SEA ICE DYNAMICS: THE ROLE OF BROKEN ICE IN MULTI-SCALE DEFORMATION

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Realistic models of Arctic Ocean behaviour should capture the influence of broken ice acting as a fault gouge between sliding floes. We performed double-direct shear friction tests on floating saline ice floes in the HSVA ARCTECLAB, Large Model Basin, Hamburg. We have focused these experiments on angularity and size to determine fault gouge characteristics. In our experiments the displacements and deformation of ice gouge were characterized during on-going frictional slip for the first time. Both stable sliding and stick-slip behaviour were displayed. It appears that there are controls on behaviour according to gouge angularity. By measuring local stress, strain and acoustic emissions along the sliding interfacial fault we have captured the mechanics of the propagation of slip from slip initiation to dynamic propagation for the first time in the presence of broken ice.

1.   INTRODUCTION

As the Arctic warms, the extent of the Arctic Ocean sea ice cover is diminishing. But also the relative proportion of thick multi-year sea ice to thinner seasonal first-year sea ice is decreasing. The impact of the former will mean increased activity in the Arctic Ocean, particularly resource extraction and shipping (both freight and cruise liners), while posing challenges to indigenous people and to wildlife (Lishman, 2014). The impact of the latter will mean greater deformation of the sea ice cover as it is thinner, with generation of broken ice at all scales, which will influence the sea ice dynamics. Understanding the evolving sea ice thickness distribution and sea ice dynamics with on-going climate change is therefore crucial if the impacts of climate change are to be understood and adaptation strategies can be implemented.

Shear zones in the Arctic sea ice cover can be seen in Radarsat images as lineaments, often in sub-parallel sets (Kwok, 2001), of in-place sliding which may exert a strong control on the overall dynamics of Arctic sea ice cover (e.g., Hopkins, 1998; Schulson, 2004; Sammonds et al., 2005). Models of sea ice thickness are strongly dependent on the ratio of shear to compressive ice strength (Miller et al., 2005). Since shear deformation and slip is controlled by friction, a better understanding of the frictional behaviour is essential for a better understanding of overall Arctic sea ice dynamics. However, broken ice, acting like a fault gouge, can dramatically alter frictional properties (Scott et al., 1994). These may act at all scales (e.g., Marsan et al., 2004). Ice rubble consisting of broken ice is generated by Arctic vessels frequenting the same channel or as floes within a shear ice mass. At the local scale, accumulations of ice rubble provide resistance to repeated transits when it is both unconsolidated and consolidated (Mellor, 1980) and ultimately prevents transit through the channels. Understanding the frictional behavior and properties of consolidated rubble in this context could contribute to better management of these problems, and in future enable the use of Arctic shipping routes throughout the year. At the ocean scale, broken ice could exert a strong control on slip on cross-basin lineaments.

