# Controls on andesitic glaciovolcanism at ice-capped volcanoes from field and experimental studies

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## ABSTRACT

Glaciovolcanic deposits at Tongariro and Ruapehu volcanoes, New Zealand, represent diverse styles of interaction between wet-based glaciers and andesitic lava. There are ice-confined lavas, and also hydroclastic breccia and subaqueous pyroclastic deposits that formed during effusive and explosive eruptions into meltwater beneath the glacier; they are rare among globally reported products of andesitic glaciovolcanism. The apparent lack of hydrovolcanically fragmented andesite at ice-capped volcanoes has been attributed to a lack of meltwater at the interaction sites, because either the thermal characteristics of andesite limit meltwater production, or meltwater drains out through leaky glaciers and down steep volcano slopes. We use published field evidence and novel, dynamic andesite-ice experiments to show that, in some cases, meltwater accumulates under glaciers on andesitic volcanoes, and that meltwater production rates increase as andesite pushes against an ice wall. We concur with models for eruptions beneath ice sheets that the glacial conditions and pre-eruption edifice morphology are more important controls on the style of glaciovolcanism and its products than magma composition and the thermal properties of magmas. Glaciovolcanic products can be useful proxies for paleoenvironment, and the range of andesitic products and the hydrological environments in which andesite erupts is greater than hitherto appreciated.

## INTRODUCTION

Currently, 254 Holocene volcanoes host glacial ice, 72% of which are arc volcanoes, and numerous high latitude and high altitude intermediate-composition (hereafter termed "andesitic") stratovolcanoes were glaciated during the Plio-Pleistocene (Edwards et al., 2020). Ice-confined lava is a well-documented product of andesitic glaciovolcanism, formed when a glacier physically confines lava to high interfluves; little to no hydrovolcanic fragmentation takes place (e.g., Lescinsky and Fink, 2000; Kelman et al., 2002; Conway et al., 2015). The rarity of reported andesitic glaciovolcanic clastic products (Kelman et al., 2002) has been taken to indicate that fragmentation is rare at glaciated arc volcanoes. Lower eruption temperatures have been suggested to reduce the rate of ice-melting for intermediate-silicic lavas compared with basalts, so that meltwater is driven out by by positive pressures in the englacial vault, impeding hydrovolcanic fragmentation (Höskuldsson and Sparks, 1997; Kelman et al., 2002; c.f. Stevenson et al., 2009). No observational or experimental data have been published, however, to support an entirely compositional control on a lava's ability to melt ice. Field observations and experiments with basaltic lava show that ice melting rates increase when flow or inflation rate is low, and that melting is faster when lava directly contacts ice, rather than snow or a carapace of breccia (Edwards et al., 2013, 2015). The only experiments to date with broadly andesitic melts show heat fluxes similar to basalts (Oddsson et al., 2016b). Low calculated heat fluxes and a lack of subaqueous deposits at the Table, an andesitic lava-dominated tuya in British Columbia, were explained by low effusion rates, a carapace of insulating breccia and meltwater drainage on steep slopes (Wilson et al., 2019). In addition, the range of clastic and coherent glaciovolcanic products from basaltic and rhyolitic volcanoes indicates production of varied volumes of meltwater by both magma types (e.g., Smellie and Skilling, 1994; Stevenson et al., 2006; Tuffen et al., 2008; McGarvie, 2009; Smellie, 2018). The apparent lack of hydroclastic rocks at many andesitic edifices arguably results from poor meltwater retention at arc volcanoes, due to steep terrain, and thin, permeable glaciers (Lescinsky and Fink, 2000; Stevenson et al., 2009). There are far fewer published studies of andesitic glaciovolcanism than for basalt and rhyolite. Also, volcaniclastic products from explosive eruptions that land on snow or ice of a cone's slopes are not preserved on the edifice, leading to a preservation and publication bias towards ice-confined lavas (Kelman et al., 2002).

We identify distinct styles of glaciovolcanism at andesitic volcanoes capped by wet-based glaciers using evidence published from Tongariro and Ruapehu volcanoes, New Zealand (Conway et al., 2015, 2016; Cole et al., 2018, 2020). The examples given represent styles of glaciovolcanism that may have occurred at many ice-capped andesitic edifices worldwide, and there is also overlap with volcano-ice interactions under large ice sheets (e.g., Stevenson et al., 2009).

