Eiríksjökull plateau icefield landsystem, Iceland.

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Abstract

A 1:9,500 scale map of the Eiríksjökull plateau icefield and its post Little Ice Age foreland geomorphology and surficial geology is presented as a modern exemplar of an asymmetrically developed mountain glacier typical of the style of glacierization that dominated during mid-latitude Quaternary cold stages. Features regarded as diagnostic for this setting include: a) ice-cored hummocky terrain, indicative of controlled moraine construction in polythermal snouts, and localized breach lobe development, incremental stagnation and rock glacierization, all indicative of a debris-charged glacier snout; b) fluted till and moraines, indicative of temperate basal ice conditions up ice from polythermal glacier margins; and c) glacifluvial and debris flow deposits, occurring as steep fans emanating from glacier snouts at the plateau edge and in ice-contact fans or ramps fed directly by debris-covered glacier margins at the Little Ice Age. Although this plateau icefield landsystem is similar to those previously reported from Iceland, a remarkable debris-covered snout/ice-cored moraine complex on the foreland of Klofajökull is a more extreme example of the depositional zone that characterizes the valleys surrounding the more sediment starved plateau ice dispersal centres.

Key words: plateau icefield; glacial landsystem; Eiríksjökull

Introduction

The mapping of sediment-landform associations (landsystems) on the forelands and around the margins of receding Icelandic glaciers continues to facilitate an improved understanding of process-form relationships in glacial geomorphology as they pertain to a variety of glacierization styles (e.g. Krüger 1994; Andrzejewski 2002; Evans et al. 2006a, 2006b, 2007, 2009a, 2009b, 2010; Kjær et al. 2008; Evans & Orton 2014; Jónsson et al. 2014; Schomacker et al. 2014). The Icelandic plateau icefields are particularly significant in this respect, because they are potential modern analogues for styles of upland glacierization that dominated for long parts of the Quaternary cold stages in mid-latitude regions (e.g. Manley 1955; Rea et al. 1998; Rea & Evans 2003, 2007; McDougall 2001, 2013). Hence detailed landsystems models of these plateau icefields are warranted if we are to gain a representative sample of modern analogues for palaeoglaciological reconstruction. Previously reported plateau icefield landsystems from the Icelandic topographic setting of volcanic uplands (tuyas) have emphasized the importance of blockfield covered summits with localized development of ice-cored (controlled) moraines lying down flow of weakly developed flutings (e.g. Þorisjökull);

more significant latero-frontal moraines, hummocky ice-cored moraine and rock glacierized former glacier snouts characterize the surrounding valleys incised into the plateau margins, demonstrating higher rates of debris turnover once the plateau icefield thickens enough to spill into the valley heads (Evans et al. 2006a). This landform assemblage has been linked to a polythermal regime for the plateau icefields of Iceland's arid and high altitude interior, particularly for the Little Ice Age maximum (e.g. Tungnafellsjökull; Evans 2010). More complex ice dynamics have also been identified using plateau icefield landform-sediment assemblages, including outlet-specific surge activity at Drangajökull (Brynjólfsson et al. 2014) and spatial and temporal landsystem change/overprinting, involving polythermal and surge signatures, at Satujökull (Evans et al. 2010; Evans 2011). Although surging of mountain glaciers and rock glacierization of debris-charged plateau and mountain icefield outlet lobes are widely reported phenomena (e.g. Gardner & Hewitt 1990; Whalley et al. 1994; Humlum 1998; Evans et al. 2006a; Farbrot et al. 2007; Brynjólfsson et al. 2013, 2014), our knowledge of the landsystem signatures of such glacier behaviour is not yet fully developed. Hence the mapping of the recently deglaciated forelands of the Icelandic plateau icefields facilitates a systematic assessment of the range of diagnostic geomorphic signatures necessary for the reconstruction of mountain palaeoglaciology.

The Eiriksjokull plateau icefield was targeted for landsystem mapping because it occupies the largest tuya in Iceland (Fig. 1; Piper 1973) and displays unusually strongly developed glacial landform asymmetry, due specifically to the construction of the large ice-cored moraine complex around the Klofajökull outlet glacier on the northeast plateau boundary (Fig. 2). Although previous plateau icefield landsystem case studies in Iceland have highlighted asymmetrical ice advance in response to the Little Ice Age climate cooling and the concomitant concentration of large ice-cored morainic assemblages in surrounding valley heads, none have highlighted examples of anomalously large lobate ice-cored moraine fields such as that represented by Klofajökull. Examples of such lobate valley bottom snouts fed by plateau icefields are more common in high arctic terrains such as the Canadian Arctic islands and northern Greenland but marked asymmetry of outlet lobes is not prevalent (Ó Cofaigh et al. 2003). The landsystem signature presented here for Eriksjökull indicates that the Klofajökull outlet glacier is transporting unusually large volumes of englacial and supraglacial debris from the plateau edge to the adjacent lowlands in a form of moraine asymmetry (cf. Matthews & Petch 1982; Benn 1989; Evans 1999). Based upon geomorphological relationships, specifically the fact that the early historical Hallmundarhraun lava field flowed around the Klofajökull lobate moraine assemblage, Guðmundsson (1998) proposed that the outermost ridges likely date to a time prior to ca. 900 AD. Since then the outlet lobe has continued to deliver significant debris loads to the valley floor, and the older ice-cored moraines have become rock glacierized.

