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Flume Studies and Field Observations of the Interaction of Frazil Ice and Anchor Ice with Sediments

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ABSTRACT

Frazil ice and anchor ice are types of ice that form in turbulent, supercooled water. Frazil and anchor ice phenomena have received a relatively large amount of study in recent years because of the problems they pose to man-made hydraulic structures. In the course of these studies, there have been many observations of interactions of frazil and anchor ice with sediment, but the relationship has never been viewed from a geologic standpoint.

This is a report of flume experiments undertaken to observe the interactions of frazil and anchor with sand-sized sediment both in suspension and as bed material in fresh and salt water. Observations of frazil and anchor ice from the Alaskan Beaufort Sea also are presented. In the flume, anchor ice resembling that seen in natural settings formed over ice-bonded sediment.

In fresh-water flume experiments, frazil ice formed flocs up to 8 cm in diameter that tended to roll along the bottom and collect bed sediment. These flocs often came to rest in the lee of bedforms, forming anchor ice that was buried as the bedform advanced. As the anchor ice was buried, it was compressed into an ice-bonded sediment-rich block. Anchor ice buried by migrating bedforms disrupts normal ripple cross-bedding and may produce unique sedimentary structures.

Salt-water frazil-ice flocs were smaller, picked up less bed sediment, and formed less anchor ice than their fresh-water counterparts. In salt water, anchor ice most readily formed on blocks of ice-bonded sediment.

A calculation based upon the buoyancy of ice in fresh water shows that floating ice masses can move sediment concentrations of up to 122 g/l. Sediment concentrations of this magnitude have not been observed in either flume or natural settings, but very few measurements have been made. The maximum sediment concentration measured in this study was 88 g/l. These high theoretical and measured sediment concentrations suggest that frazil and anchor ice are important sediment transport agents in rivers and oceans.

INTRODUCTION

Frazil and anchor ice commonly form in turbulent water bodies exposed to subfreezing air temperatures. Frazil ice is defined as "fine spicules, plates, or discoids of ice suspended in water" (Kivisild, 1970). It usually occurs as small discs 1 to 4 mm in diameter and 1 to 100 µm thick. The World Meteorological Organization (1970) defines anchor ice as "submerged ice attached or anchored to the bottom, irrespective of the nature of its formation." In this report the term will be used to describe accumulations of sticky or sediment-laden frazil ice masses that are either attached to or resting on the bottom (fig. 1).

There is a long history of published observations on the formation of frazil and anchor ice. Benedicks and Sederholm (1943) summarized observations from as early as 1708, and Barnes (1928) reported observations dating to 1788. However, detailed studies of frazil and anchor ice formation and processes began only in the last 50 years and intensified in the last 20 with the construction of engineering projects in high-latitude rivers. Frazil and anchor ice production can cause many engineering problems, including flooding caused by frazil ice jams and anchor ice accumulations, interference with hydroelectric facilities, blockage of water supply intakes, interference with shipping, and damage to hydraulic structures (Carstens, 1966; Osterkamp, 1978). To date most studies have dealt with the engineering properties of frazil and anchor ice, and have been aimed at understanding the meteorological and hydraulic conditions necessary for frazil and anchor-ice formation. Osterkamp (1978), Martin (1981), and Tsang (1982) presented reviews of the state of present knowledge on frazil and anchor ice.

Although there is a large body of literature that covers the theoretical aspects of frazil and anchor ice formation, little work has been done on the interaction of frazil and anchor ice with sediment. Most of the literature on frazil/anchor ice/sediment interaction is of an observational nature. The purpose of this study is to examine frazil/anchor ice/sediment interactions from a geological viewpoint, and specifically to address the following questions: (1) How does the presence of frazil ice in the water column affect sediment transport? (2) What products of the interaction of frazil and anchor ice with bottom sediment might be preserved in the sedimentary record?

To study these questions, experiments were conducted in a small flume under controlled conditions. A number of variables were investigated, including cooling rate, current speed, and salinity. In addition, field observations of anchor ice from the Beaufort Sea are presented, and results of the flume studies are compared to the field observations.

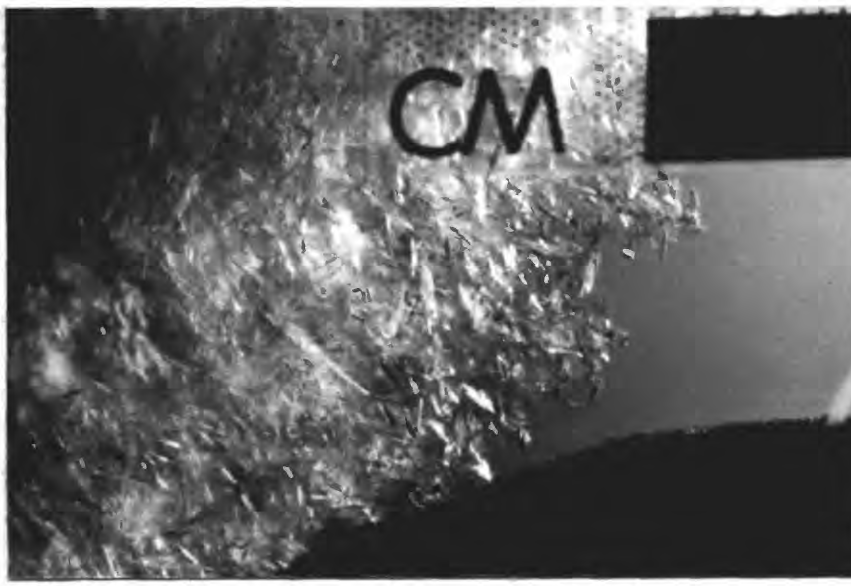


Figure 1. Photograph of an anchor ice mass composed of an agglomeration of individual frazil ice crystals. Individual disc-shaped frazil crystals are visible on the right side of the mass. The anchor ice is attached to an obstruction out of view to the left; current is from the right. The black rectangle in the upper right is 1 cm long. Flume experiment 43.

FRAZIL ICE AND ANCHOR ICE FORMATION

In fresh water, frazil ice forms in turbulent water that has become supercooled by exposure to air at sub-freezing temperatures. Turbulence, caused by currents or wind-generated waves, inhibits the formation of a surface ice cover and allows supercooling of the water column to some depth. This supercooling is generally on the order of 0.05 to 0.10°C (Schaefer, 1950; Wigle, 1970; Arden and Wigle, 1972). Water cannot spontaneously freeze at this slight degree of supercooling, and it is necessary to seed the water column to initiate formation of frazil ice. Osterkamp (1978) reviewed the various mechanisms proposed to initiate formation of frazil ice and concluded that the most likely is some form of mass exchange process at the water surface. In this model, ice particles in the air from a variety of sources such as sleet, snow, or frozen spray fall into the water and act as seed crystals to initiate the growth of frazil ice. Another possible source of seed crystals is cold dust particles that fall into the water. Upon entering the water, these dust particles could absorb enough heat to freeze a thin layer of surrounding water (Tsang, 1982). Once the original seed crystal has entered the water, it grows rapidly and is broken up by turbulence and collisions in the flow. The pieces broken from the seed crystal act as secondary nuclei, allowing the growth of more frazil crystals. Pieces of ice also are broken from these new frazil crystals to act as more nuclei, so that in a short time period many nuclei are made, and a large amount of frazil ice can be produced.

Figure 2 is an idealized curve of temperature change in a water body as it is cooled and frazil ice is produced. This curve shows water temperature dropping with time through T_f, the freezing point of the water at a given salinity. Once the temperature drops below T_f the water is supercooled. At temperature T_n, the supercooled water is seeded with ice crystals, frazil production begins, and the slope of the time-temperature curve decreases. Frazil-ice growth is slow at first because there are few seed crystals, and the latent heat of fusion released by ice formation is too small to overcome heat loss through the free water surface, so the temperature continues to drop. However, as more ice nuclei are produced through the process of secondary nucleation, the rate of frazil production increases until the latent heat of fusion produced by ice growth becomes equal to the rate of heat loss to the air. At this point, the water reaches its lowest temperature, T_m. After this, the increased latent heat released by frazil production is absorbed by the water, raising its temperature to an equilibrium temperature, T_e. The period of greatest frazil production occurs when the water temperature is between T_m and T_e. As the water temperature approaches T_e the rate of frazil production decreases, and the rate of heat loss at the water surface becomes equal to the rate of latent heat liberation associated with frazil production. T_r is the residual temperature, defined as the difference between T_f and T_e. Tsang (1982) noted that T_r is dependent upon hydrometeorological conditions. As long as there is a residual temperature frazil ice will continue to be produced. Tsang (1982) also pointed out that the values of T_n, T_m, T_e, and T_r in natural water bodies have not been well

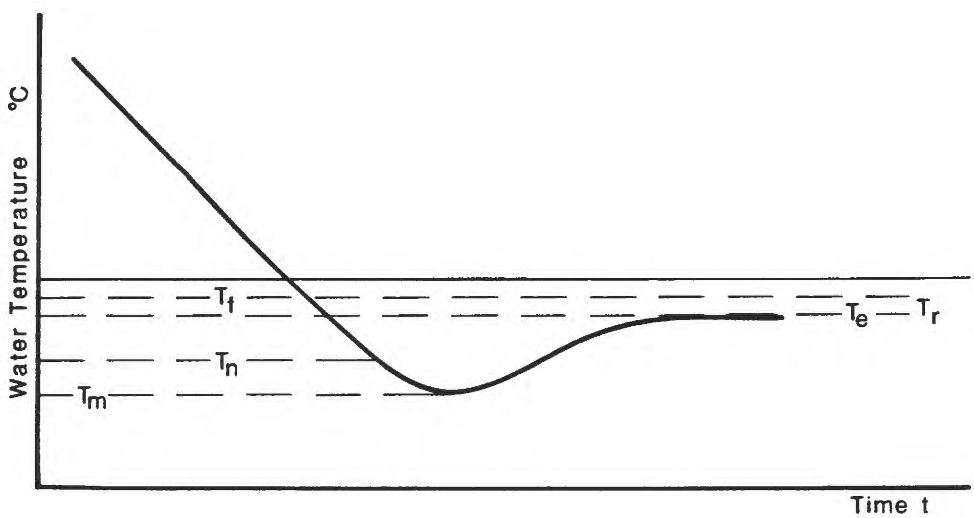


Figure 2. Idealized curve showing supercooling of a water body leading to the formation of frazil ice. T_n: nucleation temperature, point where frazil ice crystals first appear in the water; T_m: temperature minimum; T_e: equilibrium temperature, temperature at which heat lost to the atmosphere is equal to heat released by the growing ice; T_f: freezing point of the water, this may be below 0^oC because of impurities in the water; and T_r: residual temperature, the difference between T_e and T_f. This small residual temperature is the driving force for producing most frazil ice in natural systems. Modified from Tsang and Hanley (1985).

documented, but available data suggests that they are on the order of hundredths of a degree below T_f.

The method described above of supercooling turbulent water by heat exchange with the atmosphere is the only known method of producing frazil ice in fresh water. In the ocean, however, there are at least four methods of supercooling water that can lead to frazil-ice production (Martin, 1981): (1) in open water regions, supercooling and frazil ice can occur where heat is lost to the atmosphere (as already described for fresh water); (2) at the interface between 2 fluid layers, each at its freezing point and with different salinities, frazil ice grows in the less saline water as heat is lost to the more saline water; (3) frazil ice may occur where cold brine formed by development of a surface ice cover sinks and cools less saline water; and (4) adjacent to ice shelves frazil may form by direct cooling of seawater from cold ice or by raising a parcel of water from the bottom of the shelf to the water surface. The freezing point of the water parcel is depressed because of pressure at depth; as the water rises, pressure is reduced and the freezing point rises, allowing frazil ice to form. The only type of salt-water frazil growth considered in this paper is that produced by supercooling of the water through heat loss to the free-air surface.

Frazil ice in supercooled water is 'sticky', exhibiting strong cohesive tendencies between individual ice crystals and between ice crystals and materials on the bottom (Carstens, 1966). Once frazil-ice crystals form, they agglomerate to each other and form buoyant flocs 3 to 10 cm in diameter that rise to the water surface. Flocs evolve into frazil-ice pans when exposed to frigid air. Frazil pans can range from 2 to 10 m in diameter and exceed 1 m in thickness (Osterkamp and Gosink, 1983). The accumulation of frazil ice pans against an obstruction and subsequent freezing of the water between pans can lead to the formation of a solid ice cover. The present study is concerned only with the stages from frazil ice through floc formation.

