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Permafrost modelling of slopes affected by talus-sourced landslides in northern Iceland

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1. INTRODUCTION

In Iceland, permafrost thaw has been recently recognised as a new triggering factor for landslide occurrence, whose frequency has increased in the last decade. Many of these landslides share the common characteristic of being sourced from ice-cemented loose deposits. While the growing number of rock slope failures has determined a flourishing interest in the study of permafrost in steep rock walls in mountain environments worldwide, the permafrost distribution in talus and loose deposits, its response to warming temperatures in time, and its contribution to the onset of landslides are still largely unknown.

HERE WE INVESTIGATE THE PERMAFROST CONDITIONS AT THREE SITES OF THE TRÖLLASKAGI PENINSULA IN NORTHERN ICELAND (Fig. 1).

Two of them, Eyjafjrði and Hólar (Fig. 2a and b) are recent landslides and sourced from ground-ice cemented talus material, while the third – Tindastóll (Fig. 2c), is an ancient rock avalanche that tilted downslope Tertiary basalt bedrock. Interestingly, the altitude of source areas lies between c. 750 m a.s.l and c. 900 m a.s.l., which corresponds to the regional permafrost limit (Etzelmüller et al., 2007).

**RESEARCH QUESTION:
WHAT ARE THE PERMAFROST CONDITIONS AND RECENT EVOLUTION BEFORE LANDSLIDE EVENTS IN TRÖLLASKAGI?**

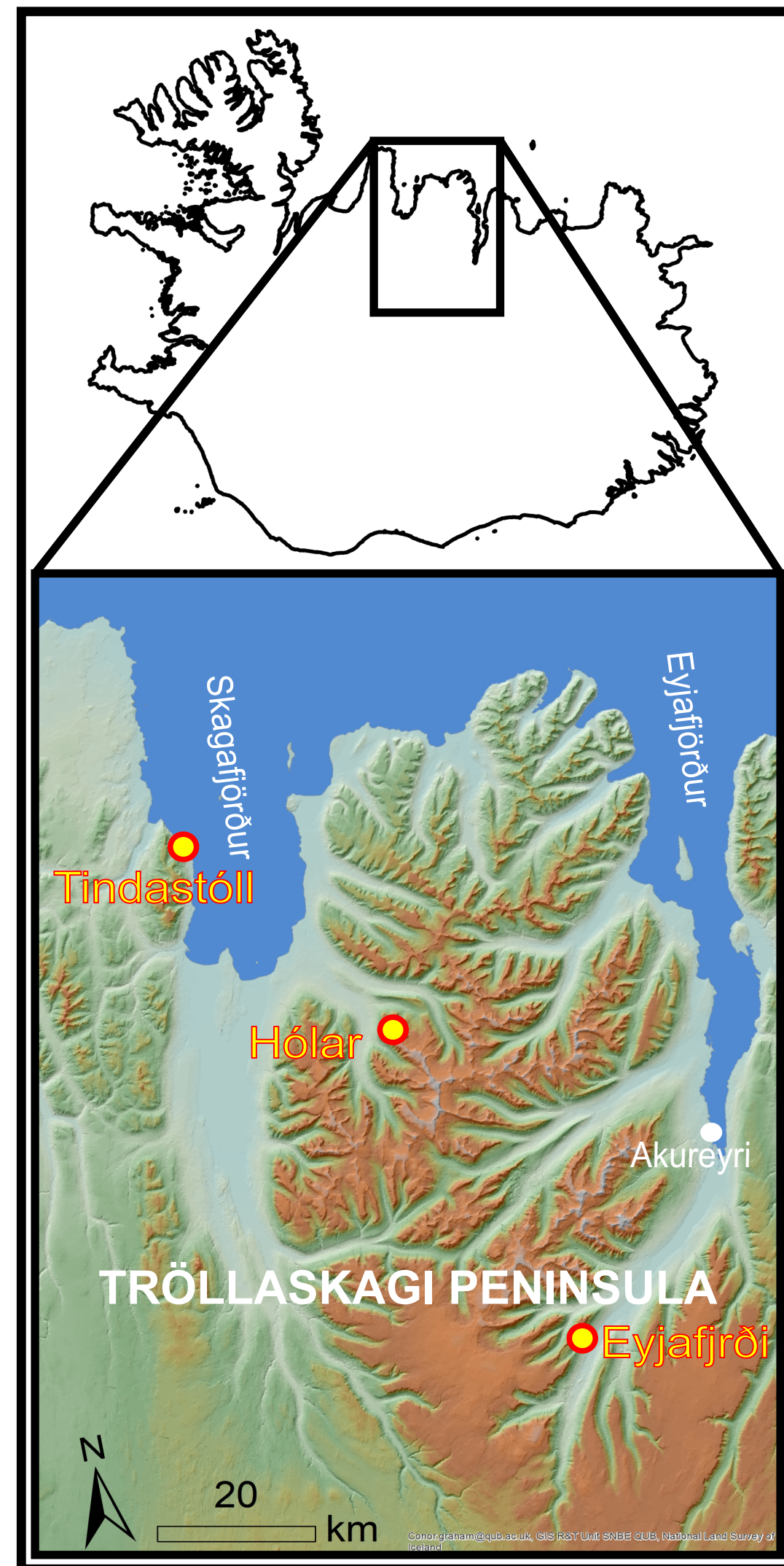


Fig. 1 - Location of the study sites in northern Iceland

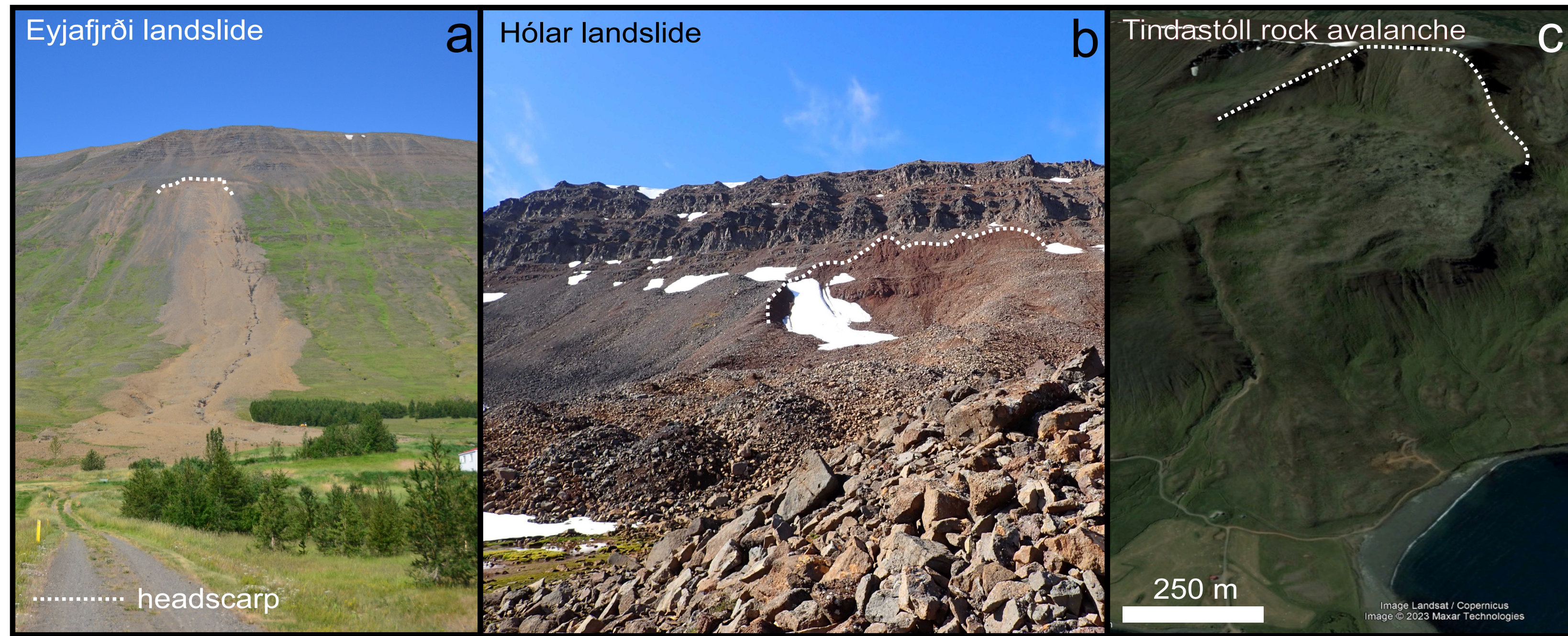


Fig. 2 - The study sites of Eyjafjrði, Hólar and Tindastóll.