New molten andesite-ice deformation experiments, building on static experiments by Oddsson et al. (2016b), tested rates of heat flux and meltwater production during dynamic lava-ice interaction. Active pushing of lava against ice has not been considered before, but it probably occurs in most natural lavas as they flow or inflate against an ice barrier or roof. Our results suggest this dynamic influence on the heat transfer is significant. Understanding the thermodynamics of intermediate-composition lava-ice interaction is important for assessing emplacement of glaciovolcanic products, and for forecasting whether meltwater may cause flooding and/or influence explosive activity (Major and Newhall, 1989; Lescinsky and Fink, 2000).

## STYLES OF ANDESITIC GLACIOVOLCANISM

Three types of glaciovolcanic product are preserved on Tongariro and Ruapehu (Fig 1; Conway et al., 2015; Townsend et al., 2017; Cole et al., 2018, 2020), recording diverse glaciovolcanic styles from magmas of similar composition. Approximately 90% of analysed lavas from Ruapehu are basaltic-andesite or andesite (Price et al., 2012; Conway et al., 2016), and 77% of visible, edifice-forming units at Tongariro are andesite, while 23% are basaltic-andesite (Pure et al., 2020). Temperatures of most historic eruptions at Ruapehu have been estimated at 950 to 1050 °C (Kilgour et al., 2013). Russell et al. (2014) defined 9 types of tuya based on eruption style and glacio-hydrological conditions, all independent of magma composition. On a smaller scale, we suggest that different glacio-hydrological conditions on an ice-capped volcano can yield at least three distinct glaciovolcanic products from three pairings of eruptive style with environmental conditions (Fig. 2):

1) ***Effusive and subaqueous.*** Effusive eruptions into ponded water lead to non-explosive, quench fragmentation forming massive hyalo-/hydroclastic breccias (Fig. 1 A and B; Cole et al., 2020). Meltwater accumulation has led to similar deposits at volcanoes in large ice sheets across the range of magma compositions (e.g., Smellie and Skilling, 1994; McGarvie et al., 2007; Stevenson et al., 2009). In glacial periods, multi-vent composite volcanoes have supported glaciers a few hundred metres thick within valleys, or on an irregular summit topography (Eaves et al., 2016; Cole et al., 2018, 2020). Thick ice combined with confining topography enables meltwater to pond locally even at generally steep-sided volcanoes, influencing glaciovolcanic interaction (Fig. 2).

2) ***Explosive and subaqueous.*** Deposits of aqueous pyroclastic currents formed from explosive eruptions into meltwater (Figs. 1C, D and 2). They were emplaced either by meltwater draining through a subglacial channel, or by currents moving through accumulated water, such as an englacial lake; deposition from eruption-fed currents in either setting produces similar features, but with different implications for glacial hydrology (Smellie and Skilling, 1994; White, 2000). Based on the surrounding topography at Tongariro, the deposits are inferred to have been emplaced in meltwater channels along an ice-capped ridgeline (ice ≤ 150 m thick; Fig. 2; Cole et al., 2018). Comparable deposits formed in Iceland where ice > 550 m thick is inferred to have overwhelmed topography (Stevenson et al., 2009).

3) ***Effusive and ice-confined.*** Ridge-capping lava flows formed from effusive eruptions, but represent a different style of glaciovolcanism to hydroclastic breccia. Their over-thickened forms and the orientation of marginal cooling joints indicate that lava was physically confined by the glacier

(Fig. 1 E and F). Meltwater is produced and contributes to cooling and fracturing in these settings, but the lavas are not emplaced in ponded water. At Tongariro and Ruapehu (Conway et al., 2015; Cole et al., 2018), and other stratovolcanoes globally (Lescinsky and Sisson, 1998; Lescinsky and Fink, 2000), ice-confined lavas are perched at high elevations on steep terrain. They erupted alongside thin, fractured alpine glaciers that allowed meltwater to drain freely from the site of interaction. In ice sheets, lava-dominated products cap edifices that became emergent, or form entire edifices where glacial conditions permit efficient drainage (Smellie and Skilling, 1994; Tuffen et al., 2002; Stevenson et al., 2006; Russell et al., 2014; Wilson et al., 2019).

The distinct deposit types (1-3) represent andesitic lava-ice interaction under different hydrological conditions on ice-capped volcanoes, but there is considerable overlap with products at basaltic and rhyolitic edifices, and also beneath thick ice sheets (Smellie and Skilling, 1994; Stevenson et al., 2006, 2009; Tuffen et al., 2008; McGarvie, 2009; Russell et al., 2014; Smellie, 2018). We concur that glaciovolcanic interaction at ice-capped volcanoes is controlled by meltwater availability and glacial hydrology, as functions of the glacier characteristics and edifice morphology (Fig. 2).