When a frazil crystal sticks to the bottom, or to a submerged object, it becomes anchor ice (Benson and Osterkamp, 1974). Before frazil crystals can stick to the bottom, the bottom must be cooled to a temperature below the freezing point of the surrounding water (Piotrovich, 1956). The bottom loses most of its heat to the overlying water, so to reduce the temperature of bottom materials to below the freezing point the water must be supercooled. Once formed, an anchor-ice mass can grow by accretion of frazil crystals or by accelerated growth of crystals already making up the mass (Piotrovich, 1956). Accelerated growth of the anchor-ice crystals occurs because the crystals are exposed to a continuous flow of supercooled water. Osterkamp and Gosink (1983) reported that the growth rate of anchor ice may increase by an order of magnitude over the growth rate of frazil-ice crystals in the flow. These two processes also can act simultaneously. Tsang (1982) pointed out that, while important, stickiness of anchor ice is not necessary for growth by frazil accretion. The rough surface of the anchor ice can easily trap frazil crystals from the water column, adding to the volume of the anchor-ice mass.

Anchor ice can grow to large sizes, and it can affect the hydrologic regime of rivers. Tsang (1982) quoted sources that document anchor ice thicknesses of up to 1 m in the Neva River and up to 0.5 m in the Niagara River. Wigle (1970) and Arden and Wigle (1972) reported that anchor ice forms in all reaches of the upper Niagara River, and that the formation of anchor ice on clear, cold nights can reduce the river flow by 20 to 30 percent. Osterkamp and Gosink (1983) observed that anchor ice modifies the hydraulic conditions in streams and can be responsible for substantial reworking of bottom sediments.

PREVIOUS STUDIES

Observations of frazil and anchor ice have been published for at least 275 years (Benedicks and Sederholm, 1943), but the modern study of frazil ice can be considered to start with the work of Barnes (1928). A large body of literature has been published since that time, but the majority of this work deals with the dynamics of frazil ice formation, and it does not deal specifically with the interactions of frazil ice with bottom materials. However, several workers have recorded observations of frazil and anchor ice interacting with sediment.

Anchor-ice growth is initiated when frazil-ice crystals in supercooled water become attached to bottom materials (Piotrovich, 1956; Michel, 1972). Frazil-ice crystals become anchor ice when they become attached to the bottom or when they collide with and stick to an obstruction (Michel, 1972; Osterkamp and Gosink, 1983). Benedicks and Sederholm (1943) and Michel (1972) have suggested that frazil-ice crystals preferentially stick to and grow on substances with a crystalline structure similar to that of ice, but this theory has never been proven. Anchor ice most often grows on bottoms composed of coarse materials, because the coarse materials overcome the buoyancy of the attached ice (Wigle, 1970; Arden and Wigle, 1972). Coarse materials also project into the flow, and are thus cooled to subfreezing temperatures by the supercooled water more readily than smooth, fine-grained materials, making it easier for frazil crystals to stick to them (Michel, 1972).

Frazil and anchor ice have been studied mostly in fresh-water settings. One common observation in rivers is that sediment-laden anchor ice often rises to the surface on mornings following cold, clear nights (Barnes, 1928; Wigle, 1970; Arden and Wigle, 1972; Michel, 1972; Foulds and Wigle, 1977). This released anchor ice has the potential to carry sediments long distances downstream, and in some cases may carry sediment to the sea, where it may be incorporated into the seasonal ice cover (Benson and Osterkamp, 1974). Not all anchor ice rises to the surface. Osterkamp and Gosink (1983) observed sheets of anchor ice tens of centimeters in diameter and 10 to 20 mm thick moving along the bottom of Alaskan streams. This anchor ice had incorporated sediment, and when sheets came to rest on top of other anchor-ice masses, an anchor-ice mass with sediment distributed throughout its thickness formed. Materials that are carried by anchor ice include boulders of up to 30 kg (Martin, 1981), sand and gravel (Arden and Wigle, 1972), and mud and vegetable material (Barnes, 1928). The importance of anchor ice as an agent of sediment transport in rivers is not known, but Tsang (1982) noted that the Niagara River transports little sediment during the summer, but a considerable quantity of large stones is found upstream of a large hydraulic structure each spring. Tsang (1982) said that only anchor ice can account for the movement and deposition of these large stones.

There are fewer observations of anchor ice in salt water than in fresh water. Zubov (1943) listed a variety of objects that were lifted off the bottom by anchor ice in Russian waters, including a tool box, sediment, and 40-cm-long rods that had been driven into the bottom until only 4 cm protruded from the sediment. He also noted that anchor ice can stay attached to the bottom for long periods of time. In some cases anchor ice persists long enough for organisms to become established on its top surface.

Dayton et al. (1969) reported on the formation of frazil and anchor ice in McMurdo Sound, Antarctica. They observed "masses of platelets frozen to the bottom" in depths of up to 33 m. The anchor ice apparently controls benthic biological and sediment zonation. Below the depth of anchor ice formation there is an abrupt increase in the number of sponges, and sediment is enriched in sponge spicules compared to sediment at shallower depths where anchor ice forms. Dayton et al. (1969) also noted that anchor ice can form rapidly, trapping motile benthic organisms. When this anchor ice is released from the bottom it can carry these organisms and sediment to the underside of the floating ice cover (Curtsinger, 1986). The anchor ice can lift large portions of the bottom, weighing up to 25 kg.

In addition to forming anchor ice, frazil ice may also interact with sediment in suspension and on the bottom. Barnes (1928) and Altberg (1938) observed that frazil ice will remove suspended sediment particles from rivers, so that "...The first run of frazil has a remarkable cleansing effect on the water" (Barnes, 1928). Arden and Wigle (1972) also observed frazil ice interacting with bottom sediments. In the Niagara River, flocs of frazil ice would strike sandy portions of the river and pick up bottom material before they were carried back into suspension.

Barnes et al. (1982), in their study of sediment-laden sea ice in the Alaskan Beaufort Sea, suggested that frazil-ice formation is responsible for the widespread occurrence of finely disseminated silt and clay found in the sea-ice cover. The frazil ice forms during fall storms associated with freezeup. Sediment concentrations measured in the ice ranged up to 1600 mg/l, 1 to 2 orders of magnitude greater than sediment concentrations normally found in coastal waters.

Osterkamp and Gosink (1984) also studied sediment-laden ice in the Beaufort Sea. They measured sediment concentrations in the ice of up to 1290 mg/l. They proposed 9 different methods of incorporating sediment into the ice cover. Seven of these call for some type of frazil or anchor-ice process to incorporate sediment into the ice cover. The proposed methods are untested, however, and Osterkamp and Gosink (1984) presented no observations (other than the observed sediment in the ice cover) to support any of their methods of sediment entrainment.

The above synopses illustrate a number of facts known about frazil and anchor ice and their interactions with sediment: (1) frazil and anchor ice are capable of moving clasts as large as boulders weighing at least 30 kg; (2) anchor ice seems to form preferentially on rocky bottoms; (3) anchor ice may form preferentially on certain materials; (4) frazil ice has the ability to clear the water of suspended particulate matter; (5) frazil and anchor ice form most often on clear, cold nights; (6) the growth of large masses of anchor ice changes the hydrologic regime of rivers, and may reduce flow as much as 30 percent. The synopses also illustrate how little is known about the details of frazil and anchor ice interactions with sediment. It is clear that these forms of ice do interact with materials in suspension and lying on the bottom, but there is no detailed information on how these processes operate or on the overall geologic significance of frazil and anchor ice.

FIELD OBSERVATIONS

Field observations of frazil and anchor ice in salt water were made in the Alaskan Beaufort Sea near Prudhoe Bay (fig. 3) during the fall freezeup in 1982. This area is characterized by an almost complete ice cover for about 9 months of the year, with a 2- to 3-month open-water season with fetch typically limited by ice. Astrological tides in the area are less than 15 cm, but strong westerly winds can drive up the water level as much as 3.4 m (Reimnitz and Maurer, 1979). Reimnitz and Barnes (1974) and Barnes and Reimnitz (1974) described the setting of this area in detail.

As part of the field observations, two diving traverses were made. Each of these traverses was about 150 m long, and each was made in water depths of 0 to 4 m. The traverses were located on the seaward side of Reindeer Island and on the east side of the West Dock (fig. 3). Observations of anchor ice and seafloor sediment types were made along the traverses. Observations of frazil ice between the West Dock and Reindeer Island were made at the same time.

For 6 days preceding the diving observations off Reindeer Island on October 5, 1982, there were continuous winds of up to 12.5 m/s (25 knots). The air temperature never rose above 0°C during this period, and frazil ice was observed forming windrows parallel to the wind on the sea surface. At the time the dives were made, the wind had died down but the air temperature remained below freezing, and much of the sea surface was covered with a grease ice layer composed of frazil ice crystals. As a

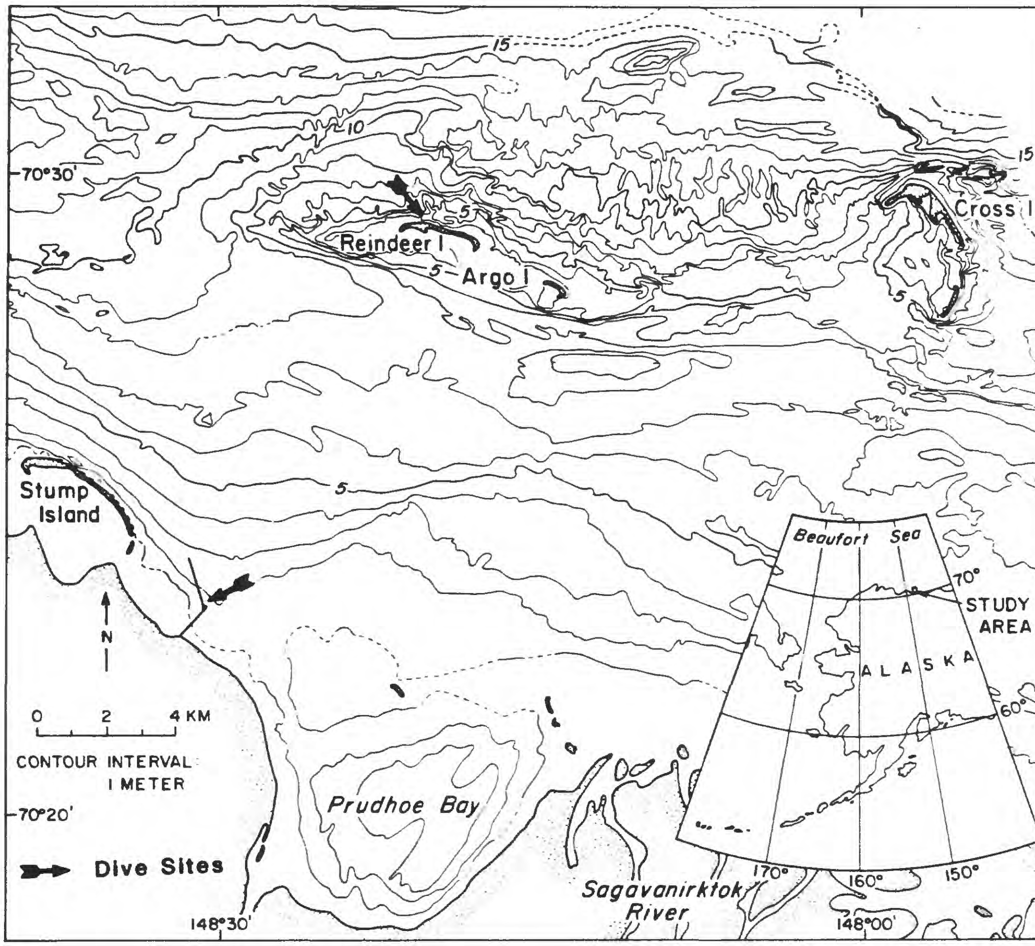


Figure 3. Beaufort Sea dive sites where anchor ice was observed in October 1982.

result of this ice cover, sea conditions were calm for diving operations.

The 130-m-long dive traverse extended from the seaward-facing beach to a water depth of 4 m. One 2-m-high bar, approximately 90 m from shore, was traversed. For a distance of 10 m out from the shoreline the gravel and coarse sand bottom was ice bonded. The ice-bonded sediment formed slabs that were up to 40 cm in diameter and 10 to 15 cm thick. Several of these slabs were collected and subsequently melted down. After melting and settling, approximately 20% excess water by volume was standing on top of the sediment. In addition to being ice bonded, some of the area within 10 m of the shoreline was covered by clumps of anchor ice up to 30 cm in diameter (fig. 4). Seaward of 10 m the bottom consisted of clean, medium, rippled sand with widely scattered pebbles. Clumps of anchor ice, with a surface of delicately intertwined ice crystals and a core of ice-bonded sediment, were observed on the sand bottom (fig. 5). These clumps of anchor ice were roughly circular in plan view, and ranged from 3 cm to 1 m in diameter. The largest clumps were about 30 cm high. In some areas, several of these clumps rested next to each other, creating anchor-ice masses that covered areas up to 3 by 4 m. The anchor ice commonly contained sediment grains resting in the interstices between ice crystals. When the crystals were disturbed they readily broke up and floated away, and the cores of the anchor-ice clumps were exposed. These cores were ice-bonded sediment, and although composed of sand-sized material they were similar to the ice-bonded gravel slabs seen closer to the beach, with the exception that they projected above the level of the surrounding sea floor.

