# Evidence for late Mesoproterozoic tectonism in northern Yukon and the identification of a Grenville-age tectonothermal belt in western Laurentia

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## ABSTRACT

New U-Pb zircon dates from gneissic xenoliths in an Early Cambrian lamprophyre point to late Mesoproterozoic metamorphism and magmatism in the crust beneath northern Yukon. The data indicate a previously unrecognized thermal event in Yukon and extend the recognition of widely spaced 1.3–1.0 Ga igneous, metamorphic and tectonic events along the western margin of Laurentia. Together, these events demonstrate that the north-western margin of Laurentia was thermally active during a period of traditionally inferred tectonic quiescence.

The tectonic setting, intensity and general nature of this late Mesoproterozoic tectonothermal activity are poorly constrained, but their recognition is key to expanding our understanding of the Proterozoic geology of North America. The recognition of this event places new constraints on the palaeotectonic reconstructions of the supercontinent Rodinia.

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## Introduction

Tectonic assembly of the supercontinent Rodinia during the late Mesoproterozoic (Dalziel, 1991; Hoffman, 1991; Moores, 1991) is a widely accepted hypothesis, although details of the continental configuration, timing and processes involved in amalgamation remain controversial (e.g. Karlstrom *et al.*, 1999; Sears and Price, 2000; Li *et al.*, 2008; Evans, 2009). In North America, intense, *c*. 1.3–1.0 Ga contractional deformation and magmatism along the eastern and southern margins of Laurentia (Hoffman, 1989; Davidson, 2008; Mosher *et al.*, 2008), culminating in the *c*. 1.09–0.98 Ga Grenvillian Orogeny (Hynes and Rivers, 2010), is regarded as the flagship of Rodinian activity worldwide. Less is known about the other margins of Laurentia during that interval; however, a growing body of evidence indicates that synchronous events in western Laurentia were more extensive than previously recognized (Fig. 1). In this article, we document metamorphism and magmatism in the crust of northern Yukon using *in situ* U-Pb dating of zircon from xenoliths in a Cambrian

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lamprophyre (Milidragovic, 2008; Figs 1 and 2). By placing these ages in the context of other late Mesoproterozoic features and events, we outline a belt of late Mesoproterozoic activity in Laurentia and evaluate its significance to reconstructions involving western Laurentia during the assembly of the supercontinent Rodinia.

## Xenolith petrography and geochronology

Five pebble-size xenoliths were recovered from an ultramafic lamprophyre dyke in northern Yukon. The dyke is part of the Quartet Mountain lamprophyres and was dated at 532.2 ± 2.9 Ma (Early Cambrian) by $^{40}Ar/^{39}Ar$ on phlogopite (Milidragovic *et al.*, 2006; Milidragovic, 2008). Three of the xenoliths are paragneiss, one is orthogneiss, and the protolith of the fifth strongly metasomatized rock is uncertain.

The U-Pb zircon data were obtained using a sensitive high resolution ion microprobe (SHRIMP II) at the Geological Survey of Canada in Ottawa. The zircon grains are small (< 100 μm), complexly zoned, and record original crystallization and subsequent metamorphic growth and recrystallization ages (Figure S1). Key petrologic and age interpretations are summarized in Table 1. Analytical methods and data are described in the data repository (Table S1).

Xenolith 1 is a finely banded garnet-sillimanite paragneiss that contains rounded to sub-rounded zircon of variable size (10–100 μm), ranging from equant to elongate. Twenty-one age determinations on 19 grains define two distinct age populations (Fig. 2a). The older population consists of cores with discordant Neoarchean to Palaeoproterozoic ages, variable diffuse, oscillatory and sector-zoned textures, and Th/U ratios (0.03–0.94) suggestive of both igneous and metamorphic recrystallization. The younger population consists of Mesoproterozoic and younger ages, obtained from both cores and rims that we attribute to the effects of metamorphism. Two discordant analyses made on diffuse oscillatory-zoned cores yielded $^{207}Pb/^{206}Pb$ ages of *c*. 1.41 Ga, which we interpret as a result of incomplete recrystallization-induced Pb-loss. Analyses obtained from weakly luminescent U-rich (648–2231 p.p.m.), low Th/U zircon (≤0.07), plot along a well-defined discordia line anchored at upper and lower intercept ages of 1246 ± 29 and 503 ± 79 Ma. The upper intercept is interpreted as the time of growth of the U-rich domains and recrystallization of the detrital cores. The lower intercept age likely represents fluid-mediated remobilization of radiogenic Pb during xenolith entrainment in the lamprophyre.