Map production

The Eiriksjokull map is based on 2008 colour aerial photography (orthophotograph and digital elevation model) provided by the Icelandic aerial survey company Loftmyndir ehf. Ground survey control was not employed due to the problems of difficult access to most areas of the field site, with the exception of the outer moraines of Klofajökull which can be accessed by a three hour walk from the end of a rough track leading from mountain road F578. The map is produced as an ISN93/Lambert 1993 projection (EPSG code 3057), or a Lambert conformal conical projection with two standard parallels at 65.25°N and 64.75°N, a central meridian at 19°W, a false easting of 500 000, a false northing of 500 000, a point of origin at 65°N and 19°W, and with the geodetic datum ISN93 (GRS80 ellipsoid). Contours at 20 m interval were generated in ArcGIS with the elevation based on the ISN93 datum. The map is at a scale of 1:9,500 if printed at A0 paper size.

The base data for the geomorphology and surficial geology was compiled using stereoscopically-viewed aerial photographs and a mosaic of digitally orthorectified images on a coloured ink film overlay. Final map design and production was undertaken in Adobe Illustrator. A raster image was used for the glacier surface by manipulating the orthophotograph, thereby creating a false blue colourised representation of the icefield and its outlet glaciers that displays features such as crevasse fields, snowlines and supraglacial debris patterns.

Eiríksjökull

The centre of the plateau icefield of Eiriksjokull is located at 64° 46’ N and 20° 24’ W, 6 km northwest of Langjokull in west-central Iceland. Like many of the small Icelandic upland ice masses it occupies the summit of an isolated volcanic plateau or tuya produced by subglacial volcanic activity during the last ice sheet glaciation of the island (van Bemmelen and Rutten, 1955; Piper, 1971, 1973). These plateaux are prime locations for icefield inception in Iceland because their extensive summits lie above the equilibrium line altitude (ELA) of regional glaciation (Manley, 1955; Rea & Evans 2003, 2007). Hence the expansion of the icefields to produce lowland outlet lobes during the Little Ice Age is a modern exemplar of the process of instantaneous glacierization (Ives et al, 1975). The outlet glacier names adopted here are those recently defined by Sigurðsson et al. (2013), who have proposed an apparent change in the location of the name Þorvaldsjökull; this name was previously used on the smaller lobe located immediately to the south and now named Ögmundarjökull by Sigurðsson et al. (2013).

The style of glacierization of the Eiriksjokull tuya is very similar to that of Þorisjökull as depicted by Evans et al. (2006a), with a summit ice dome feeding outlet glaciers that extend to lower elevations in an asymmetrical pattern that reflects the glacioclimatic regime of upland surfaces in northern hemisphere mid-latitude settings. This asymmetry involves a restricted southern and southwesterly icefield extent, with the ice front occupying the plateau summit at altitudes of 1220 m (in the west) to 1300 m (in the south), and more extensive outlet lobes occupying deeply incised bedrock trenches cut through the northern and northwestern plateau margins and terminating at altitudes as low as 640 m (Klofajökull in the north) to 820 m (Þorvaldsjökull in the east). Intermediate levels of glacier occupancy/survival are represented by the niche glaciers of Brækur-vestri and Brækur-eystri on the north and northeast plateau edge at elevations down to 980 m and 1020 m respectively, with Brækur-vestri being still partially connected to the summit ice. Hence the glaciation level rises in altitude from the northeast to the southwest, as dictated by aspect, and ice-cored controlled moraine ridges are better developed and preserved on the plateau summit where annual average temperatures are lower and the ice margins are likely prone to longer periods of basal freezing. Aerial photographs, the most recent of which is from 2008, indicate that the snowline presently lies at around 1550 m asl., and hence the equilibrium line is located at around this altitude and the summit ice dome, where ice is estimated to be around 220 m thick (Guðmundsson 1998), is acting as a small accumulation zone.

Previous work on the Eiríksjökull glacial landforms by Guðmundsson (1998) involved the dating of moraines using a combination of lichenometry and aerial photograph archives. He identified outer moraines around the forelands of Brækur in the north and Ögmundarjökull (now named Þorvaldsjökull) in the east and dated them to 1880 and 1923 AD respectively. He also ascribed an 1880 AD age to the moraines on the Stallurin foreland on the west plateau summit. The absence of older moraines at these sites was interpreted by Guðmundsson (1998) as being indicative of a lack of more extensive pre-Little Ice Age (neoglacial) ice advances. In contrast, he proposed that Klofajökull constructed the outermost ridges of its lobate ice-cored moraine complex prior to 900 AD, based upon that fact that the early historical aged Hallmundarhraun lava field (Jóhannesson 1989) was forced to flow around the moraine obstacle. Guðmundsson (1998) also concludes that, although a later Little Ice Age advance did occur at Klofajökull, the ice-cored moraine complex has remained active partially as a rock glacier and as an incrementally expanding lobate moraine assemblage.