	Eyjafjrði	Hólar	Tindastóll
Date of occurrence	6 October 2020	8-13 January 2019	12,603 ± 821 cal. Age BP (Mercier et al., 2017)
Elevation of release area (m)	880	1100	760
Source material	talus	talus	bedrock
Permafrost conditions (Obu et al., 2019)	sporadic	sporadic	no permafrost
Permafrost Zonation Index (Gruber, 2012)	NA (in buffer of 5 km to 0,01 PZI)	0,01	NA (in buffer of 1 km to 0,01 PZI)

Table 1 - Main characteristics of the three study sites.

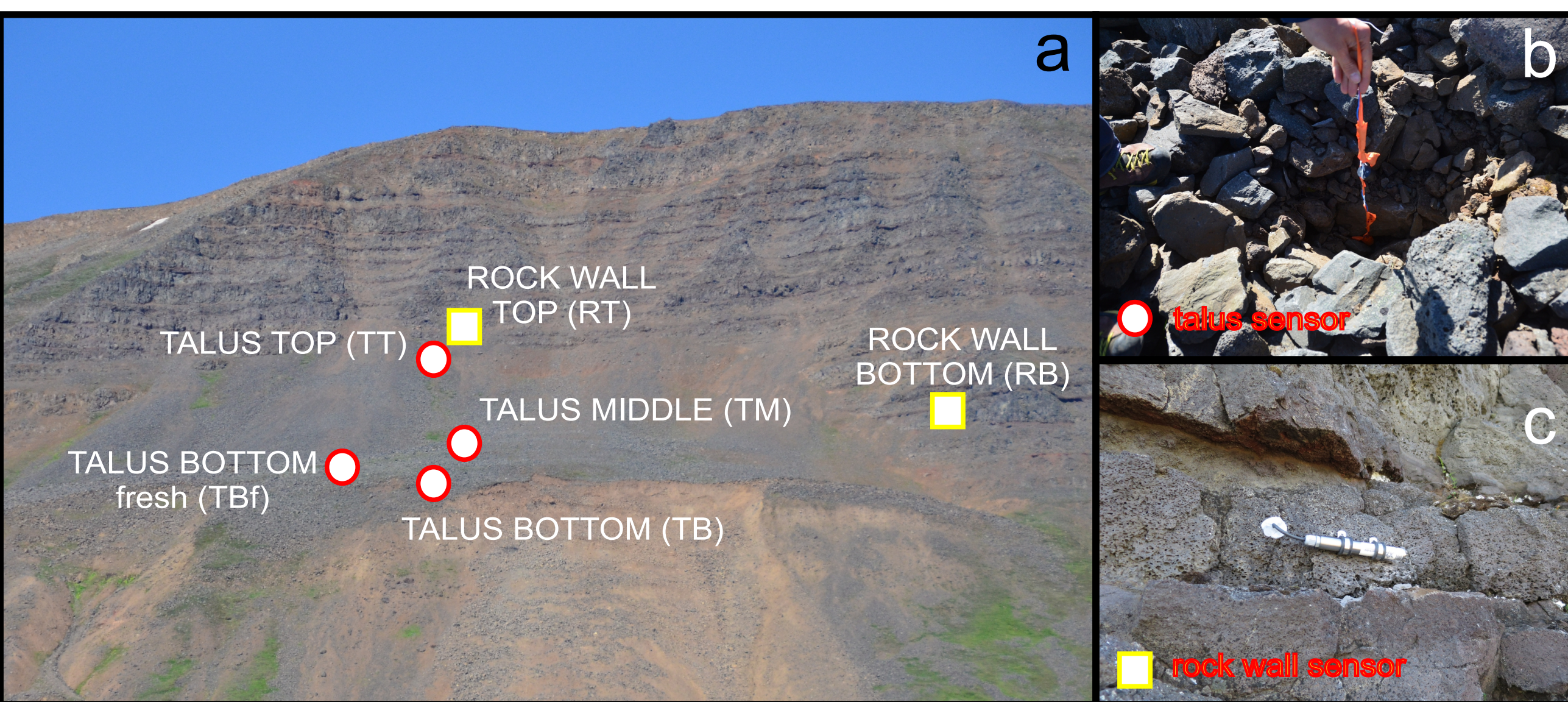


Fig. 2 - Sensors setup at Eyjafjrði site

2. METHODS

During summer 2021, we installed temperature sensors at the near surface of rock walls and talus (from 5 to 70 cm depth; Fig. 3b) of the Eyjafjrði, Hólar and Tindastóll sites following altitudinal profiles between c. 650 and c. 1200 m a.s.l. (for the case of Eyjafjrði the range is between 600 and 850 m a.s.l.; Fig. 3a), and in various ground conditions, such as uppermost sub-horizontal plateau with blocky regolith, sub-vertical rock wall, coarse and fine talus. We used Geoprecision mini data loggers, accuracy ± 0.1°C (Fig. 3c), and Ibutton DS1925L temperature loggers, accuracy ±0.5°C (Fig. 3b). Near surface temperature was measured at an hourly time step and data were retrieved during summer 2022.

Rock surface temperature (RST) is closely coupled with air temperature (AT), with a surface offset (i.e., temperature difference between the rock surface and the air) that depends on the incoming short-wave solar radiations and snow control. Therefore, it is possible to model RST history based on AT time series. We modelled rock surface temperature history based on AT time series fitting a linear regression, using the air temperature of the nearby weather station of Akureyri as it starts in the 1880s. These predictions can then be used to evaluate whether past conditions were favourable for the formation of permafrost. We used this approach to model RST for the rock wall, the bottom of the talus and the top of the talus of Eyjafjrði site.

