Reply to comments from community (Dennis Darby) on "Circum-Arctic Sediment PROvenance Database (CASPROD): A database of mineralogy and geochemistry for the Circum-Arctic surface sediments" by Yao et al.

Comment 1:

This paper provides a useful listing of provenance techniques applicable to the Arctic Ocean. It suffers for two major omissions: 1) The preprint ignores the Fe grain chemical fingerprinting method used in a dozen or more papers. 2) It avoids any scrutiny of the listed methods as to their accuracy. While the precision of several listed methods might be high, when dealing with multiple sources of ice-rafted sediment in the Arctic Ocean, the accuracy can be quite low. The Fe grain fingerprinting method has been shown to have an accuracy of less than 2% error of misidentifying the correct source or provenance.

Comment 2:

The database by Yao et al. misses an important component of provenance studies. This is the relative accuracy of source determinations. Users would greatly benefit from knowing how accurate each provenance method is. This does not mean how precise each method is!

Reply:

Thank you very much for your constrictive comments and suggestions. In response to your first point, we have added a brief review of the Fe-oxide method into the Introduction, highlighting its extensive application in Arctic research (*Page 3-4, Line 84-106*).

Revisions in the TEXT:

A range of provenance tracers, such as Sr-Nd isotopes, clay mineral assemblages, detrital (i.e., light and heavy) mineral compositions, detrital zircon U-Pb ages, major and minor elements, and Fe-oxide minerals, provide complementary constraints on sediment sources in the Arctic Ocean. Sr-Nd isotopes effectively distinguish sediments derived from juvenile orogenic belts and ancient Archean-Proterozoic cratons (Bazhenova et al., 2017; Maccali et al., 2018; Li et al., 2023), whereas detrital zircon U-Pb age spectra offer robust geochronological fingerprints that discriminate between North American and Eurasian basement affinities (Fedo et al., 2003; Feng et al., 2025). Clay mineral assemblages (e.g., Naidu and Mowatt, 1983; Stein et al., 1994, 2004; Wahsner et al., 1999; Thiry, 2000; Viscosi-Shirley et al., 2003a; Vogt and Knies, 2009; Saukel et al., 2010; Jang et al., 2023), detrital mineral assemblages (e.g., Vogt, 1996, 1997; Behrends, 1999; Stein, 2008; Wang et al., 2022), and major and minor elements (e.g., Schoster et al., 2000; Viscosi-Shirley et al., 2003a, 2003b) may reflect source-rock provenance, transport processes, and past varying climatic regimes. Fagel et al. (2014) have used mineral assemblages, trace element compositions and Nd and Pb isotope signatures to identify the detrital sediment provenance and to interpret changes in the relative contribution of the different source-areas in relationship to paleoenvironmental conditions. In addition, the chemical fingerprint of major and minor elements in specific Fe-oxide minerals, an approach developed by Darby and co-workers (Darby and Bischof, 1996; Darby, 2003; Darby et al., 2015), has been widely used to determine quite accurately sediment provenances in the Arctic Ocean and to reconstruct past sea-ice conditions (e.g., Darby, 2014; Tripati and Darby, 2018; Cofield and Darby, 2025).

To address the reviewer's concerns regarding the relative accuracy of source determinations, we have added an additional section (*3.3 Evaluating the discriminability of provenance proxies*) in the revised manuscript (*Page 20-23, Line 442-514*).

In this new section, we evaluate the relative accuracy of the provenance proxies. As we detail in the text, while single-grain techniques like Fe-oxide fingerprinting can be evaluated using traditional cross-validation accuracy, the integrated-signal/bulk proxies compiled in CASPROD (e.g., Sr-Nd isotopes, clay/detrital minerals, zircon U-Pb ages) yield distributional signatures of sediment mixtures. Therefore, we evaluate these proxies based on their discriminability—quantified as the signal-to-noise ratio (SNR) between inter-source differences and intra-source natural heterogeneity. We provided an honest evaluation of where these methods suffer from low accuracy/discriminability due to regional signal overlaps, thereby underscoring the need for multi-proxy cross-validation as intended by this database.

We believe these additions directly address your concerns and provide users with a transparent assessment to better guide their application of these provenance methods.

