Referee #1: Michel Allard

The revised manuscript is an excellent contribution to permafrost science. The authors present the result of very innovative methodological tests using non-destructive approaches to characterize permafrost, and particularly, to determine ground ice contents ("visible", excess) through Ct-Scan analysis of permafrost cores. The innovation resides in the use of a highly efficient industrial Ct-Scanner with high energy and fine resolution (small voxel size) coupled with a new image segmentation method. Their new methodology also makes use of water, ice and aluminum standards and yields results directly in material densities. This paper reports results of essays on five cores that, in my opinion, are typical of a vast array of permafrost conditions. I personally have no doubt the method will work equally well in all types of permafrost materials and ground ice. The authors provide a nice demonstration of the potential of these technologies and methods for the advancement of permafrost science and engineering. I concur with their statement that "This approach offers the potential to better understand permafrost formation, internal structure, and likely response to thaw while developing more consistent and interoperable methods applicable across different permafrost materials" (lines 61-63).

Congratulations!
I have only a few comments, or suggestions, that the authors may wish to consider for their final version for publication (per line numbers of the revised manuscript).

- **Response**: Thank you very much for your encouraging and thoughtful feedback on our revised manuscript. We appreciate the time and effort you dedicated to two rounds of precise and constructive review, as well as the insightful comments that helped improve the clarity and impact of our work. We are pleased that the methodological innovations and their broader applicability to permafrost science and engineering were well-received. Your final suggestions are all well implied in the text as below:

Comment #1: 168-160. "the proportion of the component materials and thus approximates the volumetric content in a sample" would it not be better to rather say something like "the volumetric content of components (or constituents' fractions?)"?

- **Action:** The sentence was revised to: "These densities can then be presented in a histogram, the shape of which reflects **the volumetric content of the components** in the sample"

Comment #2: 182-183. "materials with narrow unimodal density distributions close densities appear as a single peak in the histogram". Awkward sentence. Maybe delete here "narrow density distribution", or rephrase differently.

- **Action:** The sentence was rephrased to: "Materials with similar unimodal density distributions may appear as a single peak in the histogram"

Comment #3: 187. I suggest add "to" before grain size.

- **Action:** Suggestion was applied.

Comment #4: 212. add from graduated beakers (or cylinders ?). The graduations are used to measure the volume.

- **Action:** Suggestion was applied: "supernatant water should be recorded from the graduated beakers"

Comment #5: 227. “due to the lower ice content”, maybe replace by “for samples with low ice contents”.

- **Action:** Suggestion was applied: “Approximately 3 cm^3 aliquots were subsampled from the cores **for samples with low ice contents** to ensure that the cuboids did not fracture or disintegrate during sampling”

Comment #6: 241. Maybe replace “a greater degree of sampling precision” by (or add) “a greater accuracy of volume measurement”.

- **Action:** Suggestion was applied: “takes advantage of the frozen state of the material which allows for a **greater accuracy of volume measurement**”

Comment #7: 249. the sentence seems incomplete

- **Action:** The sentence was revised and completed: “The combination of the frozen bulk density results from the gamma attenuation, an estimation of soil density, and the equation for volumetric ice content (following Lin et al., 2020) can be used with the MSCL to estimate ice content non-destructively”

Comment #8: 256-258. I suggest you name in the text and on figure 4 the composition classes as in figure 5, i.e. sediment-poor ice, sediment-rich ice, ice-rich sediments and ice-poor sediments. Those words have a more direct significance for material composition in the reader’s mind than low ice, high ice, low sediments, high sediments.

- **Action:** composition classes were added to figure 4 and the text: “Otsu method resulted in the differentiation of 5 different classes of ice/sediment ratios on the basis of their relative densities; air, low ice or **sediment-poor ice**, high ice or **sediment-rich ice**, low sediment or **ice-rich sediments**, and high sediment or **ice-poor sediments** or clasts shown in Figures 4 B and C.”

Comment #9: 260. improve the sentence: I suggest: the resulting grey value of a voxel is related to the mixture composition of low-density ice and high-density mineral grains.

- **Action:** Sentence was improved: “the resulting grey value of a voxel is related to the mixture composition of low-density ice and high-density mineral grains”

Comment #10: 338-346 a few issues in this paragraph: 339. it is unclear to me if the comparison is made with Ct-scan on cubic sub-samples or on destructive cuboid analysis.

- **Action:** The paragraph was improved: “A ROI, shown as a red square in Figure 11, was then selected in each CT-scanned cube to make a direct comparison between the delineated (Otsu split) ice contents from image processing and the ice contents determined from the destructive cuboid analysis of the corresponding cube sample. As reference points, the cuboid ice content results for this cube were as follows; 22% EIC and 65% VIC. Figure 12 shows the collected data from repeat image processing steps using the Otsu method of each cube scanned at both 25 µm and 65 µm resolutions as well as the cuboid results.”

