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Late Paleoproterozoic terrane accretion in northwestern Canada and the case for circum-Columbian orogenesis

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ABSTRACT

The reconstruction of the paleocontinental configuration involving ancestral North America (Laurentia) at the Paleoproterozoic–Mesoproterozoic boundary has been developed in the last 30 years with different scenarios being proposed and different combinations of landmasses assembled together. However, the lack of information for the northwestern side of the North American craton has so far been an obstacle for the complete paleocontinental reconstruction and its tectonic history. Here we provide new age determinations on rocks of the Wernecke Supergroup and of the Wernecke Breccia of the Wernecke Mountains in Yukon to provide a more complete picture of the entire North American craton and its possible conterminous at 1600 Ma. The six youngest U–Pb ages of the detrital zircon from quartz sandstones of the Wernecke Supergroup suggest that the sedimentary succession is as old as 1640 Ma. Lu–Hf garnet ages on garnet bearing schists of the Fairchild Lake Group (lower Wernecke Supergroup) give a bimodal population of ages of approximately 1600 Ma and 1370 Ma: the first age is related to the Racklan Orogeny, and the younger event is likely attributable to a reheating episode (Hart River Sills emplacement). The younger age of the Wernecke Supergroup puts into question the previous model concerning the emplacement of the Bonnet Plume River Intrusions, and requires the development of a new tectonic model for the northwestern margin of Laurentia. This new model involves obduction of an exotic terrane on top of the Wernecke Supergroup during the latest phases of the Racklan Orogeny (ca. 1600 Ma). This exotic terrane, herein called Bonnetia, contains rocks of the Bonnet Plume River intrusions and of the Slab volcanics. During the hydrothermal event that led to the emplacement of the Wernecke Breccia, clasts and megaclasts of the overlying Bonnetia foundered down to the breccia pipes to the level of the Wernecke Supergroup, and this dynamic explains the existence of older rocks engulfed within a younger sedimentary succession. The Racklan Orogeny is now interpreted as a northwestern expression of the Mazatzal Orogeny of southwestern United States, and of the Labradorian Orogeny of eastern Canada which was in turn connected with the Gothian Orogeny of Scandinavia. The connection among these orogenic events makes plausible the hypothesis of a circum-Laurentian orogenic belt with possible extensions in other landmasses (Australia, Antarctica, Siberia, or China) where coeval deformation belts are present.

1. Introduction

The ancestral North American continent (Laurentia) resulted from the assembly of Archean to Early Proterozoic microcontinents between 2.0 Ga and 1.8 Ga, with the formation of collisional and magmatic orogenic belts within the evolving craton (Hoffman, 1989; Davidson, 2008; Whitmeyer and Karlstrom, 2007). This assembly was likely part of a broader continental amalgamation that involved other landmasses such as Australia, Antarctica, Siberia, South China, Baltica, and Amazonia. The resulting Paleoproterozoic supercontinent, named Columbia (Rogers and Santosh, 2002; Zhao et al., 2002, 2004; Meert, 2012; alternatively termed Nuna by Hoffman, 1997; Reddy and Evans, 2009; and Midgardia by Johansson, 2009), continued to evolve through a range of processes including accretion, fragmentation and dispersal during the interval 1.8–1.3 Ga (prior to the assembly of Rodinia, 1.2–0.9 Ga).

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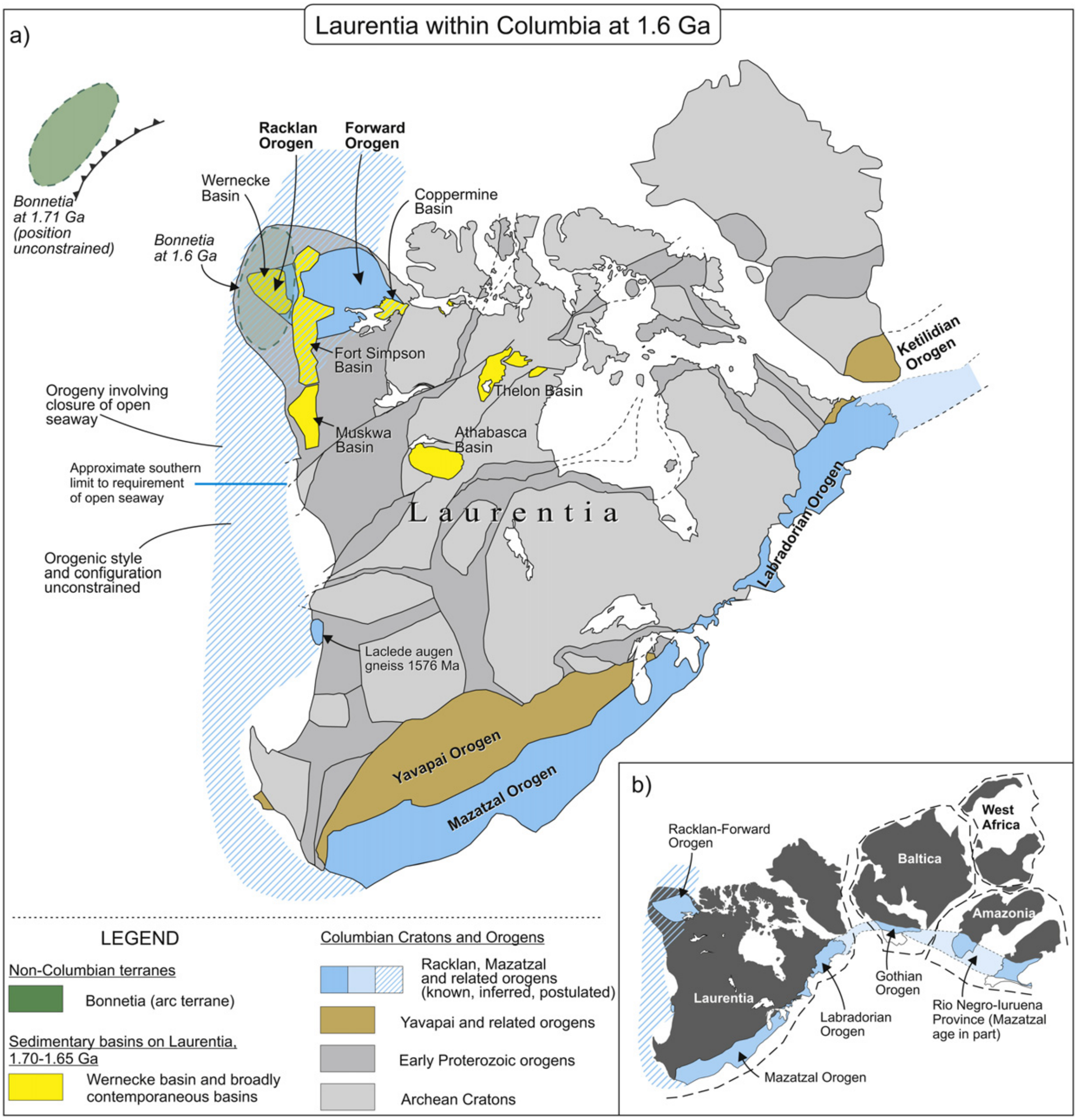

Fig. 1. A) Map of ancestral North American continent at 1.60 Ga, showing minimum extent of Racklan Orogen in context of regional features and correlative orogenic belts (modified from Whitmeyer and Karlstrom, 2007 and Zhao et al., 2004), and inferred location and orientation of Bonnetia through time (extension of terrane unknown); b) map of Laurentia and adjacent landmasses at ∼1.60 Ga, showing extension of Mazatzal-age orogens and inferred continuation to the west of North America.

Between 1.7 Ga and 1.5 Ga, a sinuous orogenic belt extended for thousands of kilometres along the southern and eastern margins of Columbia (present coordinates; Fig. 1). The Mazatzal Orogeny in southern Laurentia is perhaps the best-known segment of this orogenic belt (Condie, 1992; Karlstrom et al., 2001) and appears to have been connected with the Labradorian, Gothian and Quatro Cachoeiras (Rio Negro-Iuruena province) orogenies, linking Laurentia to Baltica and Amazonia (Ahall and Gower, 1997; Gower et al., 1992; Johansson, 2009; Ketchum et al., 2002; Santos et al., 2008). In contrast, the possible continuation of the Mazatzal Orogeny, and its precursor, the Yavapai Orogeny, to the west of Laurentia is not well understood. Indeed, candidates for the conjugate landmass that may have lain to the west of Laurentia range from domains in Australia to those in Antarctica, Siberia and South China (Sears and Price, 1978; Thorkelson et al., 2001a; Ross et al., 1992; Betts et al., 2008; Payne et al., 2009; Li et al., 2008a).

Although the identity of the conjugate landmass(es) and the nature of interactions with Laurentia remain uncertain, some fundamental tenets can be established. First, the Paleoproterozoic orogenic grain of Laurentia (Bennett and DePaolo, 1987; Hoffman, 1989; Ross, 1991) is at a high angle to the current western margin of North America. This pattern has been recognized as a truncated margin that represents the dismemberment of the western part of Columbia, or its younger counterpart Rodinia (Sears and Price, 1978, 2003; Ross et al., 1992; Colpron et al., 2002). Second, the western margin of Laurentia records a complex late Paleoproterozoic to Neoproterozoic history of tectonism, both extensional and contractional, accompanied by locally preserved records of magmatism and metamorphism (MacLean and Cook, 2004; Ross, 1991, 2002; Van Schmus et al., 1993; Aitken and McMechan, 1992; Link et al., 1993; Thorkelson et al., 2001a,b). The northern part of this margin has a particularly rich Proterozoic record (Thorkelson et al.,

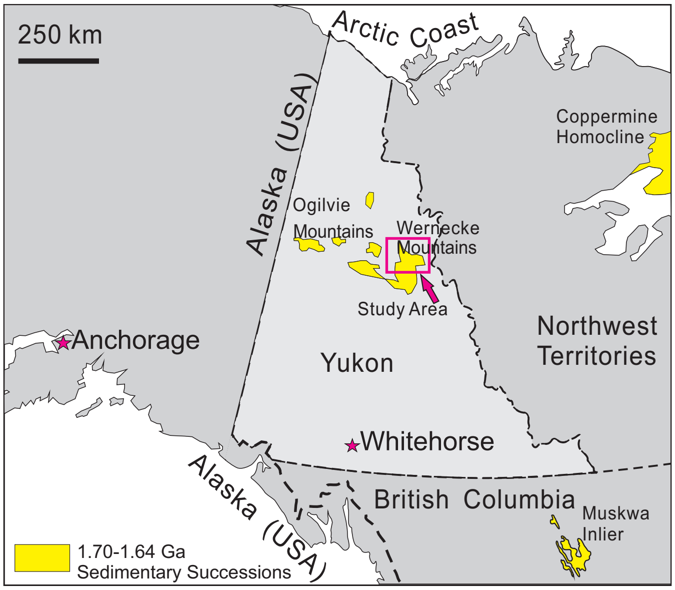

Fig. 2. Map of Yukon Territory and surrounding areas showing location of late Paleoproterozoic inliers and study area.

2005; Milidragovic et al., 2011; Hunt et al., 2011) indicating that northwestern Laurentia was inactive for some intervals, active for others, and possibly sutured to other continents for considerable durations.

In this paper we clarify the role of northwestern Laurentia in the late Paleoproterozoic and early Mesoproterozoic. We begin by re-examining the geological history of the late Paleoproterozoic Wernecke Supergroup in Yukon using existing field and analytical data plus new U–Pb detrital zircon ages, U–Pb titanite ages, Lu–Hf garnet ages, and garnet–biotite thermometry. Taken together, these data are favourably explained by a geological history involving continental separation followed by closure of an ocean basin, obduction of a landmass, and surges of hydrothermal fluids during the late Paleoproterozoic to early Mesoproterozoic. We then apply this model on a continental scale to show how contractional tectonism in northwestern Laurentia, termed the Racklan Orogeny, may have belonged to the same orogenic belt that included the Mazatzal Orogeny, and how that belt appears to have flanked much of the supercontinent Columbia.