Revisions in the TEXT:

3.3 Evaluating the discriminability of provenance proxies

Provenance accuracy is method-dependent and is linked to the analytical unit of a given proxy. For single-grain techniques like Fe-oxide chemical fingerprinting, accuracy is typically evaluated through cross-validation against a reference to quantify incorrect source assignments (Darby et al., 2015). However, this traditional concept of accuracy is not directly applicable to the integrated-signal proxies compiled in CASPROD (e.g., Sr-Nd isotopes, clay and detrital minerals, and zircon U-Pb ages), which yield bulk or distributional signatures of sediment mixtures rather than discrete grain labels. Instead, we evaluate these proxies based on discriminability, defined here as the signal-to-noise ratio (SNR) between inter-source differences and intra-source variability (Figure 7). A high SNR (generally >1) indicates that the compositional contrast between two sources substantially outweighs their internal natural heterogeneity, allowing for reliable provenance discrimination, with larger values yielding greater discriminability.

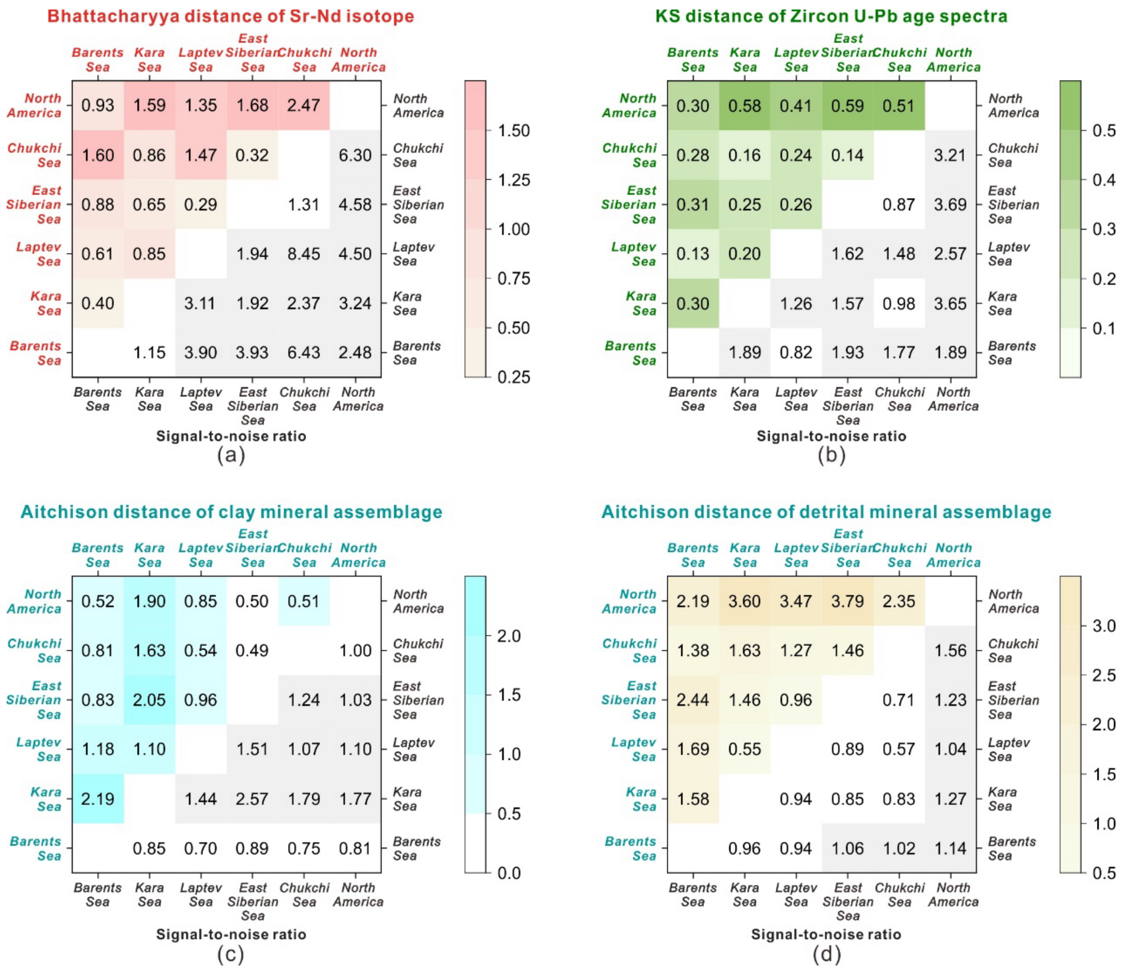

Figure 7. Distance matrix heatmaps illustrating the discriminability of four provenance proxies. In each panel, the upper and lower triangle display pairwise inter-source distances and the corresponding signal-to-noise ratios (SNR), respectively. SNR is defined as the ratio of inter-source distance to intra-source variability. Gray shaded cells denote high SNR values (>1), indicating that the corresponding two source regions can be effectively differentiated by the given proxy. KS: Kolmogorov–Smirnov.

To evaluate pairwise source-region distances and intra-source heterogeneity, we selected statistical metrics tailored to the specific data structure of each proxy. For Sr-Nd isotopes, we applied the Bhattacharyya distance (Bhattacharyya, 1946) to measure source separation in the bivariate εNd–$^{87}Sr/^{86}Sr$ space, as it accommodates substantial differences in data dispersion among source areas without assuming identical covariance structures. For detrital zircon U-Pb age spectra, we used the Kolmogorov–Smirnov (KS) distance. As a distribution-free metric quantifying the maximum vertical difference between two cumulative age-distribution functions, the KS distance is highly sensitive to overall spectral shape and serves as a standard for nonparametric age-spectrum comparisons (Vermeesch, 2012). For clay mineral and detrital mineral assemblages, we applied the Aitchison distance to measure compositional differences between source regions, because percentage of minerals are subject to the constant-sum constraint and conventional distance metrics would introduce spurious correlations (Garzanti et al., 2012). Across all proxies, intra-source heterogeneity is represented by the median distance derived from 1000 bootstrap resampling iterations within each source group.