Surficial geology and geomorphology

i) Ice-cored hummocky terrain

Around the margins of Eiríksjökull, ice-cored moraines display a variety of characteristics, including: i) Little Ice Age multiple ridge complexes (Figs. 3, 4d), which likely originated by controlled moraine construction in polythermal snouts; ii) controlled moraine on the plateau summit (Fig. 4a, b); and iii) the Klofajökull lobate moraine assemblage, which includes prominent breach lobes (*sensu* Deline 1999a, b; Benn et al. 2003) and rock glacierized masses and is indicative of a debris-charged glacier snout (Fig. 5). Also included in this map unit are areas of densely-spaced push moraines where ice content is uncertain and hence either a controlled moraine or push moraine origin is possible. It also contains discontinuous linear ridges and controlled moraine in some areas developed into rock glacier lobes. Extensive areas of ice-cored moraine have been identified previously from a variety of glacier forelands in Iceland, where they document either: a) polythermal snout conditions at the Little Ice Age maximum limits (e.g. Evans 2010, 2011; Evans et al. 2010); b) recently developed controlled or hummocky moraine (e.g. Krüger & Kjær 2000; Kjær & Krüger 2001; Evans et al. 2006a); c) the products of incremental stagnation (Eyles 1979; Spedding & Evans 2002; Bennett & Evans 2012); or d) former surge lobes (e.g. Evans & Rea 2003; Evans et al. 2006b, 2007, 2009a; Schomacker & Kjær 2007; Kjær et al. 2008). Although areas of ice-cored moraine can be specifically related to these processes, the Klofajökull lobate moraine assemblage potentially accumulated as a result of more than one of them since the Little Ice Age maximum.

ii) Till and moraines (and overridden moraines)

This map unit is characterized by fluted, subglacial deforming layer till and recessional push and lateral moraines that are unlikely to contain ice cores and date to the Little Ice Age or younger, as determined by Gudmundsson (1998). The well-developed flutings indicate that large areas of the icefield bed were temperate and hence deformation was in operation at the time of fluting construction (Benn 1994). The flutings extend to Little Ice Age maximum ice-cored moraine ridge complexes, a landform assemblage that has been reported from forelands around other Icelandic plateau icefields and interpreted as the signature of former polythermal glacier margins (Evans 2010, 2011; Evans et al. 2010). This interpretation explains the derivation of significant volumes of supraglacial debris (controlled moraine) at the margins of plateau icefields, which in the absence of extraglacial debris sources (nunataks) can only have been derived from basal freeze-on in areas down-ice of the subglacially deforming zone of the bed (see Dyke & Evans 2003; Glasser & Hambrey 2003; Evans 2009 for a full discussion of this process-form regime). Small areas of the fluted foreland on the west summit (Fig. 4c) are characterized by arcuate, low amplitude ridges, which are interpreted as overridden moraines that likely date to pre-Little Ice Age ice margins overrun during the Little Ice Age advance (cf. Evans et al. 1999, 2009b; Evans & Twigg 2002; Kruger 1994; Evans & Orton 2014). Together the extent of the "ice-cored hummocky terrain" and the "till and moraines" map units demarcate the former footprint and margins of the Little Ice Age maximum plateau icefield, which like the present day ice cover, was strongly asymmetrical, with more extensive ice descending from the northwest corner of the plateau.

iii) Glacifluvial deposits

Sands and gravels deposited by glacifluvial processes are contained predominantly within steep fans which fill the deep gorges and valleys dissecting the plateau edge and spread out over the surrounding lowlands and over the margins of the Holocene lava fields of Hallmundarhraun, as typified by Jökulkrokur in the southeast. The coalescent fans that emanate from the outermost ridges of the Klofajokull lobate moraine assemblage (Figs. 2, 5a) constitute ice-contact fans or ramps that were fed directly by the debris-covered glacier when it stood at the Little Ice Age maximum. This map unit also includes debris flow-fed alluvial fans/aprons previously activated by glacial meltwater (Fig. 6). Additionally, narrow ribbons of glacifluvial outwash occupy channels incised into the fluted tills and moraines and older tills and residuum of the plateau summit, best exemplified around Stallurinn (Fig. 4c). One esker ridge has also been identified within the LIA foreland on the western plateau surface.

iv) Paraglacial deposits

Paraglacial deposits are widespread on the steep slopes of the plateau, where large volumes of frost-shattered debris, derived from the highly frost-susceptible bedrock, have accumulated in scree slopes since ice recession. These slopes are also locally blanketed with re-worked glacial sediments temporarily stored in debris flow fans (Figs. 1 and 6). This mapping unit also includes small bedrock exposures too restricted in area to be mapped at this scale.