Comment #11: 340-and figure 12. The figure needs a more detailed caption or a legend. Are all the data points from both the 25 µm and 65 µm resolutions altogether? Do you not want to illustrate which ones are at 25 µm and which ones are 65 µm resolution?

- **Action:** Figure was edited to clearly show which points are for 25 µm and which ones are 65 µm resolutions.

Comment #12: 343. "expected" do you mean "measured VIC on samples"?

- **Action:** Suggestion was applied: "However, only the 25 µm cube captures a representative value relative to the cuboid data for the **measured** VIC."

Comment #13: 344. "sufficiency" maybe explain better: the capability of the 25 µm resolution for better extracting ice inside small pore spaces (?)

- **Action:** Suggestion was applied: "These results illustrate the capability of 25 µm resolution for better extracting trapped ice inside pore spaces"

Comment #14: 346. the use of the expression VIC becomes weird in the context of higher resolution scanning. VIC means "visible ice content" but it cannot all be seen in totality at 65 µm. However you can detect almost all of it at 25 µm benefitting from both the higher resolution and the Otsu image segmentation method. At this point the concept of "visible ice content" that is widely applied by people just looking at cores becomes irrelevant. It means just what they can see by eye. Maybe it would be better to just talk of pore ice, in large and small pores of the soil. You shall try to avoid creating confusion among permafrost scientists.

- **Response**: As it was already mentioned in line 272: "volumetric (VIC) and excess ice contents (EIC)" VIC means volumetric ice content. To make this clear for all future readers the following lines were edited in section 3.2.
- **Action**: As reference points, the cuboid ice content results for this cube were as follows; 22% excess ice and 65% **volumetric ice contents**." And "However, only the 25 µm cube captures a representative value relative to the cuboid data for the measured **volumetric ice content**"

Comment #15: 353. same comment as for figure 12. The legends of figures 13, 14, and 15 should indicate points at 25 and 65 micrometers resolutions. Or do you show all results indistinctly at both resolution?

- **Action**: "65 µm scans" were added to the captions of figures 13, 14, and 15,

Comment #16: 365. what do you mean by "at a user-defined scale". Maybe say: "at a precision suitable for research and engineering applications". (?)

- **Action**: "at a user-defined scale" was changed to "at a desired scale" to clarify that the resolution is determined by the user based on the needs of the research and engineering application.

Comment #17: 400. again the concept of VIC applied here is strange. A more accurate ice content determination at a higher resolution with a more efficient segmentation method allows in fact to detect a fraction of ice in pores that is not readily visible. This ice however is often in mixtures consisting of variable amounts of sediment particles and frozen water. The permafrost contains excess ice (mostly as segregated ice), visible ice (some segregated and in macro pores) and not visible micro-pore ice. Maybe below a minimum pore size (ex. 65 µm) the concept of visible ice should simply not be used. That would mean avoiding the use of VIC in silt and clay classes on scanned images (accepted

upper fraction size limit of 63 µm for particle size). Or, maybe say simply SIC (soil ice content) for the permafrost ice fraction that is not in excess.

- **Response**: Concept of VIC was clearly addressed in the response to comment 14 and to avoid confusion for future readers, we ensured that the term **VIC** is consistently and explicitly defined as **volumetric ice content** throughout the manuscript.

Before publishing the manuscript, I have a few remaining comments:

- Response: We appreciate the time and effort you dedicated to two rounds of precise and constructive review, as well as the useful comments that helped improve the clarity and impact of our work. Your final suggestions are all well implied in the text as below:

Comment #1: Please try to merge sections 2.1 and 2.2.

- **Action**: Sections 2.1 and 2.2. were merged into one section as follows: "Site and sampling: Five cores were investigated in this study, each representing common materials encountered in permafrost regions, such as silt (ice-poor and ice-rich), peat, silty peat, and diamicton (a coarser, mixed-grain material), and containing a relatively simple vertical cryostratigraphy to minimize the impact of lateral heterogeneity (Table 1). Lateral heterogeneity would cause noise in our results when comparing multiple data acquisition methods within the same material but not identical sample volumes (Figure 1). This effort is explained further by Pumple et al. (2024). These cores were collected as a result of two separate field campaigns during the summers of 2013 and 2019 with some cores being collected in southwestern Yukon along the Alaska Hwy and other in Central Yukon along the Dempster Hwy. All cores were collected in a sub-arcitic setting. Following extraction, the cores were bagged, labelled and stored at subzero temperatures via a pre chilled cooler and quickly transported to the field base where a chest freezer was present. The chest full of cores was then transported to the Permafrost ArChives Science (PACS) Laboratory. The samples were then archived into the PACS Lab walk-in archive freezer space. Samples were prepared for two different stages; non-destructive scans and destructive physical measurements. We took considerations in both stages to ensure the destructive and non-destructive results were comparable. As such for the non-destructive scans, physical cores were cut in half and run through all non-destructive data collection methods. For the second stage, a duplicate transect of cuboid samples was collected from the middle of the core to allow non-destructive data analysis at a higher resolution on one set of the subsampled cubes. As seen in Figure 1, this resulted in the cuboids flanking either side of the MSCL and CT results which were collected from a central transect on the half-core samples.