The frictional behavior of saline ice sliding in direct contact has already been described by empirical adaptations of Amonton's Law. Fortt and Schulson (2009). Lishman et al., (2011, 2013) have developed rate and state laws to describe this behaviour, and Hatton et al. (2011) and Schulson and Fortt (2013) describe sliding in terms of ice micromechanics and thermodynamics. What is not known is how the presence of broken ice between the sliding surfaces affects friction, and our work aims to address this
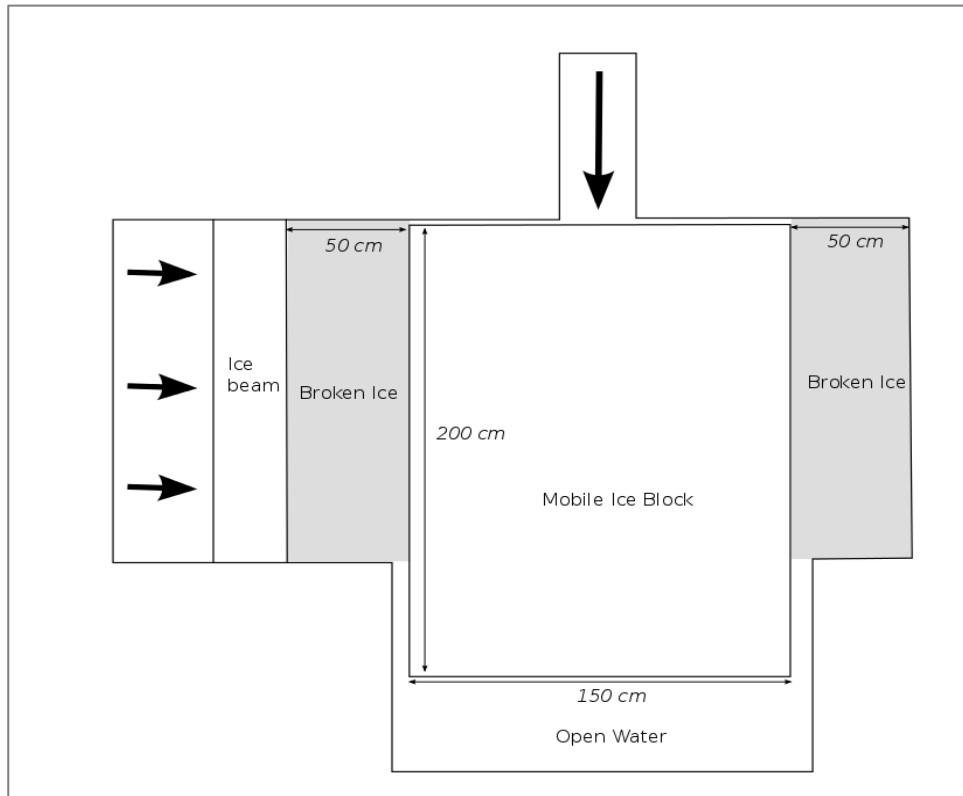
2.   METHODS

Figure 1. The experimental setup. A mobile, floating ice block is surrounded on two sides by regions of ice rubble. Side load is applied throughout the slide-hold-slide experiments by hydraulic jacks housed within a specially designed frame, denoted here by the three horizontal arrows.

Our method was to perform ice basin experiments in which a saline ice blocks, representing sea ice floes, with broken ice gouge are deformed by a pusher plate and confined by side loading panels (Figure 1). The experiments required the use of the HVSA ARCTECLAB Model Ice Basin (e.g. Lishman et al., 2009, 2011). The HSVA basin offered a controlled environment in which to conduct experiments, which contrasted with previous experimental field work in the Barents Sea in 2014 and 2015 (Scourfield et al., 2015). The ability to control variables such as temperature (which has been found to influence friction between saline ice blocks sliding in direct contact), ice thickness, applied shear stress and velocity greatly enhanced the quality of the results produced which could then be used for comparison with the aforementioned field experiments. A less challenging working environment also allowed the deployment of acoustic emissions sensors, which had previously been used to monitor fracture in ice. The advantage of using HSVA is that it allowed the use of saline water, which other comparable facilities do not.

Experiments simulated slide-hold-slide experiments (Sammonds et al., 2005; Lishman et al., 2011) (Fig. 1). A mobile, floating ice block surrounded on two sides by broken ice was held for specified "hold times" ranging from 1 second to hours. Following this, a direct load was applied to the central floating ice block and the force needed to reinitiate its movement recorded. Side load panels designed and built at UCL applied a normal force throughout. We used ice floes of up to 30cm thickness. The acoustic emissions produced during deformation was captured. Filming the ice rubble region during shear allowed analysis of the mechanisms involved during deformation (for example, the role of force chains and fracture), and where shear occurs within the rubble region.