v) Residuum and weathered pre-Little Ice Age till

Weathered bedrock (residuum) and older till surfaces are most extensive on the western plateau summit. This is a consequence of the asymmetrical coverage of the Little Ice Age plateau icefield. Evidence of older glacier margins are represented by discontinuous meltwater channels and shallow, water-filled depressions or kettle holes amongst very subdued hummocks, that together may represent highly degraded ice-cored moraine belts (Fig. 4 black arrow on main photograph). Some meltwater channels have also been cut through the residuum and weathered till by proglacial streams emanating from the Little Ice Age maximum moraine limit.

vi) Bedrock

Bedrock exposures are extensive around the plateau margins, where they form precipitous cliffs and gorges (Figs. 1 & 6), but also include the early historical lava fields typified by Hallmundarhraun to the north. Small patches of residuum and thin till, too small in area to map at this scale, may also occur in this map unit.

vii) Alluvium and lake sediments (and ephemeral lakes)

Very small areas of the map are characterized by the alluvial deposits of lowland streams that locally drain the lava fields. Areas of thin lake sediments relate to ephemeral lake bodies dammed between the lower ends of glacifluvial and debris flow fed fans and lava fields.

The plateau icefield landsystem at Eiríksjökull

The Eiriksokull landsystem contains elements that are common to other plateau icefield settings in Iceland, particularly: a) the polythermal signature of fluted till lying up flow from ice-cored/controlled moraine belts; b) the occurrence of relatively more substantial morainic topography in the outlet valleys around the plateau margins, reflecting greater debris provision from both subglacial erosion and extraglacial sources (e.g. rock slope failure) once ice descends through the dissected terrain; c) the accumulation of substantial and expansive glacifluvial outwash fans on the lower plateau slopes and surrounding lowlands.

Significantly different from the plateau icefield style of glacierization, previously based on nearby Þorisjökull by Evans et al. (2006a), is the remarkable development of the Klofajökull debris-covered snout/ice-cored moraine complex. This lobate assemblage represents significant volumes of supraglacial and englacial debris provision to the ablation zone, with local relief exceeding 60 m in areas of most advanced ice melt-out, and very clear development of multiple breach-lobes (*sensu* Deline 1999a, b; Benn et al. 2003). Breach lobes occur where debris-mantled glacier ice, hemmed in by its own substantial lateral moraines, creates a small breach in the lateral ridge during a period of advance and develops a small lobate extension which deposits a subsidiary inset sequence of latero-frontal moraine arcs. Unlike previously reported examples of multiple breach lobes which are developed in dynamic alpine settings (Deline 1999a, b; Kirkbride 2000; Shroder et al. 2000), the Klofajökull moraines are a product of very short glacier travel distances from a flat (tuya) plateau surface and therefore document very high rates of debris transport from the 1 km long bedrock trench that has been excavated by ice in the plateau edge. It has previously been reported that these settings are likely to be favourable for enhanced glacial erosion due to the strain and frictional heating induced by accelerated glacier flow in response to the steepened topography; once excavated the trough walls will also deliver significant volumes of extraglacial debris to the glacier surface by rock slope failure. Additionally, Klofajökull has until recently descended steeply over a bedrock step at around 900 m asl., thereby undergoing heavy transverse crevassing and producing reconstituted ice banding (ogives) beneath an icefall (e.g. Goodsell et al. 2002, 2005). This process has previously been highlighted as an effective way of increasing englacial debris-rich folia and delivering substantial supraglacial debris concentrations or controlled moraine on Icelandic glacier snouts (Spedding & Evans 2002; Swift et al. 2006; Bennett & Evans 2012). The input of debris both from extraglacial (rock slope failure) and subglacial sources has clearly been very effective as a supraglacial melt-out deposit, protecting the lower snout of Klofajökull from the high rates of ablation that it would normally experience at the lower elevations attained by its short but steep descent from the precipitous cliffs of the plateau. Hence the buried snout is a prime location for laterally compressed incremental stagnation (*sensu* Eyles 1979).

The Klofajökull moraines are thereby a more extreme example of the depositional zone that characterizes the valleys surrounding the more sediment starved plateau icefield dispersal centres (Rea et al. 1998; Evans et al. 2002; Rea & Evans 2003, 2007). This is an illustration of a glacier that exists below the ELA due to icefall delivery directly to substantially lower terrain and hence there is no gradual elevation change in snout position in response to a rising ELA until it rises above the altitude of the cliff top; the ablation zone is essentially foreshortened. In 2011 the bedrock step beneath the icefall had been exposed by ice thinning and hence the lobate moraine complex is now isolated from the accumulation zone and will no longer receive mass from the outlet glacier. This will likely bring to an end the process of incremental stagnation (*sensu* Eyles 1979) at the downwasting snout of Klofajökull and initiate a period of pure stagnation (cf. Hoppe 1952; Benn 1992).