Xenolith 2 is a retrograded sillimanite paragneiss that contains equant to highly elongate, typically well-
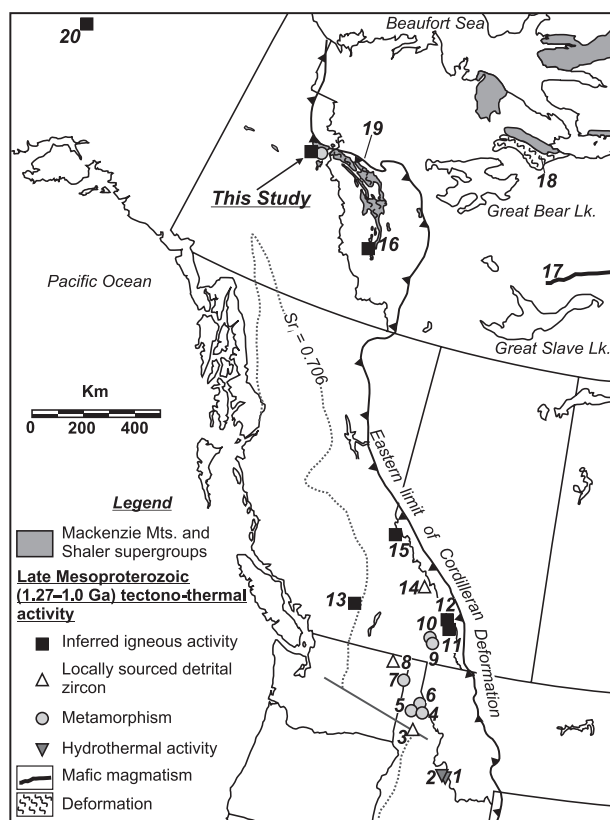
**Fig. 1** Late Mesoproterozoic tectono thermal activity in western North America. Numbered locations are from the following: (1) and (2) Gillerman *et al.* (2002), (3) Lund *et al.* (2004), (4) Vervoort *et al.* (2005) and Zirakparvar *et al.* (2010), (5) Zirakparvar *et al.* (2010), (6) Nesheim *et al.* (2009), (7) Doughty and Chamberlain (2008), (8) Ross *et al.* (1992), (9) and (10) Anderson and Davis (1995), (11) and (12) Parrish and Reichenbach (1991), (13) Erdmer *et al.* (2002), (14) Gehrels and Ross (1998), (15) Ross *et al.* (1992), (16) Jefferson and Parrish (1989), (17) LeCheminant *et al.* (2007), (18) Hildebrand and Baragar (1991), (19) Thorkelson *et al.* (2005), (20) Bradley *et al.* (2003).

rounded zircon with Palaeoproterozoic cores and Mesoproterozoic rims. The youngest reliable $^{207}Pb/^{206}Pb$ age from a core is 1781 ± 82 Ma (Fig. 2b). Four diffuse mantles with moderate U contents (450–575 p.p.m.) and Th/U ( < 0.02) were dated; three of them yielded indistinguishable concordia ages that average 1269 ± 20 Ma. Three low-U (157–340 p.p.m.), variable but higher Th/U (0.09–0.88) rims were also analysed, yielding a concordant age of 1149 ± 21 Ma.

