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Variations in Anchor-Ice Crystal Morphology Related to River Flow Characteristics

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Anchor ice, a derivative form of frazil (but not actually frazil) is often described as an accumulation of frazil ice crystals attached to the bed. This implies that anchor-ice masses are composed of agglomerations of millimeter-to-centimeter sized ice discs. Yet, anchor ice from the small, riffle-and-pool Laramie River in southern Wyoming never comprises agglomerations of frazil crystals. Instead, anchor ice crystals vary from large, crenulated, plate-like crystals exceeding 10cm in diameter to low-relief imbricated masses of mm-sized ice particles that cover large portions of the river bed. Perfect, disc-shaped frazil crystals are rarely seen in Laramie River anchor ice masses. A literature review shows that large anchor ice crystals have been reported in a variety of fluvial systems. Variations in anchor ice morphology reflect changes in local flow conditions and meteorological conditions. The large size of ice crystals seen in anchor ice masses indicates that a significant amount of anchor-ice forms as in situ ice growth. This in situ growth indurate anchor ice masses, resulting in a relatively strong bond between the anchor ice and the bed.

1. Introduction

Anchor ice, a common phenomenon in rivers subject to freezing air temperatures, has been the focus of a number of studies during the last 80 years. There seems to be a prevailing notion that anchor ice is a derivative or evolutionary form of frazil ice. That is, anchor ice forms when frazil in supercooled water adheres to coarse bed materials, making a "spongy" or "porous" accumulation of ice on the river bed (c.f. Tsang, 1982). The relatively common comment that anchor ice is composed of "an accumulation of frazil" implies that the anchor ice mass is composed of disc-shaped frazil crystals less than 1cm in diameter. This notion is erroneous.

The writers have been students of anchor ice formation for a many years. The majority of our fluvial anchor ice observations have been made in the Laramie River, a small riffle-and-pool stream located in south-eastern Wyoming (Kempema et al. 2008). Here, we commonly observe porous anchor ice masses composed of irregularly shaped, tabular ice crystals exceeding 1cm in diameter and little resembling frazil discs (Figure 1). We have sometimes been mildly confused by trying to reconcile our Laramie River observations with published anchor ice observations, but have found confirmation in findings from lacustrine anchor-ice studies, which commonly report very large crystals in anchor ice masses (Kempema et al. 2001). Our fluvial anchor ice angst peaked last year when, after presenting some Laramie River observations at a meeting, several of our colleagues took us aside and gently chided us. The gist of our gentle colleagues' comments was that Laramie River anchor ice was unlike anything they had ever experienced, and that, quite possibly, this anchor ice is unique. We beg to differ.

Our paper reviews published accounts of anchor-ice morphologies (both crystal and ice masses), presents some new Laramie River anchor ice observations, and suggests which of the flow characteristics suggested by Kempema et al. (2008) might be most important in determining the crystal morphology in anchor ice masses.

2. Review of published anchor ice descriptions

Stickler and Alfredsen (2005) note that anchor ice formation, particularly in natural rivers, has scarcely been described in the literature. This observation seems especially true with respect to anchor ice crystal morphology. A literature review reveals that most researchers report that anchor ice is usually composed of accumulations of frazil ice; beyond this there is very little mention of the individual crystals making up anchor ice masses. Table 1 lists papers that give more detail on fluvial anchor ice crystal morphology. There are two things to note about Table 1: First, references exclude lacustrine and marine anchor ice, where ice crystals larger than 10 cm in diameter are often reported. Second, the table is not exhaustive. Due to space limitations not all papers reporting anchor ice composed of frazil adhering to the bed are listed. Surprisingly, there are very few references that even mention the size or morphology of anchor ice crystals in river settings. References to ice crystal size are often made in passing in a single sentence. Ice crystal morphology must often be gleaned from published photographs. For example, Figure 2 shows a photo from Schaefer (1950) of anchor ice attached to weeds in the Mohawk River. Similar anchor ice is often found in the Laramie River. In fact, the majority of published fluvial anchor ice photographs detailed enough to show ice crystal morphology are very similar to anchor ice photographs from the Laramie River.

