

Aufeis Accumulations in Stream Bottoms in Arctic and Subarctic Environments as a Possible Indicator of Geologic Structure

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By Richard B. Wanty,¹ Bronwen Wang,¹ Jim Vohden,² Warren C. Day,¹ and Larry P. Gough¹

Abstract

Thick accumulations of ice, called “aufeis,” form during winter along stream and river valleys in arctic and subarctic regions. In high-gradient alpine streams, aufeis forms mostly as a result of ground-water discharge into the stream channel. The ice occludes this discharge, perturbing the steady-state condition, and causing an incremental rise in the local water table until discharge occurs higher on the stream bank above the previously formed ice. Successive freezing of overlapping ice layers can lead to aufeis accumulations several meters thick.

The location and extent of aufeis in high-gradient streams may be useful to relate local hydrology to geologic structure. In the Goodpaster River basin study area, mineral deposits are known to occur, the location of which may be structurally controlled. Therefore, a more thorough understanding of regional geologic structures may facilitate a more detailed understanding of the genesis of the mineral deposits.

Extensive aufeis was observed during visits to the Goodpaster River basin in east-central Alaska during 1999, 2001, and 2002. Seeps from the sides of the valleys caused ice to build up, giving the ice surface a concave-upward shape perpendicular to the stream direction. This concavity is evidence for ground-water discharge along the length of the aufeis, as opposed to discharge from a single upstream point. During thaw, streamflow is commonly observed out of the normal channel, evidence that occlusion of the channel (and shallow sediments) by ice is a viable mechanism for causing the water table to rise.

The thickest (>3 meters) and most extensive aufeis (100's of meters to kilometers along valleys) coincided with locations of laterally extensive (>5 kilometers) mapped high-angle brittle fault zones, suggesting that the fault zones are hydraulically conductive. Additional evidence of water

flow is provided by observed changes in stream-water chemistry in reaches in which aufeis forms, despite a lack of surface tributaries. Minor or no aufeis was observed in many other drainage valleys where no laterally extensive structures have been mapped, implying that aufeis formation results from more than a topographic effect or discharge from bank storage. Thus, the presence of thick, laterally extensive aufeis in high-gradient streams may be a useful aid to geologic structural mapping in arctic and subarctic climates.

Introduction

In high-latitude ecoregions, where prolonged subfreezing temperatures exist for a significant part of the year, thick accumulations of ice, called aufeis or naled, may form in areas of ground-water discharge, or where ice dams form in flowing rivers. For example, in our study area northeast of Delta Junction, Alaska, the average monthly temperature is below 0°C from October through April and the average January temperature is about -20°C (Weatherbase, 2007). Aufeis that forms as a result of ground-water discharge serves as an indicator of the location and extent of discharge. In areas with crystalline bedrock, ground-water flow is typically constrained by fractures. Aufeis that forms in such areas likely indicates locations of hydraulically conductive fractures. This paper demonstrates the coincidence of areas of aufeis formation in several alpine catchments with locations of regional-scale (from 1 kilometer (km) to 10's of kilometers) fractures. In physiographic settings such as the study area described herein, aufeis may be helpful to understand locations of geologic structures as well as to qualitatively indicate the possible hydraulic conductivity of those fractures.

Aufeis in high-gradient catchments tends to reform in the same locations year after year (Dean, 1986; Lauriol and others, 1991; Hu and Pollard, 1997a), perhaps due to relatively invariant geologic, geomorphic, and hydrologic circumstances. In such catchments, where soil cover is thin, geologic properties that control ground-water flow (for example, fractures in crystalline bedrock) may be more

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important to aufeis formation than the hydrologic properties of unconsolidated material overlying bedrock. In this context, aufeis may also serve as a guide to the existence of potential ground-water resources (Harden and others, 1977).

A useful genetic classification of aufeis that was proposed by Carey (1973) includes spring aufeis, ground aufeis, and river aufeis. Spring aufeis forms as a result of ground-water discharge from beneath a permafrost layer (Hall and Roswell, 1981; Yoshikawa and others, 2001) and is the primary focus of this study. Ground aufeis forms by discharge of shallow ground water from within the “active layer,” which is that portion of seasonally frozen ground between permafrost and the ground surface. River aufeis forms as a result of fluvial processes, often related to ice dams and commonly found in areas where the river gradient abruptly decreases (Hu and Pollard, 1997a).