The calculated SNR values reveals that low discriminability typically stems from substantial signal overlap between specific regions (Figure 7). For instance, detrital zircon U-Pb age spectra cannot effectively differentiate the Kara, Chukchi, and East Siberian seas, nor can they separate the Barents Sea and Laptev Sea (Fig. 7b). This overlap occurs because these marginal seas collectively drain extensive Phanerozoic magmatic provinces, such as the Siberian Traps and the Okhotsk–Chukotka Volcanic Belt, yielding highly convergent age distributions. Similarly, clay mineral assemblages show limited discriminability for the Barents Sea (Figure. 7c), reflecting pronounced intra-regional spatial variability driven by complex hydrodynamics and the mixing of diverse local endmembers. Detrital mineral assemblages also struggle to distinguish Eurasian interior sources, particularly the Kara, Laptev, and East Siberian seas (Figure. 7d). Sr-Nd isotopes, despite generally exhibiting high SNR values (>1), show limited discriminability between the East Siberian and Chukchi seas, or the Barents and Kara seas (Figure. 7a), underscoring the challenge of differentiating provenance with similar geological affinities.

These overlaps highlight the inherent limitations of relying on any single proxy to decipher a complex, multi-source sedimentary system like the Arctic Ocean. Accurate circum-Arctic provenance reconstruction requires a multi-proxy approach (e.g., Stein, 2008; Myers and Darby, 2022). Thus, in several studies multi-proxy approaches have been used to identify circum-Arctic sediment provenances more accurately, e.g. the combination of heavy minerals, clay minerals and major and minor elements (Schoster et al., 2000; Viscosi-Shirley et al., 2003a, 2003b) or the combination of heavy minerals, clay minerals, and chemical fingerprinting of major and minor elements in Fe-oxide minerals (Myers and Darby, 2022).

CASPROD also establishes a multi-proxy, cross-validation framework to overcome the ambiguity introduced by these overlapping signatures. By synthesizing geochemical, geochronological, and mineralogical datasets, this integrated framework provides multiple constraints on endmembers and substantially improve the accuracy of provenance identification. Furthermore, to achieve higher accuracy when interpretating highly complex mixed signals, particularly regarding ice-rafted debris, we encourage database users to couple CASPROD with other approaches, such as the Fe-oxide grain chemical fingerprinting method (Darby, 2003; Darby et al.; 2015; Myers and Darby, 2022).