Conclusions

A 1:9,500 scale map of the Eiríksjökull plateau icefield and its post Little Ice Age foreland geomorphology and surficial geology, provides an excellent modern exemplar of an asymmetrically developed mountain glacier typical of the style of glacierization that dominated during mid-latitude Quaternary cold stages. Diagnostic glacial landforms and sediments include:

a) ice-cored hummocky terrain, largely comprising multiple ridge complexes indicative of controlled moraine construction in polythermal snouts, but also including the Klofajökull lobate moraine assemblage and its breach lobes and rock glacierized masses, which are indicative of a debris-charged glacier snout. The ice-cored terrain has also been subject to glacier marginal pushing in many locations through a process known as incremental stagnation.

b) till and moraines, comprising fluted, subglacial deforming layer till and non-ice-cored recessional push and lateral moraines, as well as small areas of overridden moraines. Flutings are indicative of temperate basal ice conditions and their termination at Little Ice Age ice-cored moraine ridge complexes is diagnostic of former polythermal glacier margins.

c) glacifluvial and debris flow deposits largely arranged in steep fans that emanate from the deep gorges and valleys dissecting the plateau edge and spread out over the surrounding lowlands. Similar deposits occur also in ice-contact fans or ramps that were fed directly by the debris-covered Klofajokull snout at its the Little Ice Age maximum.

Although the plateau icefield landsystem at Eiríksjökull is similar to those previously reported from Iceland, the remarkable Klofajökull debris-covered snout/ice-cored moraine complex is a more extreme example of the depositional zone that characterizes the valleys surrounding the more sediment starved plateau ice dispersal centres.

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Figure captions

Figure 1: Aerial view from the south of Eiriksjokull, showing its location on a prominent table mountain or tuya, that rises steeply to 1600 m from the surrounding terrain at 600 m asl. Photograph by Loftmyndir ehf. The width of the tuya summit in this view is approximately 5.3 km.

Figure 2: Digital elevation model (derived from Loftmyndir ehf 2008 aerial photography) of the Eiríksjökull tuya and plateau icefield viewed from the northeast and showing the asymmetrical extent of the ice, particularly the Klofajökull outlet lobe and its ice-cored lobate moraine complex. The width of the main trunk of Klofajökull in this view is 500 m.

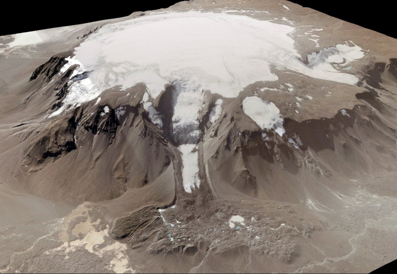
Figure 3: Aerial photograph extract (Landmælingar Islands 1995) of the Þorvaldsjökull outlet glacier snout and the foreland, showing areas of latero-frontal moraine with frontal ramps at, and

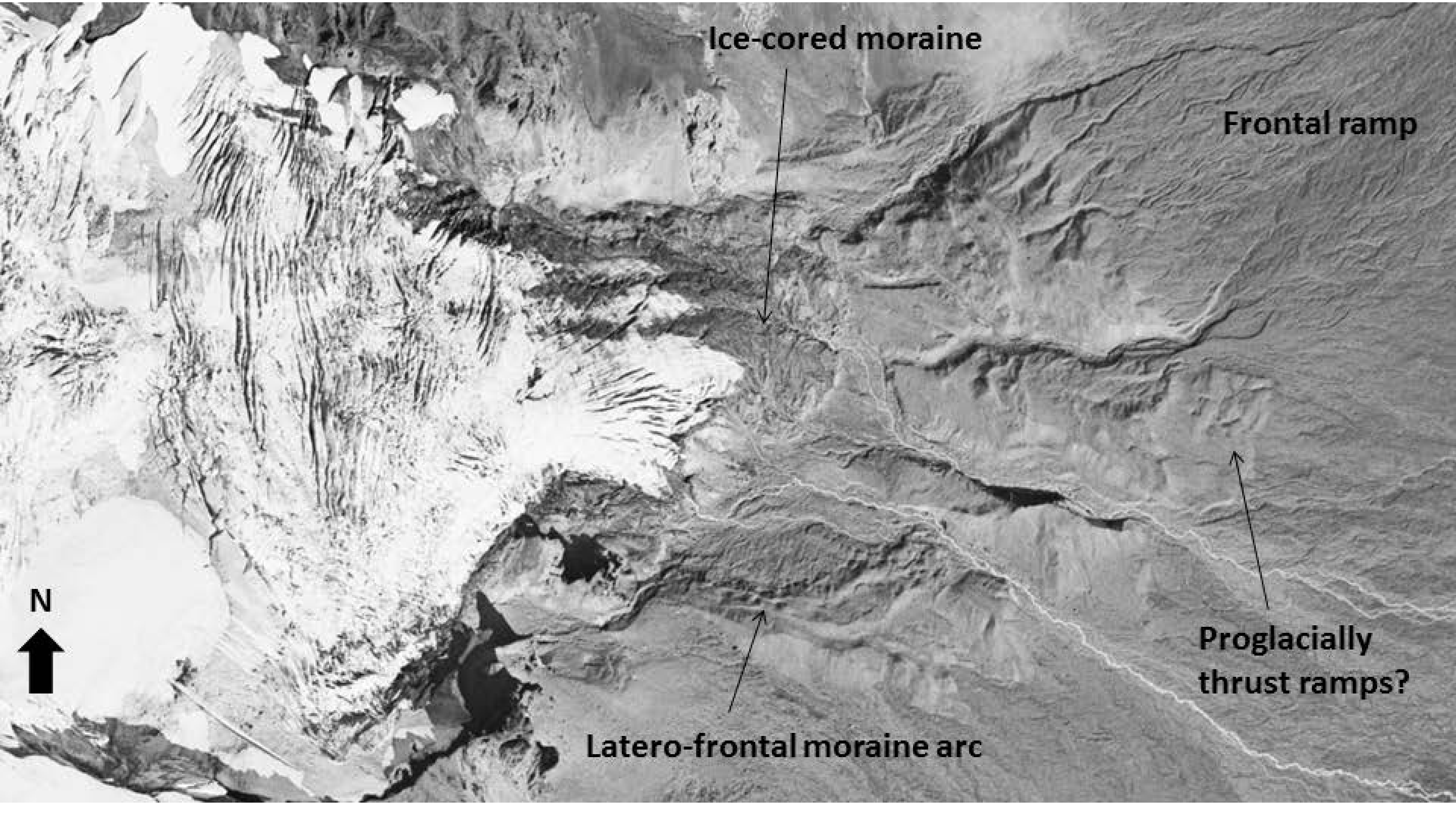
immediately inside, the Little Ice Age limit and ice-cored moraine around the ice margin. Note that many frontal moraine ridges appear to be constructed on the frontal ramps and hence may relate to proglacial thrusting of the ramps by glacier ice.

