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Detrital glass in a Bering Sea sediment core yields a ca. 160 ka Marine Isotope Stage 6 age for Old Crow tephra

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ABSTRACT

For decades, the Old Crow tephra has been a prominent stratigraphic marker for the onset of Marine Isotope Stage (MIS) 5e, the last interglaciation, in subarctic northwest North America. However, new zircon U-Pb dates for the tephra suggest that the tephra was deposited ca. 207 ka during MIS 7, with wide-ranging implications for chronologies of glaciation, paleoclimate, relict permafrost, and phylogeography. We analyzed ~1900 detrital glass shards from 28 samples collected at Integrated Ocean Drilling Program Site U1345 in the Bering Sea, which has a well-constrained age model from benthic foraminiferal $\delta^{18}O$. Except for one possibly contaminant shard dated at 165 ka, Old Crow tephra was absent from all samples spanning 220–160 ka. Old Crow tephra appeared abruptly at 157 ka, comprising >40% of detrital shards between 157 and 142 ka. This abrupt increase in the concentration of detrital Old Crow tephra, its absence in earlier intervals, and its presence at low concentrations in all samples between 134 and 15 ka collectively indicate that the tephra was deposited during the middle of MIS 6 with a likely age of 159 ± 8 ka. As a result, the late Quaternary chronostratigraphic framework for unglaciated northwest North America remains intact, and the timing of key events in the region (e.g., bison entry into North America; interglacial paleoclimate; permafrost history; the penultimate glaciation) does not require wholesale revision.

INTRODUCTION

The Old Crow tephra represents one of the largest known Quaternary volcanic eruptions in the arctic and subarctic, with an estimated eruptive volume of $\sim$200 km^3 based on its presence across unglaciated Yukon (Canada) and Alaska (USA) (Westgate et al., 1983; Preece et al., 2011). Attempts to directly date the tephra have been challenging partly because the volcanic source has never been located (e.g., Burgess et al., 2019), and diverse dating tools have yielded a wide range of possible ages (e.g., Westgate et al., 1983, 1990; Lamothe et al., 2020; Burgess et al., 2021).

Nevertheless, insights from geochronology, stratigraphy, and paleoecology have for decades shown that the tephra is consistently found directly beneath—or reworked into—prominent organic horizons that likely represent the last interglaciation (Marine Isotope Stage [MIS] 5e), suggesting that the Old Crow tephra was deposited in late MIS 6 (e.g., Preece et al., 2011). As a result of its wide distribution, consistent stratigraphic associations with presumed last interglacial deposits, and unique glass geochemical fingerprint, the Old Crow tephra is a key marker that provides subcontinental-scale correlation of terrestrial sedimentary and paleoenvironmental records for the most recent period of sustained warming in the Arctic (e.g., Hamilton and Brigham-Grette, 1991; Muhs et al., 2001; CAPE–Last Interglacial Project Members, 2006; Reyes et al., 2010a).

However, the Old Crow tephra now faces an identity crisis. Burgess et al. (2019, 2021) conducted comprehensive U-Pb, U-series, and (U-Th)/He dating on zircon from Old Crow tephra and proposed an MIS 7 eruption age of 207 ± 13 ka (2σ, here and throughout the paper; Burgess et al., 2021). This new age estimate for Old Crow tephra is problematic: Though based on high-quality radiometric geochronology, it is incompatible with the existing stratigraphic, paleoecological, paleogenomic, and paleomagnetic context for this tephra (e.g., Hamilton and Brigham-Grette, 1991; Waythomas et al., 1993; Reyes et al., 2010b; Jensen et al., 2013, 2016; Froese et al., 2017). In turn, if the Burgess et al. (2021) U-based zircon age for the Old Crow tephra is correct, it would require wholesale revision of the late-Middle and Late Pleistocene chronostratigraphy for the rich sedimentary records of unglaciated Alaska and Yukon (e.g., Muhs et al., 2001; Froese et al., 2009).

