A detrital zircon test of large-scale terrane displacement along the Arctic margin of North America

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ABSTRACT

Detrital zircon U-Pb geochronology is one of the most common methods used to constrain the provenance of ancient sedimentary systems. Yet, its efficacy for precisely constraining paleogeographic reconstructions is often complicated by geological, analytical, and statistical uncertainties. To test the utility of this technique for reconstructing complex, margin-parallel terrane displacements, we compiled new and previously published U-Pb detrital zircon data (n = 7924; 70 samples) from Neoproterozoic–Cambrian marine sandstone-bearing units across the Porcupine shear zone of northern Yukon and Alaska, which separates the North Slope subterrane of Arctic Alaska from northwestern Laurentia (Yukon block). Contrasting tectonic models for the North Slope subterrane indicate it originated either near its current position as an autochthonous continuation of the Yukon block or from a position adjacent to the northeastern Laurentian margin prior to >1000 km of Paleozoic–Mesozoic translation. Our statistical results demonstrate that zircon U-Pb age distributions from the North Slope subterrane are consistently distinct from the Yukon block, thereby supporting a model of continent-scale strike-slip displacement along the Arctic margin of North America. Further examination of this dataset highlights important pitfalls associated with common methodological approaches using small sample sizes and reveals challenges in relying solely on detrital zircon age spectra for testing models of terranes displaced along the same continental margin from which they originated. Nevertheless, large-n detrital zircon datasets interpreted within a robust geologic framework can be effective for evaluating translation across complex tectonic boundaries.

INTRODUCTION

Detrital zircon U-Pb geochronology has become widespread for investigating questions in the fields of structural geology, tectonics, sedimentary geology, and geomorphology (Gehrels et al., 2014). A transition to more quantitative approaches to data interpretation (e.g., Vermeesch, 2004, 2018; Andersen et al., 2005; Saylor and Sundell, 2016; Sundell and Saylor, 2017), along with improved analytical methods that allow for larger sample sizes (e.g., Pullen et al., 2015), has increased the application of this technique for elucidating sedimentary provenance and disentangling cryptic tectonic boundaries. However, the application of detrital mineral geochronology as a precise paleogeographic indicator, as well as the growing use of statistical dissimilarity measurements on small-n datasets, has been challenged due to inconsistency in the number of grains analyzed per sample (e.g., Vermeesch, 2004), sampling and mineral separation biases (e.g., Sláma and Košler, 2012), age fractionation between different grain sizes in modern drainage systems (e.g., Ibañez-Mejia et al., 2018), and nonunique age signatures from disparate source regions (e.g., Andersen et al., 2014). We present a case study from the northern North American Cordillera to test the efficacy of detrital zircon U-Pb geochronology for deciphering tectonic relationships across complex terrane boundaries—in particular, those that juxtapose crustal fragments displaced along the same continental margin from which they originated.

Despite decades of debate, the tectonic evolution of the circum-Arctic region remains controversial. The displacement history of the North Slope subterrane of Arctic Alaska, which borders the Arctic Ocean, played an integral role in the opening of the Canada Basin and evolution of the circum-Arctic region (Fig. 1). Competing models posit that the North Slope subterrane was either displaced >1000 km along the northern (all directions are in modern coordinates) margin of Laurentia during the Paleozoic and/or Mesozoic (e.g., Sweeney, 1982; Strauss et al., 2013), or it originated as an autochthonous continuation of the northwestern margin of Laurentia (e.g., Lane and Gehrels, 2014; Lane et al., 2016). In order to test these models and to explore the utility of detrital zircon U-Pb geochronology for reconstructing terranes juxtaposed by complex tectonic boundaries more generally, we compiled new (n = 3009; 22 samples) and previously published (n = 1317; 17 samples) detrital zircon U-Pb ages from autochthonous Neoproterozoic–Cambrian strata of the Yukon block and Mackenzie platform in northwestern Canada to compare with recently published age-equivalent data (n = 3598; 31 samples) from the North Slope subterrane in northeastern Alaska and northwestern Yukon (Fig. 1). This large-n dataset not only helps to constrain the tectonic evolution of the Arctic margin of North America, but it also facilitates an examination of common data-treatment approaches in detrital zircon U-Pb geochronology.