With a freeze-up flow of ~$1m^3s^{-1}$, the Laramie River is smaller than most of the rivers listed in Table 1. It forms a useful natural laboratory for studying anchor ice. Interestingly, photographs of Laramie River anchor ice are remarkably similar to photographs of Neva River (Altberg, 1936) and Niagara River (Wigle, 1970) anchor ice, which have average discharges of 2600 and 5700 m^3s^{-1}, respectively. Similar crystal morphologies from rivers of such disparate size suggest that the processes forming anchor ice are similar over the same size range. This leads us to conclude that the anchor ice formed in the Laramie River is not "unique" or "unusual", and that ice observations from the Laramie River are applicable to a variety of different river systems.

3. Laramie River observations

Study site and methods. Observations were made along a 300m-long reach of the Laramie River near Laramie, Wyoming on 29 mornings between 15 November and 18 December 2008. Anchor ice, in varying amounts, was seen on 24 mornings. The Laramie River is a shallow, meandering, riffle-and-pool river flowing through a large, semi-arid intermontane basin straddling the Colorado/Wyoming border. The elevation at the study reach is 2200 m and the drainage area upstream of the reach is 2,000 km^2. Pools with coarse sand beds make up 80% of the study reach. Riffles, with gravel beds and occasional bedrock outcrops make up the remainder of the reach. The study reach is divided into 4 distinct sub-reaches based on local slope and bed substrate. During the study period the reach was 8 to 15 m wide, discharges is about 1 m^3s^{-1}, water depth was 0.20 to .80 m, and flow speeds were between 0.15 and 1 ms^{-1}. A meteorological station, 20 m from the study reach, recorded air temperature, wind speed, relative humidity, and solar radiation at 2 m above ground level every 5 minutes. In addition, water temperature was measured at 5 minute intervals with a thermistor attached to a rock on the river bed in a riffle. More information on the Laramie River study reach can be found in (Kempema et al. 2008).

On 25 November a trip was made to a reach about 30 km upstream of the study reach on the Laramie River. This reach is located where the river debouches from the mountains, and is located about 150 m downstream of a low-head diversion weir. The river upstream of the weir was completely frozen. The examined reach is a riffle that is steeper than the study reach and has a bed composed of rounded cobbles up to 20 cm in diameter. There was good anchor ice at this location, which appeared to be very similar to the anchor ice in the regular study reach, so the observations from this site are included with the other observations.

A typical observation procedure consisted of arriving at the study reach around 7AM and walking the study reach. Anchor ice locations were mapped, and representative current speeds and water depths were measured at selected anchor ice locations with an EM current meter attached to a top-set wading rod. Currents were measured at a position located 40% of the water depth above the riverbed for a period of 20 seconds. Anchor ice samples were collected from the bed, placed on a 1.25 cm grid, and photographed. Estimates of the range of sizes and shapes of anchor ice crystals were estimated before and after the sample was disaggregated (Figures 1, 3). In addition, notes were made on the gross anchor ice morphology and locations of anchor ice dams. A total of 72 usable anchor-ice crystal size/current speed/depth measurement sets were collected for this study.

Results. The gross (or mass) morphology of Laramie River anchor ice is similar to published descriptions from other small rivers (Hirayama et al. 1997; Hirayama et al. 2002; Stickler and