2. Geological features, ages and relations

Five key geological components in the study area (Fig. 2) have shaped our understanding of northwestern Laurentia from late Paleoproterozoic to earliest Mesoproterozoic: (1) the Wernecke Supergroup; (2) the Racklan Orogeny; (3) the Wernecke Breccia; (4) the Slab volcanics and (5) the Bonnet Plume River Intrusions. Characterizing these elements and determining their interrelations have steadily progressed over the past 35 years (e.g., Abbott, 1997; Thorkelson et al., 2005). However, our new results require a significant revision of the geological history of the region. Below, we describe these five key components, provide new data and interpretations, and lay the groundwork for a new geological model.

2.1. Wernecke Supergroup

The Wernecke Supergroup (Delaney, 1981) belongs to sequence A of Young et al. (1979) and is the oldest unit exposed within the Proterozoic inliers of Yukon Territory (Fig. 2). It is inferred to sit on crystalline basement of the North American craton. Surface exposures indicate a thickness of ~13 km for the supergroup, although the thickness of strata that lies beneath the lowest exposures and the amount that has been eroded from the top of the succession remain unknown.

The Wernecke Supergroup comprises three conformable units: the Fairchild Lake Group (lowest unit), the Quartet Group, and the Gillespie Lake Group (highest). Lithologic units consist mainly of weakly metamorphosed siltstone, shale and sandstone, and shallow water carbonate rocks, although garnet- and chloritoid-bearing phyllite and fine-grained schist occur locally within the Fairchild Lake Group, predominantly in areas of high strain. Based on the coexistence of garnet and chloritoid, maximum temperatures were estimated to be approximately 500 °C by Brideau et al. (2002) and confirmed on the basis of our paleothermometry study, provided below. The succession is considered to have been deposited in the "Wernecke Basin" as either a deep intracratonic rift basin or a passive continental margin (Thorkelson et al., 2005). Potential correlatives proposed for the Wernecke Supergroup include the Muskwa assemblage in northern British Columbia, the Barrens Sequence of the Dubawnt Supergroup in Nunavut, the upper part of the Hornby Bay Group in the Northwest Territories, and the Athabasca Group of Saskatchewan and Alberta (MacLean and Cook, 2004; Ross et al., 2001; Rainbird and Davis, 2007; Bowring and Ross, 1985; Rainbird et al., 2006).

2.1.1. New detrital zircon ages

A detrital zircon study using a Sensitive High Resolution Ion Microprobe (SHRIMP) was conducted at the J.C. Roddick Ion Microprobe Laboratory of the Geological Survey of Canada in Ottawa. A preliminary interpretation of the results was published in Furlanetto et al. (2009a) where it is shown that the distribution of ages are similar to those of the Muskwa, Athabasca, and Thelon basins, suggesting derivation from common sediment source areas within Laurentia (cf. Rainbird and Davis, 2007; Rainbird et al., 2006).

The six youngest detrital zircon grains from the Wernecke Supergroup (Fig. 3, Table 1) are central to this paper. The interpreted ages are: 1670 ± 19 Ma, 1658 ± 17 Ma, 1646 ± 29 Ma, 1642 ± 66 Ma, 1621 ± 27 Ma, and 1610 ± 30 Ma. The ages of the grains are considered to be primary (not reset after sedimentation), and representative of mainly igneous rocks in the source region. These ages therefore indicate a maximum age for Wernecke Supergroup sedimentation of approximately 1640 Ma (mean age of the six grains taken together) because (1) peak metamorphic conditions were approximately 200 °C below the ~700 °C necessary for isotopic resetting (Rubatto et al., 2001); (2) petrography, backscattered electron and cathode luminescence studies of the zircon used in this study are consistent with unaltered and idiomorphic zircon showing no sign of chemical and structural modification such as metamictization of the grains and are therefore unlikely to have undergone low temperature (near surface) Pb-loss; (3) Th/U ratios range from 0.6 to 1.7 which fall within typical igneous values of >0.1 (Rubatto and Gebauer, 2000); (4) U abundances are higher than 80 ppm and are close to the igneous values of >100 ppm of Rubatto and Gebauer (2000); (5) multiple analyses for each grain analysed give consistent ages.

2.2. Racklan Orogeny

The Racklan Orogeny is a pre-1.60 Ga deformational and metamorphic event that affected the Wernecke Supergroup (Thorkelson et al., 2000; Brideau et al., 2002; Thorkelson et al., 2005; Laughton et al., 2005). First-generation structures include tightly overturned, east-verging folds, slaty cleavage and schistose fabric. The schistose rocks display metamorphic assemblages typical of greenschist facies dominated by quartz, chlorite, muscovite, opaques, chloritoid, biotite and garnet. Second-generation structures include younger, inclined to overturned south-verging folds, crenulations

Table 1

Sample number and location	Spot name	U (ppm)	Th (ppm)	Th/U	^{206}Pb* (ppm)	^{204}Pb/^{206}Pb	±	f(206)^{204} (%)	^{208}Pb*/^{206}Pb*	±	^{207}Pb*/^{235}U	±	^{206}Pb*/^{238}U	±	Corr. Coeff.	^{207}Pb*/^{206}Pb*	±	Apparent ages (Ma)				
																		^{206}Pb/^{238}U	±^{206}Pb/^{238}U	^{207}Pb/^{206}Pb	±^{207}Pb/^{206}Pb	Disc. (%)
FF-07-1-4-1 Fairchild Lake Group Wernecke Mountains	9560-32.1	463	704	1.57	178	0.000016	0.000014	0.03%	0.463	0.008	4.024	0.067	0.2853	0.0042	0.9284	0.10231	0.00063	1618	21	1666	12	2.9
	9560-32.2	174	176	1.04	55	0.000069	0.000073	0.12%	0.285	0.010	3.720	0.106	0.2664	0.0049	0.7291	0.10128	0.00199	1522	25	1648	37	7.6
	9560-32.2.2	156	156	1.03	49	0.000033	0.000030	0.06%	0.293	0.005	3.695	0.093	0.2616	0.0056	0.9102	0.10245	0.00107	1498	29	1669	19	10.3
	9560-32.2.3	132	129	1.01	41	0.000010	0.000010	0.02%	0.287	0.005	3.525	0.108	0.2563	0.0063	0.8633	0.09975	0.00156	1471	32	1619	29	9.2
	9560-32.2.4	116	111	0.99	34	0.000088	0.000074	0.15%	0.282	0.007	3.385	0.110	0.2446	0.0067	0.8993	0.10037	0.00143	1411	35	1631	27	13.5
FF-07-2-5-1 Gillespie Lake Group Wernecke Mountains	9561-5.1	106	70	0.69	33	0.000088	0.000054	0.15%	0.196	0.008	3.882	0.098	0.2819	0.0050	0.7819	0.09988	0.00158	1601	25	1622	30	1.3
	9561-5.1.2	83	53	0.67	26	0.000010	0.000010	0.02%	0.185	0.005	3.933	0.114	0.2838	0.0055	0.7449	0.10053	0.00197	1610	27	1634	37	1.4
	9561-5.1.3	80	54	0.69	25	0.000022	0.000073	0.04%	0.191	0.006	3.832	0.118	0.2799	0.0065	0.8278	0.09932	0.00173	1591	33	1611	33	1.3
	9561-5.1.4	84	57	0.69	25	0.000010	0.000010	0.02%	0.187	0.012	3.741	0.094	0.2635	0.0055	0.8851	0.10299	0.00121	1508	28	1679	22	10.2
	9561-23.1	353	302	0.88	115	0.000021	0.000018	0.04%	0.252	0.003	3.954	0.078	0.2807	0.0042	0.8222	0.10214	0.00116	1595	21	1663	21	4.1
	9561-23.2	217	142	0.68	68	0.000139	0.000061	0.24%	0.180	0.004	4.048	0.100	0.2853	0.0048	0.7663	0.10292	0.00165	1618	24	1677	30	3.5
	9561-23.2.2	195	124	0.65	62	0.000038	0.000030	0.07%	0.191	0.004	4.049	0.089	0.2856	0.0044	0.7793	0.10281	0.00142	1620	22	1675	26	3.3
	9561-23.2.3	170	105	0.64	53	0.000052	0.000029	0.09%	0.176	0.004	3.963	0.085	0.2816	0.0052	0.9079	0.10205	0.00093	1600	26	1662	17	3.7
	9561-23.2.4	153	92	0.62	46	0.000050	0.000045	0.09%	0.182	0.007	3.863	0.103	0.2710	0.0060	0.8907	0.10338	0.00126	1546	31	1686	23	8.3
FF-07-4-1-1 Upper Quartet Group Wernecke Mountains	9564-90.1	157	220	1.44	56	0.000104	0.000090	0.18%	0.397	0.010	3.732	0.115	0.2739	0.0045	0.6241	0.09882	0.0024	1561	23	1602	46	2.6
	9564-90.1.2	141	196	1.43	50	0.000011	0.000051	0.02%	0.389	0.015	3.784	0.118	0.2775	0.0058	0.7555	0.09889	0.00203	1579	29	1603	39	1.5
	9564-90.1.3	131	194	1.53	46	0.000077	0.000053	0.13%	0.447	0.007	3.491	0.120	0.2618	0.0063	0.7774	0.09672	0.00212	1499	32	1562	42	4
	9564-90.1.4	151	247	1.69	53	0.000048	0.000043	0.08%	0.498	0.006	3.509	0.104	0.2547	0.0068	0.9404	0.09994	0.00102	1463	35	1623	19	9.9
	9564-114.1	179	119	0.69	55	0.000091	0.000030	0.16%	0.191	0.005	3.821	0.081	0.2777	0.0047	0.8679	0.09979	0.00106	1580	24	1620	20	2.5
	9564-114.1.2	184	104	0.58	52	0.000005	0.000036	0.01%	0.155	0.005	3.752	0.089	0.2614	0.0049	0.8519	0.10411	0.0013	1497	25	1699	23	11.9
	9564-114.1.3	162	91	0.58	46	0.000026	0.000046	0.05%	0.163	0.007	3.566	0.116	0.2596	0.0063	0.8218	0.09963	0.00186	1488	33	1617	35	8
	9564-114.1.4	148	86	0.60	42	0.000029	0.000041	0.05%	0.164	0.005	3.578	0.119	0.2603	0.0073	0.8994	0.09971	0.00146	1491	37	1619	27	7.9
	9564-3.1	344	332	1.00	115	0.000064	0.000030	0.11%	0.288	0.007	3.826	0.070	0.2797	0.0041	0.8657	0.09921	0.00092	1590	21	1609	17	1.2
	9564-3.1.2	344	341	1.02	122	0.000002	0.000015	0.00%	0.297	0.004	4.076	0.070	0.2933	0.0044	0.9275	0.1008	0.00065	1658	22	1639	12	−1.2
	9564-3.1.3	312	308	1.02	109	0.000030	0.000021	0.05%	0.308	0.009	3.942	0.079	0.2887	0.0052	0.9414	0.09903	0.00067	1635	26	1606	13	−1.8
	9564-3.1.4	288	288	1.03	97	0.000009	0.000019	0.02%	0.305	0.004	3.820	0.098	0.2775	0.0060	0.8937	0.09983	0.00116	1579	30	1621	22	2.6

Notes (see Stern, 1997):

Spot name follows the convention *x-y.z*; where *x* = sample number, *y* = grain number and *z* = spot number. Multiple analyses in an individual spot are labelled as *x-y.z.z*.