Five analyses were obtained from four zircon grains from xenolith 3 (Fig. 2c), a retrograded garnet–sillimanite paragneiss. The zircon from this sample is dominantly equant, with irregular to rounded grain boundaries and very small ( < 45 μm). Two diffuse cores were analysed, but only one yielded a concordant $^{207}Pb/^{206}Pb$ age of 1747 ± 18 Ma. Analyses of three diffuse high-U ( > 1000 p.p.m.) metamorphic domains returned late Mesoproterozoic ages. Two of these domains returned a concordant age of 1149 ± 19 Ma.

Xenolith 4 is a strongly metasomatized foliated rock, composed of lenses of sericite surrounded by a matrix of crystalline to microcrystalline carbonate and chlorite. The zircon grains are small (30–70 μm), equant to elongate and variably rounded. Three zircon populations were identified on the basis of 17 analyses from 13 zircon grains (Fig. 2d). Nine zircon cores, characterized by irregular and diffuse zoning, plot close to concordia (discordance < 8%), and range in age from 1582 ± 28 to 1141 ± 38 Ma. The five oldest cores (1582–1445 Ma) have high-U contents (1430–1480 p.p.m.), very low Th/U ( < 0.02), and thus likely represent a variably recrystallized population of grains with original crystallization ages ≥1582 ± 28 Ma. Similarly, the four youngest cores are believed to represent more extensive recrystallization at *c.* 1150 Ma. Six analyses of unzoned, very high-U (2170–3828 p.p.m.), low Th/U (0.07–0.1) zircon rims and single grains yield a weighted mean $^{206}Pb/^{238}U$ age of 1184 ± 15 Ma. In

