ICE, ICE, CHEMICAL ALTERATION: USING PLANETARY ANALOGS TO INFER ANCIENT GLACIAL THERMAL REGIMES, MINERALOGY, AND CLIMATE SIGNALS. A. R. Rutledge[1], K. A. Bennett[2], L. A. Edgar[2], C. E. Edwards[1], H. A. Eifert[1], T. L. Hamilton[3], B. H. N. Horgan[4], N. A. Jones[1], E. B. Rampe[5], M. R. Salvatore[1], [1]Northern Arizona University (alicia.rutledge@nau.edu), [2]USGS Astrogeology Science Center, [3]University of Minnesota, [4]Purdue University, [5]NASA Johnson Space Center.

Introduction: The surface of Mars exhibits strong geomorphic evidence for past and recent glacial and periglacial processes, but the history of the cryosphere on Mars remains poorly understood. The majority of glaciers and ice sheets on Mars are predicted to have experienced little melt at their base [*e.g.,* 1, 2], and because melt is a major driver of erosion and transport in a glacier, these cold-based glaciers may not have left behind clear physical signs in the geologic record. Thus, while abundant evidence exists for at least transient warmer and wetter conditions on ancient Mars, we lack a clear record of the duration and extent of ice-dominated climates. However, there is also some evidence on Mars' surface for temperate, or warm-based, glaciation such as putative moraines, striations, bedrock channels, fans, and eskers [*e.g.,* 3, 4]. Warm-based glacial erosion and transport is primarily driven by meltwater and can radically physically alter the underlying landscape, as well as chemically weather the underlying bedrock. An alternative signature of past glaciation on Mars may be the geochemical record, due to alteration by interactions with cold- and warm-based glaciers. However, the mineralogy of glacial alteration products on mafic bedrock under a range of glacier thermal regimes is poorly constrained. Planetary analog studies can allow us to better constrain the alteration products that result from cold-based vs. warm-based glaciation on Mars-like substrates by leveraging the natural laboratories available to us in the field.

Cold-based vs. Warm-based Glaciation: Glaciers are classified primarily according to their temperature regime [5]. A temperate (or warm-based) is at the melting point throughout, so liquid water coexists with glacier ice, while a cold-based (or polar) glacier has basal layers of ice below the pressure melting point, so it is frozen to its bed. **Temperate glaciers** are more often found at lower latitudes and experience basal sliding due to the presence of water as a lubricant at their beds, which causes more physical erosion than cold-based glaciers. **Cold-based glaciers** are more often found in the polar regions or at high elevations and tend to move via internal deformation as there is little water present to aid in basal sliding.

Chemical Alteration in Warm-Based Glaciers. In addition to physical weathering resulting in characteristic landforms, chemical alteration also takes place in warm-based systems. In temperate subglacial environments, the presence of fine-grained sediments in glacial flour due to glacial grinding promotes significant chemical weathering [*e.g.,* 6, 7]. The low temperatures, anoxic conditions, and lack of light in warm-based alpine subglacial environments on mafic bedrock can promote unique weathering pathways that can produce secondary minerals such as silica coatings and poorly crystalline silica-rich phases [8-10]. At a warm-based ice sheet with a partially mafic substrate, kaolinite has been observed to form [11]. However, these weathering processes on Mars-relevant mafic substrates remain understudied [*e.g.,* 12].

Chemical Alteration in Cold-Based Glaciers. Until recently, cold-based glaciers were thought to do little physical erosion or chemical weathering [7, 13], but this is being challenged by observations of marginal ice processes such as melt induced by solar irradiation and geothermal flux at some cold-based glaciers [14, 15].

Low water-rock ratios in alpine soils favor the formation of poorly crystalline phases like allophane [*e.g.,* 16, 17] and a recent study of a cold-based ice sheet with a mafic substrate found amorphous alteration products [18]. Additionally, sulfates and Fe-oxides are hypothesized to be byproducts of cold-based subglacial sulfide oxidation [*e.g.,* 19, 20].

Mt. Kilimanjaro Summit Glaciers (Cold-Based): The Kilimanjaro massif is a stratovolcano at the Tanzanian-Kenyan border (Figure 1; 3°4'S, 37°21'E). Glaciers on the summit of Kilimanjaro have thinned and retreated dramatically over the past century, making recently deglaciated sediments readily available [*e.g.,* 21]. The summit volcanic bedrock is primarily phonolitic, a highly mafic rock similar to martian bedrock compositions [22]. At this location, any subglacial water will be formed either through (1) ice surface melting and subsequent percolation to and interaction with the bed, or (2) subglacial melting due to geothermal heat. However, in contrast to temperate glaciers, this melt is likely transient and may not be sufficient in volume to flush dissolved species from the system. Thus, evaporation may compete with or dominate over pressure melting and re-freezing to cause mineral precipitation in cold-based glaciers. We hypothesize that subglacial salts, oxides, and poorly crystalline phases could form under or proximal to these cold-based glaciers. A multispectral remote sensing mapping campaign is underway, and initial analyses have identified spectral signatures consistent with silica-rich alteration products proximal to the summit glaciers [23]. A field campaign in September 2022 will sample rocks, sediment, and water for analyses and to ground-truth the remote sensing study.