Uncertainties reported at 1 sigma and are calculated by using Prawn and Lead data reduction programs.

f206^{204} refers to mole percent of total ^{206}Pb that is due to common Pb, calculated using the ^{204}Pb-method; common Pb composition used is the surface blank (4/6: 0.05770; 7/6: 0.89500; 8/6: 2.13840).

Discordance relative to origin = 100 × ((207/206 age − 206/238 age)/(^{207}Pb/^{206}Pb age)).

Calibration standard 6266; U = 910 ppm; Age = 559 Ma; ^{206}Pb/^{238}U = 0.09059.

Error in ^{206}Pb/^{238}U calibration 1.5% (included).

[*] Refers to radiogenic Pb (corrected for common Pb).

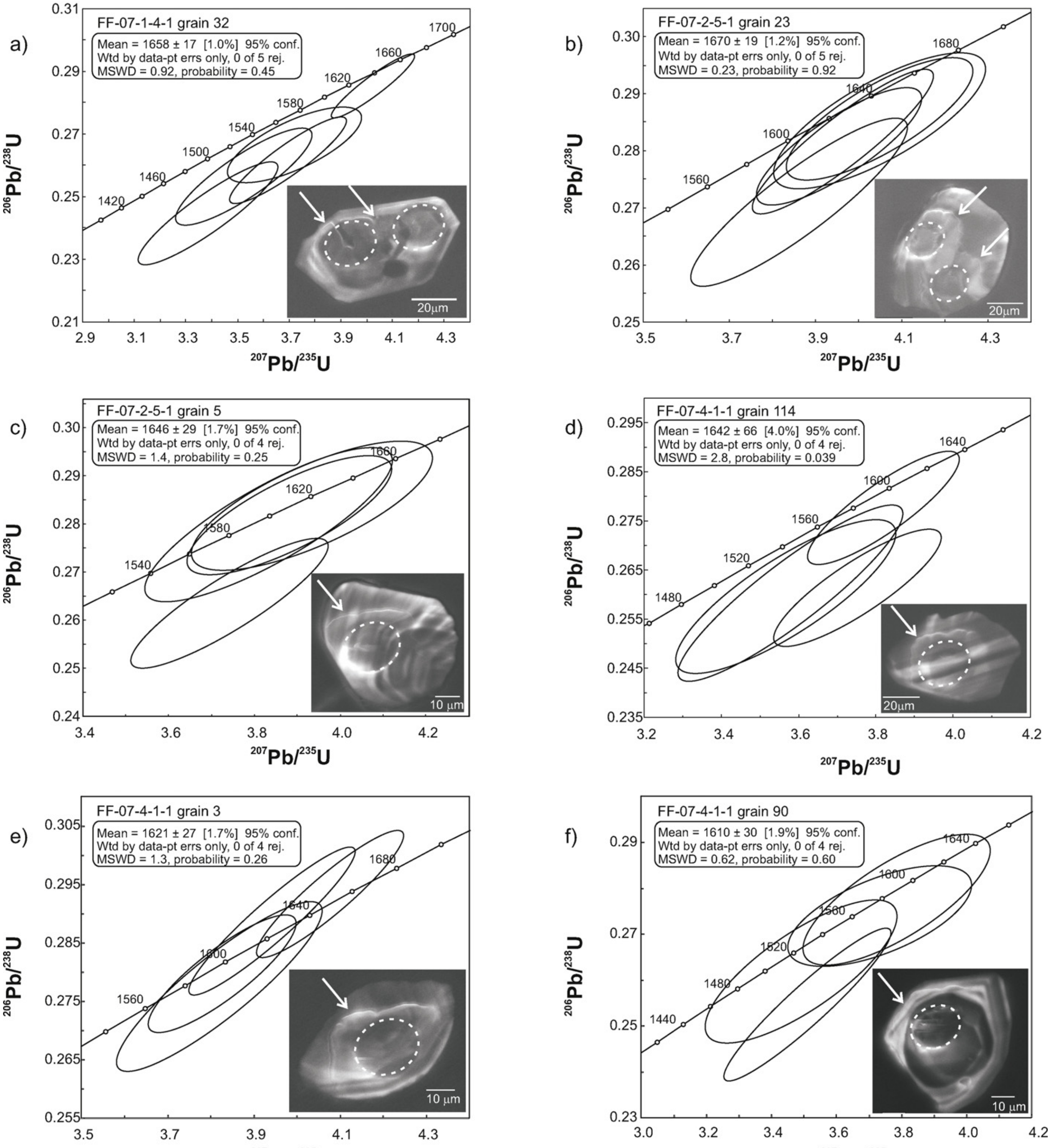

Fig. 3. Concordia plots of U–Pb dates of the six youngest detrital zircon grains analysed with the Sensitive High Resolution Ion Microprobe (SHRIMP), and associated CL images of analysed grains. Dashed ovoids delineate the analysis pits; arrows indicate the edge of the zone where the gold coating was removed prior to SHRIMP analyses. Data-point error ellipses are 2σ. Plotted with Isoplot 3.0 (Ludwig, 2003).

of the earlier foliation and kink bands, but little or no new mineral growth. These features are crosscut by the younger hydrothermal Wernecke Breccia.

The Racklan Orogeny has been interpreted as a thin-skinned deformational event that correlates with the thick-skinned contraction of the Forward Orogeny in the Northwest Territories (Cook and MacLean, 1995; Thorkelson et al., 2003). The Forward Orogeny is characterized by folds and thrust-faults that involve crystalline basement and rocks of the Hornby Bay Group, a likely correlative of the Wernecke Supergroup (MacLean and Cook, 2004). The age of the Forward Orogeny has been inferred from U–Pb TIMS isotope analyses of four zircon fractions separated from rhyolites

Table 2
Lu–Hf isotopa data for schists from the Fairchild Lake Group in the Wernecke and Richardson Mountains (Yukon).

Sample	Fraction	Lu (ppm)	Hf (ppm)	^{176}Lu/^{177}Hf	^{176}Hf/^{177}Hf	Initial ^{176}Hf/^{177}Hf	Age (Ma)
FF-07-11-2-1 Fairchild Lake Group (Wernecke Mountains)	Bomb	0.455	2.68	0.0241	0.282159 ± 4	0.28152 ± 61	1362 ± 35
	grt1	5.42	0.747	1.034	0.308336 ± 5		
	grt2	6.24	0.87	1.021	0.307566 ± 4		
	grt3	5.96	0.944	0.9001	0.304642 ± 4		
	grt4	5.64	0.722	1.114	0.310315 ± 4		
FF-07-11-3-1 Fairchild Lake Group (Wernecke Mountains)	Bomb	0.353	6.47	0.0077	0.281724 ± 4	0.28148 ± 58	1621 ± 87
	grt2	5.02	1.96	0.3652	0.292875 ± 4		
	grt5	5.28	1.96	0.383	0.293108 ± 4		
	grt6	5.29	2.04	0.3681	0.292505 ± 5		
	grt7	5.4	2.05	0.3752	0.293045 ± 4		
	grt8	5.14	1.84	0.3977	0.293894 ± 4		
DT-08-2-2-1B Fairchild Lake Group (Wernecke Mountains)	Bomb	0.3	3.66	0.0116	0.281906 ± 4	0.2814 ± 11	1593 ± 67
	grt1	5.70	0.669	1.216	0.318582 ± 4		
	grt2	5.47	0.746	1.046	0.312817 ± 5		
	grt3	5.71	1.12	0.725	0.303304 ± 5		
	grt4	5.70	0.93	0.873	0.307346 ± 3		
DT-06-3-4-2B Fairchild Lake Group (Richardson Mountains)	Bomb	0.445	4.22	0.015	0.282104 ± 4	0.28176 ± 52	1372 ± 31
	grt1	24	2.99	1.145	0.311077 ± 5		
	grt2	23.8	3.16	1.077	0.309898 ± 4		
	grt3	23.8	3.19	1.065	0.309687 ± 3		
	grt4	22.3	3.02	1.051	0.308921 ± 5		

Bomb, whole rock by bomb digestion; grt, garnet. Decay constant used for ^{176}Lu is 1.867×10^{-11} year^{-1}(Scherer et al., 2001; Söderlund et al., 2004).
Uncertainties used for age calculations are given at 95% confidence level and are based on external reproducibility of spiked standards and whole rock samples: ^{176}Lu/^{177}Hf = 0.5%, ^{176}Hf/^{177}Hf = 0.01%. Uncertainties for ^{176}Hf/^{177}Hf used in age calculations also includes within-run errors (above), added in quadrature.
Ages calculated using Isoplot 3.0 (Ludwig, 2003).

of the Narakay volcanic complex, a sequence of mafic pyroclastic rocks of 1663 ± 8 Ma age, deposited within the syntectonic Kaertok Formation (Upper Hornby Bay Group) (Bowring and Ross, 1985). Deformation of the Muskwa Assemblage is also evident but is poorly constrained in age and style (Taylor and Stott, 1973; Evenchick et al., 2005), but may correlate with the Racklan-Forward event.

2.2.1. New ages and temperatures for the Racklan Orogeny

In order to directly date the Racklan Orogeny, metamorphic garnet from four samples of the Fairchild Lake Group was analysed by the Lu–Hf isotopic method. The analytical work was carried out in the Radiogenic Isotope and Geochronology Laboratory in the School of Earth and Environmental Sciences at Washington State University. Isotopic analyses were performed on the Neptune ThermoFinnigan MC-ICPMS. Analytical methods followed Cheng et al. (2008). Fractions of garnet and whole rock (~0.25 g of weight each) were taken from four individual samples of the Fairchild Lake Group. The isotopic results are summarized in Table 2. Lu–Hf whole rock-garnet isochrons yielded the following ages: 1621 ± 87 Ma, 1593 ± 67 Ma, 1372 ± 31 Ma, and 1362 ± 35 Ma (Fig. 4). These results clearly show two events of garnet growth: one at ca. 1.60 Ga, and the other at ca. 1.37 Ga.

The garnet porphyroblasts in the ca. 1.6 Ga samples display asymmetrical pressure shadows and are interpreted to have grown pre-to-synkinematically with foliation development (Fig. 5b). The garnet in the ca. 1.37 Ga samples appears to have grown post-kinematically (Sample FF-07-11-2-1, Fig. 5a) or with uncertain timing (Sample DT-06-3-4-2B). Based on these petrographic observations, the ca. 1.6 Ga dates are interpreted as the age of Racklan Orogeny. The ca. 1.37 Ga dates appear to represent a reheating event related to the emplacement of widespread mafic intrusions of the ca. 1.38 Ga Hart River Sills (Abbott, 1997; Thorkelson et al., 2005) and possible concomitant intrusions at depth.

Peak temperatures of the metamorphic events were determined by Fe–Mg exchange thermometry using electron microprobe analyses of biotite–garnet pairs in three of the four samples that were dated using Lu–Hf geochronology. The calculated temperatures are 500–520 °C, 440–490 °C and 440–500 °C (Fig. 6). The combined temperature and age data are provided together in Table 3. Detailed description of analysis, and temperature calculations are provided in Appendix B.

Each calculated temperature is assigned an error of ±50 °C, according to Berman (1991). When considered along with plausible geothermal gradients ranging from 20–30 °C/km, the 1.6 Ga metamorphism is likely to have occurred at depths of 15–25 km at pressures of 3–6 kbar. These findings are consistent with the

Table 3
Combined age and temperature data for garnet bearing schists of the Fairchild Lake Group, Wernecke and Richardson mountains.

