Title: Understanding and anticipating dynamical changes as Greenland Ice-Sheet outlet glaciers Transition from Marine- to Land-terminating (TransMariLand)

SECTION A: STATE-OF-THE-ART AND OBJECTIVES

ICE-SHEET DYNAMICS RESPONSE TO CLIMATE CHANGE

The cryosphere is an important component of the Earth system that is undergoing drastic changes in response to climate warming. Over just two decades, the net annual ice loss of the two largest ice reservoirs on Earth, Greenland (7 m potential equivalent sea-level rise) and Antarctica (60 m potential equivalent sea-level rise), each grew on the order of about 50 Gt a^{-1} (0.15 mm a^{-1} equivalent sea level rise) in 1989-2000 to about 250 Gt a^{-1} (0.9 mm a^{-1} equivalent sea level rise) in 2010–2018[1,2]. At these increasing rates, the vast reservoirs of ice stored in polar regions will continue to drive global sea levels higher in centuries to come. To anticipate these changes, it is pressing to understand the physics associated with the main processes driving ice loss and how such physics controls the future of the cryosphere.

Among the processes that mainly drive Cryosphere evolution, those that control ice flow play a fundamental role. The faster ice flows, the faster ice is discharged in the ocean or melt. In Greenland, marine-terminating glaciers drain 88% of the ice sheet[1] and their dynamics is responsible for about half of the net annual ice loss over the past decade, the other half being caused by increased surface melt and water runoff. Properly understanding marine-terminating glacier dynamics and how it might change in the future is thus of primary importance in order to reduce uncertainties in predictions of sea-level rise with climate warming.

Predicting the evolution of ice flow, however, is a challenging task. Ice flow is largely set by basal sliding[3], which is known to be affected by complex interacting processes involving enhanced basal ice deformation[4], glacier bed deformation[5] and bed lubrication from subglacial water produced by basal and surface melt[6–8]. The frontal condition of marine-terminating glaciers and their interactions with the ocean also have been documented to play an important role on ice flow. Basal melting of ice in contact with the ocean can strongly affect grounding line dynamics[9] and subsequent flow evolution, in particular through the so-called marine ice sheet instability [10,11]. One of the main priorities of the scientific community to reduce uncertainties in ice loss predictions is to identify and hierarchize the different processes that affect glacier flow and properly incorporate them in models.

THE DISRUPTIVE DISCOVERY THAT SERVES AS BACKBONE FOR THIS PROJECT

My project TransMariLand builds up on our disruptive discovery recently published in Nature that the most pronounced large scale (few up to tens of kilometers) and lasting (few decades up to centuries) changes in glacier flow in Greenland (i) are due to surface melt water and (ii) are a function of glacier morphology, that is whether outlet glaciers are marine- or land-terminating[12]. In places where surface melt occurs, land-terminating glaciers are found to be much more slippery than marine-terminating ones (Figure 1c). We hypothesized that increased bed slipperiness as glaciers transition from marine- to land-terminating results from time-persistent (multiyear) water storage changes at the ice-bed interface[12]. Water below glaciers is expected to be mainly drained through channel and cavity networks, with channels consisting in water conduits forming mainly through ice melt by turbulent heat flow[13] and cavities consisting in pockets of water forming in the lee-sides of bedrock bumps from mechanically-driven ice-bed detachment[6,7,14,15]. Increasing evidences suggest that bed slipperiness decreases as drainage through channels and well-connected cavities drawdown water stored in surrounding weakly-connected cavities[16–18]. Being steeper and faster, we hypothesized that marine-terminating glaciers favor high pressure gradients and cavity opening rates, which lowers water pressure in the active drainage system[6] and facilitates water drawdown from weakly-connected cavities through increased pressure differential, thus lowering bed slipperiness.

These results strongly challenge current considerations about Greenland's response to a warming climate as well as model strategies used to predict it. In its 2022 special report on Ocean and Cryosphere in a Changing Climate[19], the Intergovernmental Panel on Climate Change (IPCC) concludes that "there is high confidence that for most of the Greenland Ice Sheet, increased surface melt has not led to sustained increases in glacier flux on annual timescales because subglacial drainage networks have evolved to drain away the additional water inputs[20–24]". As summers get hotter and longer, the increased occurrence and extent of channels is expected to draw additional water out of the ice-bed interface, thus to reduce bed lubrication and decrease ice speeds, resulting in a negative feedback between increased melting and mass loss and thus more resilience of the Greenland Ice Sheet to increasing temperatures (Figure 2a). Observations used by IPCC to conclude on this negative feedback, however, all concentrate on the same land-terminating sector[21,22,25,26], and are thus insufficient to assess the impact of melt across the entire ice sheet, particularly in marine-terminating regions[27], which are significantly different in terms of dynamics, and in inland areas, where channelization is inferred to have a small or inconsistent role in seasonality[28].

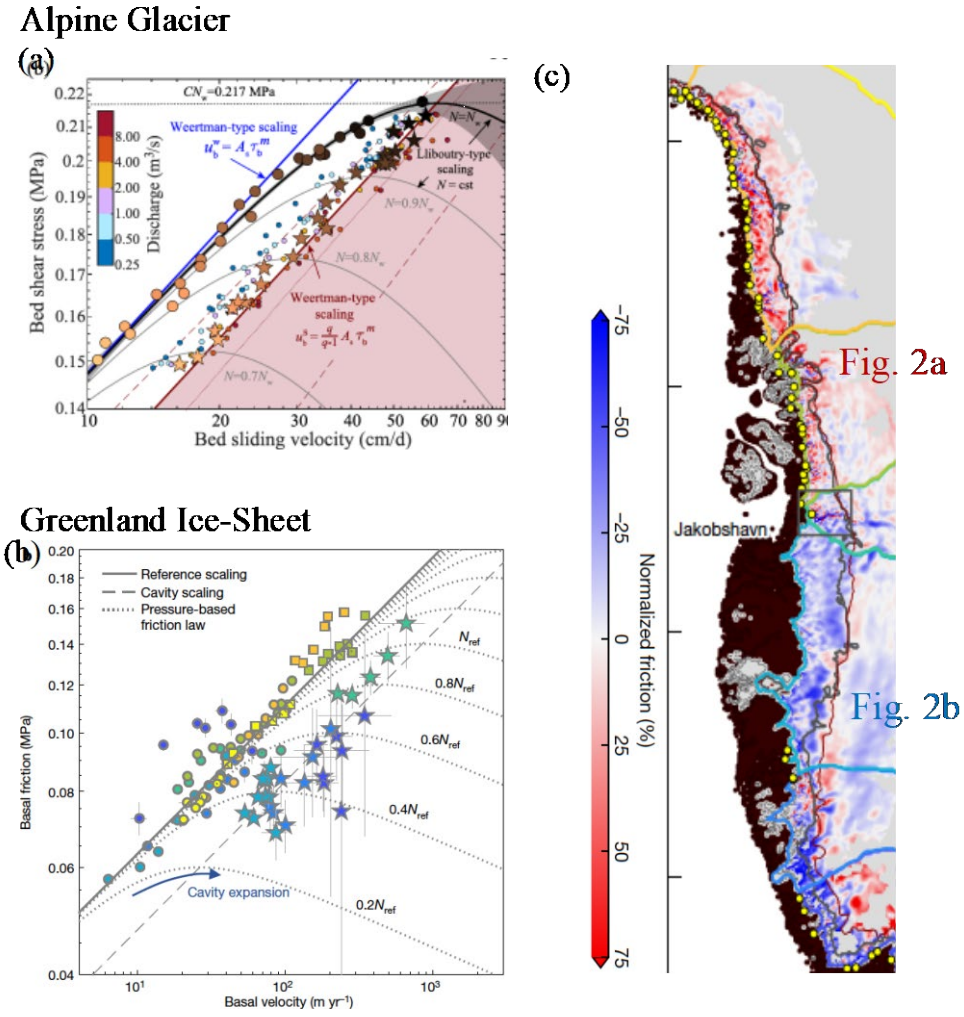

Figure 1: Summary of the recent results forming the backbone of this project. (a,b) Glacier bed friction laws reconstructed from field observations (Gimbert et al., 2021 and Maier et al., 2022)and (c) map showing bed friction anomaly across the western half of Greenland (Maier et al., 2022). The glacier bed friction law in (a) has been reconstructed based on three decades long in-situ measurements of sliding velocity below an Alpine Glacier, while that shown in (b) results from a Greenland-wide analysis combining satellite surface velocity observations with model inversions. The black line in (c) indicates the equilibrium line position, that is the line above which no surface melt occurs year-round. The colored rectangles in (c) indicate locations of field investigations in the present project, which are detailed in Figure 7.