**Table 1** Summary of geochronological results.

| Xenolith | Laboratory ID | Protolith | Interpreted age and significance |
|---|---|---|---|
| 1 | 9044 | Sedimentary | <1626 ± 45 Ma – maximum deposition age from detrital cores |
| | | | 1246 ± 25 Ma – upper intercept – metamorphic growth and recrystallization |
| | | | 503 ± 75 Ma – lower intercept – recrystallization during entrainment in lamprophyre magma |
| 2 | 9047 | Sedimentary | <1781 ± 82 Ma – maximum $^{207}Pb/^{206}Pb$ deposition age from detrital cores |
| | | | 1269 ± 20 Ma – concordia age of metamorphic recrystallization |
| | | | 1149 ± 21 Ma – concordia age of metamorphic rim growth |
| 3 | 9048 | Sedimentary | <1747 ± 18 Ma – maximum $^{207}Pb/^{206}Pb$ deposition age from detrital cores |
| | | | 1149 ± 19 Ma – concordia age of metamorphic domains |
| 4 | 9046 | Uncertain | >1582 ± 28 Ma – minimum $^{207}Pb/^{206}Pb$ age of metamorphism/minimum protolith age |
| | | | 1168 ± 28 Ma – weighted mean $^{206}Pb/^{238}U$ age – metamorphic growth and recrystallization |
| 5 | 9049 | Igneous | 1146 ± 31 – weighted mean $^{206}Pb/^{238}U$ crystallization age of igneous protolith |
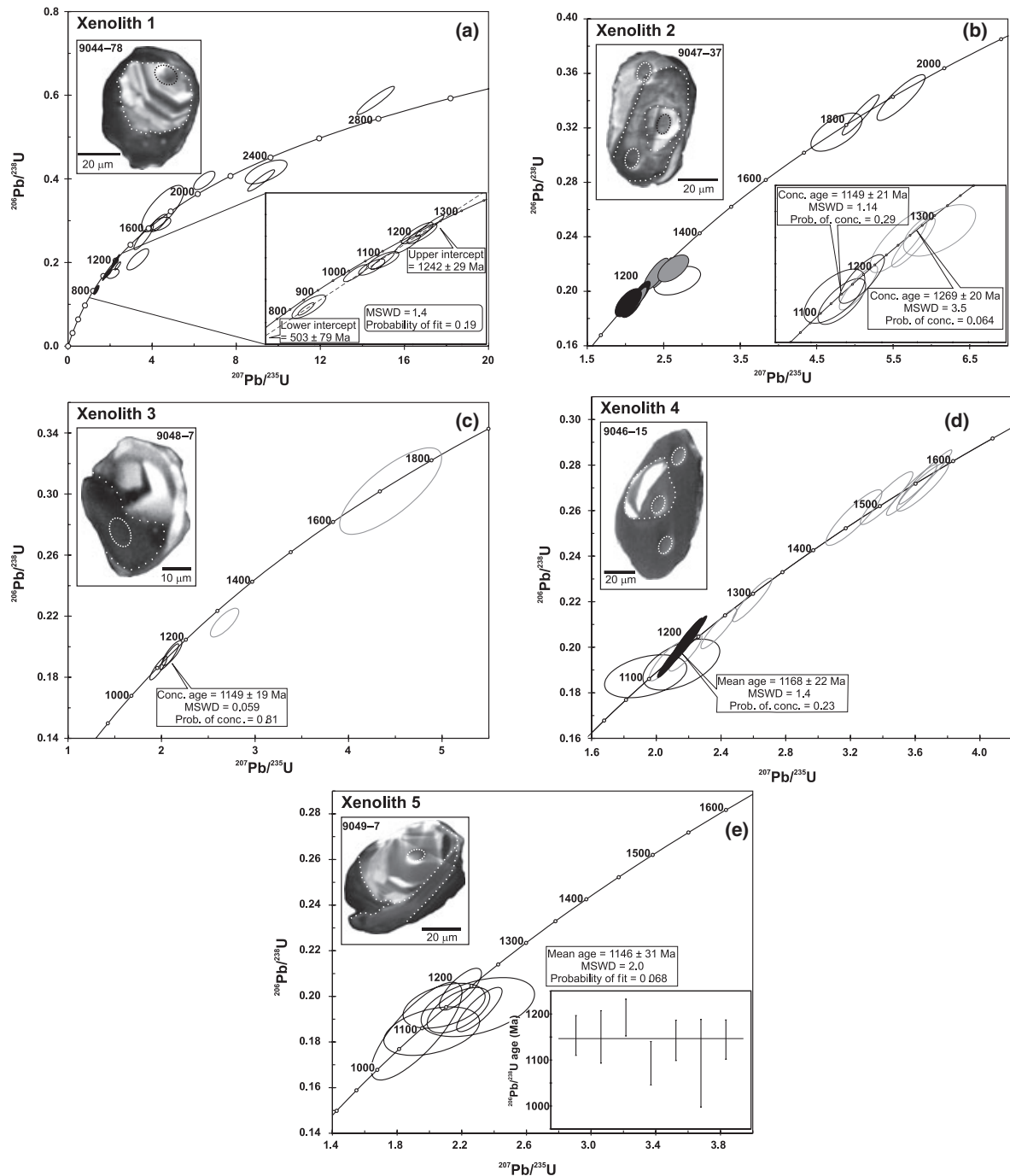
**Fig. 2** Concordia plots of SHRIMP U-Pb data from xenoliths 1–5 (ellipses at 2σ), with representative zircon crystals. Dotted ellipses and lines show the positions of analysis pits and delineate approximate domain boundaries, respectively. (a) Concordia plot of 21 analyses obtained from xenolith 1. Open ellipses represent data obtained from detrital zircon cores. Filled ellipses correspond to the homogeneous, U-rich domains. *Inset:* enlarged view of the data obtained from the homogeneous, weakly luminescent domains. (b) Plot of 11 SHRIMP analyses from xenolith 2. Empty ellipses correspond to analyses of zoned zircon cores. Light grey-filled ellipses represent analyses from low Th/U recrystallized domains formed during the *c.* 1.27 Ga metamorphic event. Black-filled ellipses represent the low-U rims formed at *c.* 1.15 Ga. *Inset:* An enlarged view of the analyses corresponding to the *c.* 1.27 Ga and *c.* 1.15 Ga metamorphic events. (c) Concordia diagram of five analyses from xenolith 3. (d) Concordia plot of 17 determinations from xenolith 4. Open ellipses symbolize data obtained from zircon cores; filled ellipses correspond to data obtained from the high-U (>2000 p.p.m.) metamorphic domains. (e) Plot of seven analyses obtained from xenolith 5. *Inset:* $^{206}Pb/^{238}U$ ages of the analysed domains. Error bars represent 2σ uncertainty.