The smallest anchor-ice clumps were observed nearest to the beach, and size increased to a maximum offshore in the trough and on the outer side of the bar. There was less anchor ice on the crest of the bar than in the deeper water on either side. The anchor ice tended to sit in small depressions on the rippled bottom (fig. 5). At the seaward end of the traverse the water surface was covered with a layer of grease ice up to 20 cm thick. This layer had up to 10 cm of relief and did not appear to have any incorporated sediment.

The weather conditions for the dive at the West Dock on the following day were similar to those at Reindeer Island. This dive was made near a gravel causeway at a distance of about 1400 m from shore and consisted of a 150-m traverse in water depths of less than 2 m. Visibility was 50 to 75 cm during the dive, so only a narrow strip of seafloor was observed. Bottom sediment along the traverse consisted of gravel, sand, and mud. Ice bonding of sediment was observed in all of these materials. The distribution of gravel was patchy, and it was all strongly cemented by ice, making it impossible to drive a spade into the bottom and difficult to dislodge even a single clast. The sand along the traverse was rippled and frozen to a depth of several centimeters. The ripples had wavelengths of 20 cm and heights of 5 cm. There was no observed difference in depth of ice bonding from the ripple crest to the ripple trough, although changes of a centimeter or less could have been missed. Ice bonding was minimal in the mud, occurring as a layer less than 1 cm thick that extended downward

Figure 4. Anchor ice resting on frozen, ice-bonded sand and gravel bottom in 1-m-deep water on the seaward side of Reindeer Island (fig. 3). Center of photograph is about 75 cm across.

Figure 5. Anchor ice in 4-m-deep water off Reindeer Island (fig. 3) in October 1982. The anchor ice masses were composed of a sediment-rich, ice-bonded core surrounded by a halo of delicately intertwined ice crystals. The masses were resting on unfrozen, clean, rippled, sand bottom. Individual ball-shaped anchor ice masses were about 40 cm in diameter.

into the sediment from the sediment/water interface. We estimated that 60 to 75 percent of the bottom was ice bonded along this traverse; but no anchor-ice clumps with free ice crystals similar to those seen at Reindeer Island were observed on the sediments. However, several pieces of trash, including a tire, steel banding, and organic debris were seen along the traverse. All of these materials had anchor ice composed of frazil ice crystals attached to them. Several twigs also were seen along the traverse, these were conspicuous because they lacked a covering of anchor ice. In some cases, the anchor ice formed a halo with a radius of 10 cm around an object. This anchor ice was so poorly attached to its substrate that the slightest touch would release it from the substrate and it would rise to the water surface. The anchor ice growing on debris was similar in appearance to the anchor ice observed resting on the bottom near Reindeer Island; the only apparent difference was the type of substrate.

LABORATORY EXPERIMENTS

Methods

Laboratory work consisted of 39 flume experiments made in a small race-track flume at the U.S. Geological Survey facility in Palo Alto, California. Flume experiments were made under a variety of conditions, and variables including cooling rates, currents speeds, and water salinity were changed to learn how they might affect frazil/anchor ice/sediment interactions. In addition, four special flume experiments, with non-routine variables, were made. These non-routine variables included injecting supercooled air into the water; seeding the supercooled water with dry ice (Shaefer, 1950); cooling the underside of the flume with dry ice to simulate cooling of bed sediment from permafrost at depth; and sprinkling cold sand into the water during the period of frazil formation.

Making Frazil and Anchor Ice

Frazil and anchor ice were made in a race-track flume similar in shape to the one used by Carstens (1966). The flume was constructed of aluminum with plexiglas windows built into one straight segment (fig. 6). The flume was 1.2 m long, 75 cm wide, and 32 cm deep. The channel width was 21 cm. During use, the flume was filled with a level layer of sand 4 cm thick overlain by 17 cm of water. The volume of water in the flume during an experiment was about 110 liters. The aluminum sides of the flume were insulated with 1.5 cm of closed-cell foam, and the bottom was insulated with 5 cm of foam, so water was cooled predominantly from the surface.

Currents in the flume were produced with a plastic propeller from a model boat. This propeller was positioned in the back straight section of the flume, and was connected to a variable speed electric motor by means of a flexible steel drive shaft. With

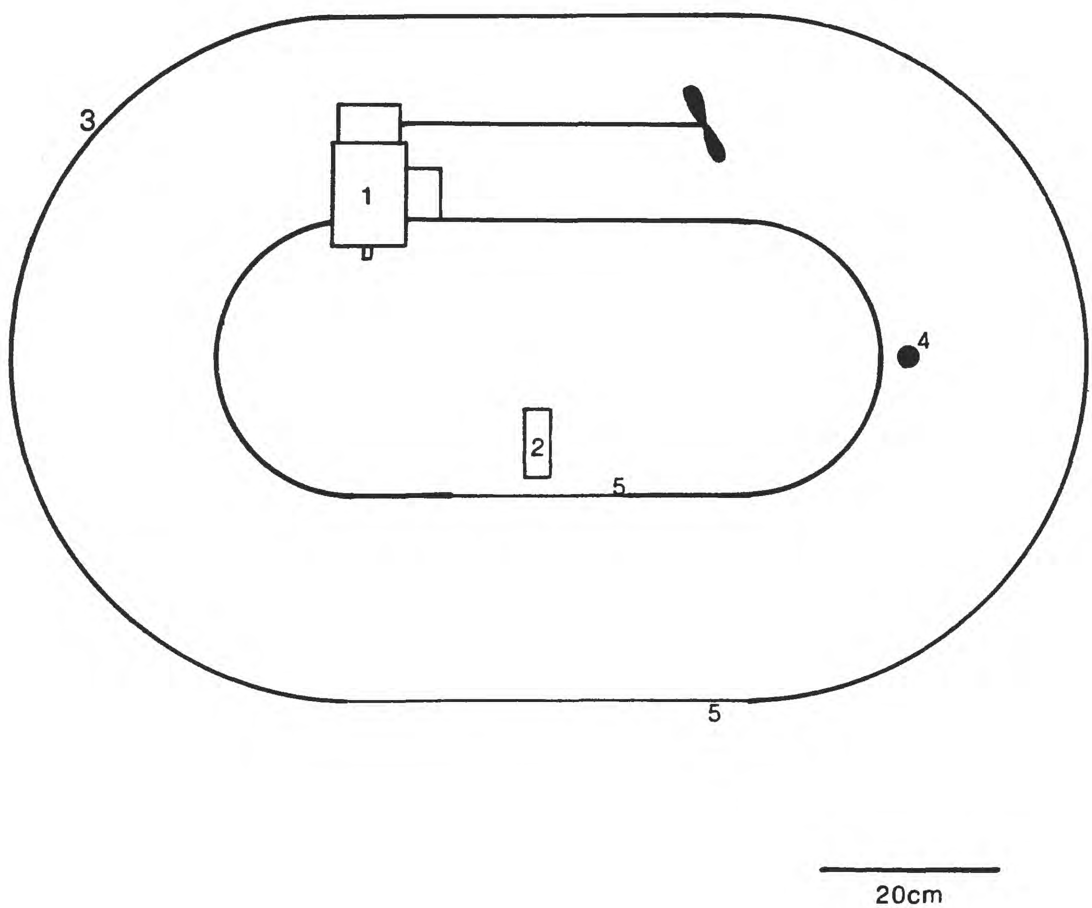


Figure 6. Plan view of flume showing: (1) variable speed electric motor attached to propeller, (2) light, (3) 1.5-cm-thick insulation, (4) thermistor, and (5) plexiglas windows.

this system, current speed in the flume could be varied between 30 and 70 cm/s. The shape of the flume and the rotary motion of the propeller resulted in non-uniform flow, and the reported current speeds are averages. Current speeds were determined by timing neutral-density disks as they traveled around the flume. For making the current speed calculations, it was assumed that the average path a disk took around the flume was equal to the path length measured along the centerline of the flume channel. All current speed calculations were carried out at room temperature and with no sand in the flume. The presence of sand on the floor of the flume probably would result in slightly lower current velocities.

For an experiment the flume was pushed into a 4X4 m walk-in freezer that maintained an air temperature of -17°C +/- 1°C. Fans in the freezer produced slight air movement at the water surface in the flume. To increase cooling during some experiments a 30-cm-diameter fan was placed so that it blew a steady stream of cold air across the water surface at a speed of 4 m/s. Air temperature was measured to +/- 0.25°C with a standard laboratory thermometer several times during each flume experiment. Water temperature was measured with a thermistor accurate to 0.004°C. This thermistor was inserted to a water depth of 9 cm at a turn in the flume (fig. 6). Care had to be taken during the period of frazil formation to assure that no frazil stuck to the thermistor, because this resulted in anomalously high temperature readings. To avoid this problem the thermistor probe was mechanically cleaned during periods of active frazil formation, or the probe was coated with silicone grease before the start of the experiment to retard the adhesion of frazil. Resistance readings from the thermistor and time were recorded on a manually triggered printer. Time and resistance readings were recorded at 10 to 20 second intervals during periods of frazil formation; at other times these readings were taken at 1 to 5 minute intervals. At the end of the experiment these readings were converted to time and temperature and plotted in graphical form.

For fresh-water experiments, tap water was used to fill the flume. For salt-water experiments 'Forty Fathoms', a commercially available aquarium salt, was used to make a saline solution. 'Forty Fathoms' was also used by Tsang and Hanley (1985) in their study of frazil formation in saline waters, and they found no significant differences in experimental results when comparing the artificial sea water with natural Atlantic Sea water. In the present group of experiments, the water salinities were about 0 parts per thousand (ppt), 29 ppt, and 36 ppt. For the saline water experiments, the salinity was determined by the method outlined by Lewis (1980).

It is important to seed the supercooled water to initiate the growth of frazil ice. In carefully controlled laboratory experiments it is relatively simple to get supercooling of at least several degrees centigrade (see, for example, Hanley and Tsang, 1984). In the present experiments, artificial seeding was not necessary. There apparently were enough ice crystals in the air that fell into the water to initiate frazil growth. The degree of maximum supercooling seen in these experiments is close to that seen in natural settings.

Flume Sediment

Two different sands were used as bed material in the flume experiments. For most experiments a clean, well-sorted, quartz-rich beach sand with a mean grain size of 2.0 phi was used. In three experiments a poorly-sorted sand with mean grain size of 2.5 phi was used. This sand was very dirty, and the silt and clay that went into suspension made the water opaque. This made viewing frazil and anchor-ice formation impossible, so the use of this sediment was discontinued.

At all current speeds used in the flume, the sand moved as both bed load and suspended load. Well-developed ripples up to 7 cm high formed in the straight segments of the flume when current speeds were below 60 cm/s. At current speeds above 60 cm/s these ripples were destroyed, and the sand assumed a flat bed configuration. Because flow in the flume was not uniform, several dead spots or depositional areas formed, especially along the inside turns of the flume and along the back straight segment just upstream of the propeller. In a similar fashion, the areas along the outsides of the turns and directly down stream from the propeller were areas of scouring and non-deposition. However, the area along the window generally maintained a cover of at least 2 cm of sediment throughout any given experiment, and it contained no regions of consistent scour or deposition. Flow conditions in the area of the window appeared uniform across the entire width of the channel; migrating bedforms usually reached from one wall of the channel to the other.

During several experiments, cobbles up to 12 cm in diameter were added to the flume to learn how they interact with frazil and anchor ice. Some of these cobbles had algae up to 20 cm long attached to them. For some salt-water experiments, ice-bonded sand blocks with a volume of about 250 ml were placed on the flume floor. These sand blocks were similar to the blocks of ice-bonded sediment observed in the Beaufort Sea. To determine if frazil ice and anchor ice preferentially adhere to certain materials, several mineral specimens and other materials were suspended on aluminum or plexiglas rods in the flow during frazil production. A list of these specimens is given in Table 1.

To determine whether sedimentary structures are produced by anchor and frazil ice, specific observations were made of ice/sediment interactions. In addition, cores were collected where anchor ice had been buried by migrating ripples. These cores were allowed to freeze and then were sawn into slabs and X-rayed. Unfortunately, the open packing of sediment and ice precluded preservation of sedimentary structures while sampling, and little can be documented from this part of the study.