In our recent study[12], we find that the marine- to land-terminating transition is associated with an increase in bed slipperiness of about 20 to 40% (Figure 1c), which is much larger than the 4 to 6% bed slipperiness decrease associated with the channel growth mechanism referred to by IPCC. This means that a MORphology-driven POsitive melt-water FEEdback (MorPoFee), rather than a channel-driven negative feedback, has the potential to dominate Greenland response to meltwater under a warming climate (Figure 2b). As air and ocean temperatures rise and glaciers transition from marine- to land-terminating, as many are expected to do over the next century[27,29,30], upgradient regions are expected to slow and flatten, increasing bed slipperiness through the above hypothesized hydrological mechanism. The associated acceleration would impact the surface geometry resulting in upgradient thinning, amplifying the SMB–elevation feedback already thought to be critical to mass-loss rates over the coming century[29]. It also implies an increase in mass flux towards the margin, possibly forcing outlet glaciers to re-advance to the marine margin resulting in another period of ice discharge.

Although expected to be dominant, MorPoFee is unlikely captured in large scale models of Ice-Sheet evolution. In these models[31,32], glacier basal sliding velocity u_b is described following seminal theory from Weertman[4] as $u_b = A_s\tau_b^m$, where τ_b is the bed shear stress and m and A_s are parameters typically assumed as constant with time (REFS). Our recent multi-decadal observations below an Alpine glacier[33] (Figure 1a) as well as our large scale observations in Greenland[12] (Figure 1b) suggest the assumption of constant m likely holds in real settings. However, the assumption of **constant A_s is highly questionable given our above finding, as it may increase by an unexpectedly large factor of about 3 to 4 as deglaciation proceeds and glaciers transition from marine- to land-terminating (see the power law scaling being shifted to the right in Figure 2b), leading to higher than currently anticipated ice loss.**

CURRENT CHALLENGES

We identified a change in bed slipperiness from spatial evaluation of the transition marine- to land-terminating glacier transition, but yet we don't have long enough timeseries of observations to actually experience MorPoFee through time, as glaciers over the modern instrumentation era have not significantly transitioned from marine- to land-terminating. To anticipate future changes, we thus rely on quantitatively understanding the processes that control MorPoFee and implement them in models. Although our hypothesis to explain increased bed slipperiness as glaciers transition from marine- to land-terminating is qualitatively consistent with current knowledge of subglacial hydrology, more quantification faces important challenges.

The known unknowns. Although existing theories incorporate thoughtful descriptions of flow drainage through channels and cavities[8,13,17,34–37], they involve numerous poorly constrained physical parameters, which strongly limits our ability to predict where channels versus well-connected cavities form and under which water pressures. In addition, these theories do not include fully satisfying descriptions of the dynamics of weakly-connected cavities. Previous conceptualizations that cavities transition from weakly- to well-connected as they reach a critical size helped understand borehole pressure records, but faces the important paradox that weakly-connected cavities are predicted to be lower water pressure than well-connected cavities[36], which is opposite to observed[16,38–40]. Weakly-connected cavities have also been envisioned as behaving as a storage volume being spatially fixed and exchanging with well-connected cavities with considerably reduced drainage efficiency[17]. In this case high water pressure weakly-connected cavities can be treated, however cavities no longer have the ability to transition from weakly- to well-connected, which is also contrary to observations[36].

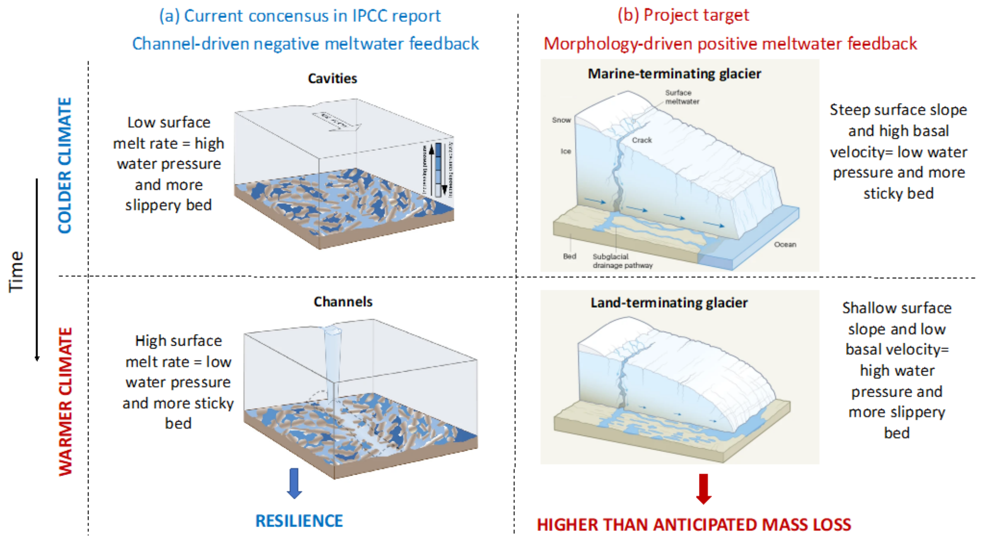

Figure 2: Sketch illustrating the (a) channel- and (b) morphology-controlled feedbacks. (a) sketch adapted from Hoffman et al., 2016). (b) sketch adapted from Livingstone, Nature News and Views, 2022.

The unmet needs. Lacking knowledge in current subglacial hydrology theories is mostly due to lacking observations. The subglacial hydrology network is known to be highly heterogeneous, with cavities transitioning from well- to weakly-connected over distances as short as few meters[16,38–40], and channels, well-connected and weakly-connected networks exhibiting a range of ramifications from scales of few meters up to several tens of kilometers[8,35,36]. Under such situation, insights from punctual observations provided by traditional water pressure measurements in boreholes are limited. Numerous boreholes must be drilled in order to resolve the spatial heterogeneity of the subglacial drainage system[36,38–40], which is particularly time intensive and costly, and which can hardly be done in remote areas like Greenland. Even when manageable, observations from boreholes are difficult to interpret and confront with models. As an example, Rada and Schoof[36,41] drilled a total of 311 boreholes in a valley glacier in Yukon over 8 years of field work (Figure 4a) and recovered highly variable signals that are challenging to make sense of in order to extract representative behaviors for model conceptualization (Figure 4c-f).

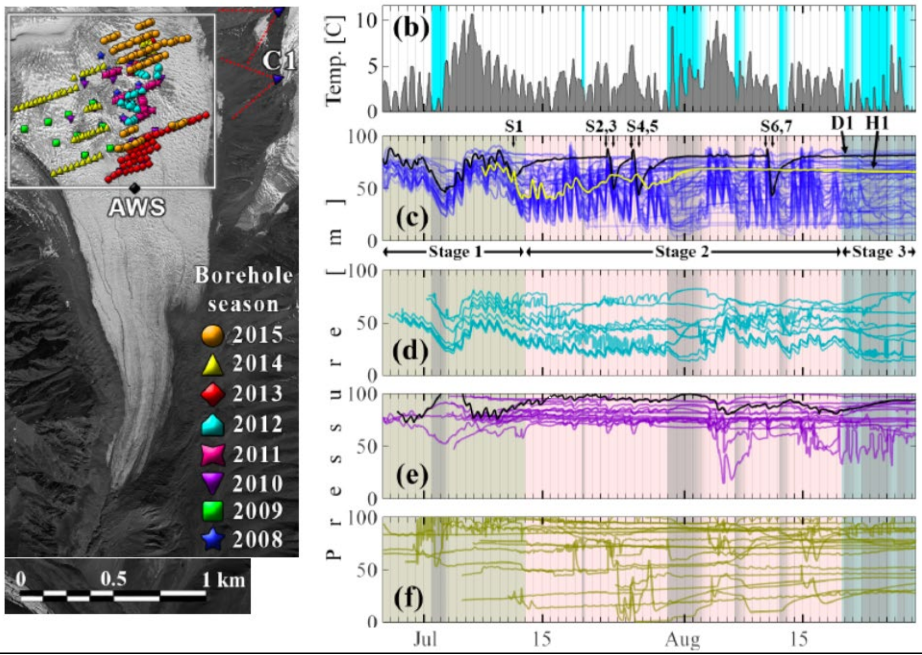

Figure 4 : Borehole pressure monitoring conducted by Rada and Schoof (2018, 2022) in a valley glacier on Yukon. (a) Map showing borehole locations, (b) temperature record timeseries and (b-f) selected pressure record timeseries.