Sample	Location	Lu–Hf age	Grt-Bt temperature
FF-07-11-2-1	Wernecke Mountains	1362 ± 35 Ma	500–520 °C
FF-07-11-3-1	Wernecke Mountans	1621 ± 87 Ma	440–490 °C
DT-08-2-2-1B	Wernecke Mountans	1593 ± 67 Ma	440–500 °C
DT-06-3-4-2B	Richardson Mountains	1372 ± 31 Ma	NA (No biotite in the sample)

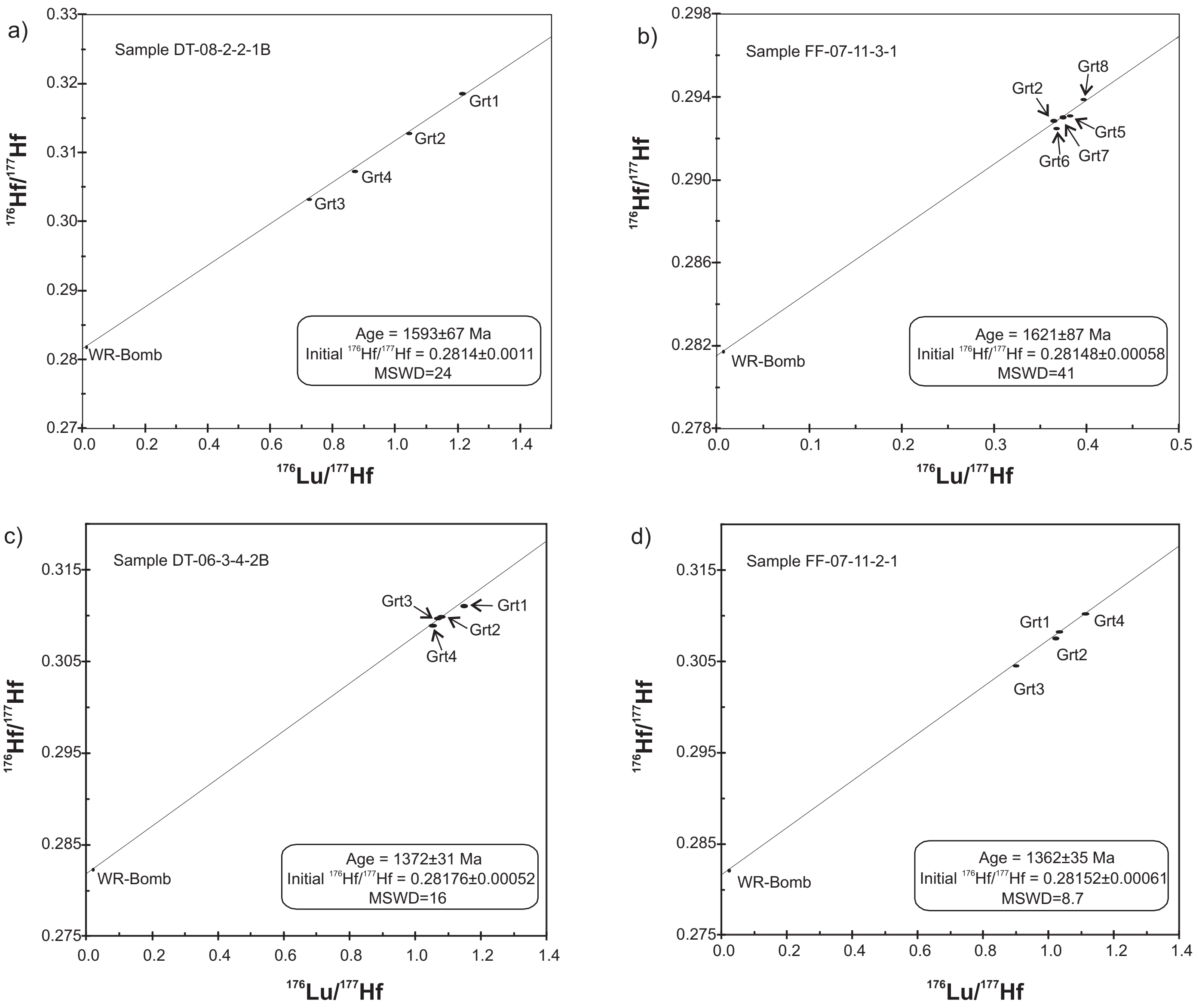

Fig. 4. Lu–Hf whole rock-garnet isochron diagrams. Lu–Hf ages were calculated using ^{176}Lu decay constant value of 1.867×10^{-11}. Isochrons plotted with Isoplot 3.0 (Ludwig, 2003) with errors at the 95% confidence interval. WR-Bomb: whole rock fraction by bomb digestion, Grt: garnet fraction.

metamorphic mineral assemblage which indicates middle greenschist metamorphic conditions. The 1.37 Ga metamorphism may have occurred in the proximity of Hart River sills or related intrusions beneath the area of exposure.

2.3. Wernecke Breccia

The Wernecke Breccia consists of numerous zones of hydrothermal breccias with variably metasomatized angular to subangular clasts in a hydrothermally precipitated matrix (Thorkelson et al., 2001b). The matrix is variable but common minerals include quartz, carbonate, chlorite, muscovite, biotite, microcline, albite, hematite and magnetite. These breccias are scattered over much of central to northern Yukon over an area of approximately 48 000 km^2. They typically crop out with irregular shapes, in sizes up to hundreds of meters in width and 5 km in length and crosscut the main foliation, folds, crenulations, and at least some of the kink bands in the Wernecke Supergroup. Many of the breccia zones are polygenetic, and some contain rounded clasts that suggest clast abrasion and milling during surges of fluid activity. The breccias are of economic interest as many of them host iron oxide–copper–gold occurrences (Hunt et al., 2005). Stable isotope and fluid inclusion studies indicate that the exposed parts of the breccia zones developed at depths of 5–10 km (Hunt et al., 2005, 2011). The source of the breccia-causing fluids is uncertain and concurrent igneous activity in this area has not been identified (Hunt et al., 2007).

Clasts and megaclasts in the Wernecke Breccia are mainly derived from the host Wernecke Supergroup. However, igneous clasts also occur in the form of fine- to medium-grained plutonic rocks (mainly diorite) of the Bonnet Plume River Intrusions (Thorkelson et al., 2001a; Nielsen et al., 2011) and of the Slab volcanics (Laughton et al., 2005). These igneous bodies were considered to be endemic to the Laurentian continent. For reasons which we develop later in this paper, they are now considered to belong to an exotic terrane which was obducted onto the Laurentian continental margin during the final phase of Racklan Orogeny.

Thorkelson et al. (2001b) obtained a 1595 ± 5 Ma U–Pb date from multigrain titanite fractions from the matrix of Wernecke Breccia. The age and metallogenetic character of the Wernecke Breccia is similar to those of breccias in Australia, including the

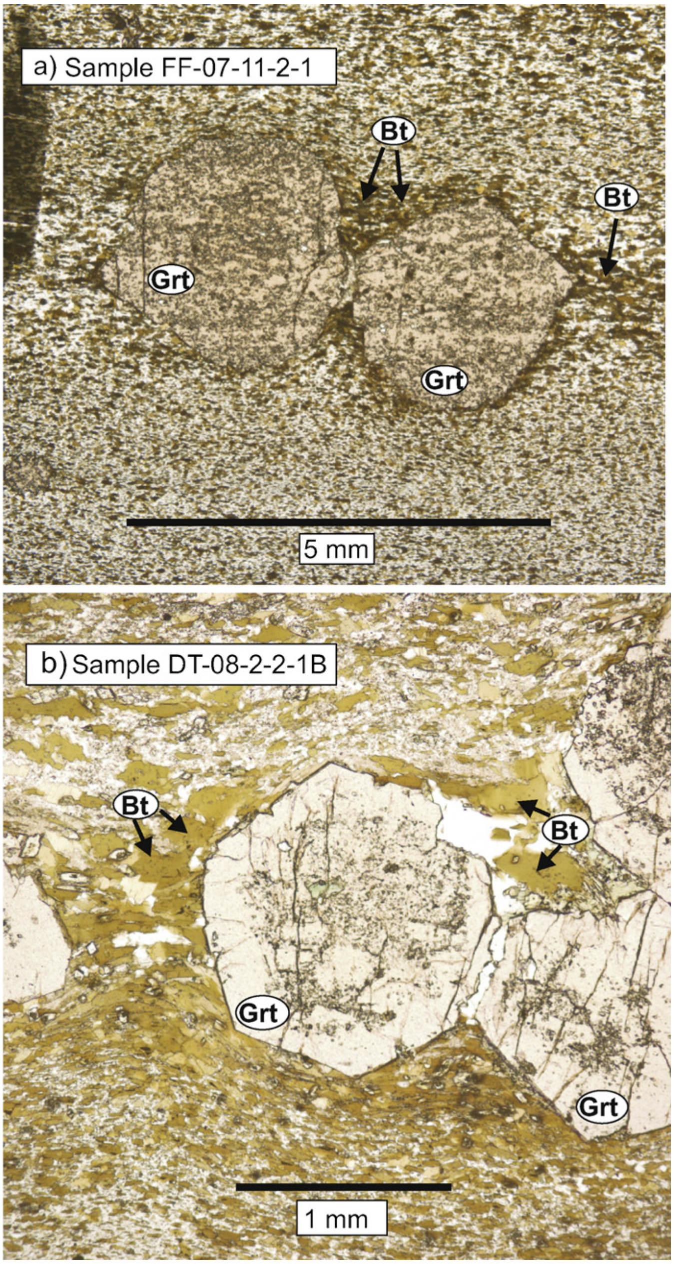

Fig. 5. Transmitted light plane-polarized images of a) syn-to-postkinematic garnets from sample FF-07-11-2-1, and b) pre-to-synkinematic garnets from sample DT-08-2-2-1B. Bt = biotite, Grt = garnet. White groundmass composed mainly of quartz and feldspar. In a) note the consistency in fabric between the matrix and within the garnet with only minor deflection of a few biotite grains around the garnet indicating the garnet growth syn to post metamorphic peak.

host rocks to the Olympic Dam mine in South Australia. These similarities provide evidence for a common hydrothermal province (Thorkelson et al., 2001b) and support speculations that the eastern parts of Australia and northwestern ancestral North America were parts of the same landmass (Columbia) in the early Mesoproterozoic (Bell and Jefferson, 1987; Thorkelson et al., 2001b; Betts et al., 2011).

2.3.1. New U–Pb titanite age

New U–Pb dates were obtained by the isotope dilution thermal ionization mass spectrometry method at Boise State University from single grains and fragments of titanite grains from the same Wernecke breccia dated by Thorkelson et al. (2001b) with the goal of obtaining a more precise age (Table 4, Fig. 7; Appendix B). Prior to dating, some of these grains were imaged with backscattered electrons. The new dates are considerably more precise than the previous ones although still slightly discordant (discordance ranges from 0.6 to 2.6%). The discordance appears to have been caused by multiple periods of Pb-loss or new titanite growth. The $^{207}Pb/^{206}Pb$ date of the oldest analysis (t8a) that is close to concordia (0.6% discordant) is 1598.8 ± 1.0 Ma. We interpret this date as a minimum age, and the true age is probably not much older given the small amount of discordance. The error on this analysis is the 2σ internal error based on analytical uncertainties only. This error should be considered when comparing our date with dates from other laboratories that used the same EARTHTIME tracer solution or a tracer solution that was cross-calibrated using EARTHTIME gravimetric standards. When comparing our date with those derived from other decay schemes (e.g., $^{40}Ar/^{39}Ar$, $^{187}Re–^{187}Os$), systematic uncertainties in the tracer calibration (0.10% 2σ) and U decay constants (0.11%, 2σ, Jaffey et al., 1971) should be added to the internal error in quadrature.

2.4. Slab Volcanics

The Slab volcanics consist of subaerial basaltic pahoehoe lava flows with minor intercalations of sandstone and volcanic breccia (Laughton et al., 2002, 2005). The volcanics are preserved only as clasts and megaclasts within the Wernecke Breccia (Thorkelson et al., 2000). The largest exposure is a block 160 m wide and 380 m long, located on Slab Mountain (informal name). The block consists of 34 lava flows that range in thickness from 0.8 m to 14 m (Laughton et al., 2002). At that locality, the zone of Wernecke Breccia that encloses the volcanic block is hosted by chloritoid-bearing schist of the Wernecke Supergroup.