Table 1. List of mineral specimens that were placed on a frame in the flume to determine if frazil ice preferentially stuck to specific minerals. In addition, fresh water algae and Macrocystis spp. were used in fresh and salt water experiments, respectively, to determine how frazil ice interacts with aquatic plant material.

ROW 1	ROW 2	ROW 3
staurolite	chert	copper
brass	flourite	chiastolite
plastic drifter	galena	epidote
quartz	garnet	black limestone
	gypsum	white limestone
	hornblende	kyanite
	specular hematite	lepidolite
	albite	magnetite

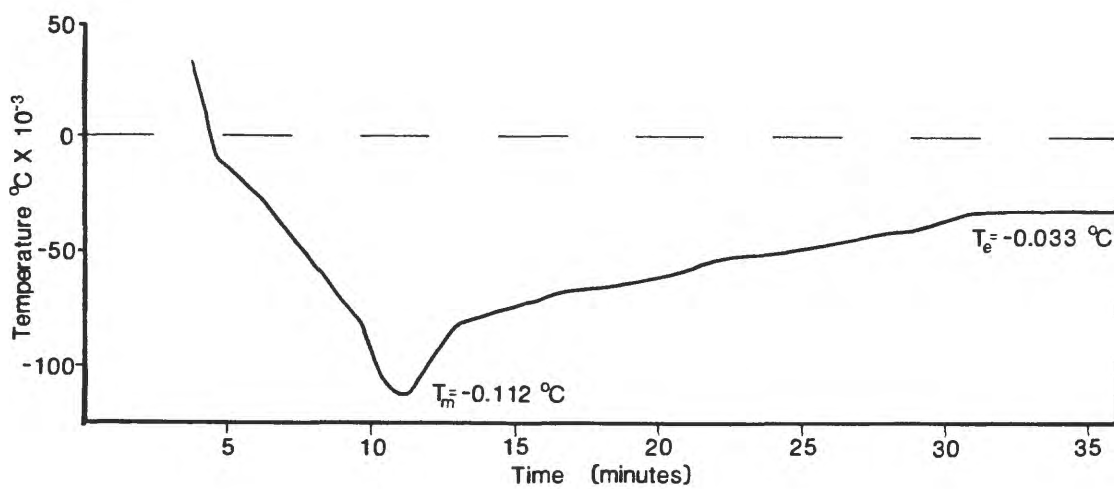


Figure 7. Cooling curve for typical flume experiment (Experiment 53, with fresh water). This curve closely approximates the theoretical curve shown in Figure 2.

Measuring Sediment Concentrations

One of the goals of the study was to monitor suspended sediment concentrations during the experiments. Suspended sediment samples were collected by lowering a 300-ml sample bottle through the water column at a constant rate so that it reached the bottom just as it filled with water (Rudolfo, 1970). Two samples were collected on most runs: one just before frazil production began and another during the period of maximum frazil production. These two samples usually were collected within 3 minutes of each other. After collection the samples were processed by measuring the volume of water to the nearest milliliter and then filtering the water through a pre-weighed 3 µm Millipore filter. The filters were then dried overnight at 50°C, weighed to the nearest 0.1 mg, and the sediment concentrations were calculated.

When possible, samples of frazil and anchor ice were collected to determine sediment concentrations. Ice samples were collected with a small strainer, and as much water as possible was shaken out of the ice before it was transferred to a beaker for melting. After the ice had melted the sample was processed in the same way as the suspended-sediment samples.

Results

Table 2 summarizes the data collected in the 39 flume experiments, including salinity, freezing point (T_f) for the salt water experiments calculated from the equation of Millero (1977), current speed, cooling rate, T_m, T_e, T_e-T_m, and whether or not anchor ice formed. Figure 7 is a typical plot of time versus temperature for an experiment with fresh water (Experiment 53). The curve is similar to the curve presented by Tsang and Hanley (1985) and shown in figure 2. A minimum temperature of -0.112°C was reached after about 6 minutes of supercooling. After reaching T_m, the temperature rose sharply, leveled off, and then slowly approached T_e. During this period a large amount of frazil ice formed. The time of approximately 30 minutes required for supercooling, frazil formation, and warming is within the range given by Tsang (1982) as typical for flume experiments.

The values of T_m, T_e, and T_e-T_m are easy to determine for the flume experiments, but it is difficult to relate these values to the amount of supercooling (T_f-T_m) or to the difference between the freezing point and the equilibrium temperature (T_f-T_e). In fresh-water experiments, the amount of dissolved salts in the water was not measured, so calculation of T_f is impossible. For salt-water experiments, T_f is calculated using the equation of Millero (1977). Knowing this value allows calculation of T_f-T_m. However, as frazil ice forms, salt is rejected, increasing the concentration of dissolved salts in the remaining water and lowering T_f. Because only the initial salinity was measured, it is impossible to determine T_f-T_e. Even with these limitations, the amount of supercooling can be estimated from the value of T_e-T_m, because T_e is within

Table 2. List of measurements made during different flume experiments.

Experiment Number	Salinity (ppt)	T_f (^oC)	Current Speed (cm/s)	Cooling Rate ($X10^{-4}$cm/s)	T_m (^oC)	T_e (^oC)	T_e-T_m (^oC)	Anchor Ice Formation
16	**	**	50	6.7	-0.076	-0.011	0.065	no
17	**	**	*	5.8	-0.062	-0.021	0.041	yes
18	**	**	*	6.1	-0.066	-0.014	0.052	yes
19	**	**	*	6.2	-0.066	-0.017	0.049	yes
20	**	**	*	6.5	-0.077	-0.010	0.067	yes
21	**	**	40	4.4	-0.066	-0.017	0.049	yes
22	**	**	70	4.7	-0.059	-0.017	0.042	yes
23	**	**	43	5.6	-0.076	-0.017	0.059	yes
24	**	**	70	4.6	-0.066	-0.027	0.039	yes
25	**	**	43	6.8	-0.079	-0.021	0.058	yes
26	**	**	70	7.8	-0.069	-0.021	0.048	yes
27	**	**	60	10.0	-0.134	-0.028	0.106	yes
28	**	**	60	4.6	-0.048	-0.045	0.003	yes
29	**	**	40	4.6	-0.131	-0.031	0.100	yes
30	**	**	60	4.5	-0.083	-0.035	0.048	no
31	**	**	43	8.5	-0.100	-0.035	0.065	yes
32	**	**	60	3.2	-0.069	-0.028	0.041	yes
33	**	**	43	5.0	-0.097	-0.021	0.076	yes
34	**	**	43	4.2	-0.097	-0.031	0.066	yes
35	**	**	57	5.0	-0.097	-0.021	0.076	yes
36	**	**	70	10.0	-0.107	-0.017	0.090	yes
37	**	**	57	#	-0.068	-0.016	0.052	yes
38	29.14	-1.590	57	#	-1.731	-1.627	0.104	no
39	29.14	-1.590	57	#	-1.718	-1.623	0.095	no
40	29.38	-1.603	40	6.1	-1.703	-1.643	0.060	yes
41	29.38	-1.603	*	#	-1.677	-1.642	0.035	yes
42	**	**	57	#	-0.107	-0.042	0.065	yes
43	36.14	-1.988	70	8.4	-2.176	-2.083	0.093	no
44	36.14	-1.988	70	4.3	-2.139	-2.073	0.066	no
45	36.14	-1.988	57	8.9	-2.142	-2.080	0.062	no
46	36.14	-1.988	57	#	#	#	#	yes
47	36.38	-2.002	40	7.6	-2.167	-2.083	0.084	yes
48	36.38	-2.002	57	3.2	-2.139	-2.067	0.072	no
49	36.95	-2.030	43	6.1	-2.197	-2.098	0.099	yes
50	36.95	-2.030	*	5.9	-2.225	-2.092	0.133	yes
51	36.95	-2.030	57	3.3	-2.126	-2.089	0.037	yes
52	36.95	-2.030	43	3.7	-2.176	-2.142	0.034	yes
53	**	**	57	6.1	-0.112	-0.033	0.079	yes
54	**	**	40	8.2	-0.088	-0.033	0.055	yes

*Current speeds were varied in this experiment.
**Fresh water experiment, salinity and T_f not calculated.
#Value not calculated because of lack of data.

hundredths of a degree of T_f (Tsang, 1982). Assuming that T_e-T_m is a close approximation of T_f-T_m, the maximum amount of supercooling occurred during a salt water experiment (#50) and has a value of $^-0.133°C$. This value is about twice as high as values of supercooling reported for natural systems. The values of T_e-T_m range from $^-0.003$ to $^-0.133°C$ (Table 2). Most values are less than 0.100°C, within the reported range of supercooling in natural systems.

Cooling rate was varied between experiments by controlling the rate of air flow across the water's surface. In different experiments, the cooling rate varied by a factor of 3, from 3.2 to $10X10^{-4}$°C/s. A plot of cooling rate versus T_e-T_m (fig. 8) shows a weak trend toward increased supercooling as the cooling rate increases. The best-fit regression lines generated from the fresh and salt water data suggest that T_e-T_m is greater for salt-water experiments than for fresh-water experiments at the same cooling rate. However, the low correlation coefficients of r=0.42 for salt-water experiments and r=0.46 for fresh-water experiments indicate large amount of scatter in the data sets. The only visual difference observed in frazil and anchor-ice formation at different cooling rates was the formation of hexagonally-shaped frazil crystals in Experiment 43. This experiment had one of the highest cooling rates of any of the salt-water experiments (Table 2); there may be a relationship between the high cooling rate and the shape of frazil crystals in salt water.

A graph of current speed versus T_e-T_m shows no apparent correlation (fig. 9). However, current speed does affect the formation of anchor ice on bottom sediment: anchor ice is more likely to form at lower current speeds. At the highest current speeds used in this study, the sand bottom was an upper flow regime plane bed, providing no shelter for anchor ice to settle. Even at the highest current speeds, anchor ice formed on objects suspended in the flow.

Formation and Characteristics of Frazil and Anchor Ice

Fresh Water. Frazil ice formed in all of the flume experiments. The main form of frazil crystals in fresh water was a thin disc 1 to 5 mm in diameter. Small amounts of needles up to 5 mm long also formed sometimes. These frazil crystals readily agglomerated into flocs up to 8 cm in diameter and roughly spherical in shape, stuck to objects projecting into the flow, and picked up sediment from the flume floor. Individual crystals in the frazil-ice flocs were randomly oriented, and there were relatively large voids between the crystals making up the floc. Sediment in the flocs appeared to be trapped in these voids between ice crystals. In many experiments, frazil flocs collected enough sediment to become negatively buoyant and settled to the bottom, usually in the lee of a ripple. Although not strictly within the WMO definition because it is not 'attached' or 'anchored' to the sandy bottom, this type of dirty ice resting on the bottom is here classed as anchor ice. Table 2 lists the experiments in which anchor ice was observed to form. Although anchor ice was common, the majority of frazil ice flocs remained buoyant and floated to the water surface where they soon congealed

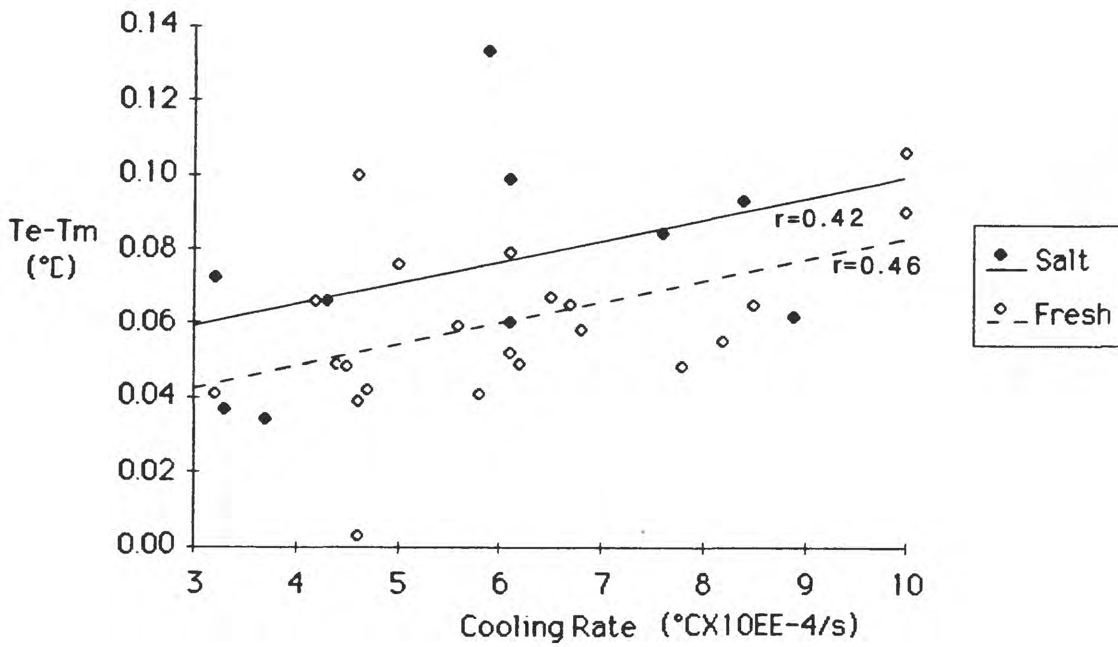


Figure 8. Graph of T_e-T_m versus cooling rate. T_e-T_m is a close approximation of the degree of supercooling. This graph shows that for a given cooling rate salt water generally reaches a greater degree of supercooling than fresh water.

