Research Article

Provenance of the Incipient Passive Margin of NW Laurentia (Neoproterozoic): Detrital Zircon from Continental Slope and Basin Floor Deposits of the Windermere Supergroup, Southern Canadian Cordillera

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The origin of the passive margin forming the paleo-Pacific western edge of the ancestral North American continent (Laurentia) constrains the breakup of Rodinia and sets the stage for the Phanerozoic evolution of Laurentia. The Windermere Supergroup in the southern Canadian Cordillera records rift-to-drift sedimentation in the form of a prograding continental margin deposited between ~730 and 570 Ma. New U-Pb detrital zircon analysis from samples of the post-rift deposits shows that the ultimate source area was the shield of NW Laurentia and the near uniformity of age spectra are consistent with a stable continental drainage system. No western sediment source area was detected. Detrital zircon from postrift continental slope deposits are a proxy for ca. 676-656 Ma igneous activity in the Windermere basin, likely related to continental breakup, and set a maximum depositional age for slope deposits on the eastern side of the basin at 652 ± 9 Ma. These results are consistent with previous interpretations. The St. Mary-Moyie fault zone near the Canada-U.S. border was most likely a major transform boundary separating a rifted continental margin to the north from intracratonic rift basins to the south, resolving north-south variations along western Laurentia in the late Neoproterozoic at approximately 650-600 Ma. For Rodinia reconstructions, the conjugate margin to the southern Canadian Cordillera would have a record of rifting between ~730 and 650 Ma followed by passive margin sedimentation.

1. Introduction

The late Neoproterozoic record of the breakup of the Proterozoic supercontinent Rodinia for western Laurentia (ancestral North America) is in the Windermere Supergroup [1–5]; an unconformity bounded, mostly siliciclastic succession that crops out over 4000 km from northern Mexico to the Yukon-Alaska border (Figure 1). The Windermere Supergroup (WSG) is associated with a still poorly understood late Proterozoic continental margin that was a precursor to the western edge of Laurentia through the Phanerozoic. To resolve this margin, it is important to recognize significant differences in Windermere basin types from north to south: in the southern Canadian Cordillera (SCC), the WSG is a rift-to-drift continental margin succession [2], whereas correlative strata in the western U.S. were deposited within intracratonic rift basins (e.g., [1, 4]).

In the SCC, the WSG has at its base rift deposits that are overlain by a thick basin floor to slope to shelf succession, a motif that is interpreted as a prograding continental margin with no western boundary [2]; consistent with limited U-Pb detrital zircon provenance data indicating
sediment derivation from the Laurentian craton (e.g., [6, 7]). Discussion of a potential western edge to the basin is hypothetical (see [8]), but the Mesoproterozoic Belt Basin should be a proxy for a western sediment source because it contains abundant non-Laurentian 1.6-1.5 Ga detrital zircon derived from a “western craton” (e.g., [9, 10]). Previously published detrital zircon data from post-rift strata of the WSG in the SCC do not have these ages, but are limited to older very low-n analyses from the 1990s (e.g., [7, 11]), and three samples using higher-n methods [6, 12]. Here, we employ modern techniques and a sampling strategy to cover most stratigraphic units in the SCC from syn-rift to postrift basin floor and slope depositional elements spanning eastern and western outcrop areas to test basin-scale sedimentary provenance. Anchored by the new U-Pb detrital zircon dataset, our discussion about the divergent tectonic setting in the Neoproterozoic is limited to the WSG, which is older than ca. 570 Ma in the SCC, and does not address subsequent extensional tectonic events in the latest Neoproterozoic and Cambrian (e.g., [13, 14]).

Figure 1: Generalized geology of western North America showing outcrops of the Windermere Supergroup and detrital zircon sample locations, the Belt Basin, and Laurentian basement domains (modified from [61–63]; Whitmeyer and Karlstom, 2007; [58]). The Windermere rifted margin of the southern Canadian Cordillera contrasts with coeval intracratonic rift basins south of the St. Mary-Moyie fault zone. Geochronology data: Idaho, Lund et al. [1], Fanning and Link [64], Keeley et al. [21]; Belt Basin, Ross and Villeneuve [10], Link et al. [55], Lewis et al. [9, 54]; northwestern Canada, Pigage and Mortensen [58], Eyster et al. [20]; Yukon-Tanana terrane, Piercey and Colpron [59], Dusel-Bacon et al. [60].