The unknown unknowns. Although our hydrological hypothesis appears as most plausible given the present state of knowledge, there remains a potentiality that other unidentified mechanisms cause marine-terminating glacier beds to be weaker than land-terminating ones. More groundwater transport due to more porous beds below marine-terminating glaciers would for example be consistent with our findings, and would make MorPoFee obsolete, as bed porosity may not necessarily change with glacier retreat. Although bed porosity changes are unlikely driven by changes in geology, since they do not match with the marine- versus land-terminating transition[42], other complex processes involving the presence of till may affect bed water drainage[43–46]. In addition, mechanisms other than subglacial hydrology could potentially also be a source of marine- to land-terminating increase in bed slipperiness, as in particular if enhanced yet unforeseen internal ice deformation was to occur near the bed of land-terminating glaciers, for example if it was localized at glacial- and interglacial-phase or cold and basal temperate ice interfaces[47]. These unknown unknowns are again inherited from lacking observations regarding the differences in till dynamics and ice structure that may operate between marine- and land-terminating glaciers, with marine-terminating glaciers being considerably harder to instrument than land-terminating ones due to being highly crevassed and often located farther from infrastructures.

PROJECT OBJECTIVES

In TransMariLand I will conduct a particularly ambitious and innovative strategy with the aims to

(AIM1) Observe the physics associated with the glacier morphology control on bed slipperiness

(AIM2) Evaluate the impact of MorPoFee on the Greenland Ice-Sheet evolution and contribution to sea-level

This proposed research pushes beyond the state of the art not only because it builds up on a recent change of paradigm regarding Greenland susceptibility to surface meltwater, but also because it involves filling long-lasting knowledge gaps on subglacial hydrology and glacier bed friction by conducting an innovative monitoring and modelling strategy. **We will apply recent advances in seismology and geodesy (see below) for the first time systematically over a range of scales in Greenland (AIM1, WP1 to WP3, see Figure 3) in order to probe key differences in marine- versus land-terminating subglacial hydrology characteristics.** Contrary to observations in boreholes, seismic and geodetic observations are by nature non-local and allow to retrieve multi-scales spatial fields, thus providing more appropriate constraints that can more easily be confronted to models. Seismic sensors purchase and deployments also involve considerably reduced financial cost and human resources compared to intense ice drilling, while satellite acquisitions are nowadays largely made freely accessible to the scientific community. These improved monitoring abilities will enable us provide unprecedented multi-spatial observational insights on the nature of active drainage (channels versus cavity flow), its associated hydraulic pressure gradients, its spatial localization, coverage and degree of heterogeneity, its conductivity and its interactions with weakly-connected cavities. **We will integrate these novel observational constraints into current modelling frameworks (AIM2) in order to quantitatively describe the physics of MorPoFee (WP4) and evaluate its impact on Ice-Sheet evolution and contribution to sea-level, from paleo-climatic timescales to the upcoming decades (WP5).** The 5 work packages of this project all have their own independent merit, but taken together they will synergistically provide unprecedent and quantitative insights on the two above-listed aims.

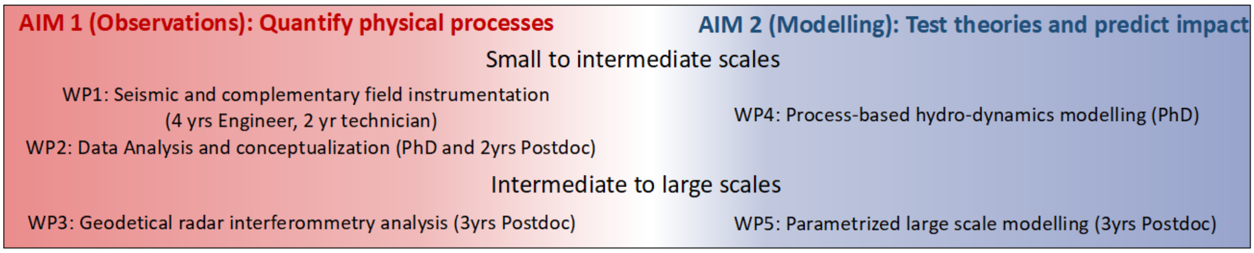

Figure 3 Box plot highlighting aims, work structure and human resources.

SEISMOLOGY AND GEODESY AS INNOVATIVE OBSERVATIONAL MEANS TO UNRAVEL SUBGLACIAL HYDROLOGY PHYSICS

Seismology. The field of seismology underwent a particularly large and exciting diversification thanks to increased capabilities in monitoring, analyzing and understanding complex signals, often referred to as background noise or tremors, generated by a wide range of environmental processes acting near the Earth's surface[48–50]. In particular, a wealth of recent discoveries, to which I actively contributed[51–58], suggests seismic observations provide unprecedent constraints on subglacial hydrology physics. Analysis of tremors generated by subglacial water flow[59] combined with subglacial discharge measurements and a dedicated theoretical framework[51] enables inferring changes in water pressure gradients and conduit sizes[60], which are key flow parameters in physical models[8,35,37] that remained previously unobservable with other techniques. One can also detect flow through both the distributed cavity and localized channel networks, and use dedicated dense array designs together with advanced signal processing techniques to retrieve source locations with high spatial resolutions of few tens of meters[53] (Figure 5a-b). These techniques will in the near future strongly benefit from added monitoring capabilities provided by distributed acoustic sensing (DAS), which yields unprecedent resolution of the wavefield and allows for dense seismic arrays being deployed vertically in boreholes, thus turning the classical two-dimensional observations into three-dimensional ones[61]. Use of coarser arrays has also been successful at spatializing the information on pressure gradients and conduit sizes and monitor their changes through time, such as prior and after surface lake drainage[54,60] (Figure 5h), or to locate fluid migrations at the much larger scales of few hundreds up to few tens of kilometers, such as done in the context of volcanoes[62] (see Figure 5d-f). Beyond source analysis, the monitoring of glacier structure using seismic noise interferometry to monitor changes in seismic velocities has also been proven to be successful at retrieving changes in subglacial hydrology characteristics such as the size and shape of cavities forming the distributed hydrological system[63].

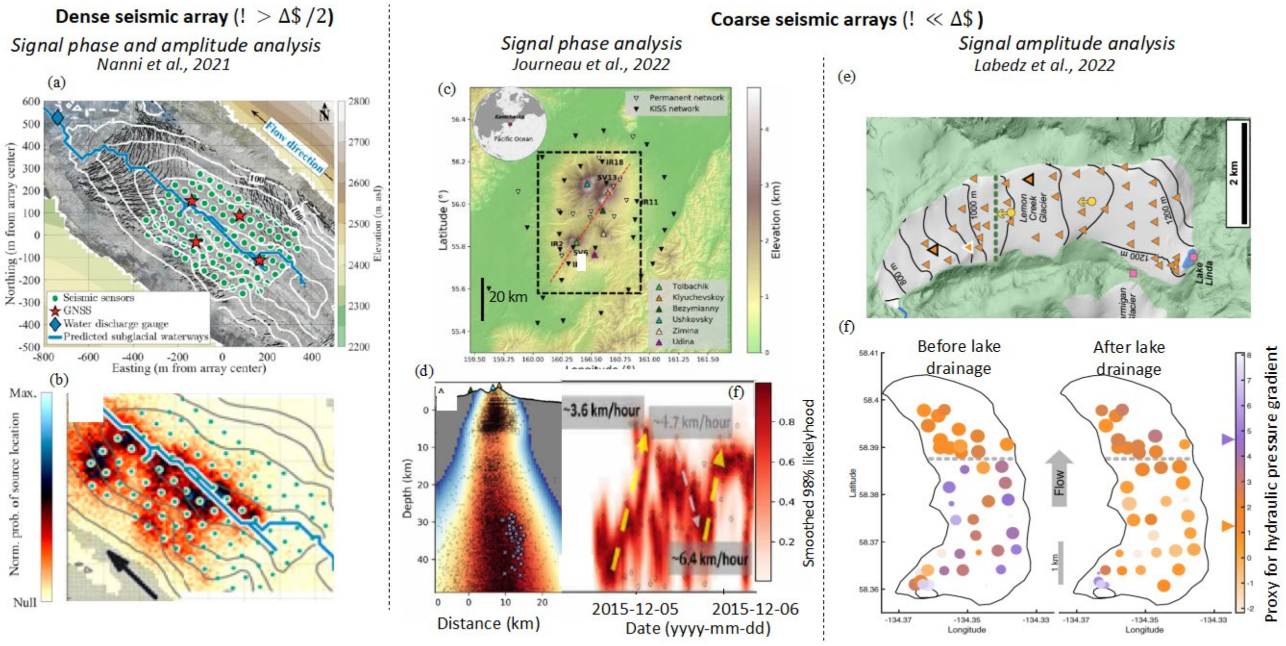

Figure 5: Selected works highlighting recent advances in seismology acting as proofs of concepts in this project, using (Left) dense and (Right) coarse seismic arrays.

