Reply to the comments of refree#2

This paper presents results of quantitative though very limited laboratory tests on a melt head intended for the RECAS probe, which incorporates water jetting to penetrate ice with embedded layers of sediment and small (cm-scale) rocks. (The paper also preliminary calculations of flow rates to suspend sediment particles and required jetting-pump pressure.) While jetting for passage of an electrically powered probe through debris-laden ice has long been reported (the authors' references I would add Rado et al.,1987), quantitative data (e..g., on flow rates required for debris with specific characteristics) seem to be, at best, very rare. This paper therefore contributes to work not only with the RECAS melt head but also more generally, despite its limited results. I therefore recommend publication, but also recommend revision to address the following points, so as to make the paper contribute more generally. With revisions to address these points, I think the paper would make a worthwhile contribution to the literature. (I will not reiterate the points made by anonymous reviewer 1, with which I agree and which the authors have already addressed).

Thank you for your valuable comments. They are very helpful for us in improving the manuscript according to your suggestions.

In the revised manuscript, the reference suggested by the reviewer regarding water jetting in an electrically powered probe has been added to the introduction section. The following sentence "*Since the first HWDDSC was developed in 1972, a wide range of such drilling systems have been developed and deployed globally (Gillet, 1975; Hantz and Lliboutry, 1983)*." has been changed to "*Since the first HWDDSC was developed in 1980s, a wide range of such drilling systems have been developed and deployed globally (Rado et al., 1987)*".

Added reference

Rado, C., Girard, C., and Perrin, J.: Electrochaude: A self-flushing hot-water drilling apparatus for glaciers with debris, J. Glaciol., 33, 236–238, https://doi.org/10.3189/S0022143000008741, 1987.

Deleted references

Gillet, F.: Steam, hot-water and electrical thermal drills for temperate glaciers, J. Glaciol., 14, 171 – 179, https://doi.org/10.3189/S0022143000013484, 1975.

Hantz, D. and Lliboutry, L.: Waterways, ice permeability at depth, and water pressures at Glacier d'Argentière, French Alps, J. Glaciol., 29, 227–239, https://doi.org/10.3189/S0022143000008285, 1983.

(1) The authors base their expectations of the volumetric concentrations and characteristics of debris in ice above their target lake on observations of ash layers in cores well above the bases of ice sheets, and on (the few) inclusions observed in accreted ice above or bordering Lake Vostok. However, at ~3600 m depth, the ice sheet upstream of their intended target lake is certainly wet at its base. Ice flow over a wet bed entrains much denser concentrations of sediment and rock than those in the authors' tests, as shown for example in data from Byrd Station (Gow et al.,1979) and in the WISSARD and SALSA project experiences. The authors, as well as others interested in melting probe entry into subglacial lakes, should therefore work toward tests with much denser debris concentrations. The first essential step to evaluate the current results and plan for further tests is to report in Section 4.3 not only the dust-laden ice layer thickness, but also the material (silica?), volumetric concentration or mass fraction of dust in the layer (especially), and dust particle size distribution (not just minimum particle size)

Thanks for your valuable and insightful comment. We agreed that denser concentrations of sediment and rock may exist at the base of ice sheet, as documented at Byrd Station by Gow et al. (1979), where basal ice contains debris weight percentages of approximately 12–16% and clasts up to ~8 cm.

In this study, the dust-laden ice sample was prepared using river sand, which consists primarily of silicon dioxide (SiO_2). The dust in the ice layer had a mass fraction of approximately 21% and a particle size ranging from 250 to 425 μm. To clarify the information, the original sentence was rewritten as "*In preparation, dust particles with size ranging from 250 μm to 425 μm were selected to ensure conservative and reliable test conditions, as this size exceeds the typical particle sizes found in Antarctic ice sheet. The dust-laden ice layer was prepared using river sand, which consists primarily of silicon dioxide (SiO_2). With a thickness of approximately 2 cm and mass fraction of approximately 21%, the dust-laden ice layer was located about 30 cm below the ice surface.*".

