Experimental Study of Hydrocarbon Transport Mechanisms in the Lake Fryxell Ice Cover, McMurdo Dry Valleys, Antarctica

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INTRODUCTION

The impetus of this study was the January 16, 2003 Bell 212 79U helicopter crash on the ice cover of Lake Fryxell in the McMurdo Dry Valleys of Antarctica. Approximately 200 gallons of hydrocarbon-based fluids, mostly JP8, JP5 and diesel with lesser oil and hydraulic fluid, were spilled out into the ice cover over Lake Fryxell. The McMurdo Dry Valley lakes have been sites of Long-Term Ecological Research (LTER) funded by the National Science Foundation. The experiments of this study tested the following hypotheses: (1) aeolian sediment on the ice cover could sorb hydrocarbons in jet fuel and, via radiation absorption and downward melting, transport contaminants below the hydrostatic level into the deeper ice and lake water, (2) the spreading rates of jet fuel in ice would be influenced by the melting point depression properties of fuel, and (3) the migration of sediment and jet fuel through ice would be influenced by structures including bubbles, fractures and grain boundaries.

METHODS

A series of experiments were carried out in an environmental chamber equipped with a shortwave radiation lamp to observe the transport processes of sediment and fuel in ice under solar loading. The preliminary experiments used both bubbly and fractured ice at different temperatures and radiation intensities. The following main set of experiments used only clear and unfractured ice in order to facilitate the study of fundamental processes involved with a system of ice, sediment, radiation and fuel. Based on preliminary results and the need to attain practical time scales, a chamber temperature of –5.1°C and solar lamp power of 590 Wm^{-2} was used which was thought to simulate Lake Fryxell conditions during November or December.

