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 79J helicopter crash on the ice cover of Lake Fryxell in the McMurdo Dry Valleys of Antarctica. Approximately 200 gallons of hydrocarbon-based fluids, mostly JP-8, JP-5, 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) achen 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 jet fuel, and (3) the migration of jet fuel and ice 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 a thin and thick clear ice sheets with 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 -0.1°C and solar lamp power of 590 W/m² was used which was thought to simulate Lake Fryxell conditions during November or December.

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). Some of these fractures were visible as figures and water veins. Most of the ice-sediment remained in place that melted downward. However, some of the finer-grained sediment percolated downward from the sediment discontinuities into 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 JP-8 fuel had no noticeable effect on melt velocities through ice.

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

Figure 2. (a) Velocities of dry and fuel-contaminated sediment were compared. JP-8 fuel did not noticeably affect the migration 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.

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 channelled 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 have the potential to move fuel below the ice 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.

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 continued effects of intercrystalline solutes and free surface energy result in a depression of the equilibrium melt 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 chemisty in response to environmental changes in ways to maintain equilibrium. This process is associated with the mass transport of water and contaminants through ice.

Another study was undertaken to observe, in dark conditions, the mobility of JP-8 fuel in unfractured ice near the melting point. Motivating this study was the potential for drilling fuel contamination of subglacial lakes beneath the Antarctic ice sheet. In this study, light was restricted to ambient conditions for 30-second image exposures. When the ice temperature was within 0.5°C of the melt point, fuel tubes formed and propagated downward along grain junctions at velocities greater than 16 cm/hr (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, in general, is not impermeable to liquid hydrocarbon fuels near the melting point.

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, thereby reducing density and free surface energy. 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 shelf. 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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