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1.1. Proterozoic Successions of Western Laurentia. Proterozoic strata distributed over northern Laurentia are subdivided into three continental-scale successions termed sequence A, B, and C [5]. Sequence A broadly spans 1.8-1.2 Ga from the formation of Rodinia until the assembly of Rodinia and includes the ~1.5-1.3 Ga Belt-Purcell Supergroup in the SCC (Figure 1). Postorogenic uplift of the Grenville orogen (1.2-1.0 Ga) in eastern Laurentia dispersed 1.5-1.0 Ga detrital zircon across the continent to be deposited in intracontinental basins between ~1.1 and 0.72 Ga [15]; although there may also have been a source west of the Canadian Cordillera prior to the breakup of Rodinia (e.g., [11]). These basins form sequence B and are a reservoir of 1.5-1.0 Ga detrital zircon (e.g., [16]).

During the breakup of Rodinia, rifting along western Laurentia led to the deposition of sequence C after 0.72 Ga. The WSG represents sequence C, and in terms of detrital zircon, sequence C often comprises sequence A or B signatures, suggesting the recycling of the older orogenic and basin history of western Laurentia (e.g., [12]).

1.2. Windermere Depositional System (SCC): Rift Basin to Continental Margin. The Neoproterozoic WSG of western North America is an unconformity bounded succession that crops out over 4000 km from northern Mexico to the Yukon-Alaska border [17]. In the southern Canadian Cordillera (SCC), the basal unconformity of the Windermere Supergroup is overlain by a 5-7 km postrift succession of siliciclastic with lesser carbonate rocks (Figure 3). The WSG post-rift succession consists primarily of deep-marine strata that, because of deformation related to the Mesozoic Cordilleran orogeny, crop out extensively over ~35,000 km², which if conservatively palinspastically reconstructed represents a turbidite system of at least 80-85,000 km², and therefore, dimensionally consistent with modern passive margin systems like the Mississippi, Congo, and Amazon turbidite systems [23]. In the eastern part of the outcrop belt, upper slope deposits, including submarine canyons filled with coarse clastic sediment flanked by fine-grained continental slope deposits crop out (Arnott and [24]). Toward the northwest, and over distances of hundreds of kilometers, these strata pass into slope and base-of-slope deposits populated locally by thickly developed (up to ~200 m thick) levee-channel complexes, and then sheetlike, sandstone-rich basin-floor strata in the northwest part of the outcrop belt [25]. Above the slope, facies are carbonate and siliciclastic strata that were deposited in shallow marine environments (e.g., [26]) (Figures 2 and 3).

Early studies recognized similar stratal successions of the WSG across the SCC, commonly turbiditic sandstone at the base overlying mostly by mudstone (now phyllitic or schistose) and capped by shallow-marine carbonates, and interpreted a single rift-pelite-carbonate sequence (e.g., [27]). Work by Pell and Simony [28] suggested that this succession consisted of two lithologically similar and southeastward-tapering wedges related to two discrete episodes of crustal extension. Ross (1991; see also discussion in [23]) reasserted that the succession was a single postrift stratal unit and interpreted a progressive upward change from deep basin floor to continental slope to continental shelf sedimentary rocks—a several-kilometer-scale, upward-shoaling trend interpreted to reflect the progradation of passive margin Laurentia into the developing Pacific miogeoclone. Owing to the absence of biostratigraphic control and only poor

![Figure 2: Stratigraphy of the Windermere Supergroup in the southern Canadian Cordillera ([30]; and references therein).](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/doi/10.2113/2021/8356327/5450477/8356327.pdf)
geochronological control, the occurrence of a distinctive marker unit, termed the Old Fort Point Formation (OFP), is central to this interpretation. Originally described by Charlesworth et al. [29] from the Jasper area in the Rocky Mountains of west-central Alberta, the lithologically and geochemically distinctive OFP was shown by Smith et al. [30], and interpreted time equivalent strata in the northern Canadian Cordillera [31], to form a single stratigraphic marker that traces-out the continent-margin clinoform marking the western margin of northern Laurentia, confirming the single wedge interpretation of Ross [2]. Moreover, a Re-Os date of 607.8 ± 4.7 Ma [32] from black shales in the Geike Siding Member provides a direct date for the OFP marker and is the only radiometric date within the postrift sedimentary pile.