## MOLTEN ANDESITE-ICE DEFORMATION EXPERIMENTS

We conducted novel experiments to investigate how much meltwater can be produced when andesitic lava flows against a glacier. We selected < 5 kyr lava (Conway et al., 2016; Townsend et al., 2017) in Ruapehu's Whangaehu Valley for its apparent freshness. X-Ray Fluorescence analysis (University of Waikato) confirms an andesitic composition (60 wt% $SiO_2$ and 5.1 wt% $Na_2O+K_2O$ with LOI at -0.15; full major element data in Data Repository). For each experiment, we melted 60-100 g of granulated andesite in a crucible at 1250 °C using an induction furnace. The experimental melt temperature higher than that of erupting andesite ($T \approx 1000$ °C; (Harris and Rowland, 2015)) counterbalances the loss of viscosity-reducing volatiles by outgassing during emplacement of the natural lava (Zimanowski et al., 1991). This overheating precludes direct comparison of ice-melt rates with those during emplacement of natural andesite, but it allowed the andesite to be deformed against ice, which is the focus of these experiments. Despite the high melt temperature, the andesite was much more viscous than remelted basalt. A squeeze apparatus was designed comprising two wooden paddles attached to scissored arms. The andesite melt was pressed against an ice block frozen to one of the paddles, and pressure sensors attached to the arms of the apparatus recorded the pressure applied during deformation (Fig. 3A). A calorimeter beneath collected meltwater. Water mass and temperature were measured during the experiments. Two additional experimental runs were performed with andesite melt placed on top of an ice block, one resting under gravity only, and the other being pushed into the ice (Fig. 3B). For these runs, only the mass of the meltwater was measured.

The molten andesite was easily squeezed against the ice block, melting a cavity in the ice that was only slightly wider than the andesite and of comparable shape. A widening glassy crust progressed across the melt sample from the margin in direct contact with the ice, while meltwater drained down from the andesite-ice interface. During the runs in which the molten andesite was placed on top of an ice block, a cavity formed beneath the andesite and partially filled with meltwater. The meltwater formed a channel that breached the edge of the ice block seconds after the start of the experiment and ran down the side, carving a vertical chute. Some meltwater refroze to the ice before reaching the calorimeter, but the majority was collected. Details of experimental procedure and heat flux calculations are in the Data Repository.

The overall heat fluxes from each experiment were between 186 and 250 kW $m^{-2}$, consistent with published observational and experimental values obtained for andesitic lava from Eyjafjallajökull, Iceland (Oddsson et al., 2016a, 2016b) and basaltic lava effusions (Allen, 1980; Höskuldsson and Sparks, 1997; Edwards et al., 2013). The fluxes are much lower than the 500-600 kW $m^{-2}$ estimated during the 1996 Gjálp eruption (Gudmundsson, 2003), and an order of magnitude lower than the 1-4 MW $m^{-2}$ estimated from ice melting during the explosive phase of the 2010 Eyjafjallajökull eruption (Magnússon et al., 2012). This difference is expected because virtually no fragmentation took place during the experiments. Our calculated heat fluxes are higher than those calculated for the emplacement of the Table in British Columbia, where endogenous emplacement within an enclosing carapace of breccia is inferred to have insulated the hot interior from surrounding ice (Wilson et al., 2019). We note that unlike a natural lava flow, the volume of andesite in the experiments was small and not replenished by continued feeding from a vent. More fragmentation would be expected in a natural lava as it cools, forms a crust, and is fractured by quenching and dynamic stressing. Heat transfer and meltwater production would be prolonged by continued feeding. If issues associated with the high viscosity of remelted andesite can be overcome, large-scale experiments with greater volumes of melt that remain molten for longer (e.g., Edwards et al., 2013) to determine heat transfer while measuring flow or strain rate would provide results more easily scalable to natural lava emplacement in ice.

