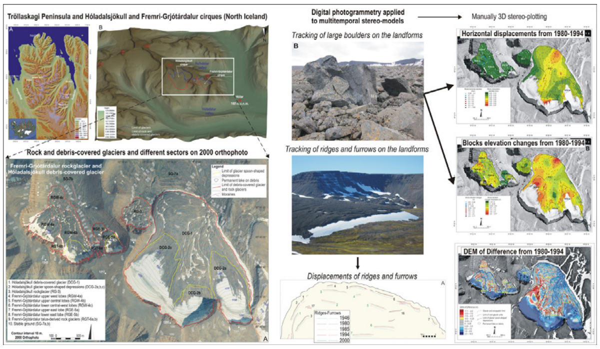
HIGHLIGHTS

- The study focused on two cirques in Tröllaskagi peninsula (Northern Iceland).
- We studied the surface evolution of rock glaciers and a debris-covered.
- We applied photogrammetry methods to detect changes in the last 54 years.
- We detected minimum changes, derived from subsidence, in all this landforms.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper analyses changes in the surface morphology of rock and debris-covered glaciers in the Hóladalsjökull and Fremri-Grjótárdalur cirques near Hólar village in the Tröllaskagi peninsula (northern Iceland) (65°43′55″N; 19°06′49″W, 160 m), to understand the dynamics and climatic significance of these landforms. The study includes an analysis of historical aerial photographs from 1946 to 2000. The aim was to evaluate surface changes in these landforms and obtain the horizontal displacement and elevation changes of large boulders and linear features (ridges and furrows) at each date. In addition, the surface elevation differences between 1980 and 1994 were obtained from digital elevation models. The horizontal displacement results obtain a mean velocity of 0.33 m yr^{-1} and an average elevation difference of −0.72 m for the boulders, with the linear features advancing 14.84 m during the period 1946–2000. Except for this slow mobility, no changes occurred in the surface morphology of these landforms during the 54 years. The low displacement rates of boulders and linear features, together with the surface lowering processes observed in these landforms, indicate that widespread melting is the most important activity in the debris-covered and rock glaciers in Tröllaskagi. This is confirmed by the recent formation of collapse depressions.

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1. Introduction

The Tröllaskagi peninsula hosts 167 alpine glaciers (Icelandic Meteorological Office, 2018), mostly north-facing (Sigurðsson and Williams, 2008). A few of these glaciers are debris-free, but most are debris-covered or end in a rock glacier (Björnsson, 1991; Wangensteen et al., 2006; Kellerer-Pirklbauer et al., 2007; Björnsson and Pálsson, 2008). Although the recent glacier evolution of Iceland is well known (see synthesis in Ingólfsson and Norddahl, 1994; Geirsdóttir et al., 2009; Geirsdóttir, 2011; Pétursson et al., 2015), the origin of the Tröllaskagi debris-covered and rock glaciers is still under discussion. Initial research into these debris-covered and rock glaciers was carried out especially during the 1970s–1990s. For some researchers, the rock glaciers formed recently, during the Little Ice Age (LIA) expansion, and are approximately 200 years old, according to lichenometric criteria and present mobility rates (Martin et al., 1994; Hamilton and Whalley, 1995a, 1995b). This young age has also been deduced from the depression of the glacial Equilibrium Line Altitude (ELA) in Tröllaskagi (Ipsen et al., 2018). However, other authors estimate the oldest age for these Tröllaskagi debris-covered and rock glaciers to be around 6 ka or even older according to streamlines based on the displacement field and surface velocities from 1985 to 1994 data (Wangensteen et al., 2006; Kellerer-Pirklbauer et al., 2007).

Debris-free glaciers, rock glaciers and debris-covered glaciers in Tröllaskagi coexist in cirques in close proximity. The limits of these three glacier types and their genetic relationships are still not clear (Berthling, 2011; Janke et al., 2015). A glacier becomes a debris-covered glacier when supraglacial debris >0.5 m thick covers >50% of the ablation area (Azócar and Brenning, 2010; Brenning, 2005; Hambrey et al., 2008; Kirkbride, 2011, 2000). The differences between debris-covered glaciers and rock glaciers are even less clear; they are considered to be rock glaciers where the surface debris layer is thicker than debris-covered glaciers and the ice content is estimated to be <30% of the total mass (Haeberli et al., 2006; Berthling, 2011). The difference in surface morphology is not clearly defined, but ridges on debris-covered glaciers tend to be more longitudinal, while lateral and central moraines are still evident and some viscous flow morphology is observed (Clark et al., 1994). In addition, rock glacier morphology is defined by the existence of pronounced transverse ridges and furrows, perpendicular to the flow direction (Capps, 1910; Wahrhaftig and Cox, 1959; Vitek and Giardino, 1987; Martin and Whalley, 1987; Whalley and Martin, 1992; Barsch, 1992, 1996; Hamilton and Whalley, 1995a, 1995b; Haeberli et al., 2006; Berthling, 2011; Janke et al., 2013; Monnier and Kinnard, 2017).