We carried out a new investigation the effect of ice rubble angularity on frictional behavior such as sliding stability and frictional strength, and the response to the application of high and low normal stresses. Experiments were performed to investigate the behavior of fracturing of ice bonds under tension, to complement the shear tests.
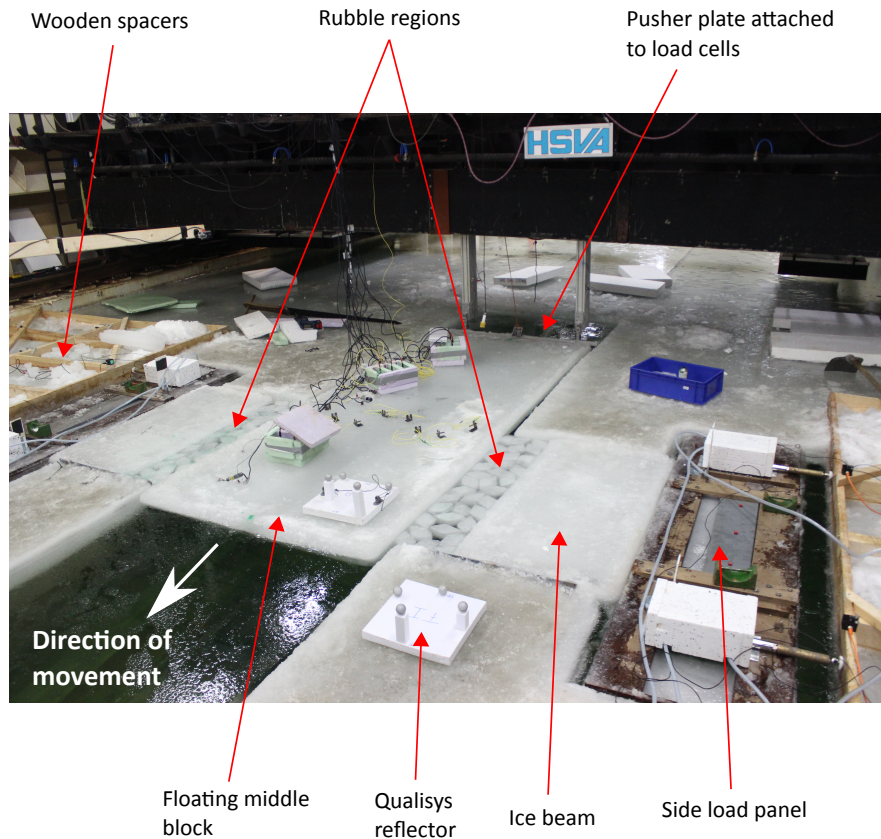
3.   RESULTS

Figure 2. A labelled photograph showing an experimental run in the HSVA ice tank.

A novel set of 4 double-direct shear experiments were performed with 4 velocity steps and 4 hold times steps. 4 fault gouges were used: flat pancakes and regular parallelepipeds of ice, each of two uniform sizes. Global loads pushing and side loads were measured by load cells and slip displacements by reflector tracking image capture. Local stresses, strains and acoustic emissions along the sliding fault interface were measured by embedded instruments. Dilatancy of the gouge was measured by laser range-finders. The experiments were recorded by a global view camera and a local view camera on the gouge. Experiments on ice-ice friction (with no gouge) and free-floating ice were also done to provide baseline data.

The level ice and stacked ice blocks were characterized by thickness measurements, temperature and salinity profiles, compression and four-point bend tests, thin sections and surface profiles (of the sliding faults and the layered ice)