3. RESULTS

For the site of Eyjafjrði, the general thermal regime of the talus (Fig. 4) is a chimney-effect type circulation (Wicky and Hauck, 2017). High porosity in coarse talus material generates gravity-driven internal air circulation induced by the gradient between outside (air) and internal (talus) temperature. The resulting thermal regime is different from the surrounding environment leading to occurrence of permafrost outside the typical permafrost zone. In Eyjafjrði, the near surface of the talus shows similar temperature as the rock wall surface in winter, revealing air suction through the snow pack and warmer conditions at the bottom of the talus. This is the first confirmation of our hypothesis that we may have sporadic permafrost at the bottom of the talus because of its specific thermal regime with a local chimney effect generated by upward motion of warm air during winter, replaced at the bottom by cold air.

The reconstructed rockwall temperature through the past (up to 1880) to get forcing data, adopting a fitting linear regression using Akureyri air temperature shows a good fit (Fig. 5a). We then used the talus temperature measured at depth as it registers the effect of both air ventilation and snow. We provide regressions for winter and summer and freezing n-factors, as shown in Fig. 5b for the bottom of the talus and Fig. 5c for the top of the talus. We tested temperature reconstruction with a two-step approach:

1. for the summer period, we adopted linear regression with summer temperature
2. for the winter period, we adopted linear regression with winter temperature or freezing n-factor (nF) calculation.

Comparison of measured data and reconstructed data are reported in Table 2. The final results of our reconstruction as far back as the 1880s (Fig. 6) shows that the conditions were favourable for permafrost at the bottom of the talus and in the rockwalls until the mid-1920s, in the late 1960s, and in the late 1970s/early 1980s.