Applying these criteria to Tröllaskagi, the current dynamics and geomorphological context of rock glaciers and debris-covered glaciers are quite similar. There are no moraine ridges in cirques with rock glaciers and debris-covered glaciers, but many occur in valleys where debris-free glaciers exist (Hamilton and Whalley, 1995a, 1995b; Martin et al., 1991; Andrés et al., 2016). Aerial photos from different dates do not show geomorphic evidence of change to their surface morphology (Hamilton and Whalley, 1995a, 1995b; Andrés et al., 2016) and advances and changes of their fronts are not apparent (Whalley et al., 1995a, 1995b; Andrés et al., 2016). Nevertheless, these observations of the absence of surface changes in debris-covered and rock glaciers contradict the analysis by some authors using photogrammetric techniques, obtaining surface boulder displacement up to 0.84 m yr^{-1} (Kellerer-Pirklbauer et al., 2007; Wangensteen et al., 2006) or up to 3 m yr^{-1} using satellite radar interferometry (Lilleøren et al., 2013). Other authors consider that Tröllaskagi debris-free glaciers are very dynamic and that their fronts are highly sensitive to climate fluctuations (Caseldine, 1985; Eyþórsson, 1935, 1931; Fernández-Fernández et al., 2017). The retreat of nearby debris-free glaciers from the LIA moraines to the present margins averages around 1300 m (Fernández-Fernández et al., 2017). This retreat was interrupted during at least five cold periods with glacier snout advances which formed many frontal moraines (Caseldine, 1983, 1985; Eyþórsson, 1935; Fernández-Fernández et al., 2017). However, various surge-type glaciers have been described in Tröllaskagi, forming several frontal moraines in the area, and therefore their origin is not directly related to climate evolution (Björnsson et al., 2003; Brynjólfsson et al., 2012).

One of the key factors when studying the origin and climatic significance of rock glaciers and debris-covered glaciers is the analysis of their dynamics and morphological changes over time (Benn et al., 2012; Bosson and Lambiel, 2016; Brenning, 2005; Capt et al., 2016; Deline, 2005; Emmer et al., 2015; Humlum, 1998; Kääb, 2008; Kellerer-Pirklbauer et al., 2008; Kellerer-Pirklbauer and Kaufmann, 2012). The aim of this present research is to study the evolution and morphodynamics of a rock glacier and a debris-covered glacier in the Tröllaskagi peninsula to gain a better understanding of the differences, origin and climatic significance of these formations, using an innovative approach. To achieve this aim, a range of consistent photogrammetric techniques and geographic information system (GIS) analyses are applied in a multi-temporal approach involving processing and comparison of historical aerial photographs.

2. Regional setting

The Tröllaskagi peninsula in north central Iceland lies between meridians 19°30′W and 18°10′W, jutting out into the North Atlantic to latitude 66°12′N and linked to the central Icelandic Highlands to the south, between the Skagafjörður fjord to the west and the Eyjafjörður fjord to the east (Fig. 1A). The peninsula is a plateau, topped by flat summits and ridges, intensely dissected by the drainage network, which forms flat-bottomed valleys, often with steep walls. It is composed of Tertiary basalt bedrock, with semi-horizontal lava flows often separated by 30–50 cm thick lithified, mainly argillaceous, sedimentary horizons known as red interbed layers (Sæmundsson et al., 1980). The slopes are often unstable, as many are affected by rock slope failures and deep-seated gravitational slope deformation, often of significant magnitude, where the red interbed layers act as decollement levels (Cossart et al., 2014; Feuillet et al., 2014; Jönsson, 1976; Whalley et al., 1983). These macro-mass movements are considered to have developed as a result of the final deglaciation during the early Holocene (Coquin et al., 2015; Cossart et al., 2014; Mercier et al., 2013) and some of them are still active (Sæmundsson et al., 2007; Wangensteen et al., 2006). Large scale failure events may originate in cirque headwalls in Tröllaskagi and the resulting landforms resemble rockglaciers (Sigurdsson, 1990; Whalley et al., 1983; Whalley and Martin, 1992).

The climate of the Tröllaskagi peninsula is characterized by a mean annual air temperature (MAAT) of 2 to 4 °C (1961–1990 data series) on the Tröllaskagi coasts and of −2 to −4 °C on the summits (Etzelmüller et al., 2007). The precipitation is relatively low, because the central highland and the ice-caps block the wet southerly winds. The precipitation is mainly contributed by northerly winds and oscillates between 400 mm in some lowland areas and 2000 mm on the summits (1971–2000 data series) (Crochet et al., 2007). The continuous permafrost limit in the Tröllaskagi mountains has been modeled and located between 850 and 950 m a.s.l. (Etzelmüller et al., 2007; Wangensteen et al., 2006). The termini of most of the debris-covered and rock glaciers are at 900–950 m a.s.l., where the MAAT is −1.8 to −2.6 °C (extrapolated with a gradient of −0.65 °C 100 m^{-1} from Hólar í Hjaltadal meteorological station at 160 m a.s.l., 1961–1990) (Kellerer-Pirklbauer et al., 2007) with precipitation around 1500 mm (Crochet et al., 2007). The current ELA of the main debris-free glaciers is 1010–1060 m a.s.l., with MAAT around −2.3 °C at the ELA (Fernández-Fernández et al., 2017). These glaciers reached their LIA maximum approx. 1865–1900 (Caseldine, 1985), with an ELA of 950–1010 m a.s.l. and MAAT 1.7–1.9 °C lower than at present (Caseldine and Stötter, 1993; Fernández-Fernández et al., 2017).