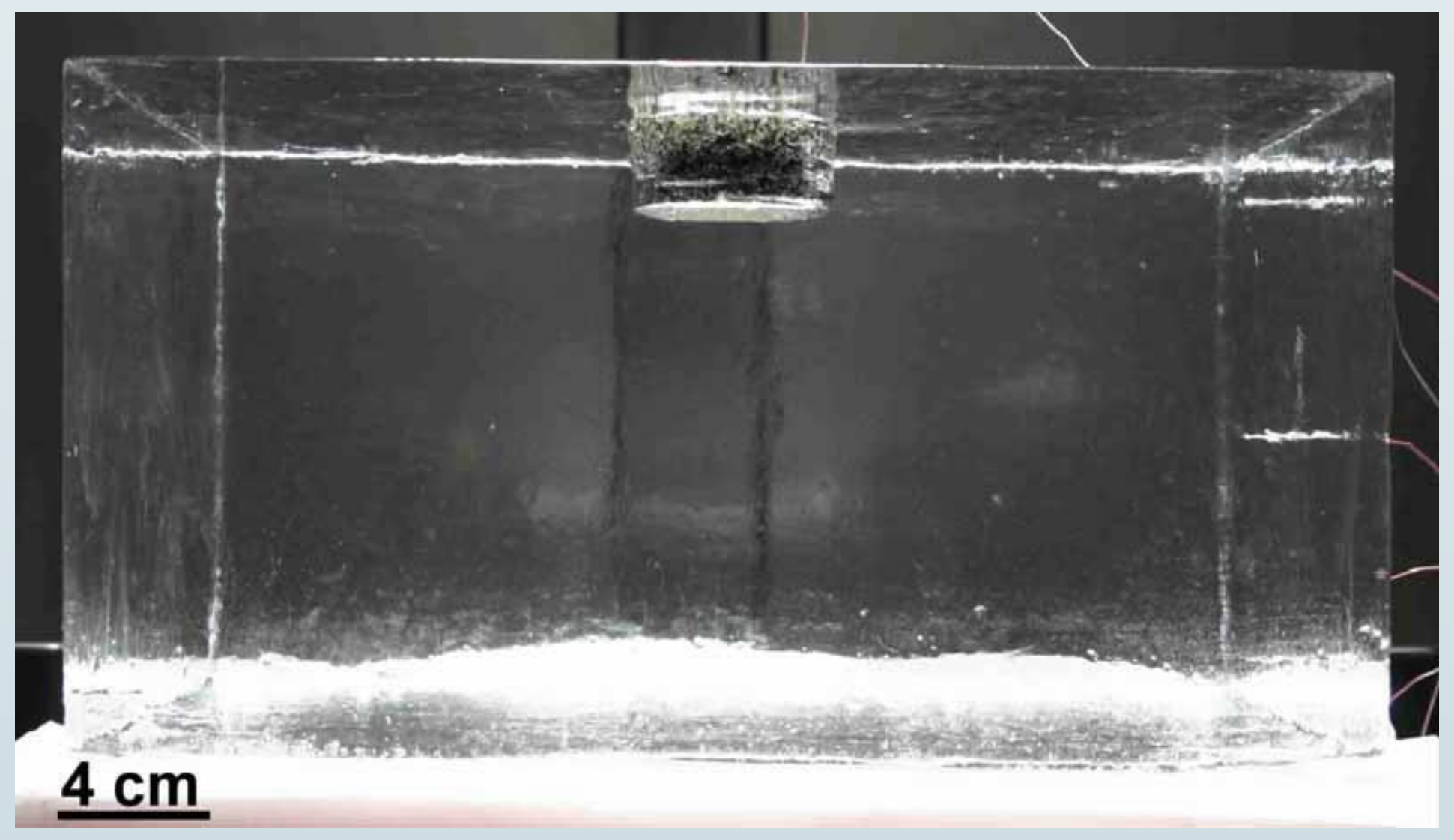

Figure 1. Clear ice block and material (sediment, fuel or combination) pocket at beginning of typical Fryxell experiment. Thermocouples on the right side.

RESULTS

The preliminary experiments established that fuel did indeed move along fractures in the ice. The following main set of experiments observed the melt dynamics of fuel and sediment in unfractured clear ice. In all experiments, the first visible melting occurred along grain boundaries well below the upper ice surface (Figure 2a). This melting took the form of swelling Tyndall figures and water veins. Most of the in-ice sediment remained in disks that melted downward. However, some of the finer-grained sediment percolated downward from the sediment disks in intergranular meltwater (Figure 2b). This enhanced intergranular mobility of the finer sediment acted as a natural sorting mechanism. The experiments also indicated that saturation of sediment with JP8 fuel had no noticeable effect on melt velocities through ice.