Here we address the relationship between the maximum effective friction coefficient when sliding commences, μ_{peak} and hold time. Values for μ_{peak} were extracted by identifying the time at which the maximum load occurred when sliding commenced and taking the corresponding value for μ at that time (Fig. 3). Two regimes appeared to exist, before and after a hold time of approximately 10^4 seconds. In the first regime, after shorter hold times, μ_{peak} changed very little. After longer hold times, in the second regime, μ_{peak} increased significantly. We believe that in the first regime (at short hold times) μ_{peak} was low because the contribution of consolidation to resistance was minimal, and the rubble pieces were free to move around. In the second regime (at long hold times) consolidation, or the shear strength of the consolidated rubble region, was the primary cause of high resistance. As such, friction was not a suitable way of describing resistance in this regime as the processes of consolidation took over. We also noted that increased acoustic emissions signals are recorded when sliding recommences after long hold times. These suggested the occurrence of fracture and supports our assumption that at long hold 2 times, the shear strength of the consolidated rubble region is responsible for the 1.5 resistance to sliding.
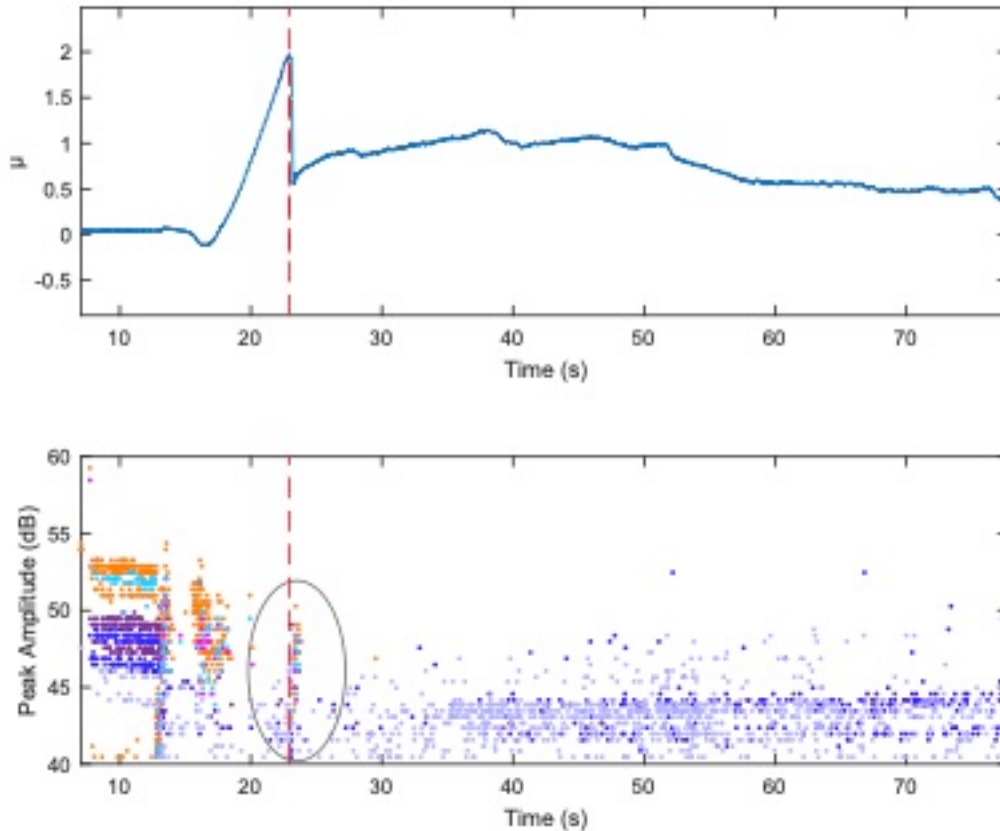
Figure 3. Experimental results showing how the effective coefficient of friction and acoustic emission activity vary during an experimental run. The peak in *µ* after a hold time of 10,000s is shown. (The increased acoustic emission activity at 22s in an artifact.)

4. DISCUSSION

Realistic models of Arctic Ocean behaviour should capture the influence of broken ice acting as a fault gouge between sliding floes. We have focused here in these experiments on angularity and size to determine fault gouge characteristics.