Hu and Pollard (1997a) describe the formation and buildup of aufeis using a three-stage model: freeze-up, obstruction, and overflow. Initial freeze-up is primarily responsible for aufeis location, while the latter two stages define the growth and abundance of individual icings. Hu and Pollard (1997b) developed a statistical model for aufeis growth during the overflow stage and found that ice thickness decreases away from the water source. In this study, relatively uniform ice thickness over distances of hundreds of meters to several kilometers implies numerous water sources or, more likely, a long continuous water source to the accumulating aufeis.

On an annual basis, aufeis serves as a reservoir for winter baseflow (Slaughter and Benson, 1986) that is released during late spring and early summer (Li and others, 1997). Aufeis formation during the winter quantitatively captures ground-water discharge, but because aufeis melts more slowly than regional snowpack, exceptionally thick (2 to 3 meters (m) or more) aufeis deposits may persist well into the summer months, continually releasing water to streams. Kane and Slaughter (1973) studied a watershed north of Fairbanks, Alaska, and found that the volume of water stored in the ice was only 4 percent of the total annual stream discharge but represented about 40 percent of the discharge for the winter months. They showed that if this ice melted within a 1-month period, there would be a significant increase in streamflow after snowmelt runoff was complete. Similarly, Osterkamp and others (1975) found significant (30–50 percent) reductions in streamflow just in the early stages of ice formation, implying temporary storage of the water as ice.

Previous studies have suggested links between aufeis formation and geologic properties of catchments. Lauriol and others (1991) noted that aufeis in the northern Yukon formed in spatial association with fault zones in carbonate bedrock. Hall and Roswell (1981) also noted a general spatial correlation between aufeis occurrences and locations of bedrock fracture zones, with greater density of aufeis in more heavily fractured areas. They proposed that the faults represent conduits along which ground water may flow between gaps in permafrost.

A baseline geochemical study was conducted in our study area (see fig. 1 of Editors’ Preface and Overview) from 1999 to 2002, prior to new mining activity. New geologic mapping also was performed to complement concurrent sampling of surface water, soils, and plants, and to relate the chemical variations in the sampled media to surface or bedrock lithology. Because this study was conducted in a remote area, no possibility existed for sampling ground water other than by sampling springs in the area. During several visits to the area, thick aufeis accumulations were observed in some areas. These observations were used to investigate the spatial and causative relations between aufeis and local and regional hydrology. In contrast to earlier work, this study presents evidence for direct spatial correlations between streams that accumulate aufeis and specific fracture sets.

Description of Study Area

The study area is in the Goodpaster River drainage (fig. F1) about 70 km northeast of the town of Delta Junction, Alaska, and includes the entire Big Delta B–2 quadrangle (U.S. Geological Survey, 1958). Elevations range from 1,433 m above sea level atop Shawnee Peak to just less than 400 m, where the Goodpaster River flows along the southwest edge of the quadrangle. Drainages from the Shawnee Peak massif and an unnamed highland that spans the southern half of the quadrangle are the source of many of the streams sampled during this study.

Climate in the study area is characterized by long, cold winters, with an average of 223 days per year below 0°C. Average snowfall is about 1 m, with about 30 centimeters (cm) of rain between May and September (Weatherbase, 2007). The study area is located within the Intermontane Boreal Ecoregion (Nowacki and others, 2003), characterized by closed spruce hardwood forest over discontinuous permafrost. On south-facing slopes, where permafrost is less pervasive, the predominant forest species are white spruce, aspen, paper birch, and balsam poplar.

The geologic framework of the area is composed of Paleozoic to Tertiary crystalline rocks, with Devonian augen gneiss, Paleozoic biotite gneiss and paragneiss, and Cretaceous granitic plutonic rocks occupying most of the area of the quadrangle (Day and others, 2003). Through its complex geologic history, the Yukon-Tanana Upland, of which our study area is a part, has experienced a number of orientations of tectonic stresses, leading to metamorphism, foliation, and faulting of the rocks. Within the study area, the dominant direction of major fault zones is north-northwest in the northeastern part, northeast in the southern part, and northwest to east-northeast in the northwest part. Mapped structures have long strike lengths, in many cases in excess of 5 km.