Figure 4: Aerial photograph extract (Landmælingar Islands 1995)showing details of the glacial landforms on the west plateau summit: a) closely-spaced and partially overprinted moraines, likely ice-cored and therefore being at least partially constructed as controlled moraine, on the south glacier margin; b) similar closely-spaced moraines, likely ice-cored, controlled moraine, with incised, snow-filled meltwater channels on the north glacier margin. Note the emergence of fresh controlled ridges on the glacier surface; c) flutings and overridden moraine (white arrows) lying inside d) the ice-cored hummocky moraine arc. The black arrow on the main photograph shows the location of the subdued hummocks and meltwater channels of an older glacier advance. The ground distance shown in the main photograph is 2.3 km from south to north.

Figure 5: The Klofajökull ice-cored moraine complex: a) aerial photograph extract (Landmælingar Islands 1995) showing the contrast between the largely hummocky and extensively pitted surface of the central area of the complex and the more linear ridges, related to pushing of ice-cored moraine by the debris-covered snout, around its margins. Also well illustrated are the ice-contact fans/ramps that have prograded from the outermost ridges. Rock glacierization is most obvious in the breach lobes on the eastern margin of the complex; b) ground view of the high relief hummocky moraine and extensive kettle holes and lakes on the western margin of the complex, with the large lateral moraines and icefall in the distance. Note that the icefall has receded above the altitude of the bedrock step in this 2011 view and hence the ice-cored lobate complex is now separated from the plateau ice.

Figure 6: Aerial photograph extract (Landmælingar Islands 1995) of the southeast plateau margin and the small, heavily crevassed outlet glaciers that have delivered large volumes of glacifluvial sediment and debris flow material into the bedrock gulleys and onto the coalescent fans that comprise Jökulkrokur. Debris flow-fed fans are indicated by white arrows.