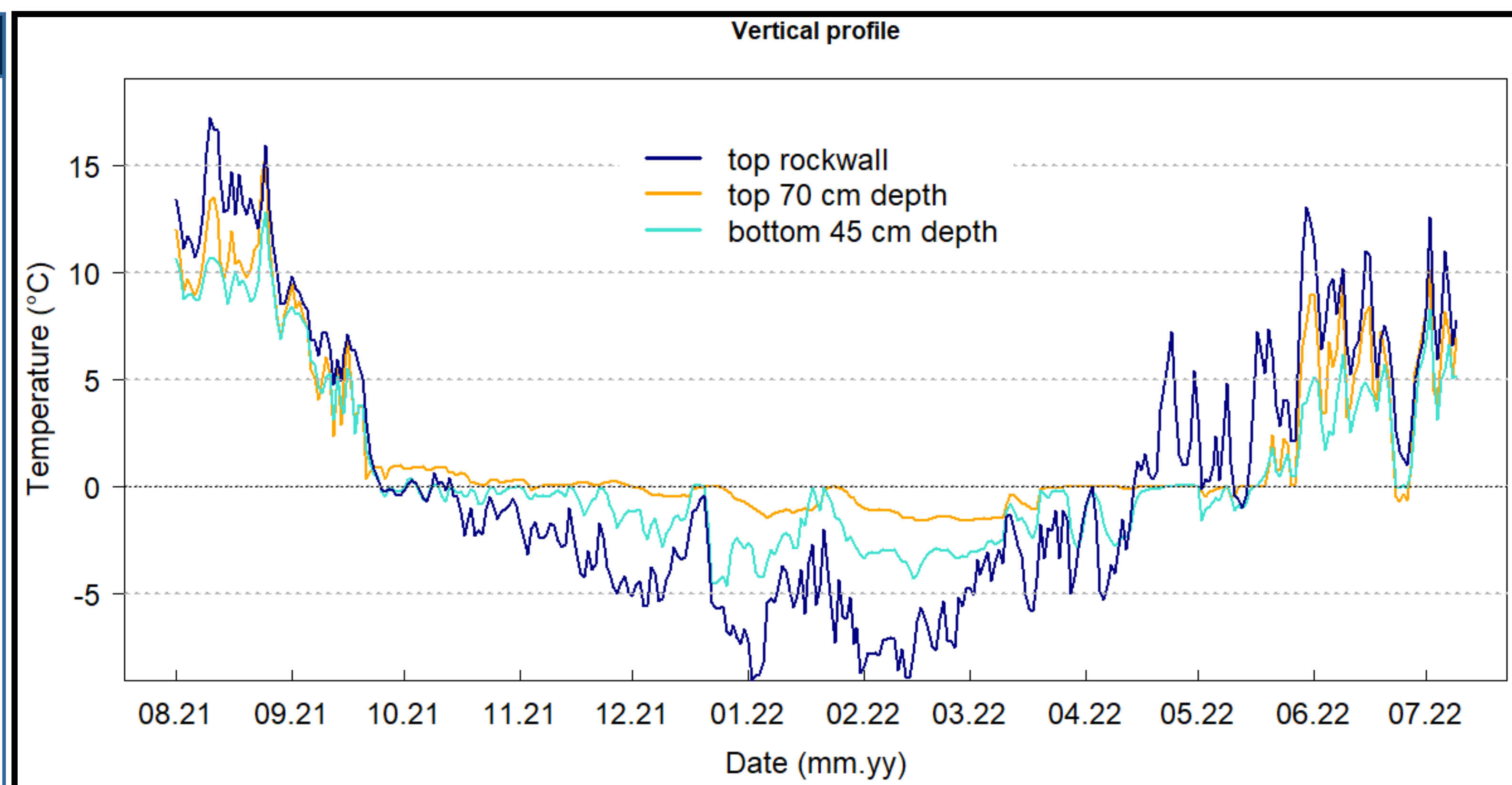


Fig. 4 - General thermal regime of rock wall, talus bottom and talus top temperature for the Eyjafjrði site.