In our experiments the displacements and deformation of ice gouge were characterized during on-going frictional slip for the first time. Both stable sliding and stick-slip behaviour were displayed. It appears that there are controls on behaviour according to gouge angularity. By measuring local stress, strain and acoustic emissions along the sliding interfacial fault we have captured the mechanics of the propagation of slip from slip initiation to dynamic propagation for the first time. By measuring friction under conditions of stepped velocities and hold times we are able to incorporate the influence of fault gouge into a modified rate and state friction law. This will be developed on the full analysis of the experimental results. The advantage of a rate and state law is that it is a relatively simple empirical law, but captures much of frictional behaviour.

The effect of hold time on the effective peak coefficient of frictions, μ_{peak}, falls into two distinct regimes - before approximately 10^4 seconds (where μ_{peak} is low), and after (where μ_{peak} increases dramatically) (Fig. 4). This trend is common to all rubble types. In the first regime, friction is controlled primarily through rubble dynamics - the contribution of consolidation is minimal. In the second regime, consolidation, or the shear strength of the consolidated rubble region, is the primary cause of high resistance. As such, at long hold times friction may not be a suitable way of addressing this problem

Novel experiments on stacked ice blocks, free floating and submerged, with both a liquid interfacial layer and none, have for the first time characterized the development of the consolidated layer under these conditions in the controlled environment of an ice tank. These will be used to test a thermal and mechanical consolidation model.

We have trialed a new experiment local strain measurement system. Difficulties we encountered included the loading pusher plate breaking under high loads and there was insufficient loading

capacity for ice consolidated beyond 10,000s. We overcame this by separate consolidation experiments on stacked ice blocks and measuring the interfacial shear strength. We used one test temperature of -10 deg C. The experiments were of such complexity and duration that repeats at a different temperature were not practical. The environmental test tank at HSVA was unavailable. We used the large ice basin which has lower salinity water. These did not detract from the overall findings from the experimental programme.
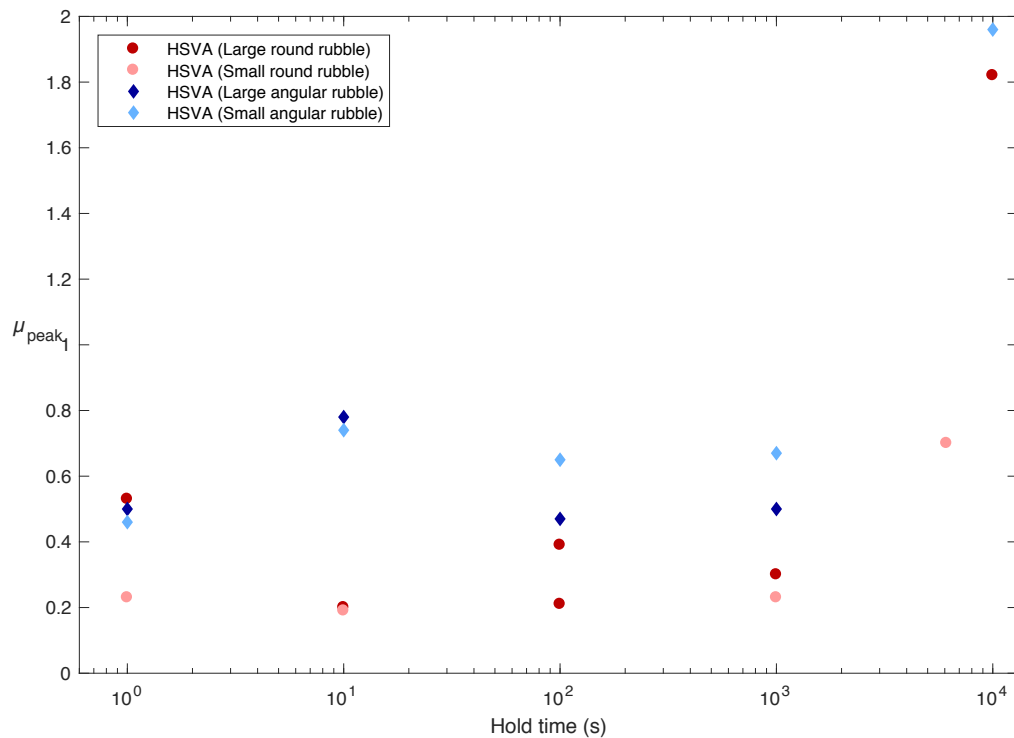