Our attempt to recreate the dynamic interaction between ice and deforming lava produced transient increases in heat flux of up to an order of magnitude, following increases in applied force, causing temporary rises in meltwater production (Fig. 3A). Compared with static molten andesite-ice interaction, meltwater was produced at a higher rate and in greater volume when the andesite melt was pressed into the ice (Fig. 3B). The increases in heat flux and meltwater production from deforming melt are inferred to result from advection of heat to the melt-ice interface, an increased interface area from lateral spreading of the deforming melt, and the formation of cracks in the solidifying andesite due to the applied force. The offset in time of a few seconds between increase in applied force and increase in meltwater production is expected due to the time taken for ice melting, the fall of the meltwater into the calorimeter and the delay in mass recording due to inertia of the balance. Overall results from additional experimental runs and the limitations of our experimental procedure, which could be developed further, are given in the Data Repository.

We find that meltwater production increases when lava flows, or inflates, against a glacier, as would occur during emplacement of ice-confined lava of any composition. An area where the deformation simulated in these experiments is likely to be most significant is at the flow front of a lava, where it presses against the glacier with the force of the remaining flow behind it. The effect on meltwater production from dynamic lava-ice interaction should be included in theoretical and experimental models to fully understand the ice-melting potential of different lavas. Lava flow rate, contact area and contact geometry with ice, and the rate and geometry of surface crust fracturing during flow or extrusion, as well as the ability of meltwater to drain away, are probably more important than magma composition in controlling glaciovolcanic interaction style and products.

## CONCLUSION

Andesite is able to generate enough meltwater during eruptions at ice-capped volcanoes to form subaqueous lithofacies. Further, heat transfer and meltwater production increase during dynamic interactions when lava flows or inflates against glacial ice. The dynamic effect should be considered in models for meltwater production from ice-confined lava, and large-scale experiments undertaken to better quantify this effect. The dominance of ice-confined lavas in known intermediate-composition glaciovolcanic sequences probably reflects preservation bias or meltwater drainage in leaky systems. Meltwater retention controlled by glacial hydrology plays a more significant role in volcano-ice interaction style than compositionally controlled differences in rates of meltwater production.

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## FIGURES AND CAPTIONS

**Figure 1:** Glaciovolcanic products preserved at Tongariro and Ruapehu volcanoes. Massive, hydroclastic breccia with quench fragmentation textures at Ruapehu (A) and Tongariro (B). C and D: a well-sorted, bedded subaqueous pyroclastic current deposit with traction structures. E and F: Ice-confined, subglacial lava flows inferred to have tunnelled through and cooled within Ruapehu valley glaciers, since retreated.

**Figure 2:** Schematic diagram showing the inferred glacial and edifice characteristics for each type of glaciovolcanic product preserved at Tongariro and Ruapehu pictured in Figure 1. 1: Fig. 1 E and F; Conway et al. (2015); 2: Fig. 1 C and D; Cole et al. (2018) 3: Fig. 1 A and B; Cole et al. (2020).

**Figure 3:** A and B: Dynamic experiment setup. (A) includes heat flux and meltwater production curves from one experiment shown in relation to applied force with time. Applied force is shown qualitatively in arbitrary units (a.u.). (B) shows meltwater accumulation during dynamic interaction compared to static.