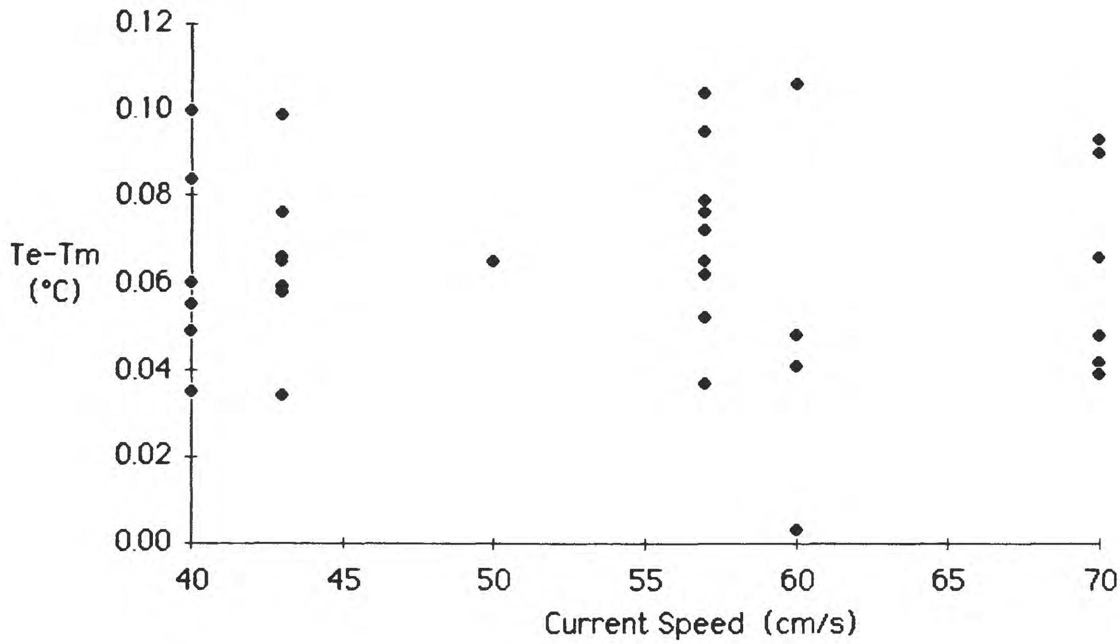


Figure 9. Graph of T_e-T_m versus current speed. This plot shows that there is no clear correlation between current speed (and turbulence) and the amount of supercooling reached in the flume.

into a solid ice cover.

Salt Water. In salt-water experiments, frazil ice usually occurred as thin discs 1 to 3 mm in diameter. Figure 1 shows a salt-water anchor-ice mass composed of frazil ice. The disc shape of the frazil crystals is clearly visible. In Experiment 43 a few hexagonally-shaped crystals were observed along with the more common disc-shaped crystals. Salt-water frazil-ice flocs were much smaller than fresh-water flocs. Individual frazil crystals in salt-water flocs were aligned with their flat surfaces in contact with each other, forming tabular bodies like jumbled piles of cards that were up to 1 cm across. Frazil crystals commonly protruded from the plane of the the main tabular body, giving the aggregates a dendritic appearance. These flocs did not accumulate much sediment, and relatively little anchor ice formed on the bottom. However, anchor ice formed readily on objects suspended in the flow, particularly on the mineral specimens mounted on the plexiglas supports (fig. 10). Unlike the fresh-water frazil ice, salt-water frazil ice stayed in suspension as long as current speeds were high enough for turbulence to overcome the buoyancy of the small aggregates. When the flow was stopped, the frazil crystals rose to the surface, but they did not freeze together into a solid mass. Even after periods of up to 1 hour, when the current was turned back on the frazil crystals disaggregated and were carried back into suspension. The frazil-ice concentrations in the water column were often high enough to obscure vision across the 21-cm width of the flume. This is a sharp contrast to fresh-water frazil crystals, which agglomerated into flocs soon after forming and rose to the water surface where they congealed into a solid mass.

Interaction of Frazil and Anchor Ice with Sediment

Two different sediment types were used in the flume experiments: a clean beach sand with a mean grain size of 2 phi and a muddy sand with mean grain size of 2.5 phi. The latter was used only in Experiments 16, 51, and 52, because it released so much clay into suspension that visual observations were not possible. Contrary to previously published observations (Barnes, 1928; Altberg, 1936), there was no noticeable improvement in water clarity after frazil ice had formed. Apparently the frazil ice did not remove much of the fine-grained sediment from suspension.

Two different methods of frazil ice interaction with sediment are considered: (1) interaction with suspended particles, and (2) interaction with bottom sediment.

Interaction with Suspended Sediment. To study the effects of frazil ice formation on suspended-sediment transport, aliquots of water/sediment/frazil masses were collected before and during periods of active frazil formation and the suspended sediment concentrations were determined. Large flocs of frazil ice and anchor ice also were collected to determine their sediment concentration. Table 3 shows the concentration of suspended sediment in the water before and during the periods of active frazil formation.

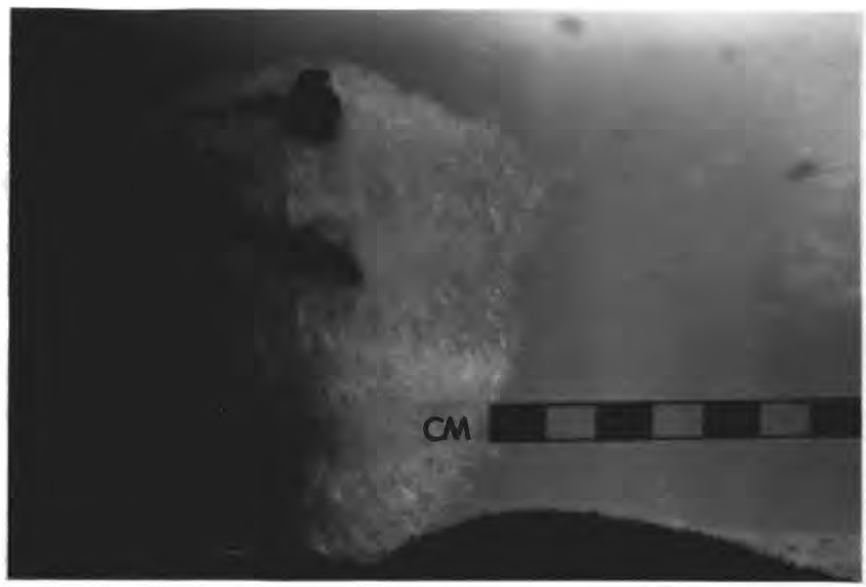


Figure 10. Anchor ice on mineral specimens and plexiglas frame in Experiment 43 (salt water). This anchor ice mass grew by trapping frazil ice crystals out of suspension. Current is from the right.

Table 3. Suspended sediment concentration in water before and during periods of frazil-ice formation.

Experiment Number	Current Speed (cm/s)	Sediment Conc. (g/l) Before Frazil Formation	Sediment Conc. (g/l) During Frazil Formation	Water Salinity (ppt)
30	60	2.300	#	fresh*
33	43	0.800	0.500	fresh*
34	43	0.400	#	fresh*
35**	57	0.300	#	fresh*
35**	57	0.350	0.21	fresh*
36	70	0.360	0.180	fresh*
37	57	0.580	0.350	fresh*
38	57	0.470	0.320	29.14
39	57	0.471	0.388	29.14
40	40	0.037	#	29.38
41	57	#	0.126	29.38
42	57	0.133	0.130	fresh*
43	70	0.745	1.460	36.14
44	70	#	1.065	36.14
45	57	1.500	0.103	36.14
46	57	1.060	0.191	36.14
48	57	0.659	0.103	36.38
49	42	0.047	0.083	36.95
51	57	0.235	0.163	36.95
52	42	0.121	0.127	36.95

*Salinity was not determined in fresh-water experiments.
**2 samples were collected before frazil ice began forming.
#No sample was collected during this experiment.

Table 3 and Figure 11 show a general increase in sediment concentration with increasing current speed, regardless of whether or not frazil ice was present. The low correlation coefficients of r=0.32 for before the period of frazil formation and r=0.54 for during the period of frazil formation show that there was substantial scatter of sediment concentration as a function of current speed. Suspended sediment concentrations ranged from 0.037 g/l at a current speed of 40 cm/s to 2.3 g/l at a current speed of 60 cm/s. At any given current speed, there tends to be more sediment in suspension before frazil ice starts forming compared to the sediment concentration at the period of maximum frazil-ice formation. In several experiments, we had the impression, based on visual observations, that suspended sediment concentrations decreased even more after T_e was reached.

Table 4 shows the amount of sediment trapped in frazil- and anchor-ice masses. These ice masses were collected after T_e was reached. Sediment concentrations in these masses range from 0.10 to 88.30 g/l. Generally, the sediment concentrations in the ice are much greater than the highest measured value of suspended sediment in the water.

Interaction with Bed Sediment. Anchor ice in the flume formed by two different methods: frazil flocs became attached to cobbles or mineral specimens projecting into the flow, or frazil ice accumulated enough sediment to become negatively buoyant and settle to the bottom in the lee of a ripple.

Frazil ice readily stuck to any flow obstruction in fresh water. Once the original frazil stuck to an object, the resulting anchor ice grew rapidly by addition of more frazil crystals. The fastest anchor ice growth occurred on the up-current side of objects.

Anchor ice formation caused by sediment-laden frazil flocs settling in the lee of ripples occurred most often in fresh water. The flocs forming anchor ice in fresh water ranged from a few millimeters to 8 cm in diameter. These flocs were carried over the ripple crest, got caught in an eddy, and were carried up-current and deposited in the lee of a ripple. As flocs were carried up-current by the eddies, they sometimes gouged faint striations on the lee side of the ripple. These striations were up to 8 cm long parallel to the current direction, 0.5 cm wide, and less than 0.5 cm deep.

When frazil flocs came to rest in the lee of migrating ripples, the resulting anchor ice commonly was buried by the advancing bedform. This burial occurred as sand avalanched down the slip face of the ripple (fig. 12). The normal motion of the avalanching sand was disrupted when it hit the the anchor ice. As the avalanching grains encountered anchor ice, they filled voids in the porous structure and cascaded down the outside of the anchor ice mass. The anchor ice was compressed by the weight of the sand, forming a compact mass of ice and ice-bonded sediment. This buried anchor ice sometimes acted as a surface for continued ice growth by frazil-crystal accretion above the sediment surface. The weight of the sediment on the buried anchor ice held the cleaner anchor ice above the sediment/water interface down,