Figure 4. The relationship between μ_{peak} and the hold time for four rubble types. It should be noted that the μ_{peak} for the large angular rubble type at the longest hold time of 10,000s is not shown due to insufficient load capacity to move the ice floe under these conditions. But the lower bound limit is 7 kN. Force.

REFERENCES

Fortt, A.L. and Schulson, E.M. (2009). Velocity-dependent friction on Coulombic shear faults in ice. *Acta Materialia*, 57(15), 4382–4390.

Hatton, D.C., Sammonds, P.R. and Feltham, D.L. (2009). Ice internal friction: Standard theoretical perspectives on friction codified, adapted for the unusual rheology of ice, and unified. *Philosophical Magazine*, 89(31), 2771–2799.

Hopkins, M.A. (1998). Four stages of pressure ridging. *J. Geophys. Res.* 103(C10), 21883.

Kwok, R. (2001). Deformation of the Arctic Ocean sea ice cover between November 1996 and April 1997: A qualitative survey. *In IUTAM Symposium on Scaling Laws in Ice Mechanics and Ice Dynamics* (ed. J. P. Dempsey & H. H. Shen), pp 315-322, Kluwer Academic Publishers.

Lishman, B., Sammonds P. and Feltham, D.L. (2009). The Rate- and State- Dependence of Sea Ice Friction. *POAC*'09.

Lishman, B, Sammonds, P. and Feltham, D. (2011). A rate and state friction law for saline ice. *J Geophys Res*, 116, 1–13.

Lishman, B., Sammonds, P. and Feltham, D. (2013). Critical slip and time dependence in sea ice friction, *Cold Reg Sci & Tech*, 90-91, 9-13.

Lishman B. `and Sammonds, P.R. (2013). Memory in sea ice friction, *POAC'13*.

Lishman, B. (ed) (2014). Arctic Risk: A Discussion of the Possible Outcomes of Two Disaster Scenarios, *IRDR Special Report 2014-02*, UCL Institute for Risk and Disaster Reduction

Mair, K., Frye, K. and Marone, C. (2002). Influence of grain characteristics on the friction of granular shear zones, *J. Geophys. Res*., 107(B10), 2219

Marson, D., Stern, H., Lindsay, R. and Weiss, J. (2004). Scale dependence and locatization of the deformation of Arctic sea ice, *Phys. Rev. Letts*, 93, 178501.

Mellor, M. (1980). Ship resistance in thick brash ice. *Cold Reg Sci & Tech*, 3(4), 305–321.

Miller, P.A, Laxon, S.W. and Feltham, D.L. (2005). Improving the spatial distribution of modeled Arctic sea ice thickness. *Geophys Res Lett*, 32(18)

Sammonds, P. et al. (2005). Experimental study of sliding friction and stick-slip on faults in floating ice sheets, *POAC'05*.

Schulson, E.M. (2004). Compressive shear faults within arctic sea ice: Fracture on scales large and small, *J Geophys. Res*, 10.1029/2003JC002108.

Schulson, E.M. and Fortt, A.L. (2013). Static strengthening of frictional surfaces of ice. *Acta Materialia*, 61(5), pp.1616–1623.

Scott, D.R., Marone C.J. and Sammis, C.G. (1994). The apparent friction of granular fault gouge in sheared layers, *J Geophys. Res* 10.1029/93JB03361.

Scourfield, S. et al. (2015). The effect of ice rubble on ice-ice sliding. *Ports and Oceans Under Arctic Conditions (POAC)*.

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