We therefore turned to the marine sedimentary record to resolve the brewing controversy and long-standing ambiguity on the age of Old Crow tephra. Curiously, the tephra has not been found as a visible bed at proximal core sites of the Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP), e.g., Sites 887 and U1339 (Fig. 1). Initial examination of more distal cores, e.g., U1417 and U1418 (Fig. 1), also failed to locate the tephra (J. Addison, 2022, personal commun.). However, shards of Old Crow tephra are present as a notable component of background detrital glass in the middle–late Holocene core HLY0501–01 from the Chukchi Sea (Fig. 1; Ponomareva et al., 2018). In that core, shards of Dawson tephra (ca. 29 ka; Davies et al., 2016) are also present as a persistent detrital component of Holocene marine mud, as are abundant detrital shards of Aniakchak tephra (ca. 3.5 ka; Davies et al., 2016) in the several thousand years following its deposition. Terrestrial reworking has also been invoked to explain persistently high post-eruption concentrations of Aniakchak tephra in core SWERUS-L2–2-PC1 in the Chukchi Sea (Fig. 1; Pearce et al., 2017). These temporal patterns of detrital glass concentration suggest that marine sedimentation in near-continental settings will be characterized by (1) substantial

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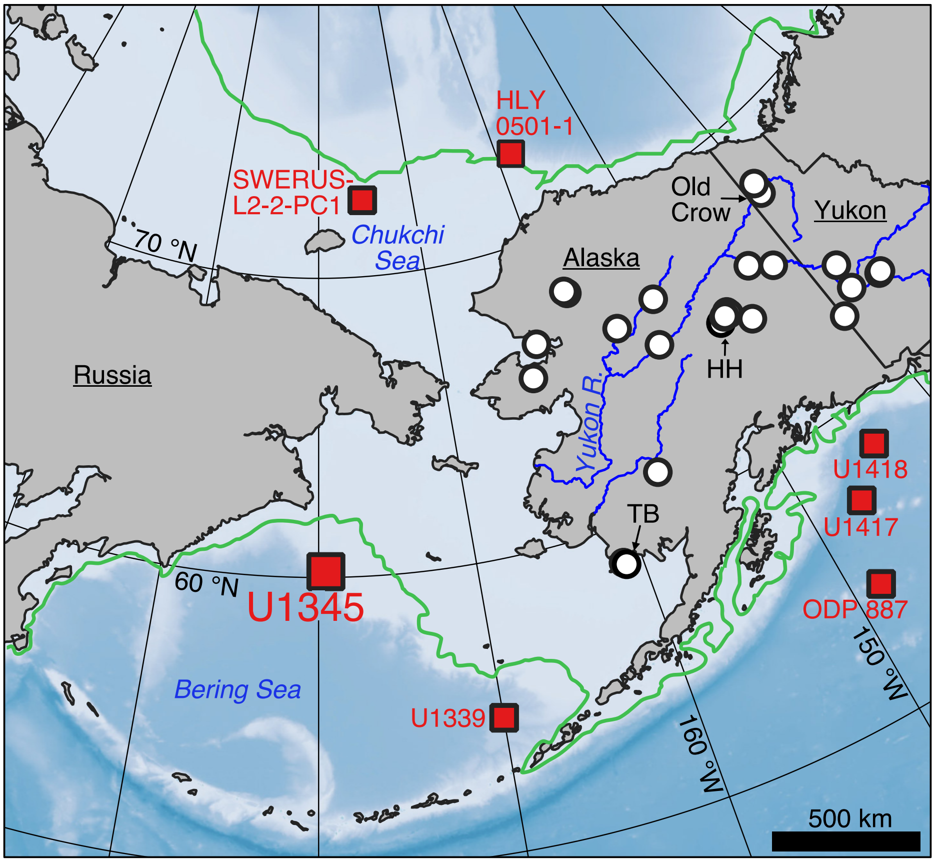

Figure 1. Study area map, including Integrated Ocean Drilling Program (IODP) Site U1345 and other relevant marine sediment cores (red squares; ODP—Ocean Drilling Program); Old Crow tephra sites in Alaska (USA) and Yukon (Canada) (white circles; Preece et al., 2011); 120 m isobath marking the approximate limit of the Beringian landmass during the Last Glacial Maximum (green lines); Halfway House (HH) and Togiak Bay (TB), representing Old Crow tephra sampling locations from Burgess et al. (2019, 2021), respectively; and the type locality for Old Crow tephra in northern Yukon.

deposition of reworked detrital glass for several thousand years following deposition of a widespread tephra on land, and (2) the presence of detrital glass shards in lower concentrations for tens of thousands of years following terrestrial deposition of a widespread tephra.