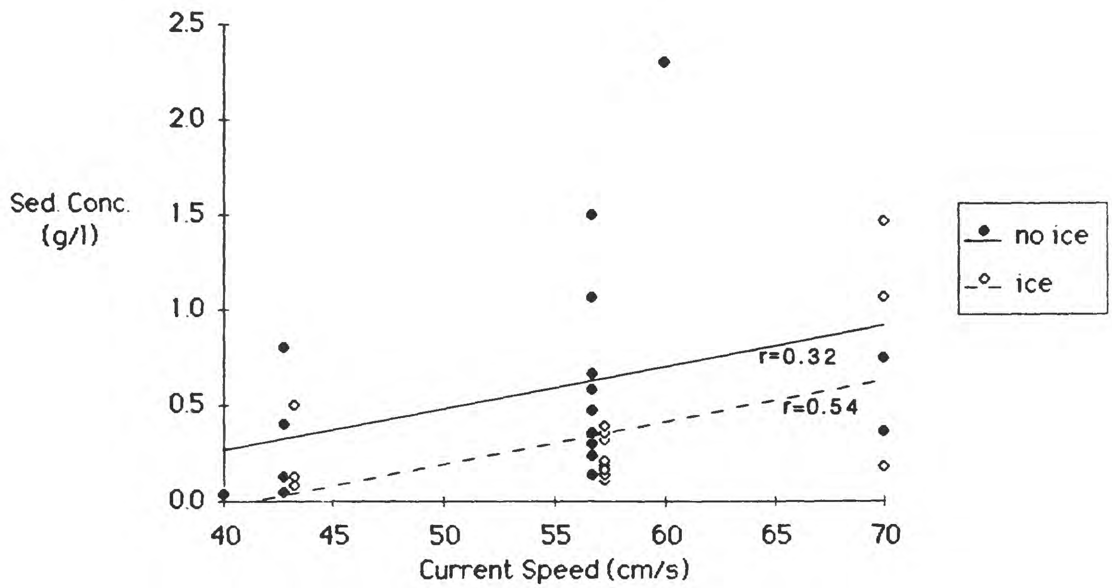
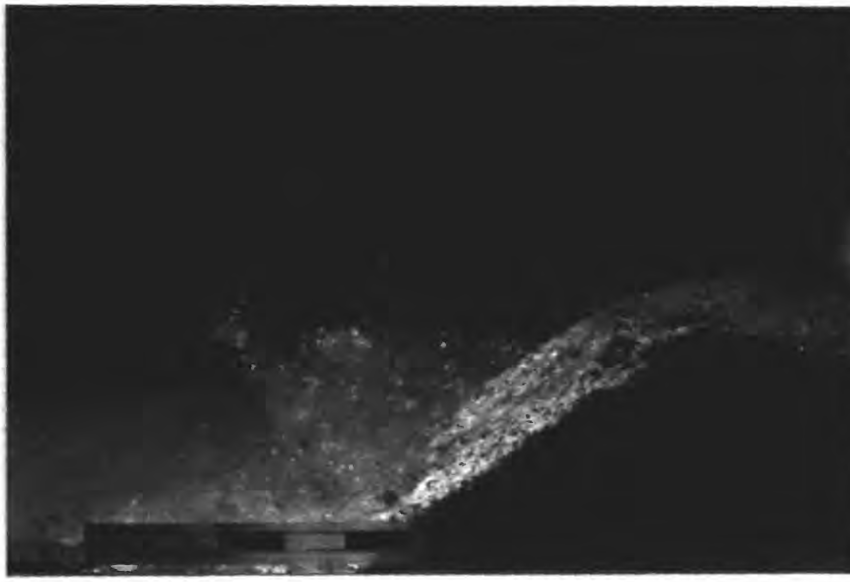
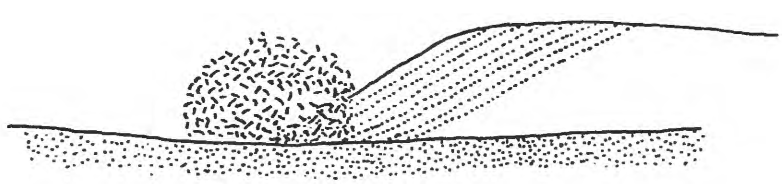


Figure 11. Graph of suspended sediment concentration versus current speed. At similar current speeds there generally are higher concentrations of suspended sediment in the water before the frazil ice starts forming than after.



A



B

Figure 12. A) Anchor-ice mass composed of frazil ice crystals lying in the lee of a 3.5-cm-high ripple (Experiment 29). B) Such masses disrupt normal avalanching and generation of cross bedding in the lee of ripples.

Table 4. Sediment concentrations in frazil and anchor ice samples.

Experiment Number	Current Speed (cm/s)	Sediment Conc. (g/l)	Sample Type	Water Salinity (ppt)
24	70	17.60	frazil/anchor ice	fresh*
26	70	42.80	frazil/anchor ice	fresh*
27	60	9.50	frazil ice	fresh*
29	43	0.94	frazil ice	fresh*
30	60	20.20	frazil ice	fresh*
37	57	3.70	frazil ice	fresh*
37	57	37.00	anchor ice	fresh*
38	57	0.02	frazil ice	29.14
39	57	0.10	frazil ice	29.14
39**	57	1.04	anchor ice	29.14
39**	70	3.39	anchor ice	29.14*
52**	42	88.30	anchor ice	36.95
52**	42	13.50	anchor ice	36.95
53	53	4.74	anchor ice	fresh*
54	42	31.25	anchor ice	fresh*

*Salinity was not determined in fresh-water experiments.
**Two anchor ice samples collected in this experiment.

so the ice above the sediment had very little sediment incorporated into its structure. If the ripple continued to migrate past the buried anchor ice, the anchor ice was excavated on the stoss side as a single block of ice-bonded sediment. This ice-bonded sediment block acted as a single large grain in the flow. If currents were strong, they scoured depressions around the ice-bonded sediment block similar to scour depressions seen around pebbles in streams. If frazil ice was still in suspension when the ice-bonded sediment block was excavated, it would become attached to the anchor ice mass.

In the salt-water experiments, frazil ice normally did not stick to cobbles or other smooth obstructions in the flow. It did, however, stick readily to mineral specimens mounted on plexiglas bars in the flow. The first frazil usually was trapped at the intersection of the mineral specimen and the plexiglas bar. A rough surface texture apparently is necessary to trap frazil crystals in salt water. Once the first ice crystals were trapped, the anchor-ice mass grew rapidly by scavenging frazil crystals from the water column. Anchor ice rarely formed in the lee of ripples in salt water experiments, and in those cases where it did form it was less than 1 cm in diameter.

Since little anchor ice formed in the lee of ripples in salt water, three different approaches were used to simulate the ice-bonded sediment seen in diving traverses. First, in some experiments a 250-ml block of ice-bonded sediment was placed on the floor of the flume. Second, in some experiments a plastic bag filled with sand saturated with brackish (~14 ppt) water was placed on the floor of the flume (fig. 13). This bag was cut open when the water temperature approached T_m, exposing the sand within. The brackish water had a higher freezing point than the overlying water, so the sand inside the bag was ice bonded when the bag was removed. Finally, in some experiments 100 ml of brackish water was injected directly into bottom sediment before supercooling began. This was not a satisfactory method for producing ice-bonded sediment; in most cases the sediment with brackish water was either transported away or buried before frazil ice was produced.

Anchor ice formed on all ice-bonded sediment at low current speeds. At higher current speeds, there was not enough adhesion between frazil crystals and the ice-bonded sediment to form anchor ice. Of the 3 methods used to artificially produce ice-bonded sediment, the first approach was best at collecting anchor ice, probably because the block projected up into the supercooled flow. Often the anchor-ice masses that formed around the block were very similar to those observed along the diving traverses (fig. 14). In salt-water experiments, anchor ice formed more readily on ice-bonded sediment than on any other material used.

At the end of several experiments, in both fresh and salt water, the sediment incorporated into frazil and anchor ice was observed to rain out of the ice when the flow was stopped. If enough sediment dropped from an anchor-ice mass, it became positively buoyant and rose to the water surface. This indicates that most of the sediment in frazil and anchor ice is trapped in spaces between ice crystals, rather than

Figure 13. View of flume showing bag containing sand and brackish water (left) and a man-made block of ice-bonded sediment (right) used as a nucleus for growth of anchor ice.

Figure 14. Salt-water anchor ice growing from the block of ice-bonded sediment shown in Figure 13. This anchor ice mass has a morphology that is very similar to the anchor ice masses observed on the diving traverses in the Beaufort Sea (figs. 5 and 6).

adhering to or being incorporated within the ice crystals.

Mineral Specimens, Frazil Ice, and Anchor Ice

Attempts were made to ascertain if anchor ice forms preferentially on certain materials. For this purpose samples of different materials, mostly mineral specimens (Table 1), were supported in the flow, either on metal rods or a plexiglas frame. In addition to the listed materials, in two fresh-water experiments a cobble with attached algae was placed in the flow, and in 2 salt-water experiments fronds of *Macrocystis* spp. (Giant Perennial Kelp) were placed in the flow to learn how frazil and anchor ice interact with aquatic plant material.

All samples except the *Macrocystis* collected anchor ice without notable selectivity. Anchor ice started growing first on samples closest to the water surface and on samples with rough surface textures. Usually the first frazil crystals were caught on rough minerals or at the intersection of a mineral sample and its support. After the first ice crystals were trapped, the anchor-ice mass grew quickly by addition of frazil-ice particles, until it filled all space between sample supports, and then continued to grow in an upstream direction. Figure 10 shows the mineral specimens and their support covered with a mass of anchor ice from salt water Experiment 43. Here the anchor-ice mass is about 5 cm thick up-current from the mineral specimens, it extends from one side of the flume to the other, and it is largest near the water surface. This is because the buoyant frazil-ice crystals are concentrated near the water surface.

Once anchor ice began forming on the mineral specimens and their supports, it trapped essentially all of the frazil. Anchor ice formed similarly on the mineral specimens in fresh and salt water. Regardless of water salinity, large masses of anchor ice formed on the minerals, materials, and their supports, except for the *Macrocystis.* Conversely, the fresh-water algae collected a great deal of anchor ice.

The above tests suggest that surface texture of an object probably is more important than composition or crystal structure for collecting anchor ice. Irregularly shaped objects with rough surfaces are best at accumulating anchor ice. The bond between anchor ice and the specimens in the flow was weak; when the supporting frame was disturbed or removed from the water the anchor ice broke free and was carried away by currents.

Special Runs

Cooling through the Flume Floor. In Experiment 37 an 11X18 cm area of the flume floor was cooled with dry ice to simulate cooling by permafrost. The dry ice was placed in contact with the aluminum floor of the tank. The sediment cover in the area underlain by dry ice was approximately 3 cm thick. The experiment was conducted in fresh water at a current speed of 57 cm/s. T_m, T_e, and T_e-T_m for this experiment were typical for fresh-water experiments (Table 2). No anchor ice or ice-bonded sediment formed over the dry ice during the experiment, but several flocs of anchor ice did collect upstream in the lee of a migrating ripple. It appears that the sediment cover was thick enough to insulate the sediment at the sediment-water interface, so that the dry ice exerted no influence.

Addition of Dry Ice to Supercooled Water. Shaefer (1950) proposed seeding supercooled water with dry ice to initiate formation of a surface ice cover and reduce supercooling. The formation of a solid ice cover inhibits the formation of frazil ice (Shaefer, 1950). In Experiment 28 the water was seeded with approximately 200 g of pea-sized dry ice at the first appearance of frazil ice. A large amount of frazil ice formed as soon as the dry ice was added, but there was almost no reduction in water temperature (Table 2). Although the water temperature remained low, frazil ice that formed was not sticky, and no sediment-laden anchor-ice flocs formed. After the dry ice had sublimed, the water temperature began dropping until it eventually reached a temperature below the initial supercooling. High turbulence in the flume inhibited the formation of a solid ice cover even with the addition of dry ice.

Addition of Chilled Sand to Supercooled Water. During Experiment 34 (Table 2) approximately 80 g of dry sand at a temperature of -18°C was added to fresh water in the flume over a 10 minute period during frazil-ice formation. The purpose of adding cold sand was to simulate sediment blowing into a water body from surrounding land. The sand was sprinkled into the flow, and it was carried at least some distance down current before settling to the bottom. Sediment-laden anchor ice flocs formed during this experiment, but not in significantly greater quantity than in those experiments where no chilled sand was added to the flow. There was no correlation observed between the addition of sand and the formation of sediment-laden frazil or anchor ice.

In some cases, when the cold sand grains fell into the water a sheath of ice instantly formed around them. This ice increased the buoyancy of sand grains and kept them in suspension. Ice that formed around the sand grains was not frazil ice, but rather a solid coating of ice that conformed to the shape of the sand grain. This ice apparently formed because the sand grains were below the freezing point of the water.

Bubbling Cold Air into the Flume. Carstens (1966) suggested that bubbling air into a supercooled water column would supply the necessary turbulence to 'freeze out' any supercooling. To test this hypothesis, in Experiment 22 compressed air at -14°C was bubbled into the flume through a scuba regulator. The addition of compressed air did 'freeze out' the supercooling (Table 2), but in the process a large amount of sticky frazil and sediment-laden anchor ice was made. This is exactly what Carstens (1966) was trying to prevent. Apparently, introducing cold air directly into the water resulted in increased heat transfer from the water to the air, producing large amounts of frazil and anchor ice. Perhaps if warm air were bubbled into the supercooled water it would 'freeze out' the supercooling while not supplying another heat sink to increase the production of frazil ice.

DISCUSSION

Comparison of Frazil and Anchor Ice in Fresh and Salt Water

Several differences were observed between frazil- and anchor-ice formed in fresh and salt water. These differences include the morphology of the frazil flocs, freezing of the floating frazil into a solid ice cover, and the formation of anchor-ice masses. The size and shape of individual frazil-ice crystals, however, appear to be identical, regardless of salinity.