The most important surface-water feature in the area is the Goodpaster River, which originates to the east of the

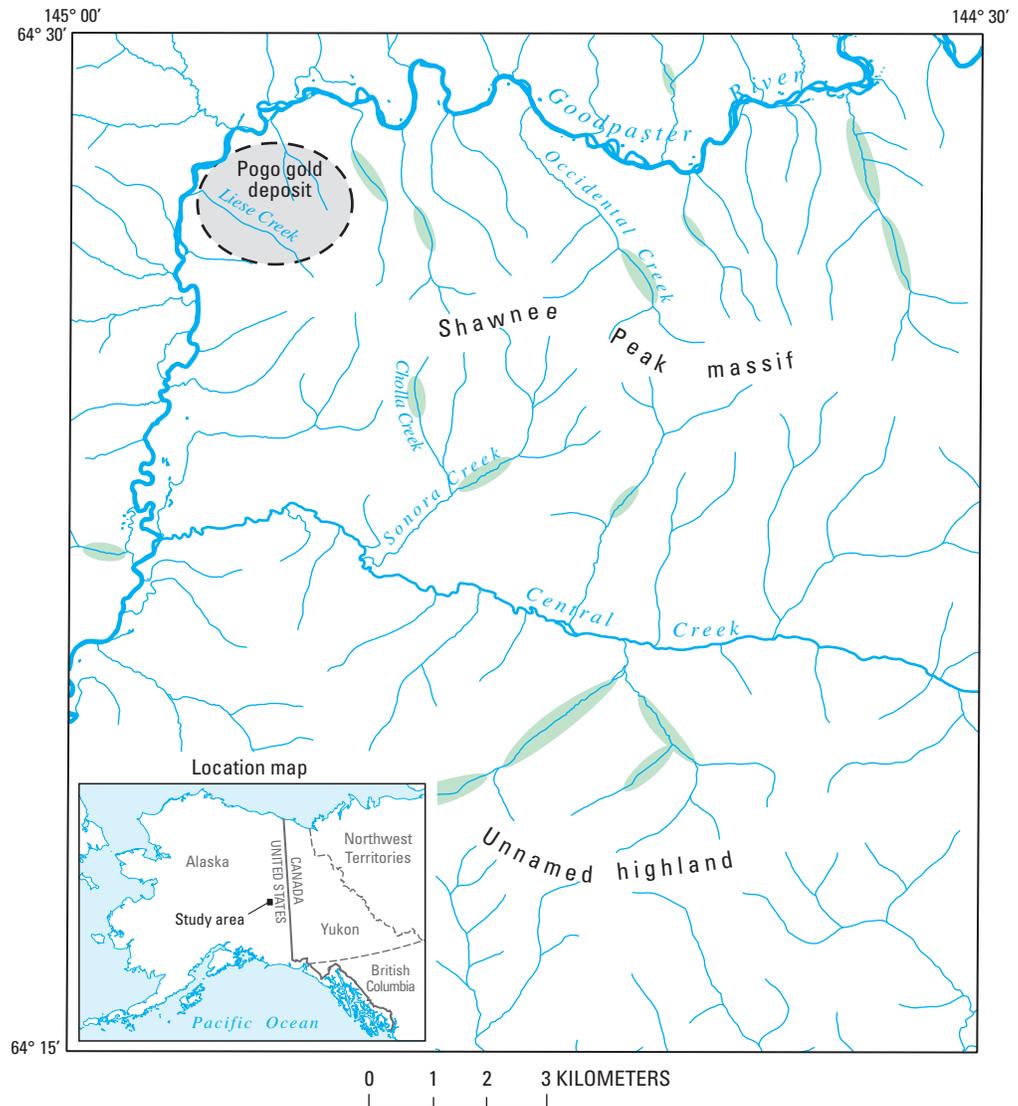


Figure F1. Map showing surface hydrologic features of the Big Delta B-2 quadrangle in east-central Alaska. Green areas show approximate extent of aufeis observed in satellite images or by ground observations. The approximate location of the Pogo gold deposit also is shown.

Big Delta B-2 quadrangle and follows the northern and western edges of the quadrangle. Central Creek flows from east to west through the middle of the study area and represents another major drainage feature. The focus of our study has been the numerous smaller streams that empty into either the Goodpaster River or Central Creek. This paper describes results of geochemical sampling along Cholla, Sonora, and Occidental Creeks (fig. F1), all of which accumulate aufeis in the winter.

Methods

Aufeis was located in stream valleys by a variety of means. In early July of 1999, remnant aufeis was observed in some stream bottoms. More aufeis was found by examining satellite images from early June 2001. In March of 2002, a low-altitude overflight of the area was made; then, in early June of 2002 fieldwork was conducted to examine aufeis

locations in greater detail. Where aufeis has occluded stream channels, it commonly has led to the formation of braided immature channels in low-gradient sections of streams. It is therefore possible to infer the presence of aufeis on the basis of channel morphology.

An attempt was made to collect several water samples along each major stream drainage in the study area, including drainages with or without aufeis. Sampling was accomplished by walking the length of each stream to be sampled from the drainage divide to the confluence with the next higher order stream, usually Central Creek or the Goodpaster River. Along each stream length we sampled at the highest elevation of continuously flowing water and worked downstream, monitoring conductivity and temperature of the stream water along the way. If any change was observed, or if there were any tributaries, samples of the tributary and of the stream above and below the tributary were collected. Using this approach commonly resulted in collection of 2 to 10 samples per catchment.