Geodesy. Geodesy is now a well-established technique to study glaciers and Ice-Sheets. The first large scale radar-derived surface velocity maps provided about a decade ago in Greenland and Antarctica[64,65] have revolutionized the field through the identification and quantification of strong changes in outlet glaciers dynamics exerting key control on Ice-Sheet mass balance[1,2]. New satellites and sensors as well as improved processing schemes now put satellite observations at another level of increased temporal and spatial coverage with unprecedented resolution, offering possibilities to target new physical processes that were unreachable before. In particular, we have recently demonstrated that differential radar interferometry (DInSAR) allows investigating tiny (centimetric) changes in surface motion resulting from underneath fluid migrations[66], such that subglacial hydrology pathways, ice-bed separation due to cavity drainage expension and associated hydro-mechanical ice-bed coupling can be inferred with high spatial resolution (XX) over areas as large as several hundreds of kilometers (Figure 6). Our recent findings[67] demonstrate that winter lake-drained water can be used as a tracer probing subglacial hydrology characteristics, with the unprecedented ability to follow the tracer propagation in two-dimension through time, rather than solely at a few measurement points as from dye tracing[68,69]. Unprecedented gain includes the ability to evaluate (i) active drainage locations, obtained from changes in ice-bed separation using surface velocity decomposition and correction from bed parallel and vertical strain uplift (Figure 6d), (ii) water drainage velocities, obtained from evaluating LoS velocity pulse migration speeds (Figure 6f), and (iii) hydro-dynamic coupling, obtained from comparing bed separation with ice velocities (Figure 6e). Interestingly, bed separation is highly heterogeneous consistent with active flow drainage exhibiting complex and tortuous pathways, drainage velocities are characteristics of cavity drainage (on the order of 0.1 m/s[68,69]) and significantly decrease along flow (Figure 6f) despite an increase in hydraulic pressure gradient (Figure 6g), and spatial changes in sliding speeds are surprisingly much smoother and larger scale (up to 100 km) than that of active drainage (about 10 km) (Figures 6d and e).

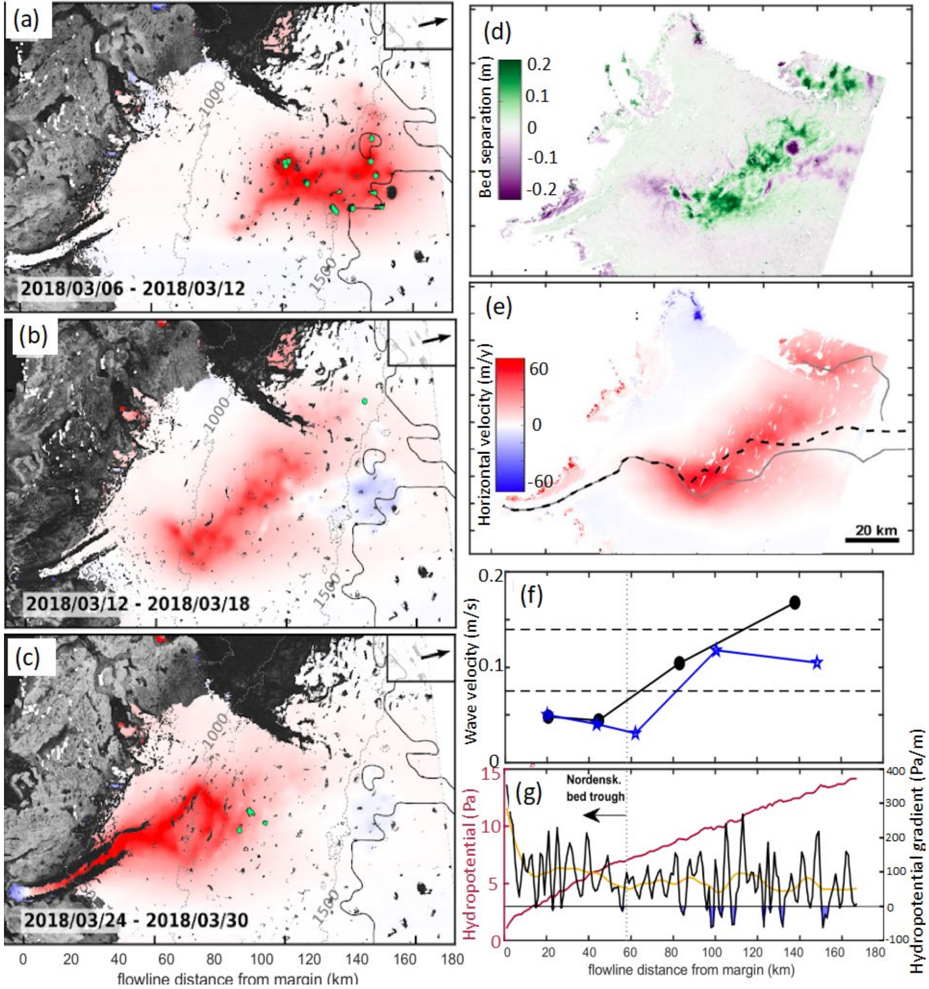

Figure 6: (a-c) Change in line-of-sight (LoS) velocity (relative to a pre-event acquisition) from Sentinel-1 interferometric (DInSAR) measurements at different times during a winter lake drainage event that occurred in 2018 in western Greenland. The locations of all lake drainages that have occurred during each considered period are highlighted by green polygons, or dots for lakes smaller than 4 km. (d) Snapshot of bed separation change associated with LoS velocity change shown in (b), obtained from vertical surface displacement decomposition and correction from bed parallel and vertical strain uplift. (e)Horizontal velocity change associated with LoS velocity change shown in (b), obtained from LoS velocity decomposition. Dashed and continuous lines show main interpreted flow pathways. (f) - Front (black) and body (blue) pulse wave velocity along the dashed line shown in (e). (g) Hydropotential and hydropotential gradient along flow pathway.

SECTION B: METHODOLOGY

AIM 1: Observe the physics associated with the glacier morphology control on bed slipperiness

Rationale. Following our hydrological hypothesis for MorPoFee, I expect that increased drainage capabilities on marine-terminating glaciers would materialize itself by subglacial flow being funneled into more localized, lower water pressure, faster drainage and larger size pathways than on land-terminating glaciers. These increased drainage capabilities would also mean that less water is stored in the distributed cavity system, and that changes in water input rates either from lake drainage or summer melt have less influence on the structure of subglacial drainage and associated friction. I plan to conduct an unprecedent multi-physics and multi-scale monitoring scheme that offers the necessary spatial and temporal coverage for testing these scenarios. We will experience changes in subglacial hydrology characteristics on both marine- and land-terminating glaciers from the few meter scales of channels and cavities up to the hundred-kilometer scale of ablation areas through conducting an ambitious multi-scale and multi-sensor observational strategy.

Although recent seismology and geodesy works have established proofs of concepts to infer these differences (see previous section), yet a multi-scale monitoring strategy enabling making full sense of observations at relevant spatial and temporal scales has not been conducted, nor in Greenland nor elsewhere. This requires monitoring schemes that offer sufficient spatial and temporal coverage for experiencing changes in boundary conditions (melt water input, bed topography, glacier morphology), which typically occur over the season and the entire Ice-Sheet scale, while ensuring sufficient spatial and temporal resolution to assess underlying mechanisms (channels, cavities) and their associated control parameters (bed roughness, glacier sliding velocity), which may typically vary over few meters and few hours[13,17,38–40]. The monitoring strategy I propose below satisfies those needs. We will select two representative glaciers for field investigations, one marine- and one land-terminating, on each of which dedicated monitoring will be conducted (i) at the scale of few kilometers over the spring-summer season, referred to as the small-scale instrumentation, with resolution down to few meters, and (ii) at the scale of an entire year and ablation zone, referred to as the intermediate-scale, with coarser resolution down to few hundreds of meters. Extrapolation to Ice-Sheet scales will be done by deploying systematic geodetic observations.

