On the geometry of core-catcher holders for hot-water based ice coring of sediment-laden ice

Analysis of sediment-laden ice accreted at the base of ice sheets provides useful information on subglacial conditions and processes that otherwise cannot be observed or are very difficult to observe. While sediment-laden accreted basal ice can be accessed directly at the terminus of alpine glaciers, the basal zone of ice sheets is only accessible by drilling. Small amounts of sediment in the ice have provided few or no problems for conventional ice-core drilling (Gow and others, 1979; Weis and others, 1997); however, the higher-sediment-content accreted ice beneath West Antarctic ice streams (Vogel and others, 2005) has not been recovered using the California Institute of Technology (Caltech) hot-water ice corer (Engelhardt and others, 2000).

Based on their drilling experience and hot-water drilling records, B. Kamb and H. Engelhardt suspected that a debris-rich basal ice layer existed beneath West Antarctic ice streams (personal communication from Kamb and Engelhardt, 2000). Several attempts to recover ice from the base of West Antarctic ice streams were made in the 1990s using the Caltech hot-water ice-coring drill (Engelhardt and others, 2000). During the 2000/01 Antarctic field season, we utilized an ice borehole camera system (Carsey and others, 2002) to obtain the first in situ live-stream investigations, and we confirmed the existence of a sediment-laden basal ice layer beneath Kamb Ice Stream. We observed the basal ice layer to be 10–14 m thick, accreted to the base of the ice sheet by the freeze-on of subglacial meltwater (Vogel and others, 2005). The sediment incorporated onto the basal ice in this process consisted of particles ranging in size from clays to pebbles and cobbles. Sediment content ranged from individual dispersed sediment clots ($\sim$5 mm in diameter, mainly consisting of clay and silt) to layers of thick frozen-on sediment (well-mixed diamictide). The acquisition of a short section (70 mm core diameter) of clear basal ice with a single layer of dispersed sediment clots (Fig. 1) from the glacial/basal ice transition confirmed the nature of the basal ice. However, our attempts to recover ice with a higher sediment content covering the subsequent portion of the 10 m thick basal ice layer were unsuccessful. After detailed inspection of the ice corer it was discovered that the core catcher had jammed. Sediment melted out from the basal ice had moved into the V-shaped gap between the core catcher and the slot in which the core catcher was mounted. Due to the geometry of this slot, a few sand-size sediment particles were sufficient to prevent the core catcher from engaging the core.

Video observations show that the 4 m long section of basal ice that we had attempted to drill was characterized by an increase in sediment content. Individual particles, mainly sediment clots up to several mm in diameter, changed to cm thick sediment layers, which were followed by thicker laminated sediment layers (Vogel and others, 2005). In the process of hot-water drilling, sediment is transported upward with the drilling fluid, cleaning the cuttings from the drill head. As the gap between the borehole wall and the corer widens at the core-catcher window, drill fluid slows down, allowing individual particles to settle into the gap. This method is commonly used in conventional rock drilling to obtain drill cutting samples during non-coring drill operations. However, in our case, particles settling in the core-catcher window became entrapped in the core catcher. A higher sediment content in the ice increases the sediment load and exacerbates the effect. A simple solution to prevent settling of sediment into the core-catcher window is to cover the outside of the core-catcher window with a shield. However, particles can still enter from the inside, either from the winnowing of sediment ahead of the drill head or from melting of the outer layer of the ice core, necessitating a review of the core catcher.

In our drill, the core catcher closes towards the inside (Fig. 2a). In this configuration, the gap between the core catcher and the core-catcher wall tapers in the direction in which the core catcher engages (towards the inside of the core barrel). In the open position, the geometry of the core-catcher holder allows particles larger than the gap on the inside of the core barrel to move into the slot between the core catcher and the core-catcher wall. When the core catcher now tries to engage, it moves towards the center of the corer, jamming larger particles into the narrowing gap (Fig. 3b). Based entirely on the geometry of the core-catcher holder and independent of the size, strength and geometry of

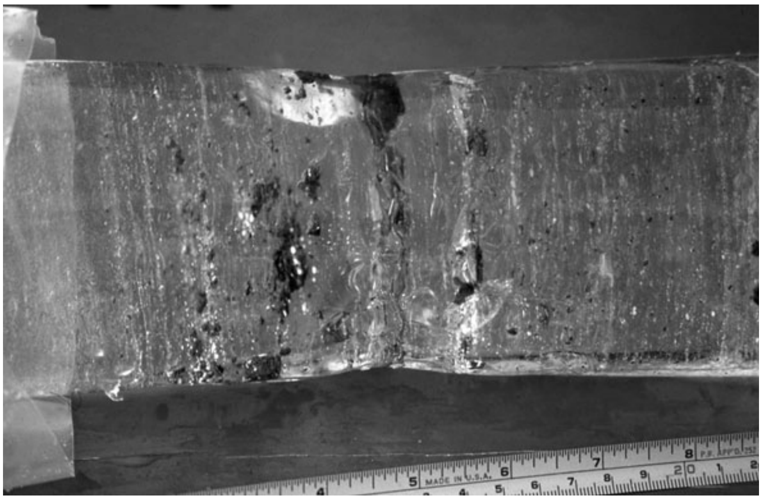

Fig. 1. Ice from the top of the basal ice layer at Kamb Ice Stream showing thin highly dispersed banded debris layers.