Ice-cored moraine
Frontal ramp
Proglacially
thrust ramps?
Latero-frontal moraine arc
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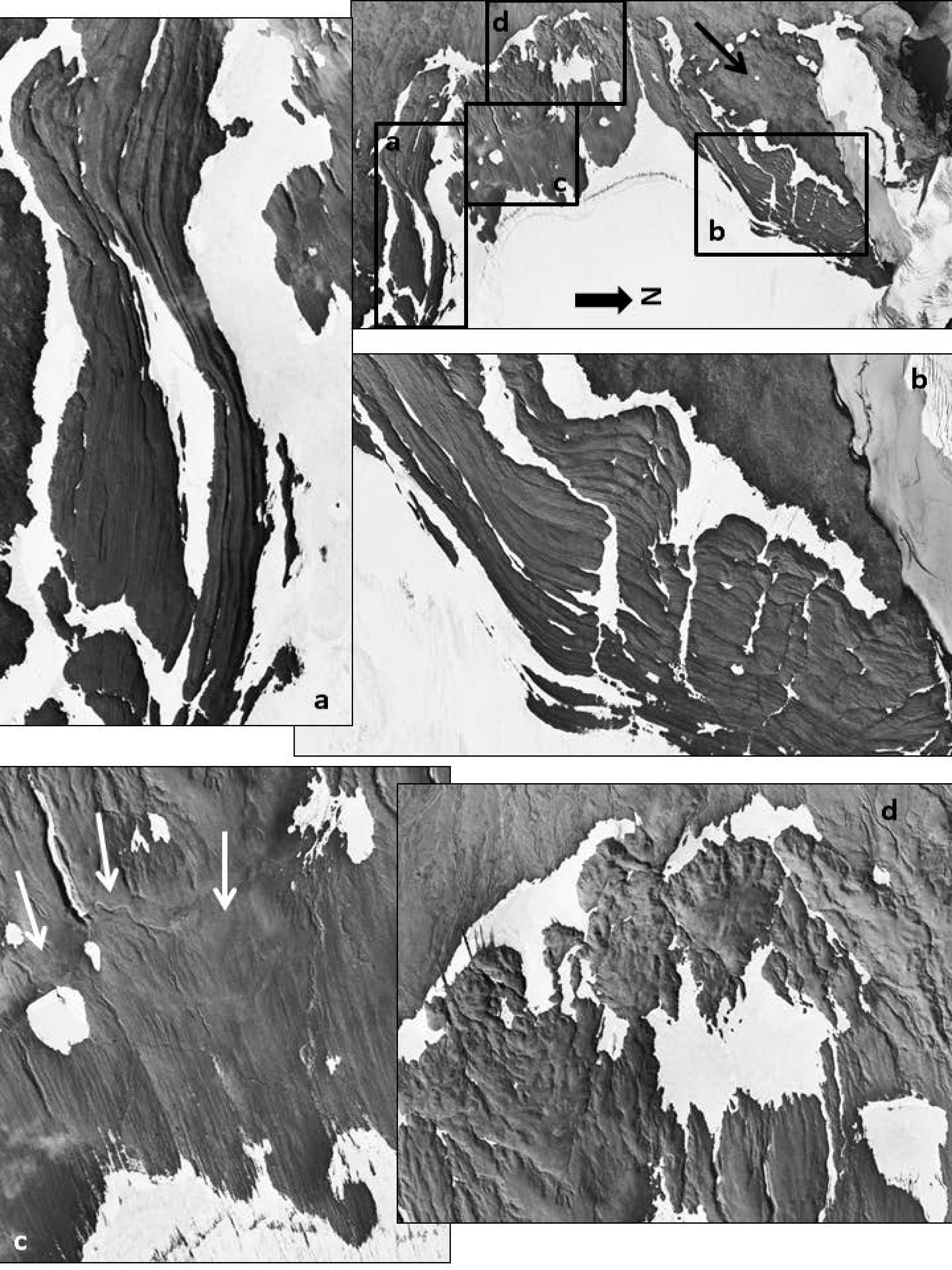