Alfredsen 2005; Terada et al. 1999; Tesaker 2004). Anchor ice forms and releases from the bed on a diurnal cycle and tends to grow on gravel or coarser substrates in riffles, though not exclusively. The typical growth cycle begins with supercooling and frazil generation in the evening and a modicum of frazil adhesion to the bed. If the water column contains supercooled water (likely in the form of unmixed tendrils or blobs), the growing anchor ice mass progresses through a series of stages loosely-attached scales, to tails, balls, sheets, and, finally, if enough ice forms, to anchor ice dams. This is essentially the growth pattern described by Kerr et al. (2002) from laboratory studies, with three differences. First, the gross morphology is not dependent on the Froude number of the flow. Second, when heat loss to the atmosphere diminishes or if the total nocturnal heat loss is not high enough anchor ice will retain its existing morphology until released from the bed. Practically, this means a section of riverbed that is covered by a massive sheet of anchor ice one night may be covered by scattered, low relief anchor ice balls the next night even though flow conditions are essentially the same. Finally, if anchor remains irrigated by supercooled water, and if its buoyancy does not lift it from the bottom, it eventually forms an anchor ice dam. Anchor ice dams should be considered a latter stage of anchor ice growth.

Once the incipient anchor ice forms by initial frazil adhesion to the bed, continued anchor ice growth occurs by a combination of continued frazil accretion and in situ ice growth; i.e. continued growth of ice crystals already attached to the bed (Qu and Doering 2007). It is the in situ growth that accounts for variations in anchor ice crystal morphology. In situ growth directly accounts for the internal strength of an anchor ice mass (by the inter-growth of ice crystals, Figures 1 & 2) and the strength of the bond between the anchor ice mass and the substrate. Thus, it is in situ growth that allows anchor ice to grow to a size sufficient to form anchor ice dams and allows formation of a strong enough bond to raft sediment when the anchor ice is released. The story of the portioning of accretionary and in situ growth in any particular anchor ice sample is contained in its ice crystal morphology. In the Laramie River, when ice crystals are small, the amount of anchor ice attached to the bed is small.

Estimates of the range of crystal sizes and shapes were made for the 72 anchor ice samples collected in this study (Figure 4). These samples were collected in areas with current speeds ranging from 16 to 1.06ms^{-1} and water depths ranging from 0.12 to 0.65m There was a range of crystal sizes in every anchor ice sample, with most samples having a minimum crystal size of <10mm. Only 9 samples had maximum crystal sizes of >50mm; the largest anchor ice crystals in this study were 150mm in diameter. A frazil-crystal morphology consisting of a near-perfect disc could not be identified in the majority of ice crystals examined in this study, although frazil discs were sometimes observed on the outer margins of anchor ice masses (Figure 5). The discs were always less than 8mm in diameter, and were never seen in the interior of anchor ice masses. This suggests that on most nights frazil crystals start growing and morphing as soon as they are attached to the anchor ice mass. Osterkamp (1978) states that ice growth rate can increase by an order of magnitude once a frazil crystal becomes attached to the bed; the greater velocity difference between ice and water flow increases heat transfer. Other authors (c.f. Schaefer, 1950) have noted that frazil crystals do not maintain a disc shape once their diameter exceeds 5-10mm, so it is not surprising that attached frazil crystals begin changing form as soon as they become attached to the bed. As a general rule, once ice crystals become larger they become more angular (compare Figures 1 and 5), although the outer edge of the crystals do not necessarily become rough or dendritic as the crystals become large.

Kempema et al. (2008) suggest 15 parameters, combined into 10 major dimensionless variables could comprise a descriptive model of anchor ice formation. We looked for simple predictive relationships between the largest crystal size observed in an anchor ice sample and Reynolds Number, Froude number, current speed, water depth, and cooling rate. No significant correlations were found. Likely, final crystal morphology results from a complex interaction of these parameters. This suggestion is reinforced by specific anchor ice samples that show variation in crystal size from top to bottom through the sample. Tsang (1982) and Ashton (1986) give examples of this ice stratigraphy, with smaller crystals overlying larger crystals. They attribute this grading to the fact that the larger crystals were deposited first, and so were exposed to a supercooled flow longer and could grow to a larger size. In the Laramie River, both increasing and decreasing crystal size with height above the bed have been observed. The change in crystal size is due to changing flow and weather conditions throughout the night. For example, a change in cooling rate associated with a passing warm or cold front could change the ice crystal size either reducing or increasing crystal size, respectively as the anchor ice mass grows. Similarly, a late-night snowfall results in accumulation of fine-grained ice crystals on top of already developed, larger anchor ice crystals. The largest anchor ice crystals are associated with anchor ice dams, and are usually found upstream of a dam. Anchor ice crystals evidently grow to larger sizes in backwater region created by a dam. It is not clear whether this increased growth is due to fewer frazil crystals reaching the bed to be incorporated into the anchor ice mass, or an increase in the level of supercooling in the water behind an upstream dam due to decreased turbulence as flow passes over a dam.