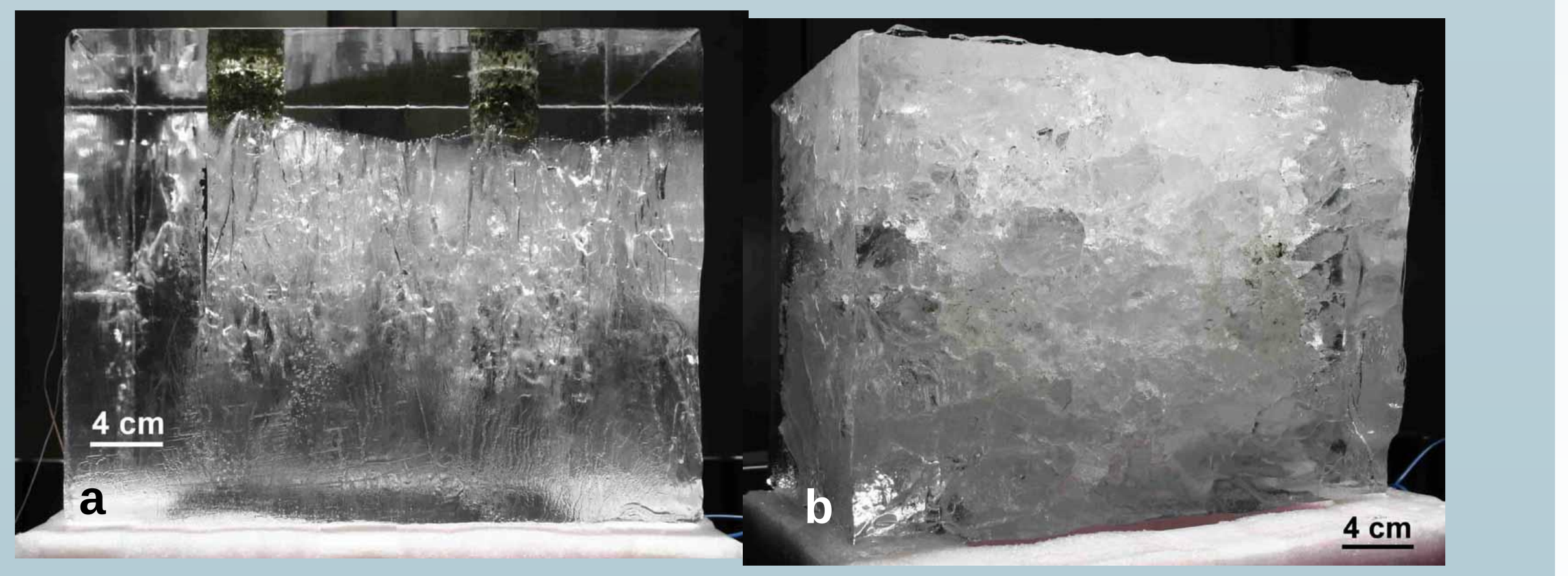

Figure 2. (a) Velocities of dry and fuel-contaminated sediment were compared. JP8 fuel did not noticeably affect the migration rate of sediment through ice. Note the initial intergranular melting below the upper ice surface. (b) Bottom view of the ice block showing patches of fine-grained sediment that was localized along grain boundaries.

Small quantities of coarse-grained sediment dispersed radially outward from the disks during the downward melt process. The initial internal melt structures in the ice propagated upward and intersected the bottom of the sediment pockets. This resulted in the downward channeling of sediment along intercrystalline water veins (Figure 3).

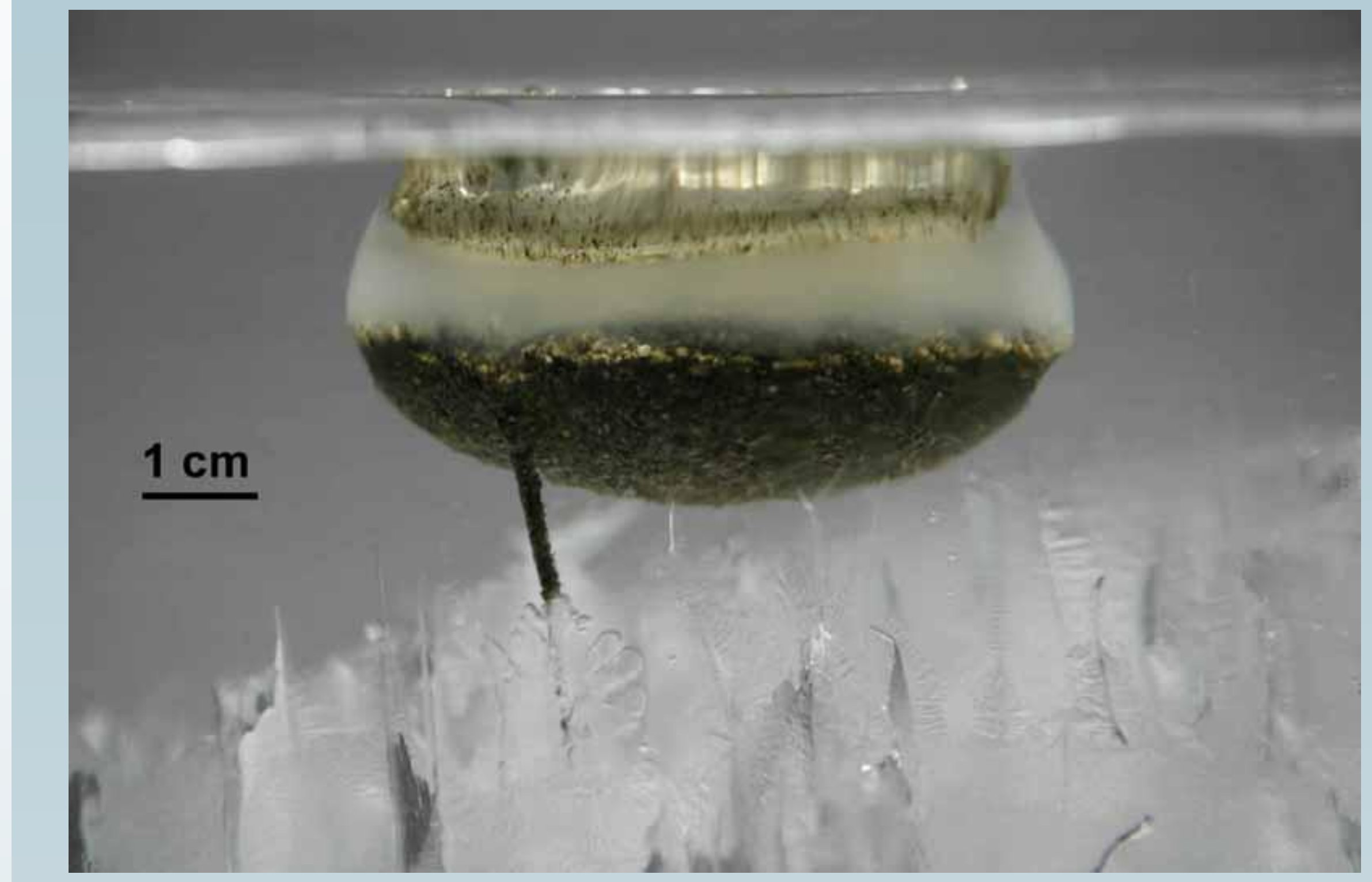

Figure 3. Sediment disk early in an experiment. An intercrystalline water vein was seen channeling sediment grains downward. The ice temperature within 0.5°C of the melting point.