At each sample site, field measurements were made for stream discharge, pH, conductivity, temperature, dissolved oxygen, and dissolved Fe^{2+} . If feasible, discharge was measured with a pygmy flow meter (U.S. Geological Survey, 2007). The pH was measured using a combination glass electrode with automatic temperature compensation. Each morning, the pH electrode was calibrated with buffers of pH 4.0, 7.0, and 10.0. Calibration was checked at least once in the afternoon by measuring the pH of a buffer solution. The measured value of the buffer was always within ± 0.05 pH units of the accepted value for the buffer. Conductivity was not calibrated and was therefore used only for relative measurements during sampling. Temperature was measured using a digital thermometer traceable to thermometric standards of the National Institute of Standards and Technology (NIST). Dissolved oxygen and Fe^{2+} were measured using CHEMetrics self-filling ampoules.

In addition to the field analyses, samples were collected and preserved for later laboratory analyses. Samples were filtered through a 0.45-micrometer (μm) Gelman Supor filter and collected into acid-washed high-density polyethylene bottles and acidified to pH of approximately 1 with ultrapure HNO_3 . These samples were analyzed for major and trace cations and rare earth elements using inductively coupled plasma–atomic emission spectroscopy (ICP–AES) and mass spectrometry (ICP–MS). A second sample was collected, which was filtered but not acidified, for anion analysis by ion chromatography. A raw sample was collected for alkalinity titration. The latter two samples were kept cool upon returning to the hotel each evening, whereupon they were refrigerated until analysis. Further details of the analytical methods can be found in Briggs (1996), Lamothe and others (1999), and Papp and others (1996).

Results and Discussion

This paper focuses on the Occidental, Cholla, and Sonora Creek catchments—all are high-gradient streams draining the flanks of the Shawnee Peak massif (fig. F1). Cholla and Sonora Creeks are located on south-facing slopes, where less permafrost is expected. Occidental Creek drains to the northwest on a north-facing slope, but the vegetation density is similar to the other two, suggesting an absence of permafrost, or incomplete permafrost in the shallow subsurface. In all three of these cases, the direct observation of aufeis extent is supported by stream-water chemical data and other measurements, including measurements of hydraulic head in the hyperheic zone at one of the sites.

Cholla Creek

Cholla Creek was sampled at two sites, numbered 44 and 45 (fig. F2), in July 1999. The two sites are about 1 km apart, with an elevation change of about 90 m. At the time of

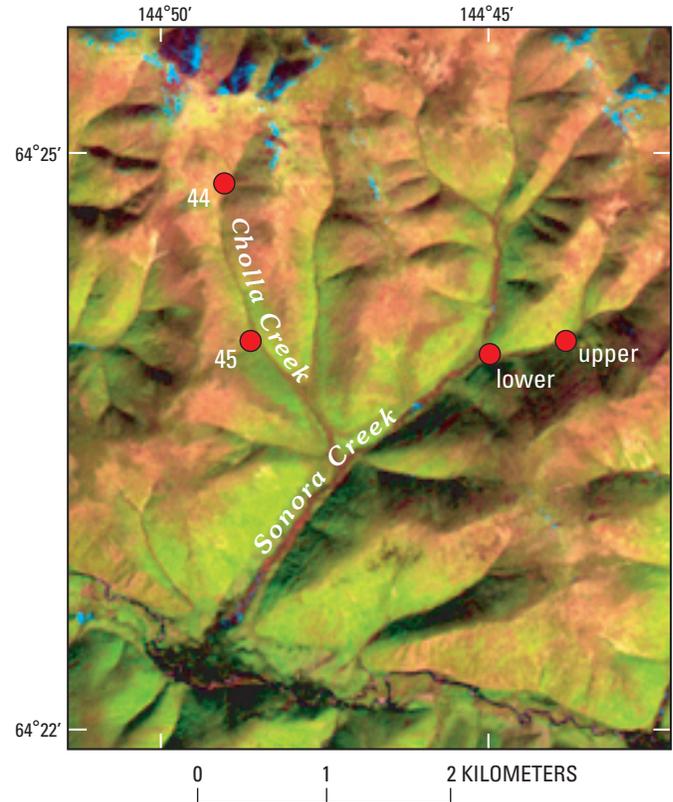


Figure F2. Landsat 7 satellite image (path 68, row 15) of the Cholla and Sonora Creek area, Big Delta B–2 quadrangle, taken June 2, 2001. Blue pixels are areas covered by ice or snow. Most of the blue area near the top of the image is snow, but some aufeis is visible along Sonora Creek just downstream from the lower site. Red dots are sample locations referenced in text.

sampling, remnant aufeis was still present in the drainage from the previous winter at elevations above site 44. No aufeis was observed in the stream between these two sites, but in a March 2002 low-altitude overflight of the area, aufeis was observed between sites 44 and 45. Given the relatively small area of the Cholla Creek drainage, it is likely that smaller volumes of ice might form and that the 1999 sampling occurred after the aufeis melted from the Cholla Creek valley between the two sample sites.