Accordingly, we used the presence or absence of detrital Old Crow tephra in a Bering Sea sediment core with clear differentiation of glacial-interglacial stages to resolve the debate on the age of this key chronostratigraphic marker. We assumed that Old Crow tephra will be present as detrital shards in marine sediments that postdate its deposition on land but absent in those that predate it. We also assumed that the concentration of detrital Old Crow tephra shards would be highest in marine sediments closest to the eruption age. Therefore, we hypothesized that detrital shards of Old Crow tephra would be present in Bering Sea sediments by ca. 200 ka if the new U-Pb chronology of Burgess et al. (2019, 2021) is accurate. On the other hand, if the late-MIS 6 age for Old Crow tephra is correct, then detrital shards of the tephra would appear from late MIS 6 onward and would be absent prior to that time.

METHODS

We sampled from the primary splice taken from IODP Site U1345 (Expedition 323 Scientists, 2011) on the northern continental slope of the Bering Sea (Fig. 1; 1008 m water depth, 60.15°N, 179.50°W). Site U1345 receives abundant terrigenous sediment from Alaska, has no evidence for depositional hiatuses during the interval of interest, and is far enough from the Aleutian arc to avoid being overwhelmed by proximal tephra (Expedition 323 Scientists, 2011). We updated the original age model for the U1345 primary splice (Cook et al., 2016) using benthic foraminifera $\delta^{18}O$ and bulk sediment $\delta^{15}N$ to yield improved precision for, respectively, MIS 7 and the MIS 6–5 transition (Table S1 in the Supplemental Material[1]). Age model uncertainty is 4–9 k.y. (2σ), with the highest uncertainty of 7–9 k.y. during MIS 6 between 142 and 181 ka (Table S2). Compared to the age model published by Cook et al. (2016), this revised age model yields ages for sampled depths in this study that are ~3 k.y. younger for MIS 5, ~1.5–2.5 k.y. younger for MIS 6, and ~2.5–7 k.y. older for MIS 7; these changes do not affect the identification of specific glacial and interglacial stages, which are based on clear patterns in benthic foraminifera $\delta^{18}O$ (Fig. 2; see the Supplemental Material).

Sample preparation and analysis followed Jensen et al. (2008), with glass major-element composition of unknowns and secondary standards determined by wavelength-dispersive spectrometry on an electron microprobe. We analyzed 50 glass shards from each sampled interval (Fig. 2), capturing a full range of shard morphologies. An additional 50 shards were analyzed from select samples—focusing on shard morphologies typical of Old Crow tephra—to maximize the chance of identifying detrital Old Crow tephra at key intervals associated with the glass fission-track and U-based zircon ages (Fig. 2; Table S2).

We used a machine learning approach to identify Old Crow tephra shards, adapting the artificial neural network and random forest ensemble of Bolton et al. (2020). Training data consisted of 1470 analyses of Old Crow tephra and >17,000 analyses of other Pleistocene and Holocene tephras from Alaska, Yukon, and Kamchatka. We used bivariate plots and expert analysis to confirm that the machine classifier did not mistakenly identify—or fail to identify—shards of Old Crow tephra (Fig. 3).

Details on the U1345 age model, samples, preparation, analyses, and machine learning classification are provided in Supplemental Material and Data Sets S1 and S2 therein.

RESULTS

Identification of Old Crow tephra in detrital glass from U1345 was facilitated by the tephra's relatively homogeneous and unique major-element composition (e.g., Preece et al., 2011). Compared to other late Quaternary tephra deposits in Alaska and Yukon, the Old Crow tephra composition is most like the ca. 29 ka Dawson tephra. However, the two are readily distinguished by their SiO_2, Na_2O, FeO_{total}, and Al_2O_3 compositions.

Old Crow tephra was not present in three samples that predated the Burgess et al. (2021) age estimate for Old Crow tephra (Figs. 2A and 3). Similarly, out of 400 analyzed shards, we did not identify any Old Crow tephra detrital shards in the five samples between 220 and 197 ka (Figs. 2A and 3), which are within uncertainty of the 207 ± 13 ka age of Burgess et al. (2021). Of 495 analyzed shards from eight samples dated to 189–160 ka, only one shard

[1]Supplemental Material. Detailed sampling, analytical, age model, and machine learning methods and Data Sets S1 and S2 (electron microprobe and machine learning results). Please visit https://doi.org/10.1130/GEOL.S.21397194 to access the supplemental material and contact editing@geosociety.org with any questions.