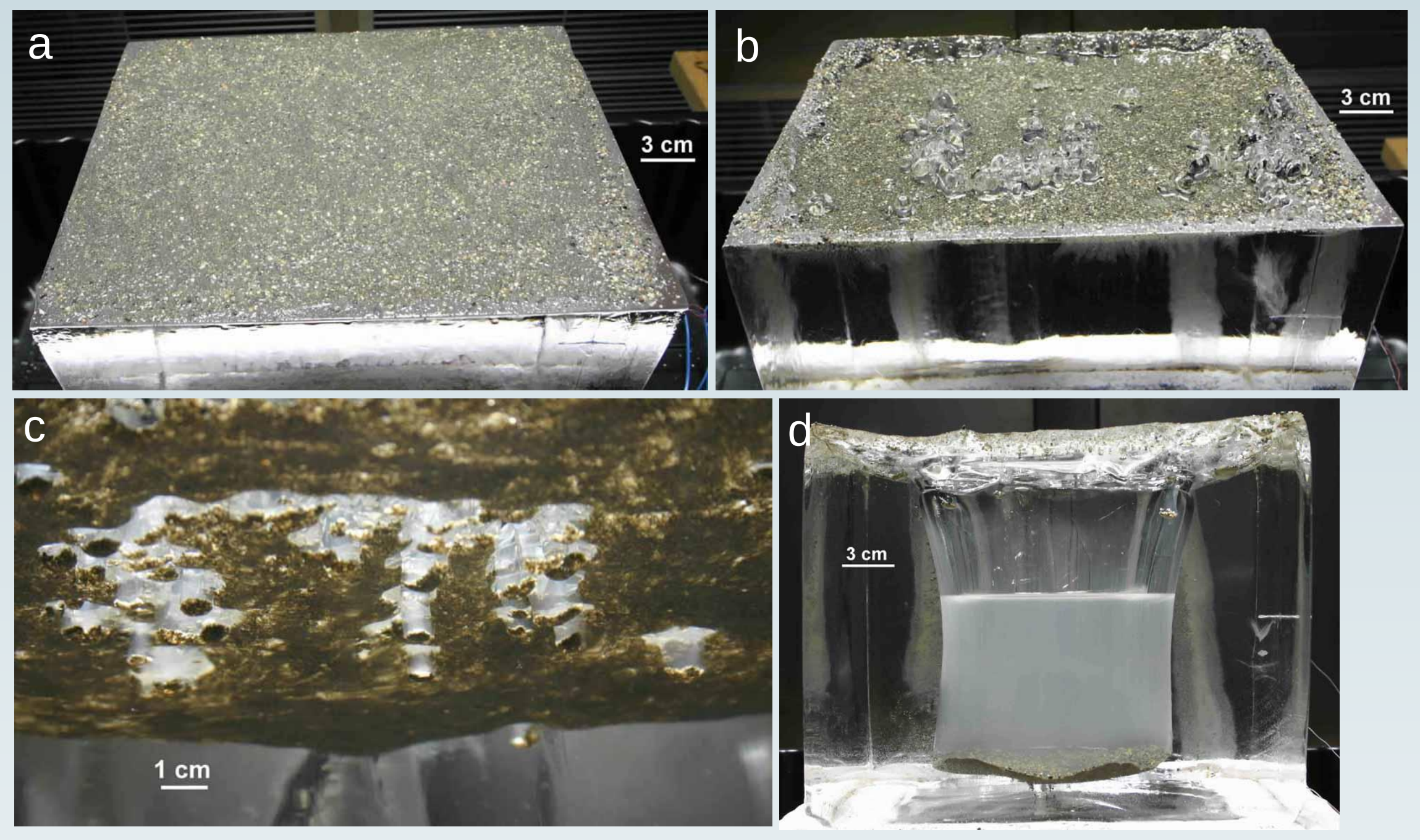

Figure 4. Observation of melt behavior of a mm-thick sediment veneer on ice. (a) Knob-like structures formed when temperature was within 1°C of melting, probably due to slight differences in initial sediment distribution. (c) Sediment coalesced beneath knobs to form numerous tubes illuminated by internal light reflections. (d) Tubes eventually merged into one large tube, pictured above during the sudden drainage of water.