Between the two sample sites, there were no surface-water tributaries, but the measured stream discharge increased from 1.1 to 2.5 liters per second (L/s) between sites 44 and 45. This observed increase in flow can be attributed only to ground-water discharge. Electrical conductivity of the stream water increased from 190 to 220 microsiemens per centimeter ($\mu\text{S}/\text{cm}$) between the two sites, which can be explained primarily by increases in calcium (34 to 42 milligrams per liter, mg/L), SO_4 (45 to 57 mg/L) and alkalinity (88 to 106 mg/L as HCO_3). Smaller increases were observed in concentrations of sodium, magnesium, and potassium. At both sites total dissolved iron was below detection (<0.02 mg/L).

On the basis of the observed changes in concentrations of dissolved constituents, the discharging ground water

must have greater total dissolved solids, and in particular, significantly higher alkalinity and concentrations of calcium and SO_4 than the stream water. The increases in calcium and alkalinity are expected, on the basis of the local aquifer material, a Paleozoic paragneiss that consists of biotite schist layers and quartzofeldspathic biotite schist layers. In an outcrop sample collected above site 44, fine-grained pyrite and possible marcasite were observed, suggesting that the incremental increase in SO_4 may be at least in part derived from the oxidation of sulfide-bearing minerals in the shallow subsurface.

Sonora Creek

Sonora Creek was sampled in July 1999 and early June 2002 at the sites marked “upper” and “lower” on figure F2. The same sites were sampled each time. In 1999, no aufeis remained along this reach of Sonora Creek, but during the 2002 sampling, aufeis covered the valley bottom continuously between the two sites, a distance of approximately 0.6 km. The vertical drop between the two sites is approximately 85 m.

The formation of aufeis in the Sonora Creek drainage is an indication of ground-water discharge throughout the winter. In July 1999, ground-water hydraulic potential in the shallow subsurface was measured using a device described by Wanty and Winter (U.S. Geological Survey, 2000). Several sites were tested, comparing the elevation of the water in the shallow subsurface (15 to 40 cm below the stream-bed) to that in the stream. In some cases, no head difference was observed, but in most cases, head differences between 1 and 5 cm were observed, with the ground-water potential always above the stream surface. This result indicates the tendency for ground-water discharge in this reach of Sonora Creek. In 1999, the stream discharge increased from 0.003 to 0.006 m^3/s between the upper and lower sites, with only one surface-water tributary between the sites. The discharge of that tributary was insufficient to make up the difference in discharge. At both times, the electrical conductivity (specific conductance, SpC) decreased slightly between the upper and lower sites, suggesting that discharging ground water had lower total dissolved solids. Chemical analyses indicated small but significant decreases in virtually all the major cations and anions. For example, in 1999, SpC decreased from 270 to 170 $\mu\text{S}/\text{cm}$, and decreases were observed for calcium (41 to 27 mg/L), magnesium (13 to 7 mg/L), sodium (3 to 2.5 mg/L), HCO_3 (140 to 80 mg/L), and SO_4 (53 to 38 mg/L) between the upper and lower sites.

Occidental Creek

Occidental Creek drains the north side of the Shawnee Peak massif (fig. F3). Occidental Creek was sampled in July 1999 and again in early June 2002 at the sites marked “upper” and “lower” on figure F3. The two sites are separated by a distance of approximately 1.6 km and an elevation drop of