WP1: Acquisition of a comprehensive dataset at small to intermediate spatial scales (4-year engineer (etude) and 2-year technician (BAPC terrain-BAPE gestion donnees))

Rationale. We will make full use of new opportunities offered by modern sensors and technologies to sample the seismic wavefield with a coverage and resolution never reached before on glaciers. Seismic acquisitions will be made with a total number of 400 hundred seismic sensors referred to as Nodes, with Distributed Acoustic Sensing (DAS) with several tens of km long optic fiber placed at the surface and in borehole, and 13 broad band stations (Figure 1a). Nodes are specifically designed for such types of deployments: sensor, acquisition and battery are embedded into all-in-one robust casing enabling fast deployment. DAS is a particularly innovative technique currently revolutionizing the field of seismology through offering monitoring capabilities unreachable before (REF). Based on Rayleigh scattering of a coherent laser pulse sent and backscattered by impurities along the optic fiber that act as a distributed interferometer, strain rate can be measured at high frequencies (>1000 Hz) over the entire fiber distance with spatial sampling as small as few meters (set by the gauge length). Crucially, DAS sensing in boreholes will enable turning the classical 2D into 3D observations, which will drastically increase resolution with depth, and DAS sensing at the surface will enable extrapolating observations at the small- scale towards the intermediate-scale.

Targeted glaciers and arrays positioning

We will instrument Russel Glacier as land-terminating (see blue rectangle in Figure 2c) and Store Glacier as marine-terminating (see red rectangle in Figure 2c). These two glaciers exhibit typical behaviors consistent with our work pre-requisites: the steeper and faster Store Glacier exhibits a less slippery bed than the shallower and slower Russel Glacier (Figure 2c and Figure 5a-c). The Russel glacier area is where most field observations have previously been made[7,36,68,69], and our instrumentation is designed in order to maximize our capability to compare our findings with previous ones. Due to their harder accessibility and more chaotic surface with lots of crevasses, little in-situ measurements have been done on marine-terminating glaciers in the past, Store Glacier being one of the few that deserved recent attention[45,47,61,70].

Arrays will be positioned in order to probe subglacial hydrology (channel versus cavity) development avor the ablation zone and up to year round. To meet this need under affordable financial and human resources, the small-scale instrumentation will be conducted at two targeted places on each glacier (at an intermediate and high elevation, see black squares in Figure 5) over a restricted part of the year (spring and summer), while intermediate-scale instrumentation will cover a large part of the glacier ablation zone and will last all year round. Exact site positions will be chosen based on preliminary DInSAR analysis of inferred flow pathways (WP3, Task 2), with the aim to maximize sensitivity to active drainage areas.

Small-scale deployment specifics

Dense low-tech and optic fiber array. To reach high resolution (see WP2 Tasks 1 and 3), subwavelength analysis of the seismic wavefield is suited, i.e. interstation distance ΔX is smaller than half the wavelength λ (about 200 to 800 meters at the 2 to 7 Hz frequencies of interest[53,54,60]). We will fulfill this condition by deploying seismic stations referred to as Nodes with few hundreds of meters interspacing (see black rectangles in Figure 2) and by conducting Distributed Acoustic Sensing (DAS) using optic fibres[61], with which sampling is set by the gauge length of typically few meters. To monitor a few km^2 representative area will use 200 seismic stations and a ten-kilometer-long fiber deployed (see black rectangles in Figure 7). Nodes are specifically designed for such types of deployments: sensor and acquisition are embedded into a single specific casing, enabling fast deployment, battery is external, facilitating maintenance, and data recovery and autonomy is on the order of 5 months, thus covering spring-summer. DAS monitoring will be done both at the surface and in 5 boreholes (see blue line in Figure 2), which will allow drastically increase resolution with depth. DAS acquisition duration will be limited by fiber lifetime, which in boreholes is on the order of few weeks (personal communication, Booth and coworkers[61]).

Complementary instrumentation. Surface instrumentation will include (i) geophysical radar surveys along repeated lines across the seismic array, to infer glacier bed topography with high resolution and potentially map the cold to temperate ice transition[47], (ii) drone imaging to recover high-resolution surface DEMs, (iii) GNSS positioning to constrain ice dynamics at high temporal resolution, (iv) strain sensing using the optic fiber Distributed Strain Sensing (DSS) technology and (vi) outlet discharge measurements on Russel Glacier. Depth instrumentation in boreholes will include (i) DSS and DTS (Distributed Temperature Sensing) to recover strain and temperature at high resolution and (iii) basal water pressure sensing similar to more traditionally done.

Intermediate-scale deployment specifics

Broad band seismic array. We will deploy 12 broad band stations over the entire glacier ablation zone with continuous acquisition also throughout winter. The GNSS sensing incorporated in the data acquisition will be used for positioning.

Optic fiber array. We will deploy a 20 km long optic fiber at the glacier surface linking both dense array deployment sites (see Figure 7ab). This will enable DAS sub-walength monitoring to be conducted over unprecedently large scales, such that results yielded through dense small-scale deployment can more readily be extrapolated to larger scales. The fiber will be consulted during field investigations of few weeks but will not be left on site due to limitations from heavy power consumption.

Team and collaboration

The research engineer hired in the project will lead this work package, under my direct supervision. He will have and develop further expertise in all instruments, such that he will be able to best set them up and conduct data quality check in the field, as well as conduct preliminary data analysis (Tasks 2 and 4). The engineer will supervise one technician, who will have in charge all technical/administrative and data management aspects (Tasks 1 and 3). Both the engineer and technician will work in close collaboration with Luc Piard, who will be in charge the construction of the hot water drill and its operation in the field.

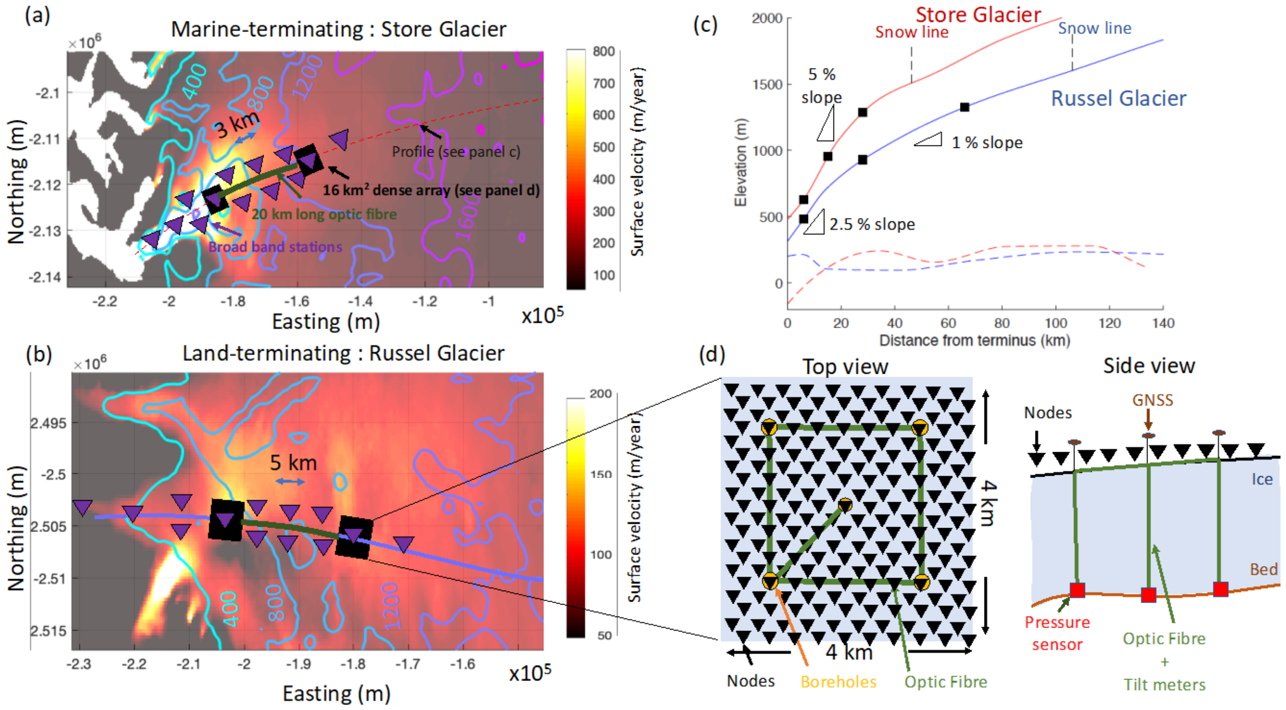

Figure 7: Schematics of the seismic deployments planned on (a) Store and (b) Russel glaciers. On (a) and (b) the colormap shows surface velocities and the line contours show ice thickness. Green triangles indicate seismic stations of the extended network and black rectangles show the spatial extensions of three dense seismic arrays (see panel (d)) located along a flow line. (c) Along flow profile of Store (red) and Russel (blue) glaciers together with dense seismic array locations (black squares). Continuous lines show surface elevations and dashed lines show bed elevations.