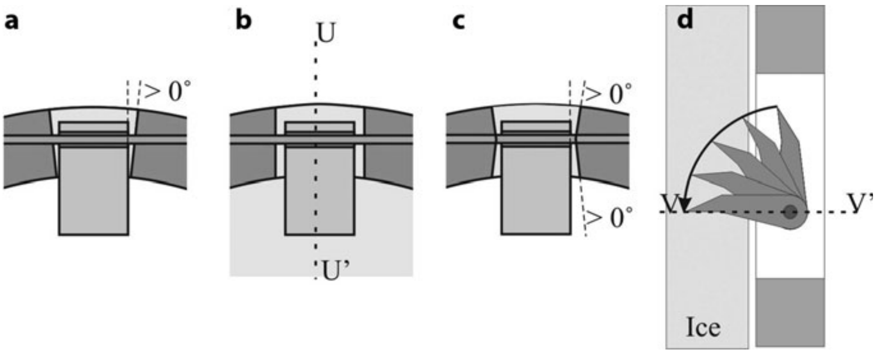

Fig. 2. Schematic cross-section V–V′ showing core-catcher holder configuration: (a) V-shaped slot converging and narrowing to the inside; (b) straight edge slot; (c) V-shaped slot opening to the inside and outside; (d) vertical cross-section showing moving of core catcher during engaging in core. Stopper mechanism not shown. For details on Caltech hot-water ice-coring drill see Engelhardt and others (2005).

the core catcher, this in turn prevents the core catcher from engaging, thus preventing recovery of the ice core.

Inspection of the core-catcher holder indicates that a change in geometry could provide a simple and robust solution to prevent the entrapment of particles. If the geometry of the core-catcher holder is changed from a V-shaped slot opening to the outside (Fig. 2a), or a flat slot (Fig. 2b), to a V shape opening to the inside (Fig. 2c) of the core barrel, particles will be moved out of the widening core-catcher gap rather than trapped in a narrowing gap (Fig. 3). This will allow the core catcher to fully engage so that an ice core, even of irregular shape, can be recovered. Unfortunately, time constraints in the field did not allow modification and testing of our new core-catcher design.

Theoretical evaluation of drilling into sediment-laden ice suggests that other mechanical components could also be affected by the same principle of sediment entrapment when drilling into sediment-laden ice. So, for example, an engaged core catcher could, in the disengaging process, trap sediment particles in the outside narrowing gap. Modifying the core-catcher holder geometry to open inwards as well as outwards may prevent such entrapment in the case of an open core-catcher window (Fig. 2c). Covering the core-catcher window with a shield (as discussed above) would trap such sediment within the core-catcher window. While significant sediment content might prevent further drilling progress within a run, it is less likely that it would prevent recovery of an already drilled ice core. A further problem area may be the geometry of the resting points of the engaged core catcher (for simplicity not shown in Fig. 2; see fig. 2 of Engelhardt and others (2000) for details). Here sediment particles could be trapped between the core catcher and the base of the slot, again preventing the core catcher from partially or fully engaging. In addition, the geometry of other openings, allowing the entrapment of particles and disabling mechanical components of the core catcher or other parts of the coring system, should be reviewed in the design and/or redesign process of ice-coring systems for drilling into sediment-laden ice.

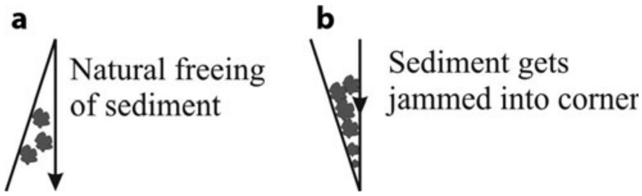

Fig 3. Illustration of (a) natural freeing of sediment from an open slot, and (b) jamming sediment into a V-shaped corner, dependent on the movement direction of the core catcher or any other moving mechanical part.

CONCLUSIONS

The present case study shows that not only the geometry of the core catcher itself but also the geometry of the core-catcher holder is of importance. In our case, sediment particles were trapped in a narrowing gap, disabling the core-catcher mechanism and preventing recovery of the core. Detailed study of the core-catcher mechanism and the geometry of the core-catcher holder suggests that the design of a future drill system should build this slot opening towards the inside of the core barrel, allowing the removal of sediment rather than its entrapment. Closing off the outside of the core-catcher window with a shield would in addition significantly reduce the accumulation of sediment in this gap; however, this would not prevent sediment from entering from the inside. In addition to reducing the possibility of sediment entrapment in the core catcher, a shield in combination with a bail should significantly aid in the removal of sediment from the drill head and thus help with the recovery of longer sediment-laden ice cores. Testing this new configuration in the laboratory will allow optimization of the slot geometry and shield for future drilling operations. In addition, attention needs to be paid to the size and geometry of other openings throughout the drill design to prevent large sediment particles from entering and allowing the natural removal of smaller particles with the flow of circulating liquids or the mechanical movement of parts.

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