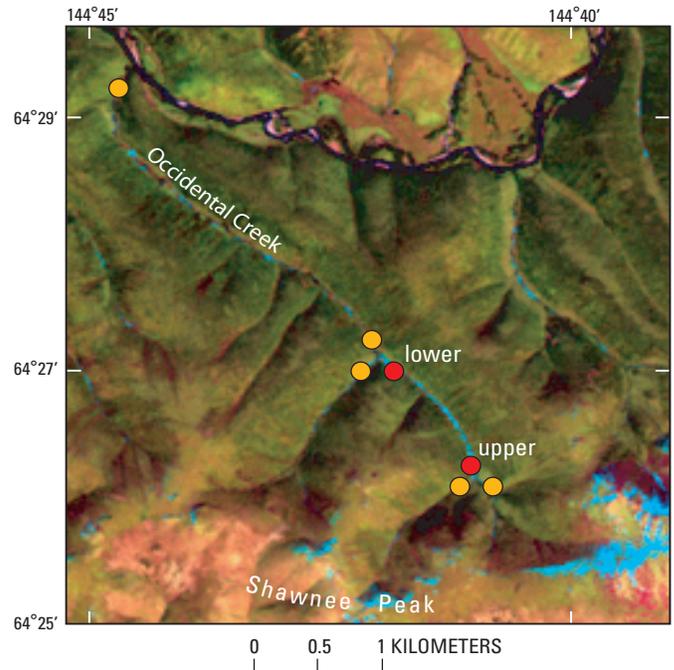


Figure F3. Landsat 7 satellite image (path 68, row 15) of the Occidental Creek area, Big Delta B-2 quadrangle, taken June 2, 2001. Blue pixels are areas covered by ice or snow. The blue areas along the southern part of the image are accumulated snow near the top of Shawnee Peak; nearly continuous aufeis is observed along Occidental Creek between the upper and lower sites. Red dots are sample sites discussed in text. Other sample sites along Occidental Creek are shown with yellow dots.

140 m. Aufeis was present at the upper site in July 1999, but in 2002, a thick (3 m or more) layer of aufeis extended continuously between the upper and lower sites. The satellite image in figure F3, taken June 2, 2001, shows the continuous aufeis in the Occidental Creek valley between the upper and lower sites.

In June 2002, the aufeis was beginning to melt but was still greater than 3 m thick at the upper site (fig. F4). Maximum thickness of the ice was probably about 1 m greater, based on observations of willows embedded in the ice that had their tops cut off at the same level, either by animals or by shearing of debris-laden water during the early stages of breakup. A notable feature of the aufeis at this location was its shape within the valley—viewed down the axis of the valley, the aufeis is concave upward and appears to climb up the valley walls. This morphology suggests that the source water for the aufeis came from spatially and temporally continuous discharge from the valley sides rather than from a point or series of points along the stream channel. A conceptual model for aufeis formation, used to explain this morphology in greater detail, is discussed later in this report.

The chemical changes observed in stream water in Occidental Creek between the upper and lower sites is similar to that in Cholla Creek in that discharging ground water is

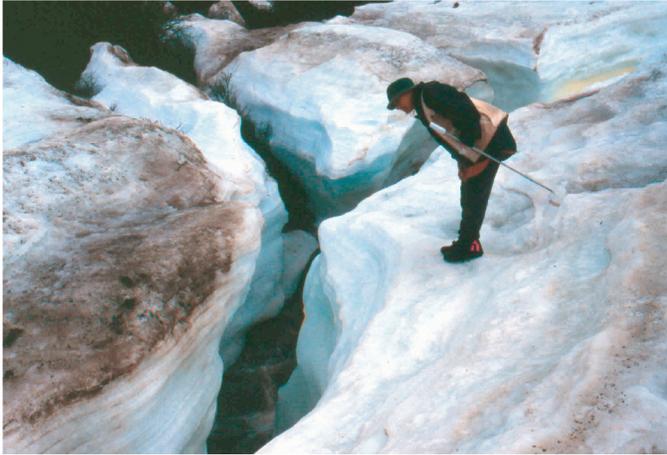


Figure F4. Photograph of thick (2–3 meters) aufeis at the upper site on Occidental Creek, taken in early June 2002 after approximately 1 meter of the ice had melted. The flowing water that is visible at the bottom of the chasm is flowing on the ground, but in many areas, most of the streamflow was still over ice at the time our samples were collected.

likely to be a source of sulfate. Resolving the contributions of ground and surface water in Occidental Creek is complicated by the inputs of a surface-water tributary that has higher total dissolved solids and whose chemical contributions explain some of the changes observed between the upper and lower site. This tributary enters Occidental Creek from the southwest about midway between the upper and lower sites (fig. F3). Measured discharges were $0.03 \text{ m}^3/\text{s}$ at the upper site, $0.006 \text{ m}^3/\text{s}$ in the tributary, and $0.04 \text{ m}^3/\text{s}$ at the lower site. Variations in stream discharge, sodium, magnesium, and conductivity can be explained by a conservative mixing model with about 85 percent of the water from Occidental Creek and 15 percent being added by the tributary. However, calcium is overestimated, and potassium, HCO_3 , and SO_4 are underestimated by this mixing model, so we propose that discharging ground water has lower concentrations of calcium and greater concentrations of potassium, HCO_3 , and SO_4 as compared to the surface-water tributary. The significance of this result is discussed in the next subsection.