In general, the artificial dust-laden ice layer has a relatively high dust concentration and a larger dust particle size than those found in ice cores. However, such dust-laden ice layers may occur successively at the base of the ice sheet, leading to cumulative hindering effects on ice penetration. In our study, the multiple dust-laden ice layers were not prepared, which is a clear limitation of the present study. In the revised manuscript, we have added a discussion of this limitation and clarified that our results should be extrapolated with caution to field conditions with multiple dust-laden ice layers. The following are the added sentences, "*Notably, multiple dust-laden ice layers may exist within the ice sheet, and their potential hindering effects on ice penetration may accumulate. In this study, the updated RECAS thermal head was tested only in a single dust-laden ice layer; therefore, its drilling performance in multiple dust-laden ice layers should be carefully assessed.*"

In addition, an outlook section has been added at the end of the manuscript to remind relevant researchers that further in-depth research is needed in the future. The following is the added outlook section, "*However, the updated RECAS thermal head has never been deployed in a real ice sheet overlying a subglacial lake. For future work, tests with multiple dust-laden ice layers and significantly higher debris concentrations, with larger volumetric fractions and larger rock sizes, are recommended to better approximate the extreme basal ice conditions above subglacial lakes*".

(2) In the case of rock inclusions (Section 4.4), it must be expected that ice above the intended lake will have debris layers with many rocks in close proximity (many more than 5). To begin to evaluate the significance of the results with so few rocks, the first question is whether melt head penetration at the specified jetting rate, and the mechanism the authors suggest (melting of a cavity large enough for the rocks to move up the sidewall of the probe as it descends), are in fact repeatable, or whether other results are sometimes obtained – the authors presently seem to have presented results so far only from a single trial. If the current results are repeatable, it would then be essential to begin to explore the relationship between successful penetration and (1) jetting rate; (2) mass fraction of rock embedded in an ice layer; and (3) rock size. I would urge the authors to add data along these lines to the paper.

We are confident that the results and mechanism are repeatable and reliable. In fact, we conducted two laboratory tests with rock clasts. The first is presented in the manuscript; the second used transparent ice blocks to directly observe water cavity formation (Figure S1). The transparent ice block had dimensions of 1 m × 0.5 m × 0.5 m.

Figure S1 Test of updated RECAS thermal head with transparent ice block

During the test, the following procedure was used. First, the pump of the updated RECAS thermal head was started to drill clean ice and observe the formation of a water cavity. Second, the pump was turned off, and drilling continued by thermal melting until the cavity disappeared. Third, the thermal head was lifted, and 10 pebbles with diameters of 0.5–1.0 cm were added to the bottom of the borehole. Finally, the thermal head was redeployed to the borehole bottom, and the pump was restarted to observe how the water cavity formed. Same as the first test, during the second test, the weight on the thermal head was stabilized at 150 N, the heating power was set to 7 kW, and the ice sample temperature was maintained at −15 °C. Additionally, the flow rate of the magnetic gear pump remained at 2.5 L min^{-1}.

As shown in Figure S2(a), a conical water cavity formed during drilling in clear ice, with both its depth and maximum diameter approximately 60 mm. After the pebbles were added, the cavity still existed, and all the pebbles settled at its bottom (Figure S2(b)). In this case, the cavity had almost the same dimensions as the one without pebbles.

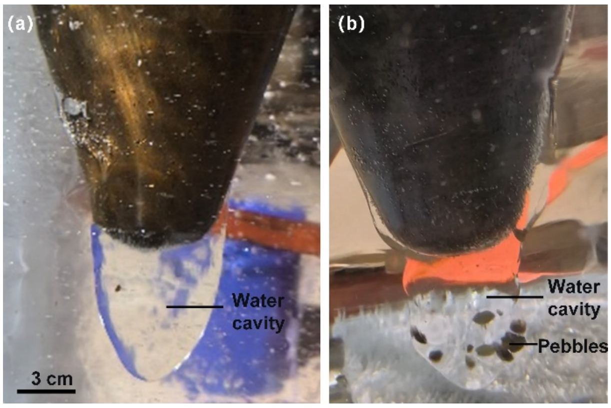

Figure S2. Photograph of the water cavity: (a) without pebbles; (b) with pebbles. (In the revised manuscript, Figure S2 has been added as Figure 15.)