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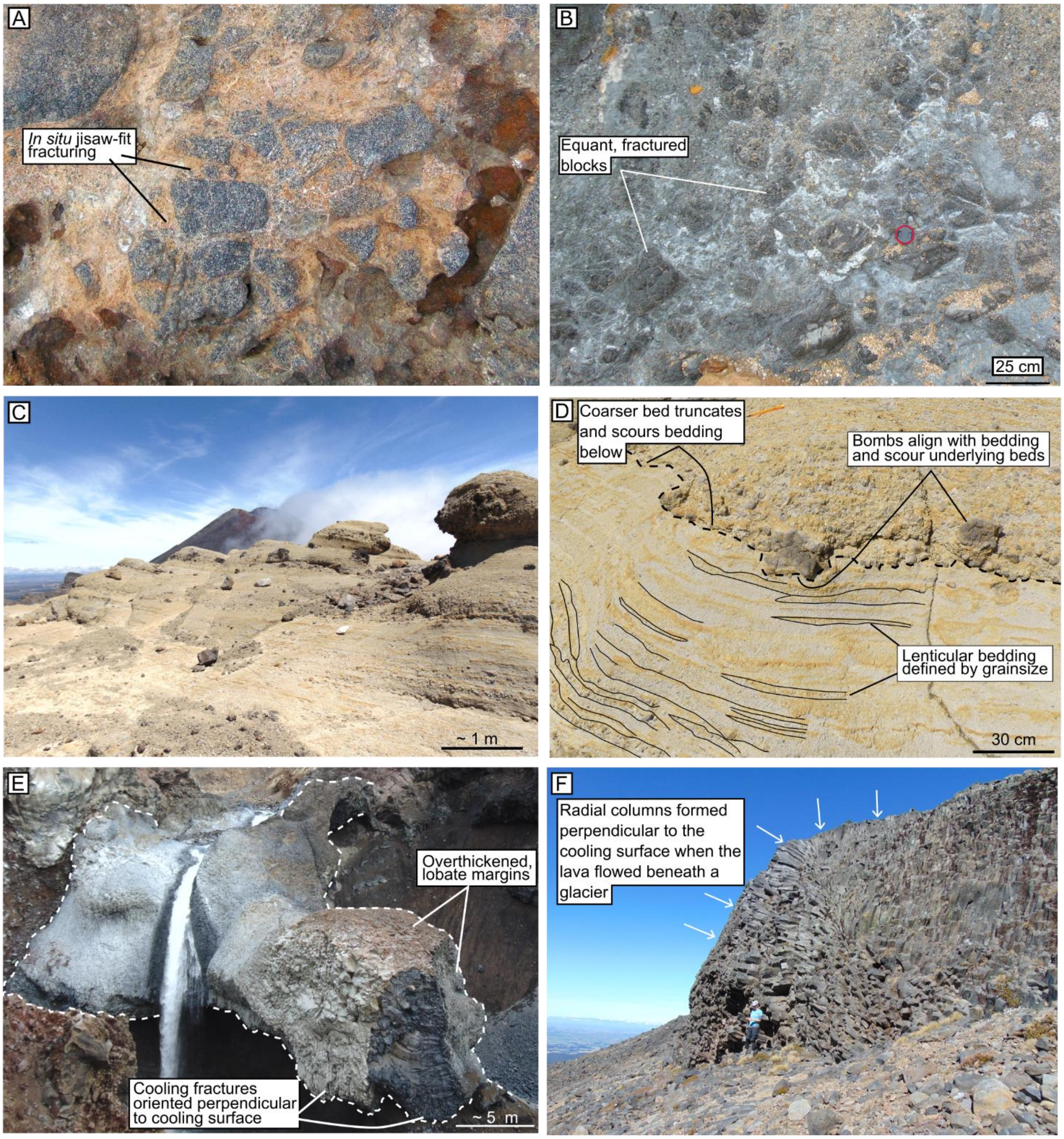
## FIGURES AND CAPTIONS

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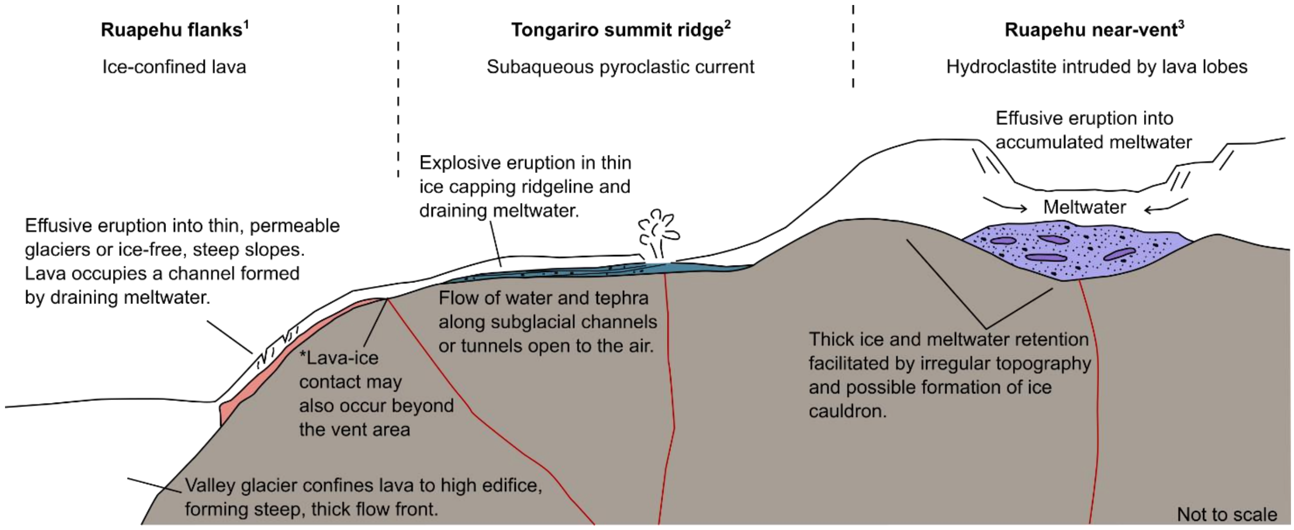