Relation Between Aufeis Locations and Fractures

Much of the data presented on the three catchments can be explained by ground-water discharge causing aufeis formation in winter. One aspect of this phenomenon that has not been discussed is the control of ground-water flow in the bedrock aquifers. During the field studies, aufeis was observed in some stream drainages but not in all stream drainages. A spatial relation between the locations of aufeis and major fracture systems as mapped by Day and others (2003) was apparent. This relation is shown in figure F5, using an expanded view of the satellite image base from which

figures F2 and F3 were taken. This relation is true for many of the locations where aufeis was studied. For example, one of the most laterally extensive fracture zones in the study area defines the Occidental Creek valley. This valley had some of the most extensive aufeis in the study area, in terms of both lateral extent and thickness. Another area with laterally extensive fractures lies in the southern part of the study area, south of Central Creek (“A” in figure F5). Extensive aufeis was observed along this creek. Ground-water discharge that leads to the formation of this aufeis continues through the summer months and serves as a significant water source to the base flow of these streams. Evaluating regional baseline geochemistry, and determining the chemical contribution of ground water to the streams, should give a “window” to the ground-water chemistry and a greater understanding of the water-rock interactions that take place in the subsurface.

An important distinction needs to be made between the depths of ground-water sources feeding the streams in the study area. It is likely that all the streams in the area are fed by ground-water discharge, but many of the streams in the area do not form aufeis. This difference may be explained by considering the depth from which the discharging ground water originates. Streams that do not form aufeis may be fed by shallower ground water, from within the “active layer.” The active layer is that range of depth within the ground that undergoes seasonal freeze and thaw. In many areas, especially on north-facing slopes, the active layer sits atop permafrost. If ground water from the active layer is the primary source of stream water, then these streams would not be expected to form aufeis, as this water source freezes in winter. If the ground water discharging into the streams originates from a deeper source, such as flow within a laterally extensive fracture or fault system, there should be perennial flow, and thus aufeis formation in winter.

A Conceptual Model for the Mechanism of Aufeis Formation in Alpine Catchments

Streams aligned with hydraulically conductive fractures serve as discharge outlets for ground water. During summer months, ground-water discharge through the streambed is unimpeded (“A” in fig. F6). At the onset of winter, the streams freeze, occluding the channel and blocking the discharge of ground water. This blockage perturbs the steady state condition that was obtained over the summer months and leads to a small incremental rise in the potentiometric surface beneath the stream. As the water table rises above the level of ice in the stream, discharge resumes along the margins of the ice (“B” in fig. F6). Throughout the winter, the water table continually rises above the level of the previously formed ice, and discharge proceeds along the margins of the valley (“C” in fig. F6). By this mechanism, the sides of the valley represent a continuous locus of discharge; therefore, the highest elevation of the ice should be along the valley sides, as was observed. In the spring and summer as the ice melts, the potentiometric