conjunction with two low-U (222–260 p.p.m.), high Th/U (0.12–0.20) diffuse sector-zoned cores that may reflect zircon re-equilibration during metasomatism, and the two youngest very low Th/U cores, these analyses yield a best age estimate of a metamorphic event at 1168 ± 22 Ma.

Zircon from orthopyroxene-bearing xenolith 5 is rounded to sub-rounded, elongate and comparatively large (50–100 μm in long dimension). Analyses produced imprecise, but tightly clustered $^{206}Pb/^{238}U$ ages ranging from 1093 ± 95 to 1192 ± 40 Ma (Fig. 2e). The zircon has low-U concentrations (73–472 p.p.m.) and is composed of irregular highly luminescent domains that crosscut or mantle oscillatory-zoned domains of lower luminescence. The highly luminescent domains likely represent sub-solidus recrystallization of the older oscillatory-zoned igneous domains, but their ages are identical within error. Thus, the weighted mean age of 1146 ± 31 Ma from all seven analyses is taken as the best estimate of the crystallization of the igneous protolith.

In summary, the zircon grains from metasedimentary xenoliths 1–3 have complexly zoned Palaeoproterozoic and rare Archaean cores surrounded by Mesoproterozoic rims. The cores are regarded as detrital material sourced from Palaeoproterozoic and Archaean Laurentian crust to the east. The metamorphic rims indicate growth and recrystallization events at *c.* 1.27–1.25 and at 1.15 Ga. Sharp contacts between chemically distinct domains corresponding to these events in xenolith 2, and the absence of evidence for the *c.* 1.15 Ga event in xenolith 1 support the inference of two discrete Mesoproterozoic metamorphic events, rather than a spurious continuum of ages caused by variable Pb-loss during a single Mesoproterozoic metamorphic episode. Zircon grains from the metasomatized xenolith 4 are characterized by diffuse cores of Mesoproterozoic age (>1582 ± 28 Ma) that have undergone variable amounts of recrystallization. The age of recrystallization is interpreted to coincide with the growth of very high-U (>2170 p.p.m.) zircon domains at 1168 ± 22 Ma. Zircons from the meta-igneous

xenolith 5 form a cluster of imprecise concordant ages at 1146 ± 31 Ma, interpreted as the crystallization age of the parent.

## Interpretation of zircon ages

The foregoing ages may be generally explained by deposition of detrital zircon of Proterozoic and rare Archaean ages followed by Mesoproterozoic metamorphic and igneous events at ≥1.58, 1.27–1.25, *c.* 1.15 Ga. The ≥1.58 event may be linked to Racklan orogeny and subsequent *c.* 1.60 Ga voluminous hydrothermal brecciation (Thorkelson *et al.*, 2005). The 1.27–1.25 Ga ages are likely a reflection of the Bear River dyke emplacement, during the Mackenzie igneous event at *c.* 1.27 Ga (Schwab *et al.*, 2004).