Two things we cannot correlate directly, but have anecdotal evidence for, are the effects of snowfall and bed grain size on anchor ice crystal growth. Snowfall of about 1cm seeds the river with many ice crystals, resulting in relatively small “soft” anchor ice masses not strongly attached to the bed. The ice crystals in these masses are less than3mm in diameter. It seems likely that high concentrations of snow in the water column inhibit supercooling, which in turn inhibits in situ anchor ice growth. Grain size has a more subtle effect on anchor ice crystal size. Large masses of anchor ice, covering tens of square meters of the bed and developing anchor ice dams composed of ice crystals to 100mm in diameter, can only grow on beds composed of medium (16mm) gravel and above. Conversely, anchor ice that grows on sand beds is always composed of poorly consolidated masses of ice crystals less than 1cm in diameter. Here, we suspect that in situ growth of crystals increases buoyancy to the point where small anchor ice masses are lifted off the bed.

4. Concluding remarks

A comparison of Laramie River anchor ice morphologies (both gross morphology and ice crystal morphologies) to what is described in the literature suggests that the large crystal sizes seen in Laramie River are not unique. These large crystals result from in situ growth of frazil crystals that become attached to the bed. Significant in situ growth appears to be necessary to generate the strong bonds that develop hard, competent anchor ice masses that are firmly attached to the bed. These strong bonds facilitate the formation of thick accumulations of anchor ice and anchor ice dams, and lead to ice rafting when large mats of anchor ice break free from the riverbed.

In closing, we would like to reiterate the difficulty in finding published information on anchor ice crystal morphology much beyond the statement that anchor ice masses are composed of accumulations of frazil crystals. More detailed descriptions of anchor ice crystals are needed to characterize potential morphologic variations in different fluvial settings.

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Table 1. Descriptions of anchor-anchor ice crystal morphology from published literature.

River	**Reference**	**Notes on anchor ice crystal morphology (Figures cited are in reference)**
Niagara	Tsang (1982)	Figures 19 and 20 show anchor ice masses composed of plate-like crystals with maximum dimensions of 2-4 cm.
	Wigle (1970)	Anchor ice crystals are described as "flat crystals or platelets roughly oval in outline and usually not more than several inches across"
Adyl-su	Piotrovich (1956)	A general statement on anchor ice morphology: "Occasionally depth-ice takes the form of angular plates some tens of centimeters in size. Such plates are formed when individual discs of depth-ice are exposed to protracted irrigation with supercooled water in the absence of other discs which could shield the growing plate from the action of water" Figure 1 is a picture, attributed to V.K. Al'tberg, looks very similar to anchor ice masses retrieved from Laramie River riffles.
Neva, Caucasus Rivers	Altberg (1936)	Figures 2, 3, and 8 show angular, blade-shaped, and rounded crystals in anchor ice masses composed of ice crystals "up to several cm in diameter." Initial anchor ice is frazil discs, these "undergo considerable deformation" during further growth.
Alaskan streams/rivers	Gilfilian et al. (1972)	". . .anchor ice formed only when frazil ice was already present in the stream." Figure 2 shows a gravel-laden anchor ice mass very similar to Laramie River anchor ice samples, with cm-sized ice crystals.
	Osterkamp and Gosink (1983)	Anchor ice consists of accumulations of frazil on the bed. However, they note two stages of growth: in early stages of growth, anchor ice consists of plate-like crystals; the later stage consists of ". . .a sponge-like mass of ice". The anchor ice shown in Figure 9 is very similar to Laramie River anchor ice samples collected in riffles, right down to the size of gravel attached to the underside of the anchor ice mass
New England Rivers	Schaefer (1950)	Schaefer distinguishes between frazil accumulations on submerged rocks and anchor ice, although he states (p.889) that frazil accumulations ". . .may resemble anchor ice particularly when a secondary transformation occurs. . ." Figure 5, which Schaefer calls transformed frazil ice deposits, would be called anchor ice by most researchers today, and looks similar to Laramie River anchor ice deposits, although there is no size scale. Figure 6 (true anchor ice, according to Schaefer, Figure 2) are intertwined "thin sheet crystals" attached to weeds. These ice plates are larger and more angular than the "frazil ice deposits", although it is impossible to determine size. Schaefer states that "true" anchor ice rarely occurs.
Niuppu	Terada et al. (1999)	Anchor ice is formed predominately from frazil crystals deposited from the flow.
Laboratory Studies	Kerr et al. (2002)	Anchor ice composed of frazil accumulation, morphology of mass consists of scales, tails, balls, and sheets with increasing Froude #.
	Qu and Doering (2007)	Anchor ice composed of frazil discs, although evidence for in situ growth is sited.