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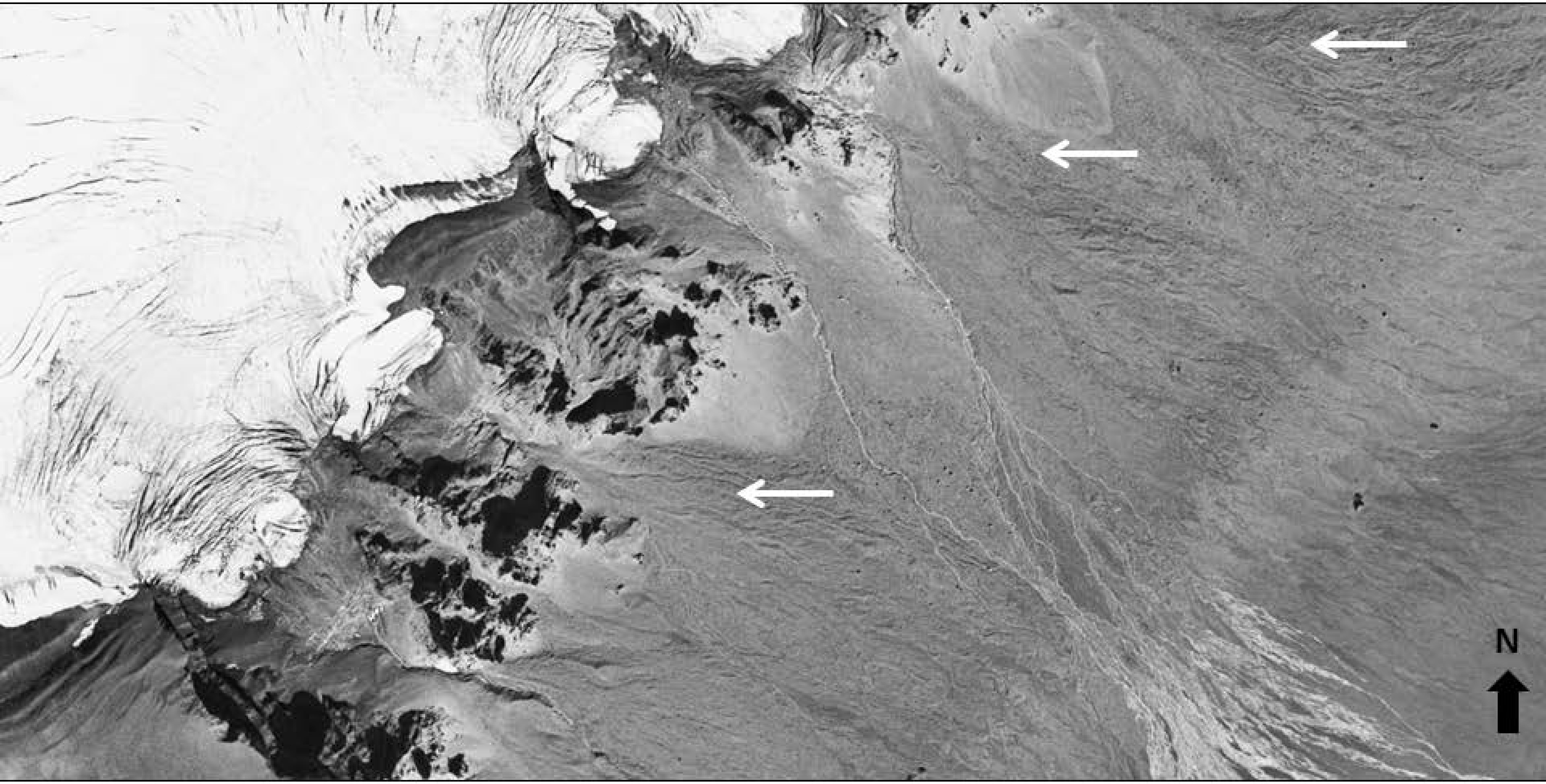
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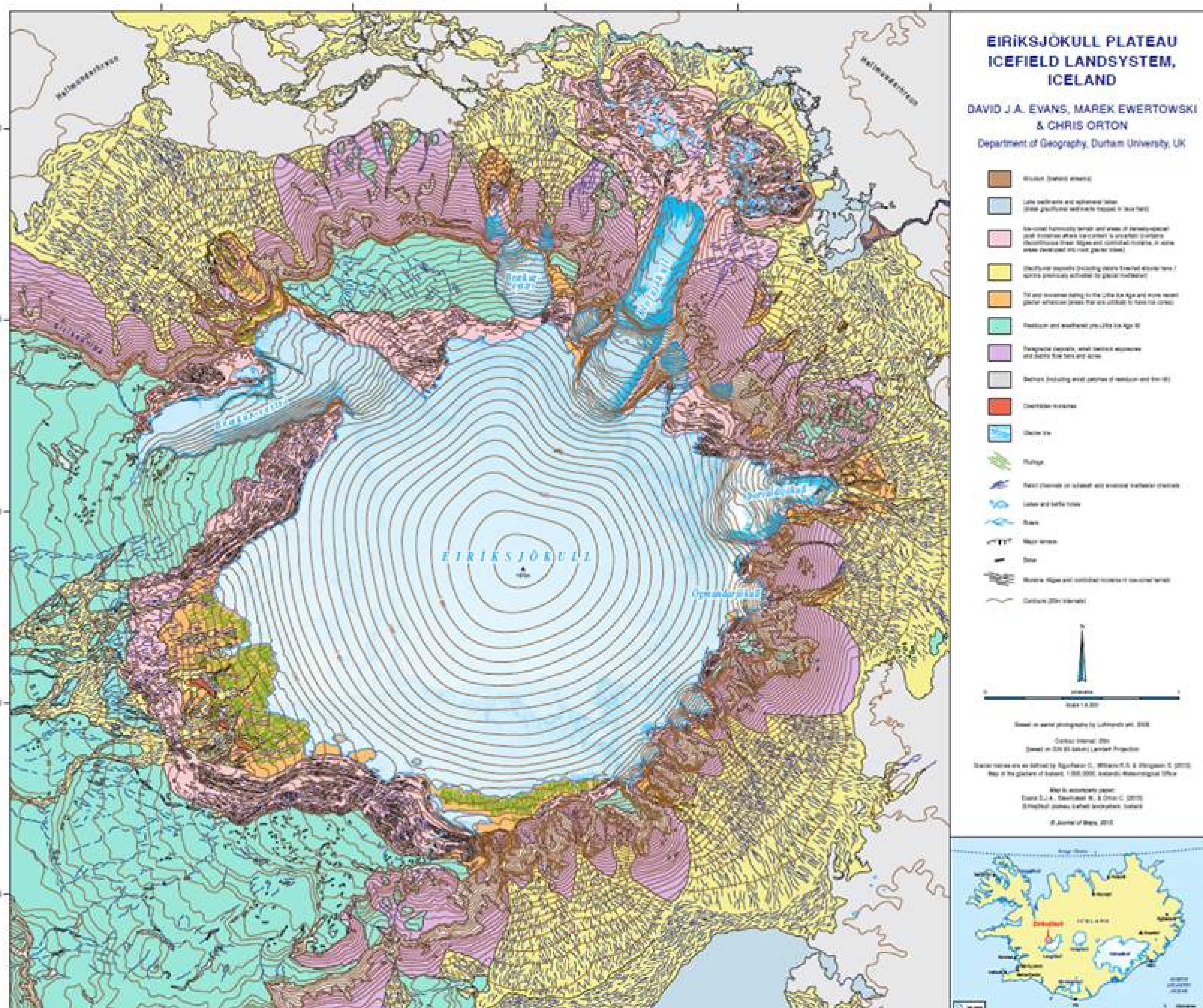
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