Most frazil crystals in the flume were in the shape of small, thin discs. In one salt-water experiment, hexagonally-shaped crystals were seen in addition to the more common discs and in several fresh-water experiments a few needle-shaped frazil crystals were observed. The disc-shape is apparently the most common form of frazil ice in both fresh and salt water, and has been reported by many authors. Martin and Kauffman (1981) saw disc-shaped frazil ice in a wave tank with salinities of 35.5 ppt. However, Hanley and Tsang (1984) reported that they never saw frazil-ice discs in their salt-water experiments. Instead, salt-water frazil ice formed whitish, waxlike crystals that "...grew three dimensionally by producing thin fingers and plates in different directions...". As Hanley and Tsang (1984) noted, systematic studies are needed to shed more light on the parameters that affect the frazil-ice crystal form.

Figure 8 suggests that, for a given cooling rate, salt water will reach a slightly greater degree of supercooling than fresh water, assuming that the value T_e-T_m is a close estimate of supercooling. However, the large amount of scatter at any given cooling rate makes the data somewhat ambiguous, and the effects of salinity on supercooling may be negligible.

The major differences observed between frazil and anchor ice formation in fresh and salt water are the ways in which flocs grow and react with bottom sediment. Relatively large flocs formed in fresh water. These large flocs either rose to the surface soon after forming or rolled along the bottom and collected large amounts of sediment. If a floc collected enough sediment, it settled into the lee of a bedform, forming anchor ice (fig. 12). No large frazil-ice flocs formed in salt water. Instead, small aggregates of two or more crystals formed. These aggregates appeared to be very similar in form to the three-dimensional crystals described by Hanley and Tsang (1984). Much less anchor ice formed on bottom sediment in the salt-water experiments than in the fresh-water experiments.

In fresh water, frazil-ice flocs rose to the surface shortly after forming and froze into a solid ice cover from the surface downward. Salt-water frazil ice tended to stay in suspension for long periods after it formed. Salt-water frazil probably stays in suspension more readily than fresh water frazil because it is easier to overcome the buoyant forces on single crystals or small aggregates than it is to overcome the buoyancy of the large fresh-water frazil-ice flocs. Hanley and Tsang (1984) also noticed that salt-water frazil ice is much less likely to form large flocs or a solid ice cover than fresh-water frazil ice.

The amount of frazil ice that formed on the mineral specimens suspended in the flow was uniform, regardless of water salinity. Whenever the mineral specimens were placed in the flume they collected large masses of anchor ice, thereby nearly eliminating the frazil ice in the flow. The *Macrocystis* in salt water did not support any anchor ice growth, whereas the algae used in the fresh-water experiments collected large amounts of anchor ice. This suggests that anchor ice sticks more readily to aquatic plant material in fresh water than in salt water, although the ability of frazil ice to stick to plant material may be more a function of the particular plant material than the salinity of the water that the frazil ice formed in.

Many of the observed differences in fresh and salt water may be a function of whether different types of frazil are sticky. Carstens (1966) noted that fresh-water frazil is sticky or 'active' in supercooled water. This stickiness makes the formation of anchor ice much more likely and probably contributes to the growth of the large frazil-ice flocs in fresh water. In water that is not supercooled, frazil ice is 'passive' and has much less tendency to stick to submerged objects. The little work that has been done on salt-water frazil- and anchor-ice formation suggests that, even in supercooled water, salt-water frazil ice is not sticky (Hanley and Tsang, 1984). This lack of stickiness is explained by salt rejection from the ice as a frazil-ice crystal forms. This salt forms a thin layer of water with higher salinity and correspondingly lower freezing point around the frazil crystal, which in turn inhibits continued frazil ice growth and apparently also reduces the stickiness of the frazil crystal (Hanley and Tsang, 1984).

The apparent lack of stickiness of salt-water frazil ice could explain why no large flocs formed in the salt-water experiments and why less anchor ice formed. Salt rejection also may have inhibited the formation of a solid ice cover in the floating salt-water frazil ice. The conclusion that salt-water frazil ice is not sticky is the result of flume studies, and these studies may not accurately duplicate natural systems, because in a small flume there is a relativly large change in the water salinity as ice is formed. These large salinity changes don't occur in the ocean, where the ratio of frazil ice to water is much lower. It is possible that frazil ice in natural salt-water environments is sticky, in fact this is suggested by the formation of anchor ice in marine environments in both the Arctic and Antarctic. More studies of naturally occurring marine frazil and anchor ice are necessary to determine whether or not it really is sticky.

Frazil Ice, Anchor Ice, and Sediment Transport

One possible explanation for the observed reduction in suspended sediment concentration during periods of frazil formation (Table 3 and fig. 11) is that sticky frazil ice crystals in supercooled water scavenged sediment particles out of suspension, as suggested by Osterkamp and Gosink (1984). Frazil ice tends to form flocs that are not uniformly distributed through the water column, and the sampling method used to measure suspended sediment concentration excluded large, sediment-rich flocs. Thus, although the amount of sediment in suspension may have been less, the total load carried in suspension and by frazil ice may have been equal to or greater than the amount carried in suspension before frazil ice formed. Another possible reason for a reduction in suspended sediment concentration during frazil formation is decreased turbulence in the water caused by the presence of frazil ice (Tsang, 1982). This decreased turbulence reduces the capacity of the flow. From the present experiments no conclusions can be drawn about which process led to the observed reduction in suspended sediment concentration during periods of frazil formation.

The high sediment concentrations measured in frazil ice compared to those in water (Tables 3 and 4) tend to support the idea that suspended sediment is scavenged by frazil ice. However, some of the sediment seen in the frazil ice clearly was incorporated into flocs as they bounced and rolled along the bottom. The same processes of flocs rolling along the bottom and picking up sediment have been described in rivers by Arden and Wigle (1972) and Osterkamp and Gosink (1974). Thus, there is some question wether scavenging occurs by the sticky action of the frazil ice, or wether it occurs by trapping of sediment particles at the interstices between ice crystals in flocs. More work is needed to determine if sediment inclusions in frazil ice occur within an individual ice crystal or just at the interstices between ice crystals. If sediment is trapped at the interstices between frazil-ice crystals, it is possible that 'stickiness' plays no part in sediment transport by ice.

The buoyant force of frazil and anchor ice has the potential to lift large amounts of sediment from the bottom and carry it away with the flow. The maximum amount of sediment a block of ice can carry is limited to the amount that brings the combined mass of the ice/sediment conglomeration to the mass of an equal volume of the surrounding water, that is

$$\rho_w V_{i+s} = \rho_s V_s + \rho_i V_i \qquad (1)$$

where ρ_w is the density of water (for these calculations, assumed to be pure water at 1.0 g/cm^3); ρ_s is the density of sedimentary particles (2.65 g/cm^3); ρ_i is the density of ice (0.92 g/cm^3); V_{i+s} is the volume of ice plus sediment in the neutrally-buoyant mass; V_s is the volume of sediment in the mass; and V_i is the volume of ice in the mass. V_{i+s} is composed of fractional volumes of sediment (f_s) and ice (f_i) such that

$$V_s = f_s V_{i+s} \qquad (2)$$

and

$$V_i = V_{i+s} - f_s V_{i+s} \qquad (3)$$

or

$$V_i = V_{i+s}(1-f_s). \tag{4}$$

Substituting the terms for V_s and V_i from equations (2) and (4) into equation (1) gives

$$\rho_w V_{i+s} = \rho_s f_s \, V_{i+s} + \rho_i V_{i+s} \, (1-f_s). \tag{5}$$

Both sides of the equation can be divided by the term 'V_{i+s}', leaving

$$\rho_w = \rho_s f_s + \rho_i - \rho_i f_s. \tag{6}$$

Substituting the numeric values of ρ_w, ρ_i and ρ_s into equation (6) leaves

$$1 = 2.65 f_s + 0.92 - 0.92 f_s. \tag{7}$$

Solving equation (7) for f_s yields

$$f_s = 4.6\% \qquad (8).$$

Thus, the volume of sediment in a neutrally buoyant ice/sediment block in fresh water is 4.6 percent of the total volume of the block. This value can be translated to the more common measure of weight of sediment per unit volume by considering a neutrally buoyant block that has a volume of 1 liter. The weight of this block would be 1000 g. The weight of sediment in the block will be equal to the volume of sediment times its density, or

$$\begin{aligned} V_s p_s &= 0.046(1000 \text{ cm}^3)(2.65 \text{ g/cm}^3) \\ &= 122 \text{ g} \end{aligned} \tag{9}$$

so the maximum sediment concentration that can be carried by a neutrally buoyant ice-sediment mass in fresh water is 122 g/l.

This value considers only the buoyant force of the ice, and does not account for increased surface area and current drag, which would add to the transport capacity of a turbulent flow. Also, salt water, with its greater density, is able to buoy up slightly more sediment per unit volume of ice.

Nearly all published values of sediment concentrations in naturally occurring frazil ice come from the Alaskan Beaufort Sea. Barnes et al. (1982) sampled sediment-laden fast ice and found maximum sediment concentrations of about 1.6 g/l. During a different year in the same area, Osterkamp and Gosink (1984) found maximum sediment concentrations of 1.3 g/l. In both of these studies, the frazil ice was sampled after a solid ice cover had formed by freezing of the interstitial water of floating frazil ice. Martin and Kauffman (1981) found that, in a floating frazil-ice mass, the maximum concentration of frazil ice is about 44 percent of the total volume. The remaining volume is water filling the voids between frazil crystals. If one assumes that all of the sediment measured by Barnes et al. (1982) and Osterkamp and Gosink (1984) was trapped in the frazil ice and none in the interstitial water, the sediment concentration in the frazil ice is calculated to be around 3 g/l. This value is about 2 orders of magnitude below the theoretical limit of 122 g/l.

In the flume, sediment concentrations in the frazil ice measured as high as 20.2 g/l, although most of the values fell below 3.7 g/l (Table 4). These lower values are in the same range as those seen in natural settings. Table 4 also lists the values of sediment concentrations in anchor ice. These values also fall well below the calculated maximum sediment concentration that an ice mass can carry, so the buoyancy of the ice should have lifted the anchor ice off the bottom. However, only the upper portion of anchor ice masses were collected to prevent contamination by bottom sediment. As discussed earlier, the excluded bottom portion of anchor ice commonly was buried by advancing ripples, so the listed values of sediment in the anchor ice probably are too low. Some water is retained in the interstitial spaces of ice samples that were collected to determine sediment concentrations (Tsang, 1982). This water results in slightly low values for the amount of sediment actually carried by frazil and anchor ice.

The literature contains numerous examples of anchor ice with large (but unmeasured) amounts of entrained sediment being released from the bottom and carried away by currents (Zubov, 1943; Dayton et al, 1969; Wigle, 1970; Arden and Wigle, 1972; Gilfilian et al., 1972; Osterkamp and Gosink, 1974; Martin, 1981, Tsang, 1982). Anchor ice is released from the bottom when the water is no longer supercooled and geothermal heat warms the bottom side of the anchor ice. In rivers, this sediment-laden anchor ice commonly rises to the surface and is carried downstream by currents (Arden and Wigle, 1973; Wigle, 1970). These anchor-ice masses can move boulders weighing up to 30 kg (Martin, 1981). Apparently not all of the released anchor ice rises to the surface. Gilfilian et al. (1972) and Osterkamp and Gosink (1983) reported that anchor ice sometimes is seen traveling just below the base of a solid ice cover or bouncing along the bottom in streams. As noted by Martin (1981), anchor ice and frazil ice increase the competence of streams, and observations by other workers and this study suggest that they also can increase stream capacity. Unfortunately, there are no published values for the amount of sediment transported by frazil or anchor ice in streams and rivers, or any estimates of the amount of sediment moved by ice compared to the total annual sediment load of a river. Both of these questions deserve further study, first to see if sediment concentrations in ice in natural systems approach the theoretical maximum of 122 g/l, and also to determine the significance of frazil and anchor ice as sediment transport agents.

Observations of Anchor Ice

Although there are numerous published observations of anchor ice resting on bottom sediment, or picking up and moving bottom sediment, there is little information on how anchor ice could affect primary sedimentary structures. If evidence of anchor ice is preserved in the sedimentary record, it could be an important paleo-environmental indicator. Reineck and Singh (1980) reported that ice-crystal imprints can be observed in bedding planes in both modern and ancient sediment. These imprints were thought to form mainly under subaerial conditions, but the present findings suggest that they also can form in subaqueous environments.

The flume experiments show that anchor ice can be deposited in the lee of migrating bedforms and become buried (fig. 12). Burial of anchor ice masses results in disruption of normal avalanching on the slip face and disrupts ripple cross-bedding. Unstable sediment precluded determining whether any sedimentary structures were formed by these processes. At the very least, melting of buried anchor ice masses should result in collapse and disruption of any structures in overlying sediment, in addition to any localized disruption of cross-bedding caused by sediment avalanching onto the anchor ice mass. Such disruption features might be hard to distinguish from features caused by other processes like bioturbation or ice gouging. It also is probable that the faint striations caused by frazil ice flocs sweeping up the back side of ripples could be preserved under favorable conditions. However, it would be difficult to distinguish these striations from similar marks formed by other tools.