South Iceland Outlet Glacier (Warm-Based): Breiðamerkurjökull is a large (~13.5 km wide) valley glacier draining the south side of the Vatnajökull ice cap in southeast Iceland (Figure 2). It has been in retreat for most of the 20th century [24]. The glacier, confined by primarily basaltic bedrock [25], has retreated approximately 5 km from its maximum extent in 1890, revealing an outwash plain with a complex glacial geomorphology [26]. This substrate, the sandur, consists of unlithified sediment including three depositional domains: (1) moraine ridges; (2) subglacial landforms such as flutes and drumlins, and (3) glaciofluvial landforms including outwash fans [*e.g.,* 27] and eskers [26]. Eskers are sinuous ridges comprised of glaciofluvial sediments deposited by meltwater flowing through tunnels at the bed of warm-based large glaciers and ice sheets, most commonly overlying crystalline bedrock [*e.g.,* 28, 29]. They provide direct evidence of basal melting of ice and preserve glaciofluvial sediments.

We hypothesize that a variety of warm-based glacial alteration minerals and amorphous materials may be forming in a glaciofluvial, mafic-substrate environment, and that these materials will be preserved at distinct strata within and on eskers and fans depending on local depositional environment. We hypothesize that esker and fan morphology at our field site will be consistent with previously mapped terrestrial proglacial features. A remote sensing survey is underway to characterize the mineralogy at this site. Field work is planned for Summer 2022 and 2023 to sample rocks and sediments and conduct sedimentological, compositional, and geomorphic analyses of eskers and fans in order to compare them to similar features (*e.g.,* sinuous ridges, fans) on Mars. Studying these features as a system will better constrain the effects of a large, warm-based ice sheet outlet glacier on mafic bedrock and define criteria for glaciofluvial feature identification on Mars.

Conclusions: These two new analog studies will allow us to better understand and interpret alteration mineral assemblages on the surface of Mars, whether they are characteristic of an icy climate, and how they can be used to define the thermal regime of ancient ice sheets and glaciers, helping to constrain the climates in which the glaciers formed.

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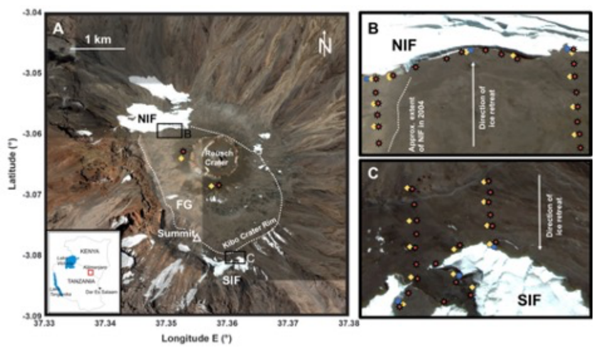

Figure 1. *(A) Kibo summit, modified from Mckenzie et al. (2010) and Pepin et al. (2014) (Google Earth/QuickBird imagery). NIF: Northern Ice Field; SIF: Southern Ice Field; FG: Furtwangler Glacier. Proposed sampling locations are marked. (B) Proposed sampling locations, NIF. (C) Proposed sampling locations, SIF. Yellow diamond: rock/sediment; blue circle: water; red sunburst: VNIR spectrum. White arrows highlight direction of glacial retreat.*

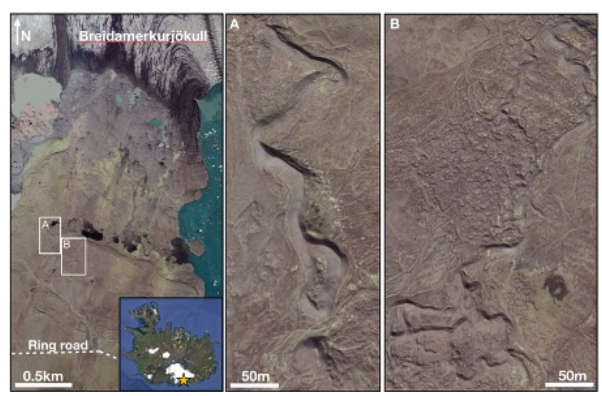

Figure 2. *Locations and overview of eskers in the outwash plain of Breiðamerkurjökull, Iceland (DigitalGlobe QuickBird, Google Earth 2020). Inset: Island of Iceland, study site at yellow star. A) Simple esker. B) Complex esker system.*