The 1.15 Ga ages, in contrast to the older Mesoproterozoic ages, are not correlative with any known metamorphic or magmatic events in Yukon. However, in broader terms, this newly identified event is time-correlative with a number of poorly understood late Mesoproterozoic events in Yukon and the neighbouring Northwest Territories. These include *c.* 1.1 Ga granitic magmatism beneath the southern Mackenzie Mountains, as determined from xenoliths in the Palaeozoic Coates Lake diatreme (Jefferson and Parrish, 1989), the emplacement of mafic dikes at *c.* 1.17 Ga in the central Slave Province (LeCheminant *et al.*, 2007), the poorly dated, *c.* 1.27–1.0 Ga, contractional deformation north-east of Great Bear Lake (Hildebrand and Baragar, 1991), and extensional deformation at *c.* 1.0 Ga during deposition of the Mackenzie Mountains Supergroup (Turner and Long, 2008). Finally, the terminal late Mesoproterozoic orogenic event in north-western Canada, the Corn Creek orogeny, produced west-directed folds and thrust faults in eastern Yukon between 1.0 and 0.78 Ga (Thorkelson *et al.*, 2005).

Evidence from farther afield (Fig. 1) provides additional support for late Mesoproterozoic tectonothermal activity in north-western Laurentia, specifically: a U-Pb zircon age of *c.* 1.19 Ga from a granitic conglomerate boulder in Neoproterozoic strata of central British Columbia
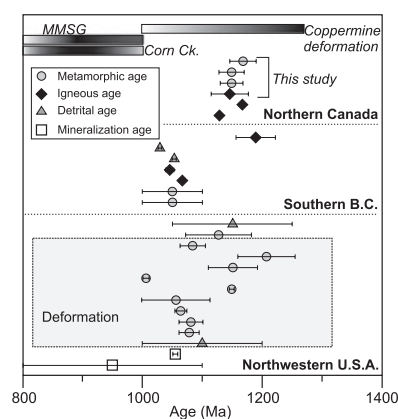


**Fig. 3** Plot of all reported late Mesoproterozoic ages (see Fig. 1 for references) and their respective errors arranged according to their relative latitude. The intensity of shading of the uppermost three bars denotes the likelihood of a given event taking place at a given time. MMSG, Mackenzie Mountains Supergroup.

(Ross *et al.*, 1992); *c.* 1.1–1.0 Ga xenocrystic zircon from Palaeozoic diatremes in south-eastern British Columbia (Parrish and Reichenbach, 1991); and *c.* 1.1–1.0 Ga metamorphic zircon and titanite from the Mesoproterozoic Moyie sills of southern British Columbia (Anderson and Davis, 1995). These data led Anderson and Davis (1995) to speculate that a belt of Grenville-age metamorphism and deformation may have existed along much of the north-western Laurentia. Since then, the evidence for *c.* 1.3–1.0 Ga tectonism that temporarily overlaps with the Grenvillian Orogeny has increased along the north-western pre-Cordilleran margin and now extends as far south as central Idaho. Lu-Hf whole-rock and garnet and U-Pb zircon dating of the metamorphic complexes in northern and central Idaho indicate a metamorphic event at *c.* 1.3–1.0 Ga (Fig. 3; Vervoort *et al.*, 2005; Doughty and Chamberlain, 2008; Nesheim *et al.*, 2009; Zirakparvar *et al.*, 2010). Erdmer *et al.* (2002) and Bradley *et al.* (2003) also reported Grenvillian detrital and igneous zircon ages, respectively, within the Cordillera, but the palaeotectonic position of the dated rocks relative to Mesoproterozoic Laurentia is uncertain.

## The significance of late Mesoproterozoic events in western Laurentia

Our new U-Pb data, in conjunction with the data summarized in the previous section, suggest that the prevailing view of relative tectonothermal quiescence along the western margin of Mesoproterozoic Laurentia (Whitmeyer and Karlstrom, 2007; Davidson, 2008), based on the lack of intense contractional deformation of this age, may be unwarranted. It is suggested herein that the late Mesoproterozoic tectonism is predominantly manifested at the lower to mid-crustal levels. The sparse and cryptic nature of the *c.* 1.3–1.0 Ga geochronological record along the western margin of Laurentian craton may reflect a series of distinct, unrelated small-scale tectonothermal events taking place close to the palaeomargin of the Mesoproterozoic Laurentia. Such events may include a combination of: emplacement of mafic magmas at depth, lithospheric thinning in response to back-arc extension or thermal erosion, terrane accretion akin to the Mesozoic collisional events of the North American Cordillera (e.g. Monger *et al.*, 1982), or margin-parallel transcurrent faulting (e.g. Ewing, 1980). Unfortunately, the knowledge of the late Mesoproterozoic geological record is insufficient to unequivocally determine which of these processes were operative.