To clarify this, the following sentences have been added to the revised manuscript. "*To clearly observe the formation of the water cavity, a transparent ice block with dimensions of 1 m × 0.5 m × 0.5 m was used for supplementary drilling. In the secondary test, the pump of the updated RECAS thermal head was first activated to drill through clean ice and observe water cavity formation. The pump was then switched off, and drilling continued by thermal melting until the cavity disappeared. The thermal head was subsequently lifted, and 10 pebbles (0.5–1.0 cm in diameter) were placed at the bottom of the borehole. Finally, the updated RECAS thermal head was lowered back to the borehole bottom, and the pump was restarted to observe the reformation of the water cavity. In the second test, the weight on the thermal head was stabilized at 150 N, the heating power was set to 7 kW, and the ice sample temperature was maintained at −15 °C. Additionally, the flow rate of the magnetic gear pump remained at 2.5 L min^{-1}*"

"*As shown in Figure 15(a), a conical water cavity formed during drilling in clear ice, with both its depth and maximum diameter approximately 60 mm. After the pebbles were added, the cavity still existed, and all the pebbles settled at its bottom (Figure 15(b)). In this case, the cavity had almost the same dimensions as the one without pebbles. Clearly, the formation of a water cavity is the main reason for eliminating the influence of pebbles on ice drilling*".

We agreed that different rock mass fractions and rock sizes require different flow rates to generate water cavities of different sizes. In addition, the accumulation of rock during drilling may also necessitate a larger water cavity. Theoretically, the larger the water cavity, the more favorable it is for drilling through debris-rich ice. However, a large water cavity also requires a large downhole pump, heated meltwater, and specialized spray nozzles, which is beyond the scope of this manuscript. In the future, dedicated research may be conducted on this issue. It should also be noted that the updated RECAS thermal head was designed to penetrate debris-rich ice with low rock mass fractions and small rock sizes. If the rock size reaches 8 cm or even larger, and the debris-rich ice layer is 4.83 m thick, as at Byrd Station (Gow et al., 1979), it would be difficult for the RECAS thermal head to drill through such an ice layer, even with a high flow rate. In this case, a conventional hot-water drill may be the only clean way to access a subglacial lake.

In the revised manuscript, the following sentences have been added to explain this issue. "*Notably, the updated RECAS thermal head was designed only for debris-rich ice with low pebble mass fractions and small pebble sizes. It would be difficult for the thermal head to drill through thick debris-rich ice with large rock clasts, as at Byrd Station (Gow et al., 1979), where the layer is 4.83 m thick and the largest clast is 8 cm. In the future, dedicated research could be conducted to optimize the flow rate and nozzle structure to create a desired water cavity that can collect as many rock clasts as possible.*"

(3) Ice temperature is likely also important to understanding how general the results presented here may be. I looked for but did not find any data in the paper on ice temperatures during the penetration experiments。

The ice temperatures during testing were presented as follows: "*clean ice samples were fabricated in a freezing container at −20 °C*" (Section 4.2); "*the dust-laden ice sample was frozen at −15 °C*" (Section 4.3); and in Section 4.4, "*each barrel was first filled with tap water to 50 % of its volume and then frozen at −15 °C for 24 h to form a dense ice layer*".

To make it clearer, the following sentences have been added

"*The ice sample was maintained at −20 °C*" (Section 4.2)

"*Specifically, the weight on thermal head stabilized at 150 N, and the heating power was set to 7 kW, and the ice sample temperature was maintained at −15 °C*" (Section 4.3)

"*Additionally, the debris-rich ice sample was maintained at a temperature of −15 °C*" (Section 4.4)

Finally, one minor editorial note: the various drilling and melt probe efforts summarized in Section 1 have been reviewed comprehensively, along with many others, by Talalay (2020). I suggest referring to that work.

References

Gow, A.J., S. Epstein, and W. Sheehy (1979), “On the Origin of Stratified Debris in Ice Cores from the Bottom of the Antarctic Ice Sheet”, Journal of Glaciology 23(89), 185-192, doi:10.3189/S002214000029828.

Rado, C., C. Girard, and J. Perrin (1987), “Electrochaude: A self-flusing hot-water drilling apparatus for glaciers with debris”, Journal of Glaciology 33(114), 236-238.

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In the revised manuscript, all the three references have been added.

References

Gow, A.J., Epstein, S., and Sheehy, W.: On the origin of stratified debris in ice cores from the bottom of the Antarctic ice sheet, J. Glaciol., 23, 185–192, https://doi.org/10.3189/S002214000029828, 1979.

Rado, C., Girard, C., and Perrin, J.: Electrochaude: A self-flushing hot-water drilling apparatus for glaciers with debris, J. Glaciol., 33, 236–238, https://doi.org/10.3189/S0022143000008741, 1987.

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