WP2: Analysis of seismic and complementary data to unravel subglacial hydrology characteristics and its links with ice dynamics (PhD 1 and 3 yr postdoc 1)

Rationale. Key to my aim is the ability to detect, locate and infer physical properties associated with a range of subglacial hydrology configurations, including channels, well-connected and weakly-connected cavities[16,17]. Being highly turbulent and associated with high flow discharges, channels are expected to be the most powerful seismic sources [51,52]. Although flow through well-connected cavities was initially envisioned to be too small for generating detectable seismic waves[51], in our recent study we demonstrated otherwise[53]: dense seismic array analysis enabled detecting cavity drainage and disentangling its contribution from that of channels. **In task 1 we will conduct source localization techniques to unravel the nature of the active drainage (channels versus cavity flow), its spatial organization and its area of coverage. In task 2 we will conduct amplitude signal analysis together with targeted seismo-mechanical frameworks to unravel spatial changes in flow drainage hydraulic pressure gradients and conduits sizes.** Since poorly-connected cavities are expected to behave mostly aseismically due to water therein being stagnant, source analysis can tell where they are (no source)[53], but cannot give insight onto their properties. Fortunately, poorly-connected cavities also happen to be expected to be the most widespread and the largest as a result of storing most of the basal water[17]. They are thus expected to be the ones that mostly influence seismic wave propagation, such that their characteristics may be studied though wave tomography as done in recent work[63]. **In task 3 we will conduct tomography analysis to monitor water volume changes in weakly-connected cavities, and evaluate links with active drainage by comparing results from those in task 1. Findings from all these steps and confrontation with all other sets of observations in task 4 will lead to the establishment of conceptual models on subglacial flow drainage and links with glacier dynamics and basal slipperiness, such that a conceptual answer to AIM1 can be provided.**

Task 1: Unravel channels and well-connected cavities from source analysis at all scales

We will locate subglacial hydrology source positions based on evaluating the wavefield spatial coherency on both the small- and intermediate-scale arrays. With this approach no a priori on waveform characteristics is required. With the small-scale array as well as the 30-km long optic fiber, high spatial and temporal resolution on source localization (on the order of few seconds and few tens of meters) will be ensured[57,71] by evaluating wavefield spatial coherency through the signal phase field and using a matched-field-processing technique[72,73] together with an efficient gradient-based minimization algorithm[53,74]. Using the borehole DAS observations in addition to surface nodes will help drastically improve spatial coverage and resolution, in particular through depth using fibers in boreholes. With the intermediate-scale broad band array wavefield coherency will be evaluated through inter-station cross correlations to locate most contributing sources using a similar approach than recently developed for volcanoes[62] (Figure 5), based on identifying dominant sources using matrix singular value decomposition and locate them based on time delays from cross-correlation function envelopes. These coarser-array observations will be best exploited in combination to the 20-km long fiber observations as well as to the satellite observations conducted in WP3.

Task 2: Unravel water pressure gradient and conduit sizes in channels and/or well-connected cavities at the ablation zone scale

We will evaluate changes in water pressure gradient and conduit sizes in both space and time using seismic signal amplitude (and not phase as in tasks 1 and 3) and a dedicated theoretical framework[51,54,56,78] applied to the intermediate-scale array (e.g. Figure 5f). Such analysis typically requires measuring subglacial discharge at the glacier outlet, which will be made at the outlet of Russel Glacier but not at the outlet of Store Glacier, since basal water finishes in the ocean. We will overcome this difficulty by exploiting the increased benefits provided by our seismic array, considering that stations at the outlet experience flow conditions at constant atmospheric or hydrostatic pressure gradient, and thus can be used as a proxy of flow discharge[52,79]. Further understanding of the type of subglacial hydrology network controlling the detected changes in pressure gradient and hydraulic radius will be brought by comparison of physical results with the present technique with source localization results obtained in task 1.

Task 3: Unravel poorly-connected cavities from tomography at all scales

We will infer poorly-connected cavity properties (changes in water pressure, size and orientation) through their effect on seismic waves propagation[63,80]. We will recover wave velocities through 2D surface-wave Eikonal-wave tomography[77,81,82] using local icequakes for the small-scale array, which thanks to crevassing are numerous in Glacier environments[55,57,83], and using noise cross-correlation[75,76] for intermediate-scale array, since icequakes may not be coherently observed on all stations at this scale. Tomography will be performed over a range of frequencies (1 to 20 Hz), such that inverse wave modelling using dedicated operational solvers[84,85] can be used to attribute surface wave velocity changes to P- and S-wave velocity changes at the ice-bed interface. Using both Rayleigh and Love waves will enable better constraining the depth of velocity changes, as well as potential anisotropy in these changes[63]. Finally, we will accurately evaluate medium temporal changes by applying double differences techniques on icequakes or the stretching method on cross-correlation functions (REFS).

Task 4: Explore other potential mechanisms as source of marine- to land-terminating increase in bed slipperiness.

Seismic and complementary observations will also be analyzed separately from the subglacial hydrology problem in order to assess other dynamical mechanisms potentially differing between land- and marine-terminating glaciers. We will pay particular attention to the potential occurrence of underground water flow in saturated till the complex variations in ice structure with depth, which can occur as a result of crevassing, changes in ice nature (pre- or post-holocene) and mechanical properties such as driven by anisotropy and water content (REFS Duval, LaChappelle)[47,61].

Task 5: Compare results with complementary observations and physical-model inversions

Seismic findings about subglacial hydrology characteristics obtained in Tasks 1 to 3 will be thoroughly compared with complementary observations in order to cross-validate results. We will compare subglacial hydrology source locations with basal water pressure measured in boreholes and bed topography inferred from radar. This will enable us to test our seismic inference of channels versus well- versus weakly-connected with respect to their expected links with basal water pressure amplitude and variations as well as with flow pathways minimizing hydraulic pressure gradient. We will also investigate hydro-dynamics coupling by confronting subglacial hydrology findings with glacier dynamics inferred from complementary observations and inverse numerical modelling (see Task 1 of WP4 for specifics about inversion modelling)[86,87].

Team and collaboration

The Ph.D. student and postdoc will be supervised by me and co-supervised by Philippe Roux (ISTerre). He will focus his thesis on observing and understanding active drainage pathways, thus conducting research involving tasks 1, 2 and 4. I anticipate that the student will write a minimum of three papers, two involving tasks 1 and 4 and a third one involving tasks 2 and 4. The postdoc will focus his work on understanding glacier structure, basal water storage and its links with active drainage based on conducting tasks 3 and 4 and using the results of the Ph.D. student as inputs.

All the work will be conducted in close collaboration with Aurélien Mordret (ISTerre), Nikolai Shapiro (ISTerre), Olivier Coutant (ISTerre), Luc Piard (IGE), Andrea Walpersdorf (ISTerre), Stephane Garambois (ISTerre) and Marc Wathelet (ISTerre).

WP3: Analysis of satellite data to unravel subglacial hydrology characteristics and its links with ice dynamics (3 yrs postdoc 2)

Rationale. Although widely used in other contexts such as for studying the Earth's crust (REFS), differential radar interferometry DInSAR has traditionally little been applied to the study of glacier dynamics, mostly as a result of signal analysis being highly challenging for such application. Signal phase discontinuity and unwrapping errors are often caused by glaciers moving too rapidly, especially on fast-moving Greenland outlet glaciers, and phase decorrelation often occurs as a result of the glacier surface reflectivity changing continuously in response to surface melt (REFS). Improved monitoring capabilities and processing schemes have allowed strongly increasing our capability to retrieve the signal, at least in situations with non-significant changes in surface properties, such as in winter. In this work package we will focus on more fully characterizing such complex physics over a range of settings including land- and marine-terminating glaciers.

Task 1: Use winter lake drainages to probe subglacial flow drainage characteristics widely

We will conduct systematic DInSAR to recover high precision and resolution velocity fields over the entire 10 years' time span of Sentinel 1 (2013-current) and all across Greenland. We will then detect transient speed-up events present in these velocity fields, which we will link to lake drainage events by searching for emptied lakes using Landsat 8 and Sentinel-2 optical images. A precursory search using DInSAR processing in the region near the observed event revealed two additional winter lake drainage events (in 2019 and 2021)[67], suggesting winter drainage events are likely relatively common, such that that at least several tens up to few hundreds of events may be detected with this approach. This will enable gathering significant statistics on flow drainage characteristics and hydro-dynamics coupling across a range of setups. Quantifications will include drained lake volume based on surface altimetry using ArcticDEM elevation data[88], average flow drainage velocity, average bed separation area and height, as well as average multi-scale bed separation spatial heterogeneity, inferred from 2D spectral analysis.