A second, but less definitive, age constraint from the postrift succession is provided by Cochrane et al. [33], who suggest that an almost 200-thick mixed carbonate-siliciclastic succession with stable isotope values as low as −6.6‰ in the Isaac Formation represents deposition immediately preceding the onset of the 580 Ma Gaskiers glaciation [34]. More recently, Canfield et al. [35] correlated this same succession with the younger (571-562 Ma) Shuram-Wonoka anomaly—the deepest and longest carbon isotope anomaly in geological history [36]. However, as pointed out below, similar-aged volcanic rocks occur >3 km above this succession and also above the unconformity that caps the Windermere Supergroup, which makes this correlation problematic (see next).

In southeastern British Columbia (B.C.), the WSG is overlain unconformably by an intercalated assemblage of sedimentary and volcanic rocks of the Hamill Group with a U-Pb zircon date of 569.6 ± 5.3 Ma [8]. The upper Windermere Supergroup in the SCC, therefore, is older than ca. 570 Ma. Problematic then is the reported occurrence of a Cloudina-Namacalathus assemblage in carbonate rocks of the Byng Formation in the Jasper area [37, 38], which according to Mountjoy [39] immediately underlies the unconformity at the top of the WSG. Although examples of Cloudina have been reported in rocks as old as 620-590 Ma [40, 41], the Cloudina-Namacalathus assemblage has only been reported from ~550-541 Ma rocks (e.g., [42, 43]), which then postdate volcanic rocks in the Hamill Group. The Byng Formation was assigned to the Windermere Supergroup before U-Pb geochronological data from the Hamill Group were available and therefore its assignment to the Windermere Supergroup should be reassessed, with the possibility that the Byng Formation may instead be part of the Hamill Group, and is in turn overlain unconformably by Cambrian rocks of the Gog and McNaughton groups (e.g., [13, 14]). This sub-Cambrian unconformity is related to at least a second episode of extensional tectonism, which, with accompanying subsidence, initiated the economically important Western Canada Sedimentary Basin (e.g., [44]).

Transverse faults that are coeval with deposition of the Windermere Supergroup are recognized in the SCC, such as the St Mary—Moyie fault zone near the Canada-U.S. border that demarcates the southern limit of the deep marine outcrop belt [45]. Moreover, profound facies changes within the Windermere Supergroup occur across other transverse faults in the SCC providing further evidence of syn-depositional fault activity [46, 47]. At a continental scale, the SW-NE faults are interpreted as initial rift and then continental margin segments with transform boundaries that separated upper and lower divergent plate boundaries (e.g., [1]).

2. Detrital Zircon U-Pb Methods and Results

Locations for 19 detrital zircon samples are shown in Figure 1, and the sample list is shown in Table 1 (18 are sandstone and 17-NJC-2 is sandstone matrix in conglomerate). Detrital zircon was separated using standard separation techniques, and isotopic signal intensities were measured for
300 grains per sample by LA-ICP-MS. Analytical methods are described in Matthews and Guest [48] and are expanded upon in the Supplementary methods and results file (available here). Preferred ages are \(^{206}\text{Pb}/^{238}\text{U}\) for dates <1500 Ma and \(^{207}\text{Pb}/^{206}\text{Pb}\) for dates >1500 Ma. Measurements with <5% probability of concordance were filtered from the dataset. A total of 5697 U-Pb analyses of detrital zircon grains yielded 2096 dates that passed our filtering criteria (Table DR1). Poor analytical efficiency (average \(n = 110\)) is the result of widespread recent Pb-loss (Table S1, Figures S1-2) that affected most of the samples (see supplementary information for further discussion (available here)), and it is for this reason that we used the restrictive <5% probability of concordance filter. U-Pb detrital zircon age distributions generally group into two sample sets that correspond to the syn-rift and post-rift sub-divisions of Ross [2] (Figure 4).