The last experiment was conducted to observe how a thin veneer of sediment would melt through the ice (Figure 4). Unlike the other experiments, internal melting was not observed. This was attributed to the absorption and blocking of radiation by the sediment, or slightly lower ice temperatures caused by experimental changes in ice insulation. The sediment showed a strong tendency to coalesce into water-filled tubes (Figure 4c). These tubes did not appear to be influenced by the location of grain boundaries. The numerous small tubes eventually merged into one large tube filled with about 1 cm of sediment (Figure 4d).

In a different fuel-ice experiment, a pocket filled with JP8 fuel was observed (Figure 5). The initial activity consisted of meltpool growth below the fuel as a result of the melting point depression effects of the water soluble hydrocarbons.

Figure 5. Fuel-ice experiment to observe JP-8 fuel in ice. Fuel is pictured floating on a meltwater pool several mm in depth.

6.3 hours into the fuel-ice experiment, a 2-mm diameter tube formed below the pocket and channeled fuel and meltwater through the ice (Figure 6). The propagation rate of the tube was about 10 cm/hr in a direction averaging 49° below horizontal. The tube contained a chain of fuel, meltwater and air bubbles that was also observed in later experiments not using shortwave radiation. The fuel pocket was empty by 12.8 hours into the fuel-ice experiment. Later, numerous tubes were see extending downward from the empty pocket (Figure 6b).