Task 2: Improve observational capabilities by exporting the technic to weaker meltwater input changes

Lacks of lake drainage occurrence in certain regions may bias statistics and complexify interpretation. To reduce potential bias, increase observational completeness across Greenland but also in the Russel and Store glaciers where field instrumentation is planned, we will evaluate DInSAR velocity changes in response to continuous changes in surface melt rates. The challenge here is that coherence loss will be much more widespread due to melt-driven changes in glacier surface properties. Nevertheless, preliminary analysis shows structures similar to reported in Figure 6 for winter lake drainage can be recovered in the late melt season when coherency is recovered and glacier slow-down is observed and inferred to be due to the dewatering of isolated channels[20,89].

Task 3: Compare results with complementary observations and physical-model inversions
In a similar philosophy than in WP2/Task 5, geodetic findings about subglacial hydrology characteristics will be thoroughly compared with seismic and other complementary observations in order to cross-validate results. We will also investigate hydro-dynamics coupling by confronting subglacial hydrology findings with inverse numerical modelling (see Task 1 of WP4 for specifics about inversion modelling)[86,87]. In particular, model inversions will enable us to test whether the horizontal velocity field being much smoother than bed separation is due to stress transmission within the ice[17,86,90] or to water pressure increases emanating beyond the uplifted region.

Team and collaboration
DInSAR analysis will be done by postdoc 2, who will be supervised by myself and by John Merryman Boncori and Anders Kusk at the National Space Institute in Denmark. This work will also be conducted in close collaboration with Jonas Kvist Andersen (now postdoc at the Geological Survey of Denmark and Greenland), who has performed all preliminary analysis to this work.

Key intermediate results
-Highly-resolved maps and physical parameters associated with active drainage in channels and well-connected cavities covering the entire glacier ablation zone and melting season, with resolutions as low as few tens of meters and few hours, and on both marine- and land-terminating settings.
-Highly-resolved maps and physical parameters associated with weakly-connected cavities governing overall basal water storage over the entire glacier ablation zone and an entire year, with resolutions as low as few tens of meters and few hours in summer.
-Evaluation of the control of differences in subglacial hydrology characteristics on bed slipperiness, both at small scales and between marine- and land-terminating glacier ablation zones.

Risk Mitigation
- Highest risk is associated with the field plan in WP1, which involves the deployment and maintenance of numerous sensors of various nature, including particularly innovative fiber optic monitoring techniques, at spatial and temporal scales never addressed before including in boreholes, and under spatially and temporally changing glacier surface conditions. However, risk is mitigated by the strong expertise the team of collaborators and I have developed in the past in Alpine environments during the RESOLVE (2018, https://resolve.osug.fr/) and SAUSSURE (2018-2023, https://saussure.osug.fr/) projects, in which we pioneered the deployment of dense seismic arrays on glaciers[57], and successfully conducted all the presently foreseen experimentation, both at the surface and in boreholes. The big change here will be the scale of investigation and the remote conditions, which leaves less backup solutions than in the Alps. Although my personal experience to field instrumentation on Ice-Sheets is limited, our technical department at IGE has strong expertise in field operations in Antarctica. The technical department of IGE also has strong experience in the development and operation of ice drilling devices, and the technical department at ISTerre has strong expertise in surface geophysics. Geophysical pools of instruments through the national facility SISMOB (https://sismob.resif.fr/) ran by colleagues from Grenoble also provide crucial grounds for making the foreseen deployments possible, as they provide sensor engineering and technical expertise with configuration, data quality check and preliminary analysis in the field. Deployments with Nodes will also strongly benefit from the expertise gained in the context of the ERC Fault Scan lead by Florent Brenguier in ISTerre. This wealth of expertise gathered within the same research environment is rare, and will be highly beneficial to maximize data acquisition and quality. Risk is also mitigated through our instrumentation timeline. We will first instrument Russel Glacier, which is more accessible, less crevassed and thinner (requiring less drilling) than Store Glacier. The experience that will be gained there will be of crucial importance for instrumenting Store Glacier in a second stage, where field deployments will be more challenging due to the glacier being farther from infrastructures, more crevassed and thicker.
- High risk is also associated with the very unlikely but not impossible scenario that our increased observational capabilities lead to the identification of a yet unforeseen process other than subglacial hydrology controlling marine- to land-terminating increase in bed slipperiness. Such a discovery would make MorPoFee and thus our AIM2 obsolete. However, I believe that even if such scenario was to occur, this result would nevertheless be crucial to share with the entire scientific community. It is possible that this other yet unidentified mechanism also exerts a feedback as glacier transition from marine- to land-terminating, in which case it will crucial to know, and I will readjust AIM2 accordingly.

- Risk is also associated with the portability of seismic proofs of concepts established on mountain glaciers to Greenland, as well as our capabilities to fully incorporate the novel optic fiber observations into the foreseen data analysis schemes. Although all pre-requisites are full-filled in the proposed plan, no investigation at these scales have been done before. Planned signal processing analysis might thus not work straightforwardly, and improvements may need to be made in signal processing schemes. Analysis of DAS measured ground vibrations will also involve potential specific developments to account for differences in the nature of the measurement compared with seismic sensors, which corresponds to strain rate rather than velocity, and is unidirectional rather than three-dimensional. This risk will be mitigated through closely collaborating with experts of these methods, namely Philippe Roux, Nikolai Shapiro, Aurélien Mordret, Olivier Coutant and Stephane Garambois from the ISTerre laboratory, and by interacting with Diane RIVET in GeoAzur (Nice, France) who leads the ERC ABYSS that aims at monitoring megathrust faults with long distance under water optic fiber monitoring.

AIM 2: Evaluate the impact of MorPoFee on the Greenland Ice-Sheet evolution and contribution to sea-level

Rationale. As stated in Part A-State-of-the-art, current large-scale ice-Sheet evolution models are typically not expected to properly capture MorPoFee, either because they do not represent subglacial hydrology (REFS?) or they represent it too simplistically as in PISM[91] or SICOPOLIS[92]. In PSIM the subglacial hydrology control on basal slipperiness is done through describing effective pressure in a till layer as a unique function of water input rate and Budd-type friction law[93] is used to predict basal sliding[94–96]. In SICOPOLIS basal friction is function of a water sheet thickness that is simply proportional to basal melt rate. In both cases, cavity and channel dynamics as key ingredients for representing the control of morphology on basal friction are ignored, which makes these models inoperant at reproducing MorPoFee. In fact, I expect that even the most elaborated frameworks including descriptions of channel and cavity drainage as well as coupling with glacier bed friction[8,35,37] very likely fail at quantitatively capturing MorPoFee spontaneously, and this for two main reasons. First, these models incorporate numerous poorly constrained physical parametrizations that, using classical parameters values, may lead to inconsistent behaviors of A_s with changes in glacier morphology. Second, these models likely still incorporate lacking important physics, as most of them do not describe the weakly-connected cavity network, although it is known to play a crucial role in Greenland[16–18]. To properly evaluate the impact of MorPoFee on the Greenland Ice-Sheet evolution, I plan to first test its reproducibility in constrained physically-based models (WP4), such that appropriate parametrized law can be established between glacier morphology and A_s, and the impact of MorPoFee on the Greenland Ice-Sheet evolution evaluated (WP5).

WP4: Refine physically-based hydro-dynamics models and test their ability to reproduce MorPoFee (*PhD*)

Rationale. We will evaluate the ability of hydro-dynamical models to reproduce MorPoFee using the state-of-the-art hydro-dynamics model we recently developed in Elmer/Ice[97] for application to an Alpine glacier[37], which incorporates channel and cavity flow using the GlaDS model[35] and a consistent two-way coupling between subglacial hydrology and basal sliding[37]. Surface-melt water input will be prescribed from surface mass balance using the regional climate model MAR[98], while lake drainage input will be prescribed from lake volume and drainage time estimates based on optical imagery[67]. After model initialization (Task 1), we will use observations obtained in AIM1 to constrain physical parameters in descriptions of channels and well-connected cavities (Task 2) and to propose physical descriptions of weakly-connected cavities (Task 3). Finally, in Task 4 we will test the ability of our revised physical model to spontaneously reproduce MorPoFee and establish a physical parametrization that will be used in WP5.