The igneous mineral assemblage is uncertain because the basalt has been completely recrystallized into secondary minerals, mainly biotite and scapolite. The flows are variably amygdaloidal, with fillings of quartz, calcite, tremolite, biotite, chlorite and apatite. These mineral assemblages may have been generated during Wernecke Breccia-related metasomatism. However, the only age determination on the volcanics is a U–Pb rutile date at 1.38 Ga (Thorkelson et al., 2005) which implies a second event of heating and fluid circulation, likely related to emplacement of the Hart River Sills (Thorkelson et al., 2005). The geochemical composition of the Slab volcanics has affinities to both volcanic arcs and mantle plumes. The schistose fabric is crosscut by the breccia zone, and is not expressed in the clasts of the Slab volcanics.

2.5. Bonnet Plume River Intrusions

The Bonnet Plume River Intrusions consist of dominantly diorite and gabbro with minor quartz–albite syenite and microanorthosite. They occur as clasts and megaclasts in the Wernecke Breccia in the Wernecke, Ogilvie and Richardson mountains. The largest clast measures 200 × 900 × 30 m (Nielsen, 2011). The intrusions were originally thought to intrude the Wernecke Supergroup (Thorkelson et al., 2001a) but more recent work indicates that these igneous bodies were emplaced by hydrothermal fragmentation into zones of Wernecke Breccia (Nielsen et al., 2011).

The Bonnet Plume River Intrusions have been altered by the breccia fluids as evidenced by veining, fragmentation, chloritization and epidotization. Nevertheless, geochemical patterns, including a modest Nb–Ti negative anomaly, are surprisingly consistent and favour an origin in a calc-alkaline arc to back-arc environment (Nielsen, 2011). Major and trace element patterns of the Bonnet Plume River Intrusions are broadly similar to those of the Slab volcanics, although the latter are more alkaline and appear to contain

Table 4
U–Th–Pb isotopic data.

Sample (a)	Th/U (b)	^{206}Pb* × 10^{-13} (c)	Mol% ^{206}Pb* (c)	Pb*/Pb$_c$ (c)	Pb$_c$ (pg) (c)	^{206}Pb/^{204}Pb (d)	Radiogenic isotope ratios							
							^{208}Pb/^{206}Pb (e)	^{207}Pb/^{206}Pb (e)	% err (f)	^{207}Pb/^{235}U (e)	%err (f)	^{206}Pb/^{238}U (e)	%err (f)	Corr. Coef.
DT-08-2-1-1B														
t1	1.024	12.7752	99.77%	148	2.51	7309	0.302	0.098295	0.011	3.774770	0.025	0.278522	0.021	0.895
t2	0.947	10.6971	99.35%	50	6.14	2482	0.282	0.098159	0.018	3.688509	0.031	0.272534	0.025	0.801
t3	0.968	5.6187	99.38%	53	3.04	2649	0.290	0.097424	0.025	3.611812	0.038	0.268879	0.027	0.759
t4	1.261	5.5284	99.66%	104	1.62	4949	0.376	0.097175	0.022	3.619711	0.035	0.270157	0.023	0.780
t5	1.184	6.4148	99.74%	133	1.44	6448	0.351	0.097419	0.031	3.681366	0.042	0.274072	0.027	0.665
t6	0.872	3.5227	99.48%	62	1.59	3224	0.261	0.096340	0.037	3.517748	0.051	0.264823	0.028	0.695
t7a	1.081	0.7739	98.72%	27	0.85	1367	0.322	0.096896	0.107	3.605345	0.159	0.269861	0.095	0.759
t7c	0.940	0.5814	98.78%	28	0.60	1492	0.279	0.097903	0.139	3.696452	0.207	0.273833	0.125	0.753
t8a	**0.894**	**1.5704**	**99.41%**	**56**	**0.79**	**2960**	**0.264**	**0.098652**	**0.055**	**3.802981**	**0.084**	**0.279588**	**0.053**	**0.766**
t8b	0.834	1.1093	98.51%	21	1.45	1127	0.247	0.098371	0.086	3.764256	0.120	0.277529	0.071	0.706
t8c	0.779	0.3783	98.53%	22	0.46	1264	0.232	0.098579	0.201	3.748081	0.316	0.275755	0.208	0.782

Isotopic ages						
^{207}Pb/^{206}Pb (g)	± (f)	^{207}Pb/^{235}U (g)	± (f)	^{206}Pb/^{238}U (g)	± (f)	Disc. (%) (h)
DT-08-2-1-1B						
1592.02	0.21	1587.39	0.20	1583.92	0.29	0.51
1589.44	0.34	1568.88	0.25	1553.65	0.34	2.25
1575.39	0.47	1552.14	0.30	1535.11	0.37	2.56
1570.60	0.41	1553.87	0.28	1541.60	0.32	1.85
1575.29	0.59	1567.34	0.33	1561.44	0.38	0.88
1554.42	0.69	1531.21	0.40	1514.47	0.38	2.57
1565.21	2.00	1550.71	1.26	1540.09	1.31	1.60
1584.57	2.61	1570.60	1.65	1560.23	1.73	1.54
1598.79	**1.03**	**1593.38**	**0.68**	**1589.29**	**0.75**	**0.59**
1593.48	1.60	1585.16	0.96	1578.91	1.00	0.91
1597.42	3.75	1581.70	2.53	1569.95	2.90	1.72

(a) t1, t2 etc. are labels for fractions composed of single titanite grains or fragments. Letters a, b, c following a number represent fragments from the same grain.
(b) Model Th/U ratio calculated from radiogenic ^{208}Pb/^{206}Pb ratio and ^{207}Pb/^{235}U date.
(c) Pb* and Pb$_c$ are radiogenic and common Pb, respectively. mol% ^{206}Pb* is with respect to radiogenic and blank Pb.
(d) Measured ratio corrected for tracer solution and fractionation only.
(e) Corrected for fractionation, tracer solution, and common Pb; up to 0.5 pg of common Pb was assumed to be procedural blank: ^{206}Pb/^{204}Pb = 18.60 ± 0.80%; ^{207}Pb/^{204}Pb = 15.69 ± 0.32%; ^{208}Pb/^{204}Pb = 38.51 ± 0.74% (all uncertainties 1σ). Excess over blank was assigned to initial common Pb. ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ratios corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.
(f) Errors are 2σ, propagated using algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(g) Calculations based on the decay constants of Jaffey et al. (1971). ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb dates corrected for initial disequilibrium in ^{230}Th/^{238}U using Th/U [magma] = 3.
(h) Disc. = discordance = 100 − (100 × (^{206}Pb/^{238}U age)/(^{207}Pb/^{206}Pb age)).

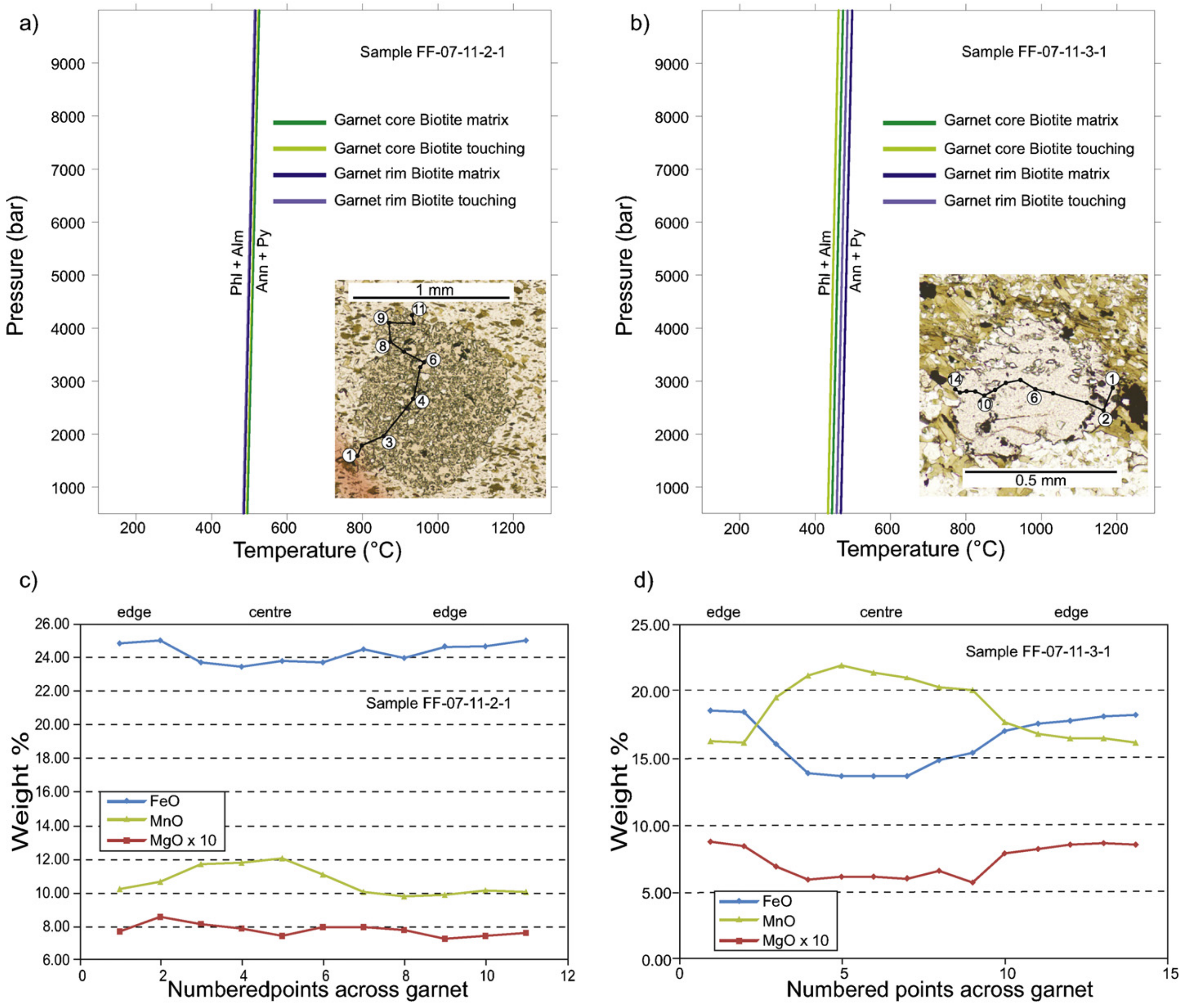

Fig. 6. Temperature diagrams with combined transmitted light images, and rim-to-rim major-element compositional zoning profiles of representative garnet from analysed samples FF-07-11-2-1 and FF-07-11-3-1.

a mantle plume geochemical component (Laughton et al., 2005; Nielsen, 2011).

U–Pb ID-TIMS zircon ages on four samples of the Bonnet Plume River Intrusions average 1710 Ma, with the two most precise ages at 1709.0 ± 1.4 Ma and 1705.9 ± 2.0 Ma (Thorkelson et al., 2001a).