Figure 1. Laramie River anchor ice sample; the largest, blade-shaped ice crystals are 5cm long.

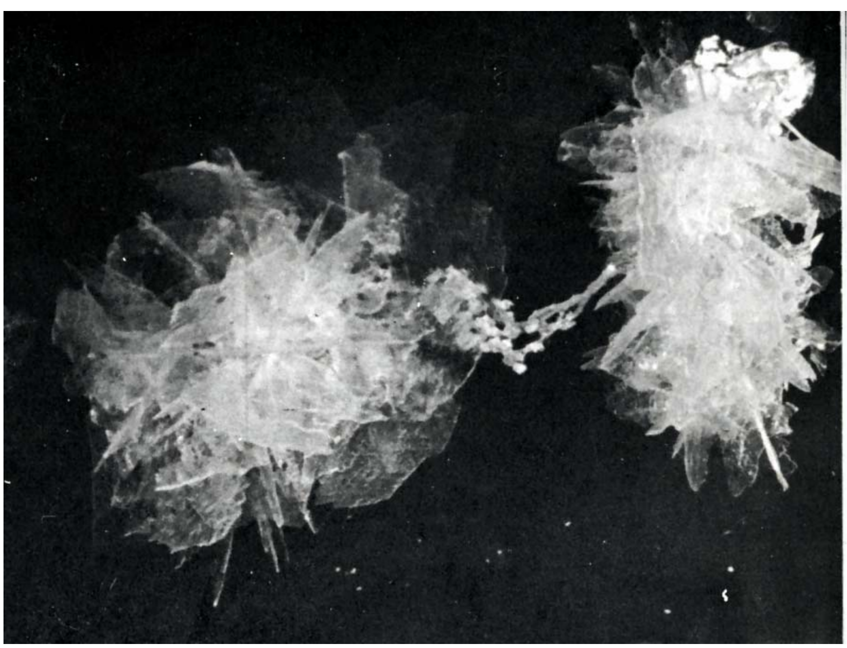

Figure 2. Copy of Figure 6 from Schaefer (1950) showing anchor ice growing on weeds on the Mohawk River floodplain. The individual crystals are up to several cm in diameter.