**Figure 2:** Schematic diagram showing the inferred glacial and edifice characteristics for each type of glaciovolcanic product preserved at Tongariro and Ruapehu pictured in Figure 1. 1: Fig. 1 E and F; Conway et al. (2015); 2: Fig. 1 C and D; Cole et al. (2018) 3: Fig. 1 A and B; Cole et al. (2020).

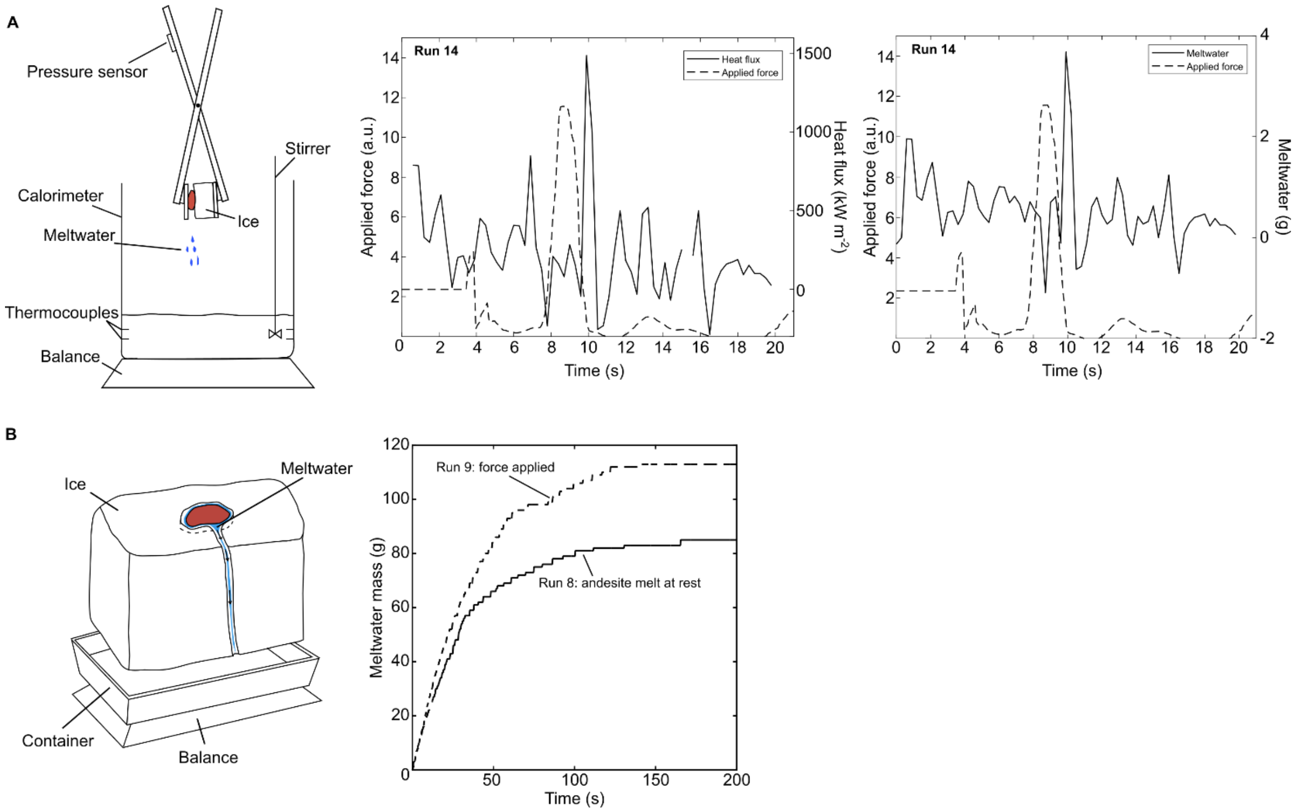


**Figure 3:** A and B: Experimental setup for the dynamic experiments. (A) includes heat flux and meltwater production curves from one experiment shown in relation to applied force with time. Applied force is shown qualitatively in arbitrary units (a.u.). (B) shows meltwater accumulation during dynamic interaction compared to static.