It is also important to consider the position of the Mesoproterozoic western Laurentia within the supercontinent Rodinia and to evaluate possible interactions with other continents, with the most likely options including Australia, Antarctica, Siberia and South China (Li *et al.*, 2008 and references therein). In this regard, the models that propose a link between Australia and Antarctica and the western margin of Mesoproterozoic Laurentia fall into two broad categories. In the SWEAT class of models (see summary by Li *et al.*, 2008), a joint Australia-East Antarctica continent is juxtaposed against Laurentia, so that east Australia and north-western Canada form conjugate margins separated by late Neoproterozoic rifting. A complex set of palaeomagnetic data places important constraints on the viability of the SWEAT model, restricting its window of feasibility to the late Palaeoproterozoic (Li *et al.*, 2008), or to a narrow *c.* 1.0–0.8 Ga time interval (Evans, 2009). In contrast, the AUSWUS (Karlstrom *et al.*, 1999, 2001; Burrett and Berry, 2000) models place the proposed conjugate Australia–Antarctica landmass adjacent to the south-western USA, far south of the area considered in this article. The Siberian model (Sears and Price, 2000) calls for a prolonged *c.* 2.0–0.52 Ga joint Siberia–Laurentia continent that further requires a connection to a northern Australian, 1.61–1.51 Ga zircon source for the Mesoproterozoic Belt–Purcell Supergroup. Recent geological and palaeomagnetic data do not corroborate such a model, placing Siberia at a substantial distance from the northern margin of late Mesoproterozoic Laurentia, with a number of intervening continents (Pisarevsky *et al.*, 2008; Evans, 2009). Finally, the 'missing-link' option places the South China craton between western Laurentia and eastern Australia and most clearly involves late Mesoproterozoic tectonism. We investigate this
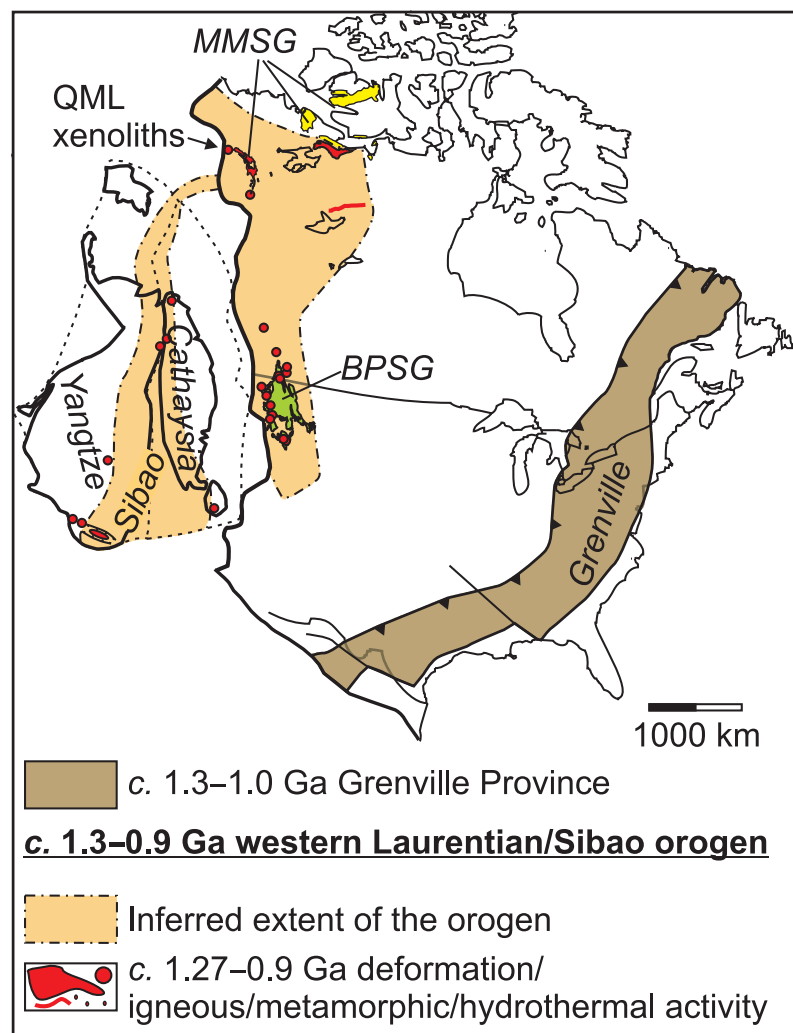