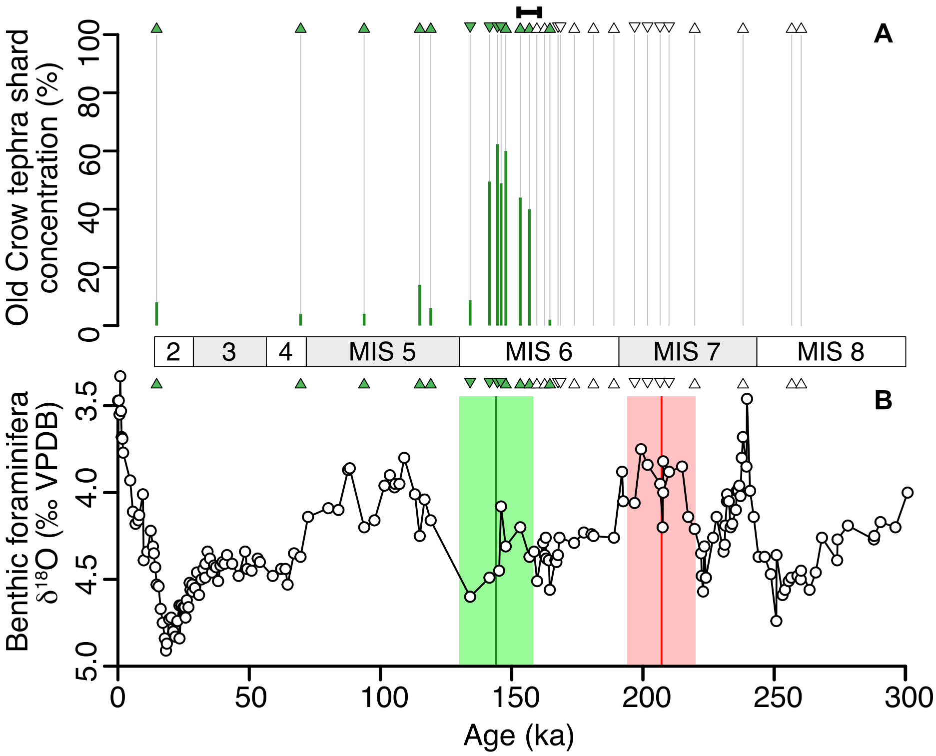

Figure 2. (A) Proportion of analyzed glass shards in each Integrated Ocean Drilling Program (IODP) Site U1345 sample identified as Old Crow tephra (green bars). (B) Site U1345 benthic foraminifera $\delta^{18}O$ (see also Fig. S1 [see footnote 1]). Green triangles indicate samples with detrital Old Crow tephra; up- and down-pointing triangles are samples with ~50 and ~100 analyzed shards, respectively. Error bar at the top of A is ±9 k.y. age model uncertainty for the first major appearance of detrital Old Crow tephra at 157 ka. In B, 144 ± 14 recalculated glass fission-track (Buryak et al., 2022) and 207 ± 13 U-based zircon (Burgess et al., 2021) ages for Old Crow tephra are indicated by green and red windows, respectively. MIS—marine isotope stage; VPDB—Vienna Peedee belemnite standard.

at 165 ka can plausibly be identified as Old Crow tephra (Figs. 2A and 3).

Old Crow tephra appeared abruptly in U1345 at 157 ± 9 ka, comprising 40% of the detrital shard sample in that interval (Fig. 3) and marking the onset of ~15 k.y. of detrital glass sedimentation dominated by the tephra. In all six samples dated 157–142 ka, which spanned ~3 m of core depth and coincided with high benthic foraminifera $\delta^{18}O$ values indicative of high global ice volume, Old Crow tephra made up 40%–62% of the analyzed detrital shards (Figs. 2 and 3). The tephra was also present—albeit at low concentrations of 4%–14% of the analyzed detrital shards—in each of six samples dating to 134–15 ka (Figs. 2A and 3).

DISCUSSION

Marine and lacustrine sediments that postdate a prominent tephra in their catchment commonly contain reworked glass shards from that tephra immediately following its deposition on land (e.g., Boygle, 1999; Goldfinger et al., 2017; Pearce et al., 2017; McLean et al., 2018; Ponomareva et al., 2018). Consequently, we assert that the lack of Old Crow tephra in samples dated to 220–160 ka (Figs. 2 and 3), the presence of abundant detrital Old Crow tephra shards ca. 157–142 ka, and its persistence at low concentration from 134 to 15 ka indicate that this key tephra was deposited between 160 and 157 ka during the middle of MIS 6 (Fig. 2). A simple sequential Bayesian age model run in OxCal4.4.4 (Bronk Ramsey, 2009) gave an estimated eruption age of 159 ± 8 ka (2σ) using the bounding ages of 160 ± 9 ka (Old Crow absent) and 157 ± 9 ka (Old Crow present).