Comment #2: Line 88: "Five cores were compared in this study." What do you mean with "compared"? Instead, I would propose to use for instance "investigate".

- **Action:** Suggestion was applied: "Five cores were investigated in this study"

Comment #3: Line 88: Couly you please specify in the text what you mean with "common materials encountered in permafrost regions"?

- **Action:** Text was edited to clearly addressed the comment and make this also clear for all future readers. "Five cores were investigated in this study, each representing common materials encountered in permafrost regions, **such as silt (ice-poor and ice-rich), peat, silty peat, and diamicton (a coarser, mixed-grain material),** and containing a relatively simple vertical cryostratigraphy to minimize the impact of lateral heterogeneity."

Comment #4: Line 92: Where did the field campaigns take place? Please add in the text the location and types of field sites (arctic, alpine,...).

- **Action:** Location of test campaigns were added to the text as follows: edited to clearly addressed the comment and make this also clear for all future readers. "These cores were collected as a result of two separate field campaigns during the summers of 2013 and 2019

with some cores being collected in southwestern Yukon along the Alaska Hwy and other in Central Yukon along the Dempster Hwy. All cores were collected in a sub-arcitic setting."

Comment #5: Line 98-99: "An insulated sample container was used to keep the samples frozen during the scanning process discussed further in section 2.3." This sentence is not related to "Field site and coring".

- **Action:** Thanks for the good comment, these lines were deleted from "Filed sites and coring" section and were added to "Industrial Micro Computerised Tomography" section.

Comment #6: Line 101-106: My impression is that the lines here are not really related to "Sampling process". Please try to merge it with section 2.1 (see above).

- **Response**: This comment was addressed earlier please see the response and action of comment #1.

Comment #7: Line 132-145: It's hard to follow these two paragraphs. Please try to reformulate them.

- **Action**: These two paragraphs were reformulated as follows: "An insulated sample holder was developed for this project to ensure samples remained frozen during CT scanning. Both cubes and cores were housed in the same style of a styrofoam container, however, the internal setup varied due to the size of the sample under investigation. Full cores were taken from a nearby chest freezer and placed vertically into a larger container (12 cm inner diameter), with a -80 °C ice pack positioned directly above (Figure 2B and C). In contrast, the cubes were placed in smaller containers (9 cm inner diameter), held in plastic vials beneath a foam divider, and cooled with dry ice on a perforated foam layer to circulate cold air over the sample (Figure 2D). These configurations were tested in advance using internal, surface, and air temperature probes, confirming that both setups maintained sub-zero temperatures for the full scan duration. It should also be noted that full core scans produced partial results due to vertical stage height limitations in the CT scanner. While the scanner can hold samples up to ~30 cm wide by 35 cm high, the maximum scan height depends on voxel resolution and sample width. This limitation was resolved once the cores were subsampled for destructive testing. As a result, for some cores, such as the peat core, it was not possible to compare full vertical data sets across MSCL, CT, and destructive methods."

Comment #8: Line 139-140: Was the core's surface temperature measured or is that an assumption?

- **Response**: Thanks for your attention. The core's surface temperature was not directly measured during this specific project, but our conclusion that the core was not exposed to temperatures above 0 °C is based on repeat CT scan runs conducted prior to this project. **In those tests, we used internal, surface, and air temperature probes to monitor temperatures throughout the scan.** These measurements consistently confirmed that the core surface remained below freezing during scanning, validating our assumption in this study.
- **Action**: To make this clear for all future readers the following lines were edited: "These configurations were tested in advance using internal, surface, and air temperature probes, confirming that both setups maintained sub-zero temperatures for the full scan duration."

Comment #9: Line 149: Please try to be concise regarding the histograms. They are just a visualization tool for a number of values. (see also line 178)

- **Response**: We agree that histograms are, in general, visualization tools. However, in our study, they were calibrated to display values in g/cm^3, which allowed them to serve not only as visual

aids but also as tools for extracting quantitative frozen bulk density values from each ROI. To address your concern, we have revised the text to be more concise while clarifying the specific role of histograms **after calibration**.

- **Action**: To address this comment the following lines were edited: “In this study, all cores were calibrated so the histogram values were displayed in g/cm³. **Following calibration, the histograms served not only as visualization tools but also as a means to extract quantitative information.** To extract the frozen bulk density from each ROI, the mean grey values were extracted in calibrated density values (g/cm³).”