GEOLOGICAL SETTING

Northwestern Laurentian Autochthon

The Yukon block, Selwyn basin, and Mackenzie platform of northwestern Laurentia span from east-central Alaska (USA) into the southwestern Northwest Territories (NWT, Canada), and collectively reflect a broad zone of Neoproterozoic–Paleozoic shallow- to deep-water sedimentation along the autochthonous northwestern margin of Laurentia (Fig. 1; Cecile et al., 1997). These depocenters are bounded to the southwest by the Late Cretaceous–Paleogene
Tintina fault and to the northwest by the Paleozoic–Eocene (?) Porcupine shear zone, the latter of which delineates a prominent tectonic boundary with the North Slope subterrane of Arctic Alaska (von Gosen et al., 2019). Proterozoic strata of the Yukon block and Mackenzie platform are exposed across central Yukon and western NWT (Fig. 1; see the Supplemental Material and Figure S1 therein) and comprise three unconformity-bounded successions: the ca. 1.7–1.2 Ga Wernecke Supergroup, the ca. 1.2–0.8 Ga Mackenzie Mountains Supergroup, and the ca. 0.8–0.5 Ga Windermere Supergroup (Young et al., 1979). Lower Paleozoic carbonate, siliciclastic, and volcanic deposits overlie these Proterozoic units and record a complex history of passive-margin development (Cecile et al., 1997; Beranek, 2017; Moynihan et al., 2019). Here, we focused on marine sandstone samples from the Neoproterozoic Mount Harper, Rapitan, Hay Creek, and Rackla Groups of the Windermere Supergroup, as well as various ungrouped Cambrian units throughout the Yukon block and Mackenzie platform (Fig. 1; see Supplemental Material).

North Slope Subterrane of Arctic Alaska

The North American Cordillera terminates at its northernmost extent within the Arctic Alaska–Chukotka microplate, which is a composite terrane made up of Neoproterozoic–Devonian crustal fragments with diverse tectonic affinities (Moore et al., 1994; Strauss et al., 2013; Hoiland et al., 2018; Miller et al., 2018). The Arctic Alaska terrane can be broadly subdivided into two regions characterized by distinct pre-Mississippian geological histories—the North Slope and southwestern subterranes (e.g., Strauss et al., 2013; Hoiland et al., 2018). Whereas the southwestern subterranes have peri-Baltic or Siberian affinities (Patrick and McClelland, 1995; Dumoulin et al., 2002; Amato et al., 2009; Miller et al., 2011; Hoiland et al., 2018), the stratigraphy, sedimentary provenance, paleobiogeographic affinity, and magmatic history of the North Slope subterrane all indicate a peri-Laurentian origin (e.g., Moore et al., 1994; Strauss et al., 2013, 2019a, 2019b; McClelland et al., 2015; Johnson et al., 2016; Colpron et al., 2019). Although a Laurentian origin for the North Slope is undisputed, its pre-Mississippian position along the ancestral continental margin remains contentious, with some models emphasizing a northwestern Laurentian origin (e.g., Lane and Gehrels, 2014; Lane et al., 2016) and others preferring links to the northeastern (Franklinian) margin of Ellesmere Island, Canada, and Greenland (Fig. 1; e.g., Strauss et al., 2013, 2019a, 2019b; Johnson et al., 2016; Colpron et al., 2019). Both end-member models rely heavily on detrital zircon geochronology; however, attempts to deconvolve the tectonic affinity of the North Slope subterrane using detrital records have been hampered by small-n datasets (e.g., McClelland et al., 2015; Lane et al., 2016).