3. Northwest Laurentia and terrane obduction

3.1. Previous model

Previous depictions of the northwestern margin of Laurentia during the late Paleoproterozoic and early Mesoproterozoic were provided by Thorkelson et al. (2000), Laughton et al. (2005), and Hunt et al. (2007). These authors based their models on the understanding that the Bonnet Plume River Intrusions intruded the Wernecke Supergroup prior to their incorporation into the Wernecke Breccia, and the assumption that all of the Proterozoic geological units under consideration were deposited on or emplaced within Laurentia. In these models, the Wernecke Supergroup was deposited on Laurentia prior to 1.71 Ga at which time the Bonnet Plume River Intrusions crystallized within the Wernecke Supergroup. After deposition, the Wernecke Supergroup was deformed, metamorphosed, uplifted, and eroded during Racklan Orogeny. This orogenic event was responsible for the denudation of structural culminations within the deformed sedimentary succession, resulting in localized exposure of the Fairchild Lake Group (Brideau et al., 2002). Eruption of pahoehoe lava flows (Slab volcanics) at the surface may have occurred at this time, or shortly thereafter. At 1.60 Ga a massive surge of hydrothermal fluids invaded the crust, leading to fragmentation of the Wernecke Supergroup, the Slab volcanics and the Bonnet Plume River Intrusions, and formation of Wernecke Breccia. Given the spatial coincidence of the Wernecke Breccia and Bonnet Plume River Intrusions rocks, the hydrothermal fluids were considered to have invaded the crust along the same pathways as the Bonnet Plume River Intrusions (Hunt et al., 2007). All of these geological events were thought to have taken place on the Laurentian continent.

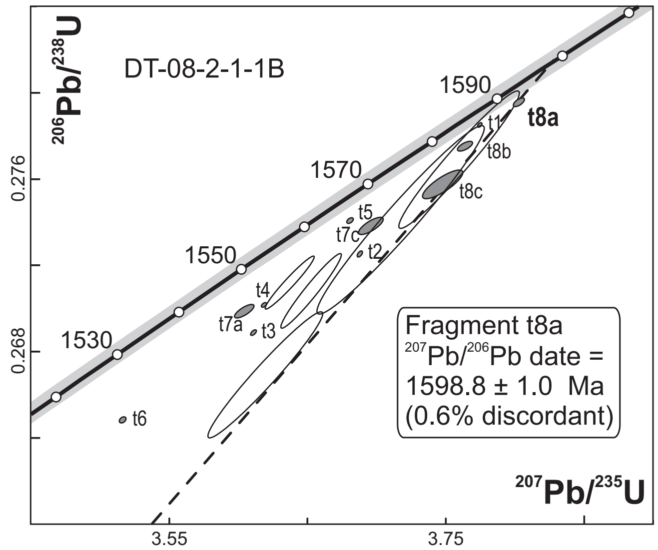

Fig. 7. Concordia plot of U–Pb dates from titanite analysed by the isotope dilution thermal ionization mass spectrometry method. Error ellipses are at the 95% confidence interval. Data from this study are shown by grey ellipses with labels of the titanite fractions. Letters a, b, c following a number in the label represent fragments from the same grain. Data from previous study (Thorkelson et al., 2001b) are shown by white ellipses. Grey band represents the error on Concordia upon addition of the decay constant uncertainties. Dashed line is a reference chord from 1599 Ma to 0 Ma. Age interpretation based on date from fragment t8a; see text for details. Plotted with Isoplot 3.0 (Ludwig, 2003).

3.2. *Impetus for a new model*

Our new detrital zircon ages and field relations are inconsistent with the foregoing model and require a new explanation. Specifically, the detrital zircon data from the Wernecke Supergroup require a reversal in the interpretation of the relative ages between the Wernecke Supergroup and the Bonnet Plume River Intrusions. The new data show that the Bonnet Plume River Intrusions crystallized at 1.71 Ga and that the Wernecke Supergroup wasn't deposited for at least another 70 Ma, at <1.64 Ga. In addition, a re-examination of the field relations of the Bonnet Plume River Intrusions determined that these intrusive rocks occurred only as clasts within the Wernecke Breccia and were not emplaced into the Wernecke Supergroup (Nielsen, 2011).

In order to arrive at a new model, we needed to address the question of how clasts from the older Bonnet Plume River Intrusions became entrained within the Wernecke Breccia, at the level of the Wernecke Supergroup. One scenario, that we reject, is that the intrusions were part of the substrate to the Wernecke Supergroup and were then fragmented and forcibly moved *upward* during development of the Wernecke Breccia. The weakness of this explanation is that many of the clasts are very large (hundreds of meters across), and some are located in breccia zones hosted by the Gillespie Lake Group which sits at least 8 km above the base of the Wernecke Supergroup (Delaney, 1981; Thorkelson et al., 2000). We consider it highly unlikely that hydrothermal fluids moved these megaclasts upward through the crust for such distances.

A second and more plausible option is that the clasts of the Bonnet Plume River Intrusions foundered into the Wernecke Breccia from a source above the Wernecke Supergroup. This relationship is consistent with the apparent downward motion of clasts of the Quartet Group and of the Gillespie Lake Group which are found at lower stratigraphic levels than their source stratigraphic levels (Nielsen et al., 2011). The mechanism of foundering is similar to what has happened in the development of diatreme facies in some kimberlitic breccia pipes, which are largely composed of fall-back breccias that contain clasts derived from overlying rock units (Hubbard, 1967; Cookenboo et al., 1998; McCracken et al., 2000; Laughton et al., 2005).

To account for the older age of the intrusive rocks relative to the Wernecke Supergroup, the source of the intrusive clasts must have been located within a nappe or terrane which was thrust over the Wernecke Supergroup prior to brecciation (Furlanetto et al., 2009b). Nielsen (2011) regarded the hypothetical terrane as the source of four igneous clast types: the Bonnet Plume River Intrusions, the Slab volcanics, and two newly identified units termed the Devil volcanics and the Blackstone River megaclasts (Nielsen, 2011; Peters and Thorkelson, 2011). On the basis of petrology, geochemistry, and isotope geochemistry, Nielsen et al. (2011) characterized the terrane as a volcanic arc with a minor intraplate component that was probably built on older continental lithosphere.

Deformation associated with the Racklan Orogeny, prior to obduction, is implied by the great range of stratigraphic positions in the Wernecke Supergroup to which the terrane-derived megaclasts were emplaced. The megaclasts of these igneous units are hosted in zones of Wernecke Breccia that lie within all of the groups in the Wernecke Supergroup, which has a total thickness of >13 km. If the strata were structurally unmodified at the time of obduction, a possibility that we reject, then megaclasts of these igneous lithologies that came to rest alongside the Fairchild Lake Group would have had to descend all the way through the Gillespie Lake and Quartet groups and part of the way into the Fairchild Lake Group, for vertical distances of at least 8 km. To address this issue, Laughton et al. (2005) noted that much smaller transport distances would be required if the Wernecke Supergroup were deformed and exhumed prior to brecciation. Deformation prior to Wernecke Breccia formation is consistent with metamorphism and fabric formation in the Wernecke Supergroup prior to Wernecke Breccia formation (Brideau et al., 2002). By applying this information to the terrane hypothesis, we recognize the need for an interval of contractional deformation followed by erosional denudation, prior to terrane obduction. In this manner, all of the stratigraphic units would have been exposed at the surface in close proximity to one another, much as they are at the present day. At the end of obduction, some regions of the terrane would have come to rest atop the Gillespie Lake Group, some above the Quartet Group, and others above the Fairchild Lake Group. Subsequent brecciation would have allowed clasts of the obducted terrane to descend relatively short distances (1–2 km) into all of the groups of the Wernecke Supergroup.

3.3. *Summary of events*

The sequence of events that best satisfies the field relationships and analytical data is simplified in Fig. 8 . The model begins with genesis of a volcanic arc at ∼1.71 Ga located offshore the northwestern margin of Laurentia (Fig. 8a). We call this volcanic arc Bonnetia, as it would later become the source for the megaclasts of the Bonnet Plume River Intrusions, as well as the Slab Volcanics, the Devil Volcanics, and the Blackstone River unit. There is no contemporaneous record for this part of Laurentia at this time; therefore it is likely to have been connected to another landmass as part of the supercontinent Columbia (Fig. 1). The obducted terrane apparently covered a region that encompasses the distribution of the megaclast-hosting breccias, i.e., parts of the present-day Wernecke, Ogilvie and Richardson mountains, an area of approximately 90 000 km^2.

At ∼1.64 Ga, in the northwestern margin of Laurentia, the Wernecke basin developed and was rapidly infilled with at least 13 km of clastic and carbonate strata of the Wernecke Supergroup (Fig. 8b). The basin was presumably formed in response to rifting of

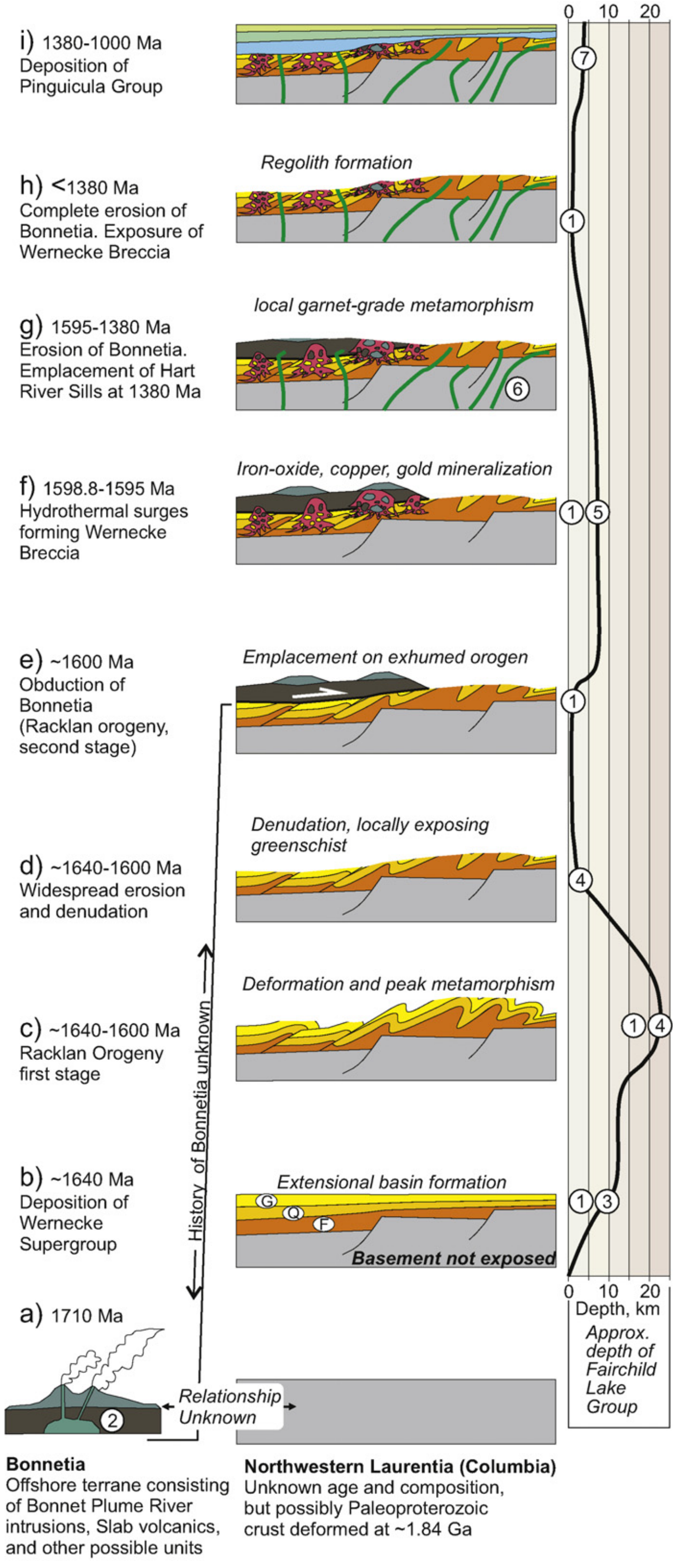

Fig. 8. Synopsis of events from 1.71 Ga to 1.0 Ga (a–h). a) Genesis of Bonnetia outboard of the northwestern margin of Laurentia (1.71 Ga); b) Wernecke Basin formation onto northwestern Laurentia (1.64 Ga) and deposition of clastic and carbonate successions of the Wernecke Supergroup (F = Fairchild Lake Group, Q = Quartet Group, G = Gillespie Lake Group); c) Racklan Orogeny affecting the Wernecke Supergroup: contraction, folding, metamorphism, exhumation, and erosion of the deformed Wernecke Supergroup; d) eroded Wernecke Supergroup with exposure of all three groups; e) obduction of the purported terrane Bonnetia onto the Laurentian margin during second stage of Racklan Orogeny; f) surges of hydrothermal fluids intruding the Wernecke Supergroup and Bonnetia, and engulfment of clasts from the Wernecke Supergroup and Bonnetia (1598 Ma); g) erosion of Bonnetia and emplacement of Hart River sills at 1.38 Ga; h) complete erosion of Bonnetia between 1.38 Ga and deposition of Pinguicula Group; i) rifting event that led to deposition of Pinguicula Group.