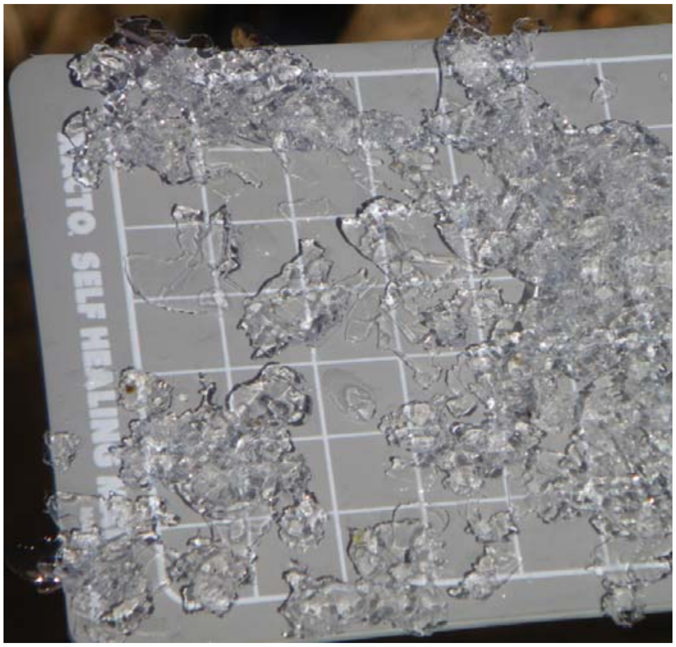

Figure 3. Disaggregated frazil crystals on a plastic grid. Note irregular, 2 cm diameter bladed ice crystal in left center of photograph. Gird spacing is 1.27 cm.

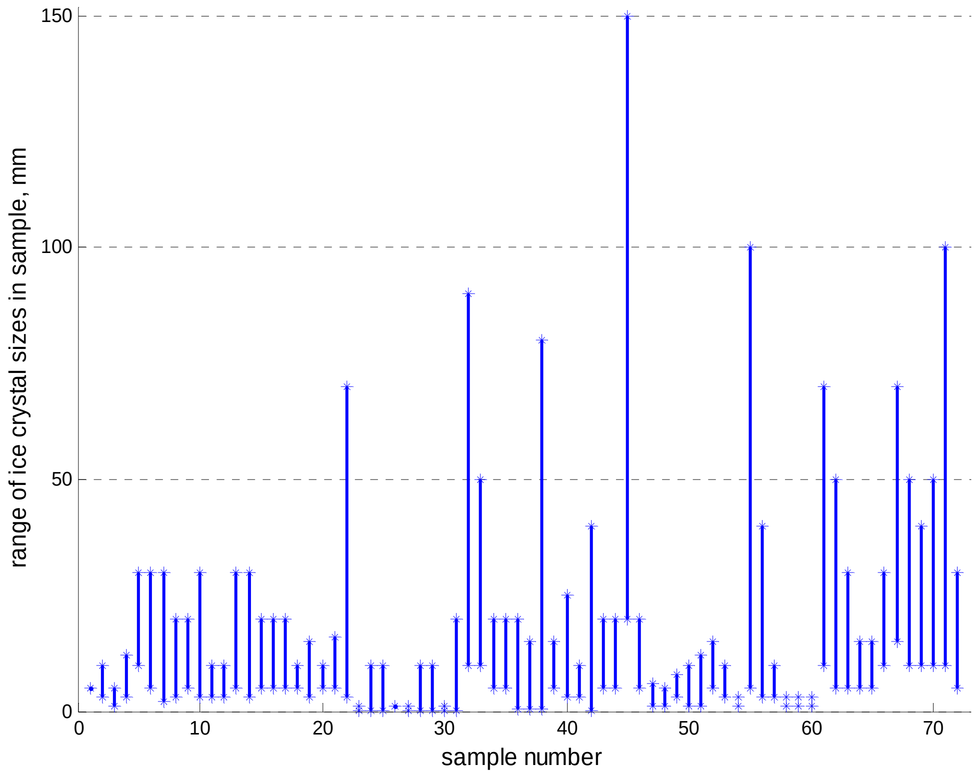

Figure 4. Range of individual ice crystal sizes collected from Laramie River anchor ice masses during fall 2008

Figure 5. Disc-shaped frazil crystals incorporated into a Laramie River anchor ice mass. The striking frazil crystal in the upper left center of the image is 5mm in diameter. Although several frazil discs are visible on the edge of the anchor ice mass, ice crystals in the interior of the mass have grown into irregular shapes.