The syn-rift sample set \((N = 2)\) of the Toby Formation yields dates between 1.9 and 1.0 Ga with modes at ~1.75, 1.43, and 1.25 to 1.1 Ga. Archean grains are uncommon (<3%). The post-rift sample set \((N = 17)\) exhibits a bimodal distribution consisting of a diverse array of Archean fractions between 3.5 and 2.5 Ga and a prominent late Paleoproterozoic fraction between 1.9 and 1.75 Ga. Minor Mesoproterozoic fractions at 1.43 Ga and 1.12 Ga occur in most samples. An atypical sample has prominent early Paleoproterozoic detrital zircon fractions (modes at approximately 2.3, 2.1, and 1.9 Ga), variably present throughout the sample but only dominant in sample 19-CCK-IS-2. A 25% fraction of grains in sample 17-JSP-1 yields a weighted average age of 665.8 ± 9.7 Ma (total uncertainty; CI 95%; MSWD 2.2; 2 of 26 grains rejected) and a maximum depositional age (MDA) of 652.2 ± 8.9 Ma (Figure S4) (YGC2; [49, 50]).

3. Discussion

3.1. Syn-Rift Provenance. The syn-rift sample set has a detrital zircon signature with prominent 1.5-1.0 Ga age probability that is a characteristic of sequence B strata and also consistent with 1.4-1.0 Ga detrital zircon from e.g., syn-rift deposits of the Windermere Supergroup associated with the Gataga volcanics to the north ([20]; Figure 1). Considering the restricted detrital zircon age signature in conjunction with the depositional setting and the many coarse and angular clasts derived from the underlying strata [45] suggests that sedimentary provenance was probably local. The local source is likely from erosion of the unconformity bounded strata at the top of the Purcell Supergroup in the SCC that Root [51] considers to be part of Proterozoic sequence B. Such lower Neoproterozoic strata would correlate to those above the Belt Supergroup in the northwestern U.S., such as the Buffalo Hump Formation, that are dominated by Mesoproterozoic detrital zircon [9, 52, 53].

3.2. Post-Rift Continental Margin Provenance. Post-rift samples from all stratigraphic units hosting basin floor and continental slope deposits (Kaza, Miette, and Horsethief Creek groups and the Isaac Formation) (Figures 2, 3, and 4), at all sampling locations in Figure 1, produced the bimodal “archetype” detrital zircon signature that is so characteristic of northwestern Laurentia (e.g., [12]) (Figure 4). These results are compared to detrital zircon spectra of the Belt-Purcell Supergroup because the Windermere Supergroup unconformably overlies the Belt-Purcell Supergroup so sedimentary recycling of detrital zircon should be considered, and the Belt-Purcell Supergroup is a proxy for sampling of basement rocks by a large sedimentary system.
during the Mesoproterozoic. Detrital zircon age distributions of the Belt-Purcell Supergroup indicate three main source areas [9, 10, 54, 55]: (1) a since-displaced western craton (1.6-1.5 Ga), (2) Laurentian basement from the western U.S. (<1.7 Ga), and (3) the Laurentian craton mainly from western Canada (prominent 1.95-1.75 Ga). The southern and northwestern areas of the Belt Basin have detrital zircon age ranges that are younger than those in the post-rift Windermere (Figure 4), eliminating the southern Belt Basin, the western U.S., and the western craton as source areas. Samples from the northeastern Belt Basin with U-Pb detrital zircon age probabilities that overlap with the postrift Windermere sample set identify a potential proximate source of recycled zircon and further support provenance from 1.9-1.8 Ga orogens of the northwestern Laurentian craton (Figure 1). In summary, the main provenance for the post-rift continental margin system is (1) recycling of the potential eastern extent of the Belt Basin over the craton, since eroded, and (2) ultimately the Laurentian craton of western Canada.

In addition to the typical bimodal distribution of the postrift assemblage, one sample from slope channel deposits of the Miette Group at the Jasper locality (Figure 1; 17-JSP-1) yielded a significant number (26) of Neoproterozoic grains with a mean age of 665.8 ± 9.7 Ma (Figure 3). Prior to this result, grains of this age had only been reported from Cambrian strata and were inferred to have been recycled from the Windermere Supergroup [12, 22]. This sample confirms a pulse of igneous activity in the Windermere Basin between ca. 676 and 656 Ma and indicates that submarine fan sedimentation is younger than the MDA of 652.2 ± 8.9 Ma.