The single Old Crow shard at 165 ka is peculiar. We do not suspect downward mobility of glass shards because the tephra was absent from the two samples preceding the abrupt appearance of abundant detrital Old Crow tephra at 157 ka. Furthermore, there is no evidence of bioturbation in the core sections spanning 181–146 ka (Table S2). This single Old Crow shard may be due to trace laboratory or sampling contamination, or it may be an artifact of a poor single-point microprobe analysis. Regardless, even if the single shard at 165 ka marks the earliest evidence for Old Crow tephra deposition, this still places the eruption within mid-MIS 6.

Our proposed 159 ± 8 ka age for the Old Crow tephra cannot be reconciled with the recent zircon U-based eruption age of 207 ± 13 ka nor with the interpretation that the tephra was deposited during the MIS 7 interglaciation (Burgess et al., 2021). The 159 ± 8 ka age for the Old Crow tephra is slightly older than the tephra's recalculated glass fission-track age of 144 ± 14 ka (Buryak et al., 2022), which is based on a revised $^{40}Ar/^{39}Ar$ age for the moldavite reference material (Schmieder et al., 2018). However, the recalculated glass fission-track age and our inferred age from Site U1345 detrital glass are both consistent with stratigraphic and paleoenvironmental age constraints for Old Crow tephra, which is typically found either (1) in eolian, lacustrine, or fluvial sediments that suggest deposition in a (shrub) tundra environment, stratigraphically beneath a prominent buried organic-rich horizon with interglacial paleoecological indicators (e.g., Matthews et al., 1990; Waythomas et al., 1993; Reyes et al., 2010b); or (2) reworked into a similar prominent organic horizon with interglacial proxy indicators and sharp lower contacts indicative of presumed interglacial thaw-related unconformities (e.g., Péwé et al., 1997; Muhs et al., 2001; Reyes et al., 2010a).

Accordingly, even though some earlier glass fission-track determinations for Old Crow tephra (e.g., 124 ± 20 ka; Preece et al., 2011) have median ages that ostensibly place it within the MIS 5e last interglaciation, most researchers in the region have proposed that the stratigraphic and paleoecological contexts for the tephra likely preclude its deposition during an interglaciation (e.g., Matthews et al., 1990; McDowell and Edwards, 2001; Reyes et al., 2010b). In turn, the Old Crow tephra has been used to constrain a range of key late Quaternary events in northwest North America, for example, the timing of bison entry into North America during MIS 6, based on a bone found in direct stratigraphic association with Old Crow tephra (Froese et al., 2017); the magnitude of last interglacial warming in the western Arctic (CAPE–Last Interglacial Project Members, 2006); permafrost persistence and the magnitude of ground thaw through MIS 5e, based on stratigraphic relations between relict ice wedges, thaw unconformities, and Old Crow tephra (Reyes et al., 2010a); and the timing of extensive late Quaternary glacial advances, based on the presence of Old Crow tephra above buried outwash and till deposits (e.g., Turner et al., 2013).

In light of the detrital glass record presented here, it is worth considering why the comprehensive dating of zircon from Old Crow tephra by Burgess et al. (2019, 2021) yielded a 207 ± 13 ka age that is likely 40–50 k.y. too old. Zircon U-Pb and U-series dates constrain the timing of crystallization and thus may substantially predate the actual eruption. Burgess et al. (2019) attempted to control for this bias with (U-Th)/He ages that should provide a more direct eruption age, but with a larger error (207 ± 34 ka). In