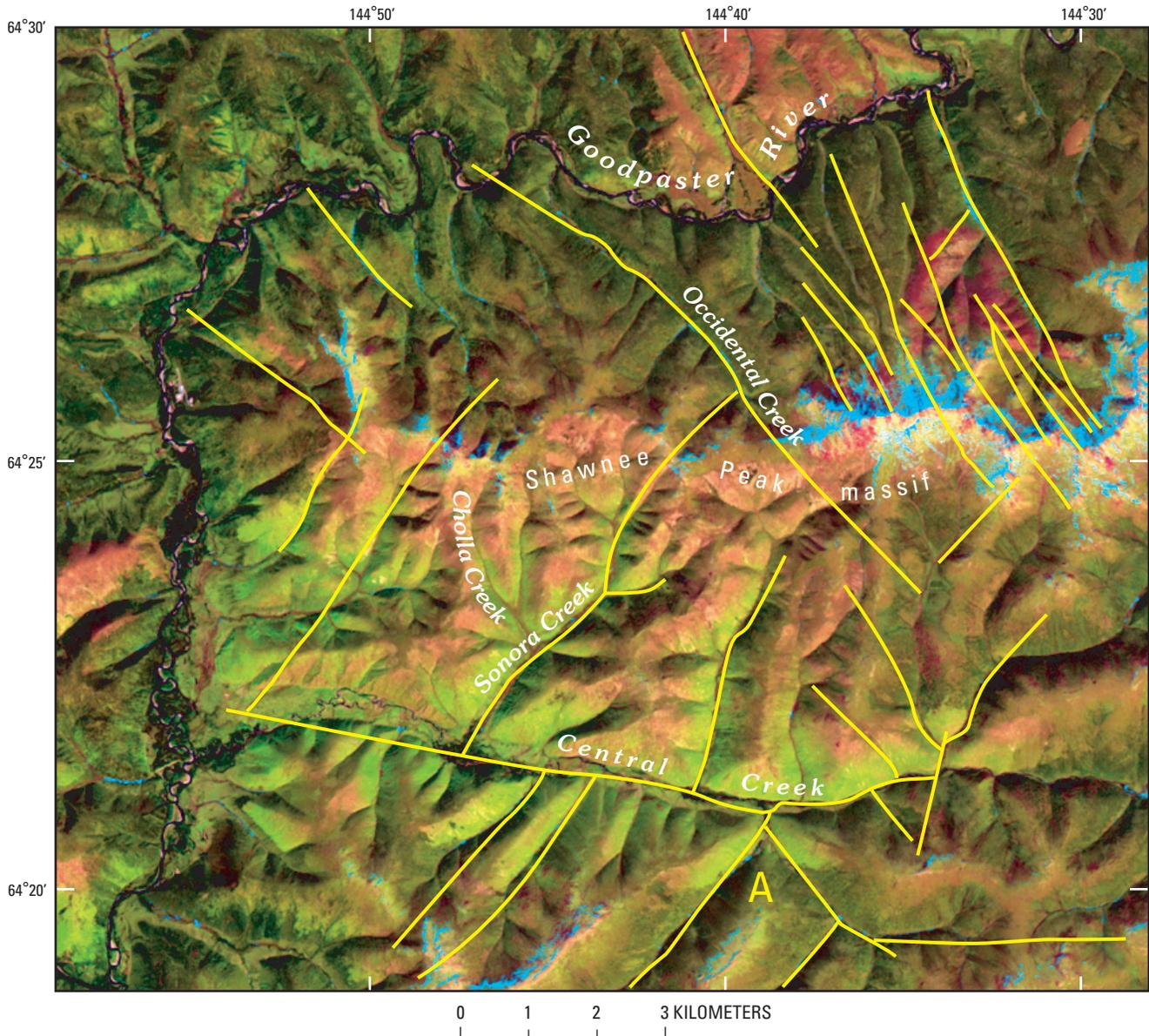


Figure F5. Landsat 7 satellite image (path 68, row 15) of the northern portion of the Big Delta B-2 quadrangle, taken June 2, 2001. Yellow lines show major faults as mapped by Day and others (2003). Location A is an additional area of laterally extensive fractures with aufeis.

surface retreats to the position of “A” in figure F6, and a new annual cycle begins.

Summary

Aufeis forms during the winter in high-gradient alpine streams in arctic and subarctic environments. There is a spatial correlation between streams that accumulate aufeis and regionally extensive fractures. Significant changes in stream-water chemistry were observed in stream reaches that accumulate aufeis. These changes can be explained on the

basis of the chemistry of ground water in contact with local aquifer rocks.

The proposed conceptual model for aufeis formation begins with occlusion of normal ground-water discharge flowpaths as streams freeze solid at the beginning of winter. The ground-water level rises incrementally, and discharge proceeds throughout the winter by a succession of freezing of onlapping layers of ice followed by the next incremental rise in the water-table level.

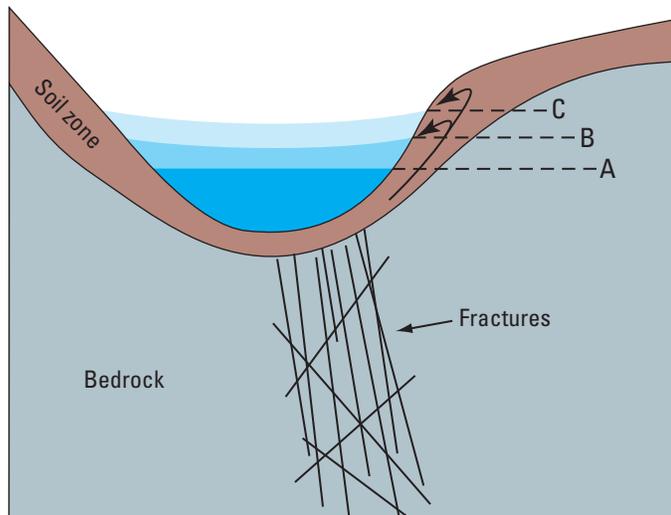


Figure F6. Schematic cross section of a stream fed by discharging ground water that is carried by regionally extensive fractures. See text for explanation.

Acknowledgments

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