Numbers within circles indicate the source of data from literature: 1) this paper; 2) Thorkelson et al. (2001a); 3) Delaney (1981); 4) Brideau et al. (2002); 5) Hunt et al. (2005); 6) Thorkelson et al. (2005); 7) Medig et al. (2010).

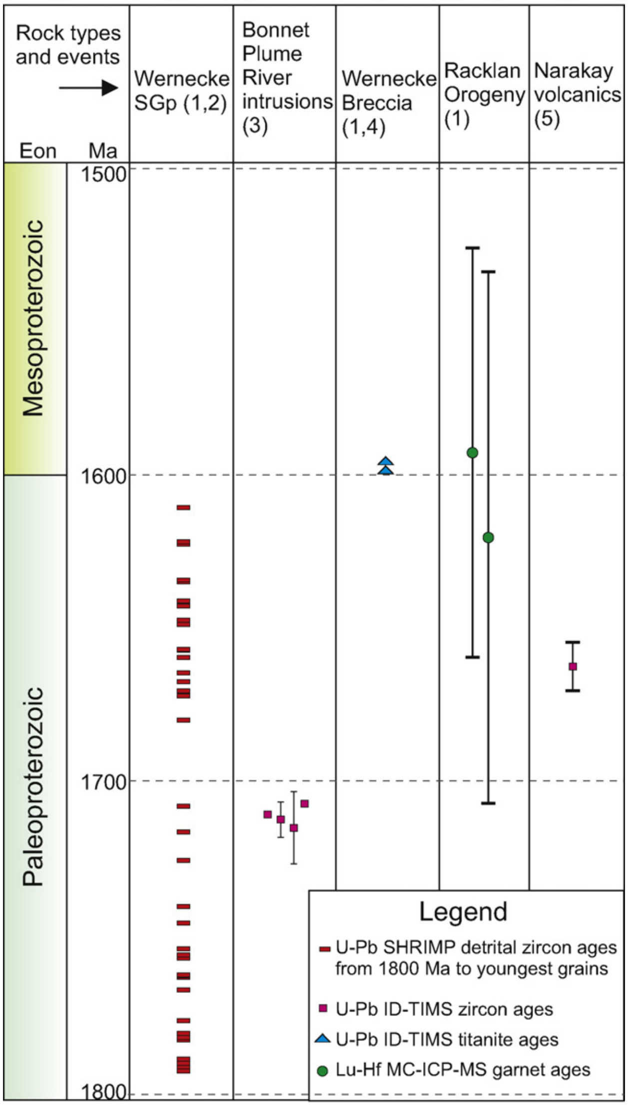

Fig. 9. Summary of geochronological data for the Paleoproterozoic Wernecke Supergroup, Bonnet Plume River Intrusions, Wernecke Breccia, Racklan Orogeny, and Narakay Volcanics from the Coppermine Homocline, Northwest Territories. Ages are grouped by lithotype and method of investigation, and are respectively: U–Pb SHRIMP detrital zircon ages on quartzite of the Wernecke Supergroup, U–Pb ID-TIMS zircon ages on the Bonnet Plume River intrusions, U–Pb ID-TIMS titanite ages on the Wernecke Breccia, Lu–Hf MC-ICP-MS garnet ages on schist of the Wernecke Supergroup.

The following sources of data are indicated in parentheses in column headings: (1), this paper; (2), Furlanetto et al. (2009a); (3), Thorkelson et al. (2001a); (4), Thorkelson et al. (2001b); (5) Bowring and Ross (1985).

Columbia, but the identity of the conjugate landmass to Laurentia is a topic of debate. Nevertheless, the Wernecke basin received sediment from Laurentia to the east, and north (Delaney, 1981), while the western and southern margins were apparently open to the ocean. As shown in Fig. 7 of Furlanetto et al. (2009a) the detrital zircon populations record predominantly Laurentian provenance for the sedimentary rocks but a Bonnetian source of detritus is not precluded, given the potential diachroneity of collision and obduction (Fig. 9). Perhaps the limited areal extent of Bonnetia, and/or paucity of zircon within it, versus the much larger and more sialic ancestral North American continent, could have biased the detrital mineral provenance signature with consequent underrepresentation of Bonnetia.

Following sedimentation, but prior to Wernecke brecciation at ~1.60 Ga, the Laurentian continental margin was affected by at least three phases of contractional deformation of the Racklan Orogeny. The first involved folding, metamorphism (up to garnet grade in present-day exposures) and fabric development. The second phase, which may have included more than one episode, involved additional folding, crenulation and kink band development. During these two phases the Wernecke Supergroup was exhumed and eroded with consequent exposure of all the presently observable stratigraphic levels (Fig. 8c–d). Following this episode of deformation, the third phase involved obduction of Bonnetia over the Laurentian continental margin (Fig. 8e). Docking of Australia, Siberia, South China (or another continent) against northwestern Laurentia (Betts and Giles, 2006; Betts et al., 2008; Li et al., 2008a; Sears et al., 2004) may have accompanied and assisted the tectonic emplacement of Bonnetia. These events are probably related to the assembly and growth of the supercontinent Columbia.

Following obduction, at 1.60 Ga, hydrothermal fluids surged through the crust, leading to development of widespread hydrothermal activity, development of numerous zones of Wernecke Breccia, and foundering and engulfment of megaclasts from the Wernecke Supergroup and the newly obducted Bonnetia (Fig. 8f). The hydrothermal activity may have been triggered by some combination of tectonic burial, overpressuring of trapped crustal brines, fracturing of the continental margin, and metamorphic dewatering. This model accords with the findings of Hunt et al. (2005, 2007, 2011) and Kendrick et al. (2008) which demonstrate that the Wernecke Breccia were generated by crustal fluids with little or no input from concomitant igneous intrusions. Subsequent erosion removed Bonnetia and the thrust zone in their entirety (Fig. 8h) (except for the igneous clasts in Wernecke Breccia) prior to Meso-Neoproterozoic deposition of the Pinguicula Group, which occurred sometime in the interval 1.38–1.0 Ga (Thorkelson et al., 2005; Medig et al., 2010) (Fig. 8i).

4. Late Paleoproterozoic deformation: nearly circum-Laurentian?

A possible connection between the Racklan Orogeny in Yukon and the Yavapai and Mazatzal orogenies in the southwestern United States and northern Mexico was proposed by Thorkelson et al. (2001a, 2003), based on a common late Paleoproterozoic age of deformation. The Yavapai and Mazatzal orogenies have been well established as accretionary orogens in which juvenile arc terranes collided with the southern Laurentian continental margin (Condie, 1992; Karlstrom et al., 2001). The Racklan orogeny has been characterized as either contraction of an intracratonic basin due to far-field stresses originating from the Yavapai/Mazatzal orogenies, or collision along the continental margin and inversion of a passive margin succession (Thorkelson et al., 2001a). Our proposed model involving oceanic terrane obduction is consistent with the origin of the Wernecke Supergroup as passive margin succession, and the idea that the Racklan Orogeny represents closure of an ocean basin and collision along the Laurentian continental margin.

As a collisional and accretionary orogen, Racklan Orogeny shares similarities with other late Paleoproterozoic orogens in Laurentia and elsewhere. The Racklan is most similar to the Mazatzal Orogeny in which oceanic igneous rocks of 1.70–1.65 Ga were accreted to Laurentia between 1.65 Ga and 1.60 Ga (Condie, 1992; Whitmeyer and Karlstrom, 2007). The Mazatzal Orogeny is broadly equivalent to the Labradorian Orogeny in eastern Canada (Gower and Krogh, 2002; Gower et al., 2008; Thomson et al., 2011) and the Gothian Orogeny in southern Scandinavia (Zhao et al., 2004; Ahall and Connelly, 2008). Throughout this belt, arc magmatism occurred either on terranes that later became accreted, or on the Laurentian continental margin.

Subduction appears to be a necessary process to drive Bonnetia onto the continental margin of Laurentia, but the absence of arc magmatism in northwestern Laurentia suggests that Laurentia was not the overriding plate. Instead, subduction is likely to have taken place beneath Bonnetia with Laurentia attached to the downgoing oceanic slab. Shortly before 1.60 Ga, Laurentia and Bonnetia collided, and part of Bonnetia was thrust over the Laurentian margin and onto the deformed and exhumed Wernecke Supergroup in the manner of ophiolite obduction outlined by Shervais (2001), or terrane obduction as proposed for the Himalaya and the North American Cordillera during Cenozoic time (Smith et al., 1994; Monger et al., 1982). The deformation and metamorphism in the Wernecke Supergroup before terrane obduction is regarded as the earlier stages of the Racklan Orogeny, when the continental margin underwent contraction due to a previous phase of collision, possibly with Bonnetia or an intervening region of buoyant crust.

The broadly contemporaneous and apparent genetic connection between the Racklan and Mazatzal orogenies and the apparent similarity in tectonic evolution suggest a common origin: the Mazatzal province is composed of 1.68–1.60 Ga juvenile crust that accreted during the 1.65–1.60 Ga Mazatzal orogeny. This orogeny extended from the southwestern United States to the Atlantic margin of Canada where it is known as the Labradorian Orogeny (Gower et al., 1992; Nunn et al., 1985). The Mazatzal-Labradorian belt continues northeastwards into the Gothian orogenic belt of Scandinavia (Ahall and Gower, 1997) and into the Quatro Cachoeiras Orogey of the Rio Negro-Iuruena Province (SAMBA configuration by Santos et al., 2008). The Mazatzal tectonometamorphic event also affected parts of the older Yavapai and Mohave provinces, (Whitmeyer and Karlstrom, 2007; Williams and Karlstrom, 1996).

North of the Mohave province, along the west side of Laurentia, there is little evidence for Mazatzal-aged deformation except for the Laclede augen gneiss of the Priest River complex in Idaho (Doughty et al., 1998) which records 1576 ± 13 Ma magmatism. From that point northward, there is no direct evidence for late Paleoproterozoic–early Mesoproterozoic deformation until the Racklan Orogeny in Yukon and the neighbouring Forward Orogeny in the Northwest Territories (Fig. 1). Deformation in the Muskwa assemblage in northern British Columbia (Taylor and Stott, 1973; Evenchick et al., 2005) is a possible candidate, but the timing and nature of the deformation are too poorly constrained to reliably correlate to the Mazatzal and Racklan events.

The lack of evidence on Laurentia for a continuous orogenic system extending from the Mazatzal to the Racklan orogens can be explained by two general scenarios. In one, the Racklan and Mazatzal were separate events that were never connected along a common plate boundary or deformational belt. In the other, the Mazatzal and Racklan events were part of the same orogenic system that lay mostly to the west of the present western margin of Laurentia and was subsequently separated from Laurentia by one or more events of rifting and continental separation that occurred during dismemberment of Columbia, Rodinia, or later (Ross et al., 1992; Sears and Price, 2003; Thorkelson et al., 2005). Although the option of no orogenic connection is possible, we consider the second option of a common orogenic system to be worth exploring.