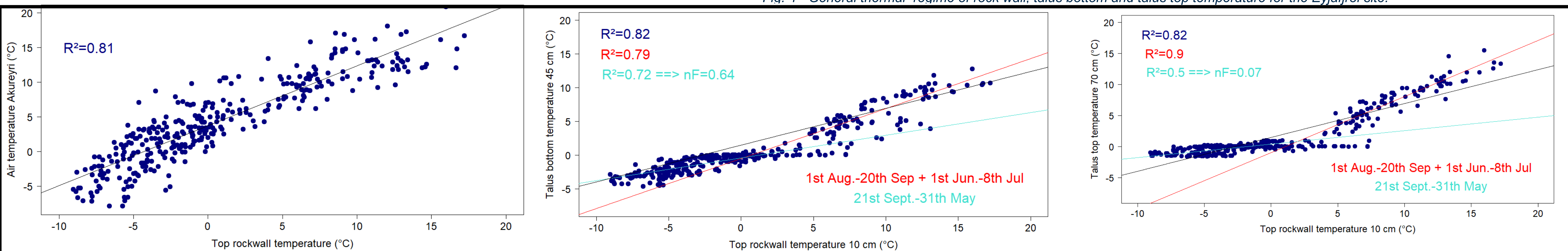


Fig. 5 - Reconstructed temperatures of rock wall, talus bottom and talus top for the Eyjafjrði site.

4. DISCUSSION AND OUTLOOK

Our first results suggest that chimney-effect circulation is involved at the Eyjafjrði site, sensu Wicky and Hauck (2016). This involves that convective heat transfer has the potential to develop a significant temperature difference between the lower and the upper part of the talus slope with a seasonal alternating regime. Next steps of this study will be:

- Use reconstructed air temperature during the Holocene (as in Etzelmüller et al., 2020; Fig. 6) to force the model further back in time and simulate ground thermal regime over millennia, as current permafrost might be a result of former colder periods.
- Use Feflow finite elements numerical code for thermal modelling applied specifically to a talus-bedrock reconstructed geometry. Initial setup parameters for the model will include a 30% ice-content (i.e. porosity) in the talus and 5% ice-content in the rock wall.

	Talus top	Talus bottom
Measured 1st August 2021 - 8th July 2022	1.77°C	0.7 and 0.75°C
Reconstructed with Summer regression + Winter regression	1.62°C	0.5°C
Reconstructed with Summer regression + n-factors in winter	1.5°C (with N-Factor = 0.1)	0.6°C

Table 2 - Measured and reconstructed data for Eyjafjrði site.

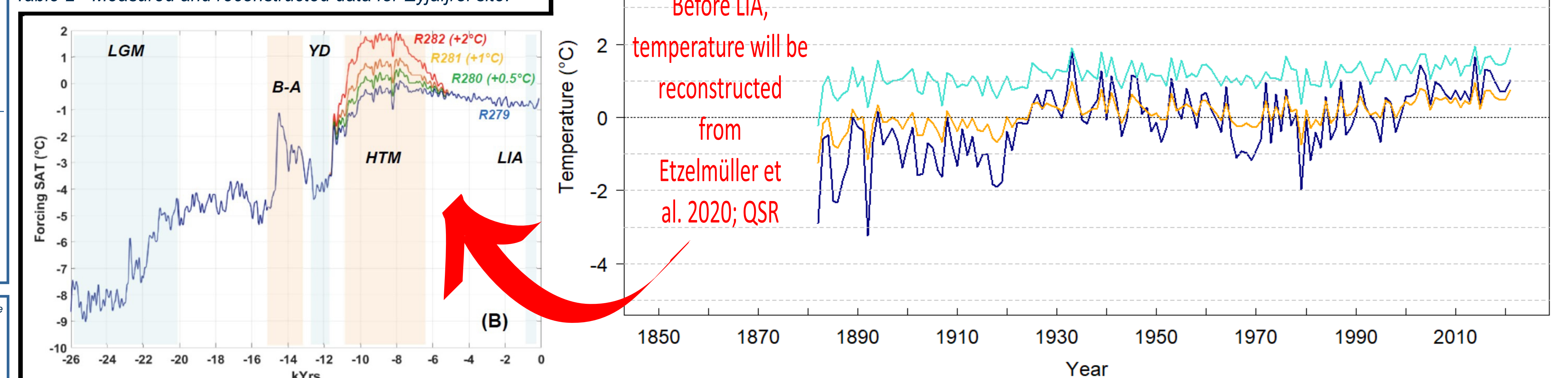


Fig. 6 - Reconstructed temperatures of rock wall, talus bottom and talus top for the Eyjafjrði site.

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