Anchor ice masses buried by advancing ripples are infiltrated by large amounts of sediment and then compacted. If ripples migrate past the buried anchor ice mass, the sediment-rich block is excavated and exposed to overlying water once again. This is one possible mode of formation of the sediment-rich cores seen in anchor ice clumps on the diving traverse off Reindeer Island and shown in figures 4 and 5. This process also would explain the 20 percent excess water by volume found when the cores were melted and the sediment was allowed to settle. When similar ice-bonded sediment blocks were placed in the flume in salt-water experiments, they collected halos of delicate crystals that are similar to the anchor ice clumps seen along the diving traverse (fig. 14).

Reimnitz et al. (1986) present another hypothesis to explain the presence of the sediment-rich ice bonded cores seen in the anchor ice masses off Reindeer Island, and also to explain the ice-bonded sediment seen during the diving traverses off the West Dock and Reindeer Island. In the summer, ice melt and river discharge reduce the salinity of nearshore water, and of interstitial water in nearshore sediment. During freezeup, water output from rivers is low, and water of higher salinity moves from offshore into shallow-water areas. This higher-salinity water has a lower freezing point than the interstitial water. During storms, the high-salinity water is cooled to below the freezing point of the less saline interstitial water, and it supplies a heat sink for freezing of the interstitial water. This theory explains the large areas of frozen sediment seen near the beach off Reindeer Island and the West Dock, but it does not adequately explain the presence of sediment-rich ice-bonded blocks surrounded by unbonded sediment like those observed in deeper water off Reindeer Island. This method of formation also does not account for the excess water observed in the cores after melting. One possible method of producing blocks from a large area of ice-bonded sediment is to break up the large area of ice-bonded sediment by wave and pack-ice activity during storms and transport the smaller blocks to quiet spots in troughs between offshore bars. In the dying stages of a storm, frazil ice crystals could be plated onto the ice-bonded sediment core, forming the open, delicate crystal structure observed in the anchor ice clumps off Reindeer Island.

There is no information on how long anchor ice lasts in the Beaufort Sea. Prior to 1982, we had never observed anchor ice in the Beaufort Sea, although we have made over 100 research dives in a variety of settings and seasons. In addition, we have talked to other researchers and consultants who have made numerous winter dives in the Beaufort Sea, but have not observed anchor ice. However, none of these winter dives were made earlier than middle to late November, and any anchor ice that had formed could have already disappeared. Observations from the Antarctic, in McMurdo Sound (Dayton et al., 1969) suggest that anchor ice has a short life span of only two weeks. Similarly, in the Niagara River anchor ice usually rises to the surface a few hours after it forms (Arden and Wigle, 1972). The release of anchor ice from the bottom is caused by a rise in the surrounding water temperature. Anchor ice in the Beaufort Sea probably lasts no longer than that in McMurdo Sound, but observations will have to be made in the period immediately following freezeup to determine its actual life span. It is important to note that the absence of anchor ice in late winter does not necessarily mean that no anchor ice formed during the freezeup.

Both of the above methods may play a part in forming the sediment-rich cores of the anchor-ice masses observed off Reindeer Island, and careful study is needed to determine the exact nature of formation of both the sediment-rich core and the delicate outer crystal array. Unfortunately, gathering information on the mode of formation of anchor ice is difficult because it involves working in a very harsh environment.

Regardless of the method of formation of the ice-bonded sediment and anchor ice seen in the Alaskan Beaufort Sea, these sediment-rich ice blocks obviously are moved by waves and currents. It is common to see such blocks thrown up onto beaches by storms during freezeup, and often in the summer plaques of fine-grained sediment in a coarser grained matrix are found on seaward-facing beaches (fig. 15). These ice-bonded blocks and sand plaques in a coarse matrix are evidence that ice-bonded sediment is transported onto beaches during freezeup. It also is possible that such material is transported offshore, especially if the ice-bonded blocks contain enough ice to significantly increase their buoyancy. This could be an important sediment transport mechanism in shallow-water shelf areas where anchor ice forms.

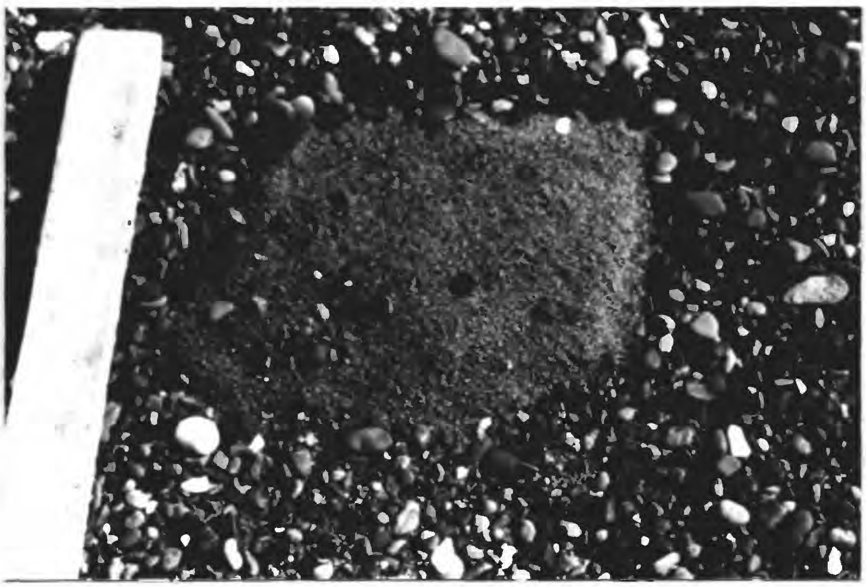


Figure 15. A small plaque of sand in a gravel matrix on a seaward-facing barrier-island beach in the Beaufort Sea. This plaque was transported and deposited as anchor ice during a fall storm. Such plaques are common on seaward-facing beaches. Wood in left corner is 5 cm across.

Anchor-ice formation and ice-bonding of sediment affects the sedimentary regime in rivers and oceans by armoring the bottom. Armoring of the bottom reduces the ability of waves and currents to move sediment, but the effects of armoring the bottom during a dynamic event are only a matter of speculation. Anchor ice can form along the entire length of the Niagara River, regardless of water depth or velocity (Arden and Wigle, 1972). In this situation, the presence of anchor ice may result in a significant reduction in suspended sediment load. However, this reduction in suspended sediment load would last only a few hours, since the anchor ice usually forms at night and is released from the bottom on the following day (Arden and Wigle, 1972). Along the West Dock diving traverse in the Beaufort Sea, up to 75 percent of the bottom was ice bonded. On the Reindeer Island traverse there was considerably less ice bonding. This ice bonding occurred during a major fall storm, a period of major sediment reworking on the shelf. The presence of ice bonding and anchor ice might have played a major role in armoring the bottom from storm waves at this time, but the distribution of anchor ice and ice bonding is not known so it is impossible to evaluate its significance.

In addition to armoring the bottom, the formation of anchor ice can reduce the amount of water carried by rivers, as discussed earlier. This flow reduction should result in a net reduction of suspended sediment transport. However, these losses may be balanced by possible increased sediment transport caused by frazil ice and anchor ice lifting and carrying bottom sediment because of their buoyant forces. Thus, the net result of frazil and anchor ice formation on sediment transport in rivers and oceans is unknown, and systematic studies of the interactions of sediment with frazil and anchor ice in both fresh and saline water are needed.

CONCLUSIONS

The field observations and flume studies presented in this report indicate that frazil and anchor ice are important geologic agents. The main findings of this report include:

> (1) Anchor ice and ice-bonded sediment form on the shallow shelf of the Alaskan Beaufort Sea during cold storms associated with freezeup. Anchor ice consists of mounds of delicate ice crystals attached to ice-bonded sand and gravel seafloor, tires, and steel banding. The regional extent of anchor ice and ice bonding is not known, but along the diving traverses up to 75 percent of the sea floor was ice bonded. Ice bonding was observed in gravel, sand and mud substrates, with an apparent inverse correlation between sediment grain size and depth of ice bonding.

> (2) Flume experiments show that frazil ice forms readily in both fresh and

salt water. Frazil ice crystals have the same morphology in fresh and salt water, usually forming thin discs up to 5 mm in diameter. However, the morphology of frazil-ice flocs and the way frazil ice interacts with sediment varies with salinity. Fresh-water frazil flocs are larger and more cohesive than salt-water flocs, and individual ice crystals have a random orientation. Salt-water flocs are tabular masses with the flat sides of individual crystals in contact with each other. Dendritic arms, composed of individual frazil crystals, sometimes grow out from the main tabular body. Frazil-ice flocs in fresh water are more likely to collect sediment than salt-water flocs, and they freeze into a solid ice cover more rapidly.

(3) In the flume, anchor ice forms more readily in fresh water than in salt water. Anchor ice forms from frazil ice, either when frazil flocs stick to the up-current side of projections in the flow or when frazil-ice flocs come to rest in the lee of ripples.

(4) Anchor ice forming in the lee of ripples commonly is buried by migrating bedforms. As the anchor ice is buried, it is compressed and sediment is incorporated into its structure, forming an ice-bonded sediment block similar to those seen in the Beaufort Sea. These ice-bonded sediments may be the site of later anchor-ice growth by accretion of frazil ice. When ice-bonded sediment blocks were placed in the flume during salt-water experiments, they formed anchor-ice masses that were very similar in appearance to the anchor ice seen in the Beaufort Sea.

(5) Burial of anchor ice results in disruption of normal ripple cross-bedding and may result in unique primary sedimentary structures. The form of any sedimentary structures produced by frazil and anchor ice was not determined in this study.

(6) Experiments performed to test if anchor ice forms preferentially on specific materials show that a rough surface texture is more important than material type for initial formation of anchor ice. Anchor ice forms on all of the materials tested except for *Macrocystis* spp., a marine alga.

(7) Analysis of flume data suggests that the suspended sediment load decreases during periods of frazil formation. However, the scatter in the data makes this conclusion somewhat tentative. More measurements of suspended sediment concentrations before and during frazil ice formation should be gathered from natural settings.

(8) Frazil ice and anchor ice are able to lift bed sediment with their buoyancy. Calculations show that ice is able to lift up to 122 g of sediment per liter of ice/sediment mixture by buoyant force alone. Sediment concentrations of this magnitude have never been observed, but there are very

few measurements of sediment concentrations in frazil and anchor ice. The sediment carried by frazil and anchor ice offsets the reduction in suspended sediment in the water column. Thus, the net effect of frazil and anchor ice on sediment transport is unknown, but the scanty data suggest that frazil and anchor ice increase the capacity and competence of streams and ocean currents.

Many questions remain about frazil and anchor ice as geologic agents. These questions may be difficult to resolve with flume studies, because the short periods of supercooling and the small amounts of water, sediment, and ice in flumes make extrapolation of flume results to larger natural systems difficult. Problems that need to be examined in more detail include: (1) What is the geographic extent of anchor ice and ice bonding in the sea, and what are the life spans of these phenomena? (2) How important is sediment transport by frazil and anchor ice in natural environments? To study this question, sediment budgets of fluvial and marine systems where frazil and anchor ice form should be determined, and the amount of sediment moved by ice should be compared to the total sediment load. (3) Does frazil ice in natural settings carry anywhere near the calculated amount of 122 g/l of sediment? Samples of sediment-laden frazil and anchor ice should be collected from a number of river and marine settings to get a better understanding of how much sediment these types of ice actually carry. (4) What causes the differences observed in fresh- and salt-water frazil and anchor ice? If these differences are caused by salinity, is there some critical value at which the behavior of the ice changes? (5) Are unique sedimentary structures formed by frazil and anchor ice? The present study suggests that sedimentary structures are formed, but these structures have not been described. If unique sedimetary structures are formed by frazil and anchor ice, they would be important paleoenvironmental indicators.

Frazil and anchor ice can form wherever there is turbulent, supercooled water. The surface waters of 48 percent of the rivers and lakes in the Northern Hemisphere freeze annually (Encyclopedia Britannica, 1981), and 25 percent of the world's continental shelf areas less than 200 m deep have an ice cover for part of each year (Barnes and Reimnitz, 1974). Under suitable conditions frazil ice and anchor ice can form in any of these waters. Thus, the area of subaqueous sediment potentially affected by frazil and anchor ice is very large. Until now, the role of anchor ice and frazil ice as geologic agents has received little attention, probably because of the difficult weather conditions that must be worked under to study these phenomena. More work is needed to define the extent of their influence.

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