**METHODS**

We present 3009 new U-Pb detrital zircon ages (3590 before filtering) from 22 samples of Tonian–Cambrian fine- to coarse-grained marine sandstone units from the Yukon block of northwestern Canada (Fig. 1; Figs. S1 and S2; Tables S1 and S2). Following standard mineral separation techniques, zircons were analyzed via laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the University of Arizona (Tucson, Arizona), University of

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1Supplemental Material. Supplemental methods, sample descriptions, and U-Pb results, as well as Figures S1 and S2 and Tables S1–S3. Please visit https://doi.org/10.1130/GEOUL.S.13377206 to access the supplemental material, and contact editing@geosociety.org with any questions.
Table 1. Statistical results comparing detrital zircon age populations between strata from the Northwestern Laurentian autochthon versus the North Slope subterrane

<table>
<thead>
<tr>
<th></th>
<th>Same parent</th>
<th>Different parent</th>
<th>Tonian–Cryogenian</th>
<th>Ediacaran</th>
<th>Cambrian</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-correlation coefficient</td>
<td>&gt;0.75</td>
<td>&lt;0.5</td>
<td>0.18</td>
<td>0.16</td>
<td>0.55</td>
<td>0.28</td>
</tr>
<tr>
<td>Likeness coefficient</td>
<td>&gt;0.8</td>
<td>&lt;0.8</td>
<td>0.51</td>
<td>0.46</td>
<td>0.69</td>
<td>0.56</td>
</tr>
<tr>
<td>Similarity coefficient</td>
<td>&gt;0.95</td>
<td>&lt;0.95</td>
<td>0.84</td>
<td>0.82</td>
<td>0.94</td>
<td>0.89</td>
</tr>
<tr>
<td>K-S test D statistic</td>
<td>&lt;0.1</td>
<td>&gt;0.1</td>
<td>0.44</td>
<td>0.55</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td>Kuiper test V statistic</td>
<td>&lt;0.1</td>
<td>&gt;0.1</td>
<td>0.49</td>
<td>0.55</td>
<td>0.32</td>
<td>0.45</td>
</tr>
<tr>
<td>Northwest Laurentia sample size</td>
<td>-</td>
<td>-</td>
<td>2209</td>
<td>664</td>
<td>1453</td>
<td>4326</td>
</tr>
<tr>
<td>North Slope sample size</td>
<td>-</td>
<td>-</td>
<td>552</td>
<td>862</td>
<td>2184</td>
<td>3598</td>
</tr>
</tbody>
</table>

Note: K-S—Kolmogorov-Smirnov. Values for determining whether populations were derived from the same versus different parents were approximated from Saylor and Sundell (2016) for n ~500. Shading relates to statistics, where lighter is more similar, and darker is more dissimilar.

Figure 2. (A) Probability density plots (solid lines), histograms, and kernel density estimates (dashed lines), and (B) cumulative probability plot showing new and compiled U-Pb data binned by age from the North Slope subterrane and the northwest Laurentian autochthon (Yukon block and Mackenzie platform). Plotted using AgeCalcML (Sundell et al., 2020) with a kernel bandwidth of 10 m.y. and a bin size of 30 m.y. (C) Statistical parameters (Table 1) comparing detrital zircon U-Pb age populations between the North Slope subterrane and northwest Laurentian autochthon. Significance thresholds for determining whether populations were derived from the same versus different parents were approximated from Saylor and Sundell (2016) for n = 500. K-S—Kolmogorov-Smirnov.
Adelaide (Australia), or Boise State University (Boise, Idaho) (see the Supplemental Material). We then compiled 3598 previously published U-Pb detrital zircon ages for 31 samples from the North Slope subterrane and an additional 1317 ages for 17 samples from the Yukon block and Mackenzie platform (Fig. 1; Fig. S1, Tables S1 and S3). These previously published Tonian–Cambrian marine sandstone samples each provided >40 individual zircon analyses and were of similar composition, grain size, and depositional setting to the new data presented herein. New and previously published data were filtered using error propagation on discordance to exclude analyses where the 2σ uncertainty for either the 206Pb/238U or 207Pb/206Pb isotopic date was >10% or where discordance was >10% or reverse discordance was >5% within 2σ uncertainty (see the Supplemental Material).

All filtered new and compiled data were grouped by stratigraphic age into Tonian–Cryogenian, Ediacaran, and Cambrian bins to facilitate age-equivalent comparisons. We computed common statistical metrics (cross-correlation, likeness, and similarity coefficients and Kolmogorov-Smirnov and Kuiper tests on sample probability density plots) using DZstats (Saylor and Sundell, 2016) to test the null hypothesis that Neoproterozoic–Cambrian samples from the North Slope subterrane and northwestern Laurentia were derived from a common source region (Table 1; Fig. 2). A 1500 Ma “best age” cutoff was used for these statistical comparisons.