3.3. Basin Tectonics. The extreme magnitude of subsidence to plunge a continental setting to depths forming a large basin-floor and slope turbidite system, overlain by a topset of shelf deposits, is the hallmark for initiation of a passive continental margin (e.g., [56]). In terms of reconstructing the Neoproterozoic-early Paleozoic passive margin of western Laurentia, the Windermere Basin is one of the few places where the scale of subsidence that occurs after breakup is well displayed, even so it was underlain by continental crust, and has been translated eastward by over 100 km during the Cretaceous (e.g., [46]). The syn-rift Irene volcanics remain undated but likely correlate with ca. 700-680 Ma volcanic rocks reported elsewhere (see above). A later pulse of magmatism at ~670-640 Ma is reported from the western US and northwestern Canada [57, 58]. Data here confirm that slope channel deposits locally contain sediment from a ca. 676-656 Ma igneous source and are younger than 652.2 ± 8.9 Ma, and we speculate that the timing of breakup and rapid continental margin subsidence was approximately 650 Ma. Post-rift subsidence resulted in the deposition of submarine fans, with at least one matching the scale of
present-day passive margin turbidite systems [23], and then the fan-slope-shelf system prograded to build much of the continental shelf prior to 570 Ma.

The southern limit of this well preserved continent-margin wedge coincides with a transverse structural zone that separated segments of the western North American passive margin [1, 46]. Lis and Price [45] recorded 9 km of Windermere strata, including boulder conglomerate with Purcell Supergroup clasts, on the north side of the approximately east-west-trending St. Mary Fault in southeast B.C. (Figure 1), but Lower Cambrian overlying Purcell Supergroup strata on its south side. South of the fault zone, in the northwestern U.S., strata of the Windermere Supergroup were deposited within rift basins and continental breakup either occurred after deposition of the Windermere Supergroup or the rifted margin lay farther to the west (see discussion, [1, 4]). Accordingly, the St. Mary-Myokie fault zone could mark the southern edge of the newly formed continental margin associated with the Windermere Supergroup in the SCC, or the margin simply stepped westward to the south.

To the north of the SCC, continental margin strata of the Windermere Supergroup extend into northern BC and the southern Yukon (Figure 1). The basement of Yukon Tanana terrane includes the Snowcap Assemblage with 2.0-1.8 Ga detrital zircon typical of the Laurentian craton [59], and in Alaska the equivalent metasedimentary basement has the same detrital zircon character [60] (Figure 4). Those studies suggest that the continental margin associated with the Windermere Supergroup may have extended northward.

4. Conclusion

Previous work has shown that the Windermere Supergroup in the southern Canadian Cordillera has the scale and depositional architecture of a passive continental margin, for which the basal rift deposits are younger than ~730 Ma, and topset shelf facies are older than 570 Ma. Our U-Pb detrital zircon analysis indicates that the detrital zircon provenance of two syn-rift samples is interpreted as local recycling from remnants of Neoproterozoic Sequence B strata. Detrital zircon samples of the post-rift assemblage of basin-floor and slope facies (17) yielded 1724 U-Pb ages that are dominated by 1950-1750 Ma age probability peaks suggesting that (1) there was no sediment input from the western Belt Basin or a western craton; (2) areas far to the south of the Canada-U.S. border are unlikely source areas; and (3) the two main options for sources of detrital zircon in the Windermere Supergroup are the since eroded eastern extent of the Belt Basin as a recycled source, and the Laurentian craton of western Canada as the ultimate source. A near depositional age fraction confirms a pulse of igneous activity in the Windermere Basin at ca. 676-656 Ma and indicates that postrift slope deposition is younger than 652 ± 9 Ma. These new detrital zircon data are consistent with an incipient passive margin setting for the Windermere Supergroup in the SCC. To reconcile different tectonic settings across the Canada-U.S. border during deposition of the Windermere, the St. Mary-Myodie fault zone was likely part of a major transform boundary separating the southern edge of the rifted continental margin in western Canada from intracratonic rift basins in the western U.S.

4. Conclusion

Data Availability

The supporting data are submitted to the GSA data repository with this manuscript.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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Supplementary Materials

Supplementary materials include a data table (DR1) and a supplementary U-Pb geochronology methods and results file. Figure S1: concordia diagram for sample 17-MQ-1. Figure S2: discordance versus U concentration for rejected measurements. Table S1: upper and lower intercepts of binned measurements from 17-MQ-1. Figure S3: photomicrograph of zircon grains that yield discordant dates. Figure S4: maximum depositional age plot and concordia diagram. (Supplementary Materials)

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