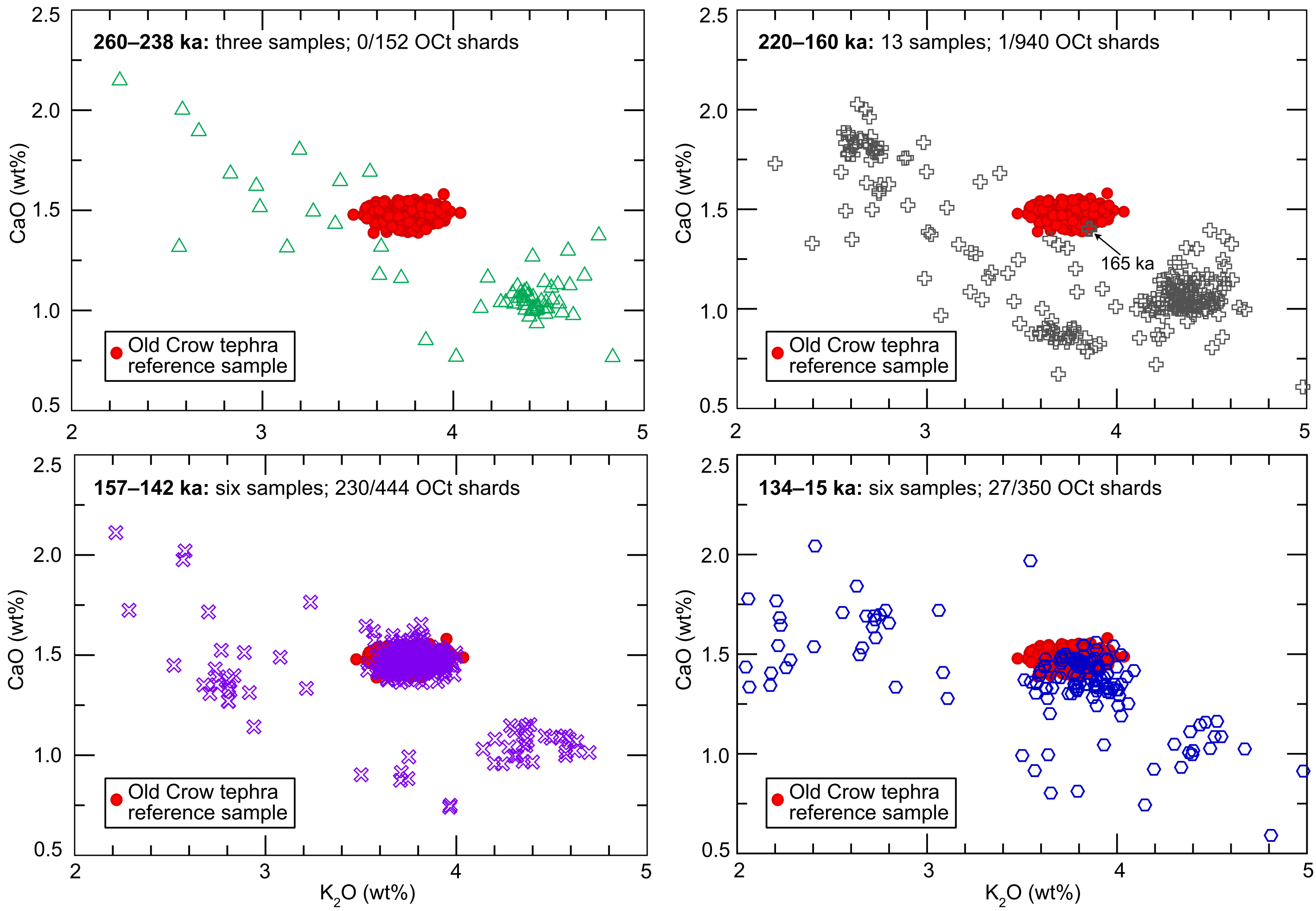

Figure 3. CaO and K_2O biplots for Integrated Ocean Drilling Program (IODP) Site U1345 detrital glass shards. Red circles are reference Old Crow analyses (*n* = 256) run with Site U1345 samples. Other symbols represent all analyzed shards within each age interval, noting the number of samples and the number of Old Crow tephra (OCt) shards to the total number of analyzed shards. For clarity, biplots only display shards with 73–77 wt% SiO_2, capturing the ~74.8 to ~75.7 wt% compositional range of Old Crow tephra (Preece et al., 2011).

addition, Buryak et al. (2022) showed that U-Pb ages derived from zircons are sensitive to the method used to average the pool of dates, with weighted mean methods yielding age estimates up to 5%–10% older than those from Bayesian age modeling and maximum likelihood approaches. Buryak et al. (2022) also emphasized the need to consider corroborating evidence from stratigraphy, paleoecology, paleomagnetism, and other independent constraints when evaluating radiometric ages for Pleistocene tephra deposits.

Independent of the nuances of zircon U-Pb dating, the U1345 record of detrital Old Crow tephra shows that the tephra was deposited across the landscape of unglaciated Alaska and Yukon during the latter half of the MIS 6 glaciation. Consequently, the Old Crow tephra can continue to underpin the regional chronostratigraphy for diverse paleoenvironmental studies in subarctic northwest America as a prominent isochronous stratigraphic marker for the onset of MIS 5e, the last interglaciation. Our results also suggest that detrital glass records from well-dated marine sediment cores in other settings may provide valuable geochronology for important tephra markers that are difficult to date by other means.

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