Then, to assess the effects of using different cutoffs for selecting the 206Pb/238U or 207Pb/206Pb isotopic date as the “best age,” we applied 900, 1200, and 1500 Ma cutoffs to all individual and binned data in our compilation. The resulting three datasets were analyzed using the same suite of statistical analyses to test the null hypothesis that detrital zircon age spectra were indistinguishable regardless of selected cutoff date (Fig. 3). Statistical values used to assess whether to accept or reject these null hypotheses were a function of sample size (Saylor and Sundell, 2016); they should not be regarded as strict cutoffs, but rather guidelines for assessing the relative probability that age populations were drawn from the same or different parent population, or cannot be determined and remain ambiguous.

**DISCUSSION**

Competing tectonic models for the evolution of the Canada Basin of the Arctic Ocean provide testable hypotheses regarding the provenance and tectonic affinity of the North Slope subterrane. Previous detrital zircon investigations...
of pre-Mississippian strata of the North Slope subterrane had insufficient sample sizes to definitively constrain these models (e.g., McClelland et al., 2015; Lane et al., 2016). In contrast, statistical metrics applied to the large-n detrital zircon data set presented herein demonstrate that age spectra of Neoproterozoic–Cambrian strata from the North Slope subterrane and northwestern Laurentian autochthon are distinct from one another—i.e., they consistently plot in fields that suggest different parent populations (Table 1; Fig. 2). Our compilation displays a subtle secular increase in statistical similarity in detrital zircon age populations of Cambrian strata relative to the older age bins. However, these results do not meet the criteria to indicate they were derived from a common parent (Table 1, Fig. 2). This prolonged difference in provenance between age-equivalent marine sandstone samples of broadly similar maturity, grain size, and depositional setting is inconsistent with models in which strata from the North Slope subterrane were deposited near their current position adjacent to the Yukon block. Rather, these statistical results are better resolved with an origin for the North Slope subterrane independent from autochthonous northwestern Laurentia, consistent with models that evoke large-scale Paleozoic and/or younger strike-slip displacement along the northern margin of Laurentia (e.g., Sweeney, 1982; Colpron and Nelson, 2009; Strauss et al., 2013; Dissing et al., 2020).

We also leveraged this large-n dataset to examine some common techniques in data treatment and associated assumptions in detrital zircon U-Pb geochronology. When individual samples were assessed using different $^{206}\text{Pb}/^{238}\text{U}$ or $^{207}\text{Pb}/^{206}\text{Pb}$ “best age” cutoffs and reinforce the pitfalls of statistical similarity metrics applied to small-n datasets. However, when integrated with relevant geological context, such as structural and sedimentological/stratigraphic data, large-n detrital zircon U-Pb geochronology may be one of the best tools for reconstructing cryptic margin-parallel displacements, especially where crustal-scale fault zones between (para)autochthonous terranes have not been recognized or fully appreciated.

ACKNOWLEDGMENTS

This work was funded by U.S. National Science Foundation (NSF) Tectonics Division grants EAR-1624131/-1947074 to McClelland and EAR-1624132/-1947075 to McClelland. Gibson acknowledges support from the Agouron Geobiology Fellowship. We thank the Tr’ondëk Hwech’in and Na-Cho Nyäk Dun First Nations for permission to conduct field work on their traditional lands. Partial support for field work was provided by the Yukon Geological Survey (Canada) and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Germany). The Arizona LaserChron Center was supported by NSF grant EAR-1649254. We acknowledge G. Halverson and T. Maeder for providing unpublished data; G. Cox, M. Kunzmann, L. Nelson, E. Spering, and W. Ward for aid in sampling; M. Pech, N. Geisler, J. Crowley, D. Pierce, and T. Allen for laboratory assistance; and G. Gehrels, M. Colpron, B. Johnson, and D. Moynhian for discussion. Elizabeth Miller and an anonymous reviewer provided suggestions that greatly improved this manuscript.

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