Task 1: Initialize the model through inversion

Model initialization will be done by inverting basal velocity and shear stress through best fitting surface velocities given constraints on surface and bed topography and ice rheology. Ice rheology will be obtained from ice temperatures from a paleo-spin-up model[99] at large scales as well as from borehole temperatures and strain rates at the small scale, either observed by us in this project or by others[90,100]. Modelling will be applied at the scale of glacier ablation zones with a mesh scale on the order of few hundreds of meters, with mesh refinement down to few meters in places associated with the small-scale instrumentation. Proper boundary conditions will be prescribed using surface and bed DEMs from ArcticDEM[88] and Bedmachine3 (REF) at the intermediate scale and from Drone and Radar imaging at the small scale. Bed slipperiness as inferred from the ratio between basal velocity and basal shear stress resulting from this inversion will be used in AIM1 (see WP2/Task5 and WP3/Task3) to diagnose the effects of subglacial hydrology characteristics on basal friction.

Task 2: Constrain the current hydro-dynamical framework

We will run forward hydro-dynamical model predictions through time in all glacier and scale configurations investigated in AIM1 in order to constrain underlying physical parameters through best matching observations yielded therein (see **Key intermediate results** in page XX). Observations in AIM1 being made throughout the season and at different elevations will enable us to constrain the physics of cavity flow separately from that of channel flow, which occurs preferentially at low elevation and high melt-rates[69]. Confirmation of cavity versus channel flow occurrence will also be done based on seismic sources locations, which are more spatially distributed for cavity flow[53], and subglacial drainage speeds as inferred from satellite observation of lake drainage, which are lower (on the order of 0.1 m/s) for cavity flow[69]. We will constrain cavity drainage conductivity based on flow speed, resolved in WP3, and flow spatial heterogeneity, resolved in both WP2 and WP3. I expect smaller conductivity to be associated with slower cavity drainage as well as more tortuous flow pathways, since hydraulic pressure gradients are in that case . We will constrain parameters setting channel drainage evolution (associated with conduit wall melt, creep closure rates and water drawdown from cavities) based on seismic inference of channel inception as surface melt rate increases, channel localization with respect to hydropotential and temporal evolution of channel size and pressure gradient in response to changes in melt-water input.

Task 3: Implement weakly-connected cavities

In subglacial hydrology theories, higher water pressure means bigger cavities (REF) and higher cavity connectivity (), which is inconsistent with observations that pressure in weakly-connected cavities is higher than in well-connected cavities (REFS). We will aim at solving this inconsistency following previous consideration that cavities can only connect when exceeding a critical size[36], but with the added necessary complexity critical cavity size for connectivity is spatially heterogeneous. This added complexity is I believe central to the problem: a spatially heterogenous critical size for cavity connectivity allows a population of cavities to be large and high-water pressure while not necessarily being connected to the overall, lower water pressure drainage system. This hypothesis also physically makes sense to me when envisioning real beds, which are characterized by various bump geometries and respective organizations that may either facilitate or impede cavity connectivity. We will test this hypothesis by conducting model predictions considering a range of distributions for critical cavity sizes, and compare these with our observations of cavity drainage patterns inferred from seismic source localization (AIM1/WP2/Task1) as well as with our observations of cavity volume and geometry from seismic wave tomography (AIM1/WP2/Task3).

Task 4: Test model ability to spontaneously reproduce MorPoFee

We will test the ability of MorPoFee to spontaneously arise in our hydro-dynamics model by performing simplified modelling scenarios using an analogous slab of few square kilometers corresponding to grid size in large scale models with geometry prescribed to iteratively vary from a steep, thick and fast glacier corresponding to a marine-terminating glacier to a shallow, thin and slow glacier corresponding to a land-terminating glacier. For each steady-state situations we will calculate the effective coefficient $A_s = u_b/\tau_b^m$ where u_b is averaged over the whole domain and τ_b in that case equals driving stress $\rho_i g H S$, with ρ_i the ice volumic mass, g the acceleration due to gravity, H the glacier thickness and S the glacier surface slope. We will test if the predicted change in A_s between a marine- and a land-terminating glacier configuration match those observed in our recent study[12], and if varying melt-water input rates has negligible influence on A_s, as also found in our observationally-based study[12]. Finally, we will establish a parametrization of A_s as a function of u_b, S and potentially H for use in WP5.

Team and collaboration

This work package will be conducted by Ph. D. 2, who will be supervised by me and Adrien Gilbert, in collaboration with Olivier Gagliardini and Fabien Gillet-Chaulet.

WP5: Evaluate the impact of the morphology control on bed strength on Ice-Sheet evolution from paleo-climatic timescales to upcoming decades (*2 yrs postdoc 3*)

Second, we will implement these links in the large-scale numerical models GRISLI (REFS) and Elmer/Ice (REFS) in order to properly predict the impact of MorPoFee on a full deglaciation (120 kyr until now) and up to year 2200, respectively.

We will quantitatively test the ability of large-scale numerical models to represent MorPoFee using the numerical codes GRISLI (REFS) to investigate paleo-climatic timescales and ELMER/Ice (REFS) to investigate modern times associated with coming decades up to few centuries. In both cases we will use existing Ice-Sheet model setups in which we will formulate the relationships between effective pressure and sliding velocity established in task WP4, and for which we will have already demonstrated that MorPoFee spontaneously arises with magnitude similar to presently observed. We will then compare model outputs such as glacier mass balance and glacier front positions with and without improved subglacial hydrology physics, which will enable us to conlude on the importance of MorPoFee on Ice-Sheet evolution.

Task 1: Evaluate a synthetic deglaciation case
Run the physical model on a targeted glacier in which front position is prescribed based on ISMIP 6, compare with predictions using constant A_s and establish A_s dependency on surface slope and basal sliding velocity in order to match large scale predictions with those from the physical model.

Using existing calving law, a parametrized description of front buttressing

Task 2: Evaluate the effect of MorPoFee in decades to centuries to come
Prendre etats initiaux ISMIP6 et regarder si le resultat de Nate est prédit. Evaluate model initial states
Test if large scale models in ISMIP6 reproduce the pattern in Figure XX, and evaluate if the ones that don't are also associated with a misrepresentation of basal friction

Goelser : Taux retrait front –

Task 3: Evaluate the effect of MorPoFee in paleoclimatic predictions
GRISLI
Improved parametrized law on link between N and tau_b – 21000 ans – 3 Myr Plyocene Deglaciation – Define timescales

Key anticipated results

Risk

- *High risk associated with our ability to implement weakly-connected cavity descriptions, and if an appropriate parametrization ends up depending on that parametrization.*

Key intermediate goals

Team and collaboration
Postdoc 3 will conduct both tasks, and will be supervised by me and Aurelien Quiquet. He will also interact with Adrien Gilbert, Olivier Gagliardini and Fabien Gillet-Chaulet.

IMPACT OF THE PROJECT (Vision beyond the project): TECHNOLOGICAL AND WHAT WILL WE LEARN ? OTHER QUESTIONS THAT WILL BE STUDIED. PALEO SISMO GEOCHIMIST LONG TERM ICE SHEET

OVERALL FEASABILITY – AVAILABILITY FOR THE COMMUNITY
Expertise – Experts – Preliminary results before the project – Proof of concept

Why I need this funding? why now – why me - why now, for me and the community

Figure 7: Time Schedule Chart

REFERENCES

Testing and enriching the physics of hydro-dynamics models requires a thoughtful strategy to constrain physical laws from observations, as well as to develop new ones if needed. To test the impact of MorPoFee on Ice-Sheet evolution, I plan to proceed in two steps. First, we will evaluate physically-based models against the unprecedent observational constraints yielded with our newly acquired data (AIM1) in order to constrain all required physical components including flow within channels and cavities, as well as water storage in weakly-connected cavities (WP4). This will enable us to establish calibrated and physically sound descriptions of the links between glacier morphology, effective basal pressure and basal sliding speed.

Physically-based descriptions of subglacial hydrology and basal friction based on observational findings from AIM1

We will compare our observations with model predictions through successive steps of increasing complexity. First, we will initiate the dynamical-model by conducting model inversions of basal sliding velocity and bed shear stress from surface velocity observations (Task 1). Second, we will constrain physical parameters inferring in the description of channels and well-connected cavities through applying the hydro-dynamical model in the wide range of contexts documented with our observations (Task 2). Third, we will use our observational constraints to propose more satisfying physical descriptions of weakly-connected cavities and their interactions with the other components of subglacial hydrology (Task 3). Finally, we will

A key ingredient in our interpretation of bed slipperiness decrease as glaciers transition from marine- to land-terminating is the increased ability of active drainage in cavities and channels to drawdown water from weakly-connected cavities. Yet

In current theory, higher is the water pressure, bigger are cavities and higher is their connectivity. , higher is the water pressure. This representation fails at reproducing weakly-connected cavities, which are inferred to be higher water pressure than well-connected ones (REF), and that can switch for weakly- to well-connected under sufficient meltwater inputs (REF). In our model as well as others, , which is in contradiction with observations.