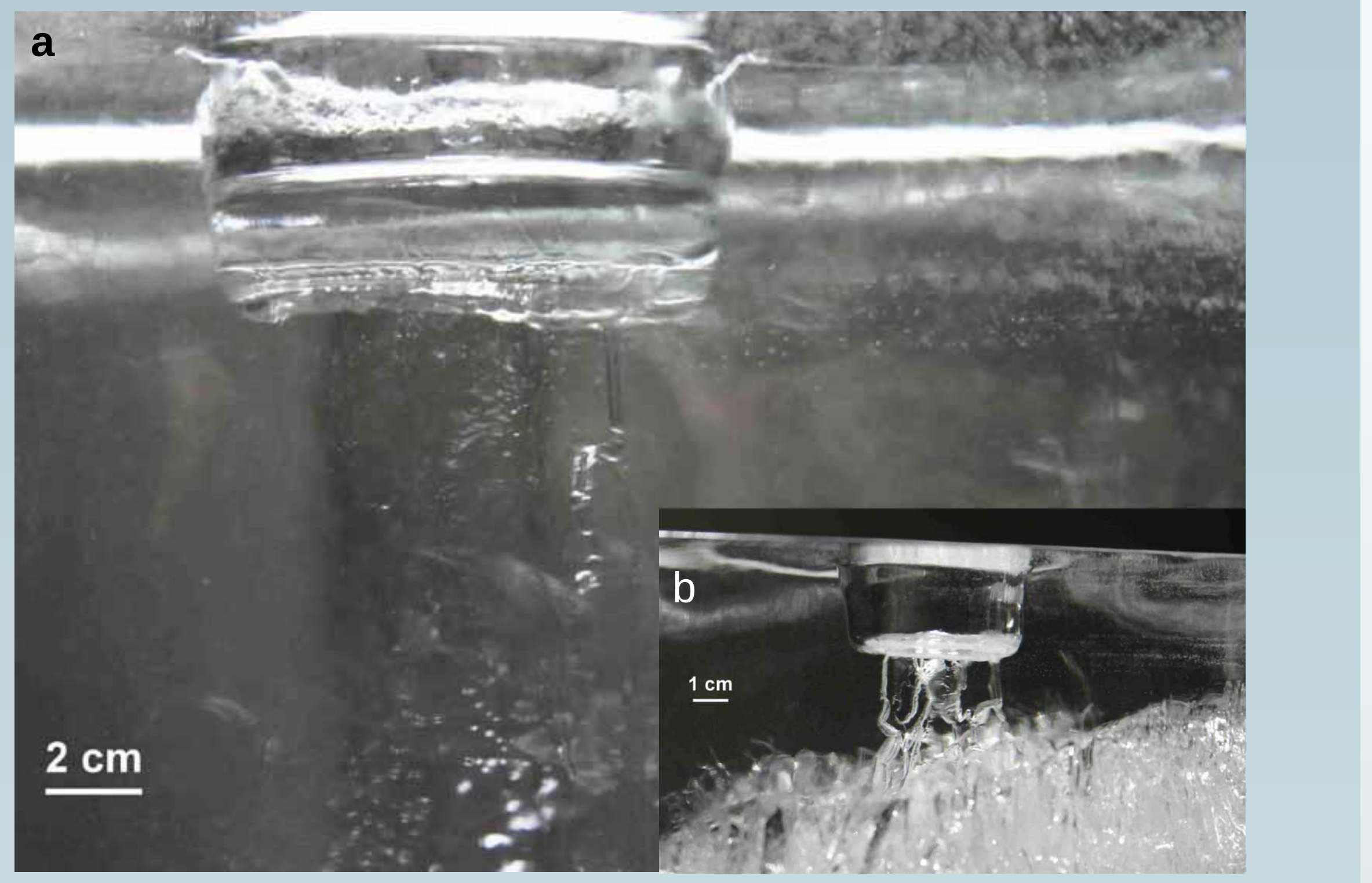

Figure 6. (a) Propagating fuel tube, 6.3 h into the fuel-ice experiment. Tube was ~2 mm in diameter and contained a mixture of fuel, meltwater and air bubbles. Ice temperature was within 0.5 C of melting point. The tube propagated at about 10 cm/hr and intersected the back surface of the ice block. (b) Veins visible below pocket after complete drainage of fuel, 12.8 h into experiment. Note the barely-visible vein below the left side of the fuel pocket in (a).

Another study was undertaken to observe, in dark conditions, the mobility of JP8 fuel in unfractured ice near the melting point. Motivating this study was the potential for drilling fluid contamination of subglacial lakes beneath the Antarctic ice sheet. In this study, light was restricted to ambient conditions suitable for 30-second image exposures. When the ice temperature was within 0.5°C of the melting point, fuel tubes formed and propagated downward along grain junctions at velocities greater than 16 cm/h (Figure 7). This "fuel tunneling" mechanism was observed in two different experiments, herein referred to as "Dark Fuel-Ice Experiments." This fuel tunneling phenomenon was absent in an experiment that used ice grown from distilled water. This ice would have had much smaller water veins due to lower impurity concentrations.This observation indicated that water veins played a key role in the mechanism of fuel tunneling. The conclusion was that solid ice is, in general, not impermeable to liquid hydrocarbon fuels near the melting point.

Following the Dark Fuel-Ice Experiments, the positions of the fuel-tubes were examined with respect to grain boundary locations. The presence of grain boundary surface grooves and triple junctions, visible between crossed polarizers, confirmed that all fuel tubes followed intersections between three or more grains (Figure 8).