**Fig. 4** Tectonic model for the cryptic late Mesoproterozoic metamorphism along the western margin of ancestral North America. The model is an adaptation of the 'missing-link' model of Li *et al.* (2008) and calls for prolonged (*c.* 1.27–0.9 Ga) oblique collision between the joint Laurentia–Cathaysia continent and the Yangtze craton to the west. Locations in south China from Li *et al.* (2009) and Wang *et al.* (2010). BPSG, Belt–Purcell Supergroup; MMSG, Mackenzie Mountains Supergroup; QML, Quartet Mountain lamprophyres.

latter model in more detail because, while being palaeomagnetically permissible (Li *et al.*, 2008; Evans, 2009), it most clearly involves late Mesoproterozoic tectonism. In this model, Cathaysia was accreted to western Laurentia by early Mesoproterozoic time, provided sedimentary detritus for the Belt–Purcell basin, and hosted the western continuation of the 1.5–1.35 Ga mid-continental granite bloom (Li *et al.*, 2008). How long Cathaysia could have been in that position is unclear, but docking may have occurred during the late Palaeoproterozoic Racklan–Yavapai–Mazatzal orogenic events (Karlstrom and Bowring, 1988; Laughton *et al.*, 2005; Whitmeyer and Karlstrom, 2007). Alternatively, Cathaysia may have obliquely converged with western Laurentia at *c.* 1.47 Ga, leading to transtensional opening of the Belt–Purcell basin (Ross and Villeneuve, 2003).

During the late Mesoproterozoic (Fig. 4) the western (outer) margin of Cathaysia began to collide with the eastern edge of the Yangtze Craton, forming the Sibao orogen (Li *et al.*, 2008). Building on this scenario, we suggest that western Laurentia was not entirely insulated from the effects of the Sibao orogeny, and that the late Mesoproterozoic features described herein may reflect the elevated heat flow at depth and limited stress propagation well inboard of the collisional zone. In this light, the missing-link model provides an explanation for many of the late Mesoproterozoic features in western Laurentia, particularly if the direction of transport were oblique to the continental margin. An obliquely transpressional orogen would favour the development of localized releasing and restraining zones and is most consistent with the lack of intense deformation, voluminous magmatism and the scattered nature of late Mesoproterozoic tectonothermal record.

In summary, it is tentatively proposed that the belt of late Mesoproterozoic magmatic and tectonic activity in western Laurentia may be the inboard complement of the *c.* 1.14–0.83 Ga (Li *et al.*, 2009; Wang *et al.*, 2010) Sibao orogen, which forms the suture between Cathaysia and the Yangtze Craton (Li *et al.*, 2008). The eastern end of the Sibao orogen records ophiolite obduction at *c.* 0.90 Ga (Li *et al.*, 2003, 2008, 2009), and may represent the continuation of the poorly understood contractional event in north-western Laurentia recorded by the Corn Creek orogeny in Yukon.

## Acknowledgements

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Cathodoluminescence photomicrographs of representative zircon grains from samples 1–5.

**Table S1.** [204]Pb corrected U-Pb SHRIMP analytical data for crustal xenolith samples 1–5.

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