The model of rifting of Laurentia to form the Wernecke basin followed by the obduction of Bonnetia can be recast in terms of fundamental plate interactions and dimensions. Genesis of the Wernecke basin suggests that Laurentia was part of a larger landmass (Columbia) that underwent rifting and passive margin formation at ca. 1.64 Ga. That ocean basin was large enough for the Bonnetia volcanic arc, which was active at 1.71 Ga and possibly at other times, to move toward and collide with Laurentia at ca. 1.60 Ga. This sequence of basin opening and closure occurred over an interval of no more than 40 m.y. If sea-floor spreading took place at a modest average rate of 5 cm/yr, then 40 m.y. of extension would have produced an ocean basin 2000 km across. However, if ¼ of that interval is assigned to plate convergence at a rate of 100 km/m.y. (10 cm/yr), then the amount of spreading would be reduced to 1500 km, and the remaining 10 m.y., assigned to subduction, would consume 1000 km of oceanic lithosphere. Although there is no way to verify these rates or durations, these sample calculations demonstrate that an interval as brief as 40 m.y. will allow for the genesis and consumption of large tracts of ocean floor. Arguably not all of the activity in this 40 m.y. cycle of basin opening and terrane collision would be as vigorous and constant as indicated by these rates. The processes of rifting prior to the sea-floor spreading, and terrane obduction following collision, would likely occur more slowly, resulting in a narrower calculated basin width. In particular, the earlier phases of Racklan Orogeny and the exhumation of the Wernecke Supergroup would also need to occur during the available 40 m.y. Nevertheless, the size of the basin related to Wernecke basin formation may have been considerable, and possibly on the order of 1000 km.

Another key element is the origin of Bonnetia. One possibility is that Bonnetia was generated in an oceanic setting with no connection to another landmass. As outlined in Nielsen (2011), the Nd isotopic characteristics of the igneous clasts in Wernecke Breccia are consistent with the possibility that the Bonnetia arc may have been built as an island arc on a fragment of continental crust, or as a continental-margin arc on the leading edge of a larger terrane or continent. Could that continent be the same one that separated from Laurentia to form the Wernecke basin? That scenario would need to accommodate the requirement that Bonnetia was on the overriding plate of an active subduction zone approximately 70 m.y. earlier than the deposition of the Wernecke Supergroup, which would involve an open seaway. One tectonic configuration that would satisfy these constraints is for the Bonnetia volcanic arc to have been built on a free margin of the conjugate continent prior to its separation from Laurentia, i.e., a part of the continental margin of Columbia which was facing an open ocean. Subsequent rifting and drifting to form the Wernecke basin followed by ocean closure could have rotated the conjugate continent and its continental-margin arc, bringing Bonnetia into collision with Laurentia. Returning to the possibility that Bonnetia was built on a fragment of continental crust, could the fragment have come from Laurentia? This option is possible although there is no record on northwestern Laurentia of any magmatic activity that fits with the age of magmatism of Bonnetia (ca. 1.71 Ga). The lack of a volcanic record in the Wernecke Supergroup appears to negate the possibility that Bonnetia originated on the edge of Laurentia as a continental-margin arc that rifted away from Laurentia and left the Wernecke basin as a coeval continental back-arc basin.

In summary, Bonnetia is most favourably characterized as part of an arc built on a terrane or continental margin that collided with Laurentia. Bonnetia was emplaced onto Laurentia after growth and consumption of an open seaway associated with the genesis of the Wernecke basin. These findings permit a more advanced view of how the Racklan Orogeny may have related to the Mazatzal Orogeny to the south. As noted, the Mazatzal Orogeny is characterized by the accretion of juvenile arc terranes to the southern Laurentian margin. If Bonnetia were an island arc complex, then its relationship to Laurentia would be very similar to that between Laurentia and the terranes of the Mazatzal orogen, with the possible exception that Bonnetia may have been built on a substrate of continental crust. Conversely, if Bonnetia were part of a continental margin, then the Racklan would represent a collision between Laurentia and another continent – which may or may not have been the same landmass that was attached to Laurentia prior to Wernecke basin-related rifting. In either scenario, the Racklan and Mazatzal orogenies may have occurred along a shared free margin of Laurentia (as part of Columbia) that extended from the current southwestern United States to Yukon, Canada.

The Laclede augen gneiss (1.58 Ga; Fig. 1) is a unique feature of western Laurentia that bears on the question of how the Racklan and Mazatzal orogenies may have been connected. The age of the Laclede gneiss lies within the 1610–1490 Ma North America magmatic gap (NAMG), (Ross and Villeneuve, 2003) meaning that few rocks of this age are known from Laurentia. According to Ross et al. (1992), this unit and its host, the Priest River complex, may have originated on South Australia and then been abandoned on the truncated margin of Laurentia during the Mesoproterozoic breakup of Columbia or the Neoproterozoic breakup of Rodinia, or a later rifting event. Rocks of similar age from the Mount Isa inlier and other areas within central and eastern Australia (Betts et al., 2006; Giles et al., 2006) may also be appropriate sources for the Priest River complex.

In addition to Australia (combined with East Antarctica) as a possible conjugate continent to western Laurentia in the Proterozoic (Bell and Jefferson, 1987; Moores, 1991; Dalziel, 1991; Ross et al., 1992; Thorkelson et al., 2001a,b; Betts and Giles, 2006; Payne et al., 2009), two other continents, namely South China (Li et al., 2008a) and Siberia (Sears and Price, 1978; Sears and Price, 2003), remain as popular candidates. Siberia is commonly considered to have been part of Columbia (Zhao et al., 2004; Pisarevsky et al., 2008), but whether Siberia was connected to Laurentia on its western side (Sears and Price, 1978, 2003; Piper, 2011) or northern side (Hoffman, 1991; Condie and Rosen, 1994; Frost et al., 1998; Rainbird et al., 1996) remains a subject of debate (Piper, 2011). Collectively, these studies show or infer that Siberia may have become connected to Laurentia during collisions in the Paleoproterozoic (ca. 2 Ga), and then separated during the breakup of Rodinia in the Neoproterozoic to early Cambrian (Piper, 2011). The South China model involves suturing of the Cathaysia block to Laurentia during the late Paleoproterozoic to Mesoproterozoic, and subsequent collisions in the Neoproterozoic involving the Yangtze block, Australia, East Antarctica and Laurentia to form part of Rodinia (Li et al., 1995, 2008a,b). Although the proposed South China and Siberian connections to western Laurentia have merit on certain grounds for specific time intervals, neither is overtly compatible with the ca. 1.6 Ga Racklan Orogeny and the 1.58 Ga magmatism recorded in the Laclede gneiss. Similarly, neither model readily provides a source of clastic detritus with NAMG detrital mineral ages which are required for the Mesoproterozoic Belt-Purcell basin (Fig. 1; Ross et al., 1992; Ross and Villeneuve, 2003).

Given the paucity of geochronological and geochemical data available for Siberia and South China, the Australian option is arguably the most plausible one for the late Paleoproterozoic to early Mesoproterozoic (Ross and Villeneuve, 2003; Betts et al., 2011). East Australia and Antarctica contain belts of deformation in the 1.6–1.5 Ga range (Payne et al., 2009), making them an ideal counterpart to Laurentia in late Paleoproterozoic to Mesoproterozoic time. Additionally, both Australia and Laurentia host large, early Mesoproterozoic provinces of iron oxide copper gold occurrences (Hitzman et al., 1992; Thorkelson et al., 2001b; Hunt et al., 2005, 2007), which may have originated as parts of the same metallogenetic province, spanning parts of Australia and Laurentia during an interval of juxtaposition. However, the near-absence of magmatism on Laurentia with NAMG ages implies that Australia may not have been attached to western Laurentia until during or after the Laclede magmatic event at 1.58 Ga. Nevertheless, Australia was likely adjacent to

Laurentia before the onset of rifting that formed the Belt-Purcell basin at 1.47 Ga (Ross and Villeneuve, 2003). Hence, 1.58–1.47 Ga is the most reasonable interval for continental juxtaposition between Australia and Laurentia near the Belt basin, along west-central Laurentia. The oldest part of that time interval is close to the 1.65–1.60 combined age-range for the Racklan and Mazatzal orogenies.

5. Summary and conclusions

New isotopic ages (summarized in Fig. 9), that place new constraints on sedimentation, orogenesis and hydrothermal brecciation require a new model for the late Paleoproterozoic to early Mesoproterozoic evolution of northwestern Laurentia. The model involves tectonic emplacement of an arc complex onto the continental margin of northwestern Laurentia. In turn, this scenario requires the northwestern margin of Laurentia to have been open to the ocean during the latest Paleoproterozoic, and involved in continental-margin orogenesis contemporaneously with the Mazatzal Orogeny in southwestern Laurentia.

The new tectonic model for northwestern Laurentia follows the ca. 2.0–1.8 Ga accretionary events that led to the assembly of the supercontinent Columbia (Zhao et al., 2004). At ∼1.71 Ga, offshore from Laurentia, the Bonnet Plume River Intrusions and related volcanics rocks formed in an arc complex named Bonnetia. At ca. 1.64 Ga, northwest Laurentia underwent rifting, leading to the separation of Australia or another landmass from Laurentia (here we continue to apply the term Columbia to the supercontinent that contained Laurentia). Sediments of the Wernecke Supergroup were deposited into the Wernecke Basin Folding, foliation development and metamorphism of the Wernecke Supergroup occurred in the early phases of the thin-skinned Racklan Orogeny at ∼1.60 Ga. The maximum metamorphic grade of present-day surface exposures is greenschist, with garnet–biotite paleothermometry indicating temperatures of 440–500 °C. Lu–Hf dating of garnet confirms an age of ∼1.60 Ga. The cause of the orogenesis remains unknown, but seems to require convergence with buoyant lithosphere such as a terrane or continent, possibly part of Bonnetia. Exhumation and erosion of the Wernecke Supergroup occurred during Racklan Orogeny. Thick-skinned deformation of the Forward Orogeny occurred inboard of the Laurentian margin at ∼1.663 Ga. The final phase of Racklan Orogeny is characterized by obduction of Bonnetia onto the denuded continental margin. Terrane emplacement may have been part of a larger system of continent convergence, with Australia as the most plausible colliding landmass (leading to another iteration of the supercontinent Columbia). Surges of hydrothermal fluids from crustal sources invaded the orogen and produced widespread, voluminous breccia zones known as the Wernecke Breccia, at 1.60 Ga. The hydrothermal surges may have been triggered during the obduction of Bonnetia as it overrode, depressed and fractured the continental margin during the latest phases of the Racklan Orogeny.

Our findings demonstrate that the Racklan Orogeny (and its inboard equivalent, the Forward Orogeny) represents an interval of accretionary tectonics along western Laurentia that was broadly coeval with the Mazatzal and Labradorian orogenies and related events in Baltica and Amazonia. We suggest that the Mazatzal orogen, rather than entering into the interior of Australia (Karlstrom et al., 2001), or being truncated against Antarctica (Zhao et al., 2004), continued north along the western margin of Laurentia and accommodated accretion of terranes and/or collision with Australia. In this manner, the Racklan Orogeny is geodynamically connected to other belts of similar age which collectively flanked much of the supercontinent Columbia. The absence of evidence for Racklan-aged deformation along most of western Laurentia may be explained by subsequent rift events in the Mesoproterozoic to earliest Paleozoic (Eisbacher, 1978; Colpron et al., 2002). The axis of these rifts apparently lay inboard from the location of the earlier sutures with Australia and other continents, except where the Priest River complex was stranded. In this way, the process of rifting removed both the conjugate landmasses and their suture zones, and left western Laurentia with a truncated margin that was stripped of an orogenic belt.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2012.10.010.

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