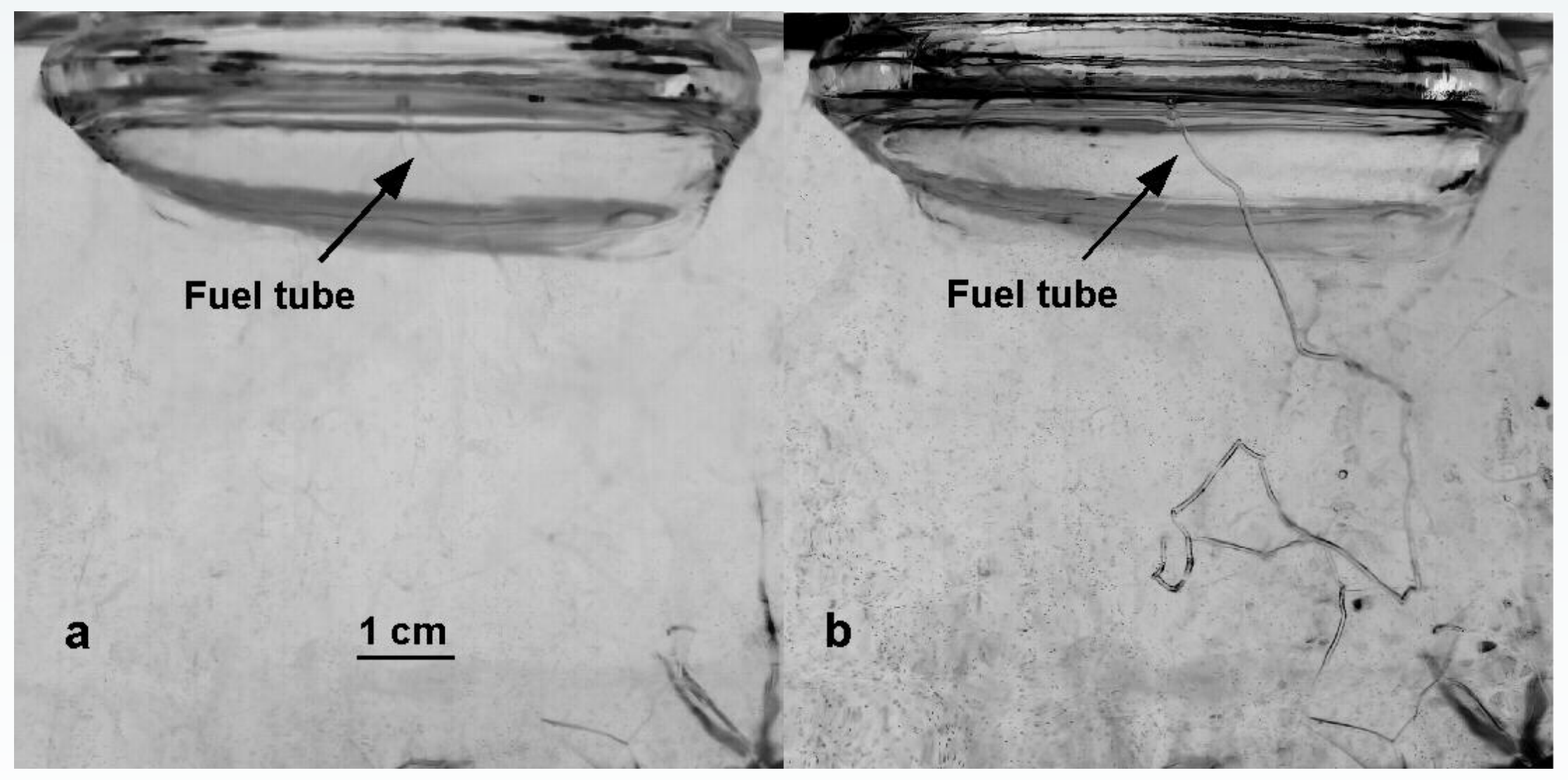

Figure 7. (a) Initial formation of fuel tube in Dark Fuel-Ice Experiment. (b) Fuel tube three minutes after it's initial formation. Fuel tube was 0.5 mm in diameter and propagated vertically through 8 cm of ice in less than 3 minute.

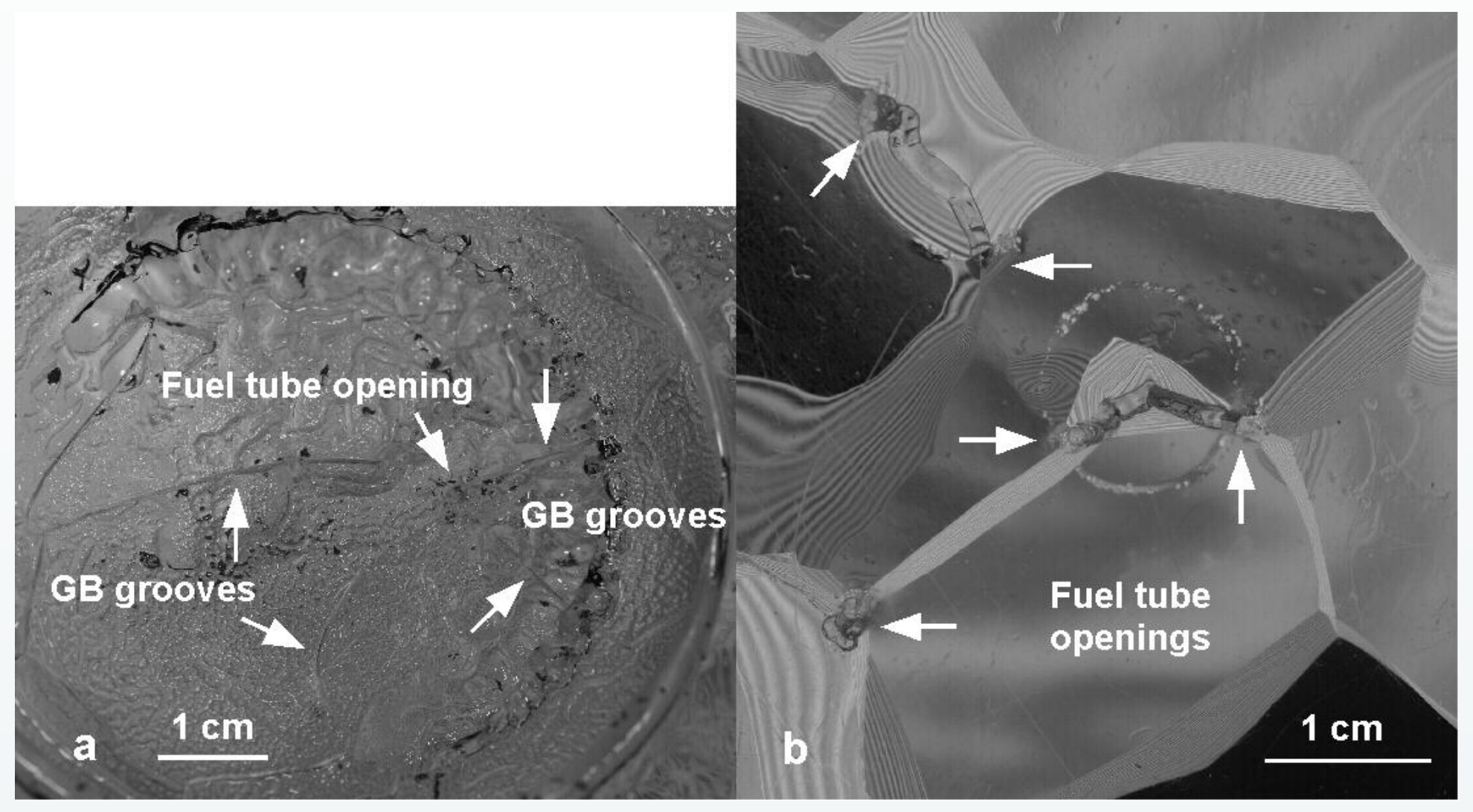

Figure 8. Sections of ice from Dark Fuel-Ice Experiments where fuel tunneling occurred. (a) Intersection of grain boundary grooves at fuel tube opening. (b) Ice section between crossed polarizers, showing spatial coincidence of all fuel tubes with triple junctions.

DISCUSSION

Many impurities in ice tend to be rejected to grain boundaries, particularly the grain junctions that form the intersections between three or more grains. The combined effects of intercrystalline solutes and free surface energy result in a depression of the equilibrium melting temperature, a phenomenon sometimes referred to as *undercooling*. As a result of undercooling, water vein networks exist in equilibrium along grain junctions in ice. These veins evolve in breadth and chemistry in response to environmental changes in ways to reestablish equilibrium. This process is associated with the mass transport of water and contaminants through ice.

The absorption of solar radiation by ice resulted in the growth of intercrystalline water veins. Experimental observations indicated that most water vein growth did not occur at the ice surface, but rather further down in the ice. These veins channeled sediment, water, and fuel downward along triple junctions and played a significant role in permeability development. The continuing question regarding Lake Fryxell is whether fuel tunneling could occur *prior* to the seasonal saturation of the ice cover up to the hydrostatic level. Both of these processes occur when the ice is very close to it's melting point. Fuel tunneling is a rather curious process by which water-immiscible hydrocarbons may potentially travel through Dry Valley Lake ice and contaminate deeper sediment where microorganisms exist.

CONCLUSIONS

This study was carried out to identify and study different mass transport mechanisms of hydrocarbons in ice. One main finding of the study was that the melting process of ice was very complex and largely localized along grain boundaries, which in turn drove permeability development. The phase changes that occurred in intercrystalline water veins were associated with the observed fuel-tunneling process whereby fuel was able to rapidly migrate along grain boundaries in unfractured ice. This fuel tunneling process was perhaps the most fascinating finding of the study and presented a potentially significant hydrocarbon transport mechanism in solid ice. Another important finding of the study was that sediment melted quite rapidly through ice and, upon exiting, retained strong hydrocarbon odors. Lastly, the presence of sediment in ice had no obvious effect on overall melt rates.

FUTURE WORK

Fuel-tunneling along intercrystalline water veins is a fascinating process that merits additional studies for further understanding. This process appeared closely related to ice chemistry and temperature and has important implications in the clean exploration of subglacial lakes beneath the Antarctic ice sheet. Another fascinating, but incompletely understood, process was the dynamics of ice permeability in association with water vein growth and subsequent drainage. A better understanding of this process would help to understand and predict physical developments in lake ice.

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