The Boring Billion as told through the Mesoproterozoic Belt and Purcell Supergroups

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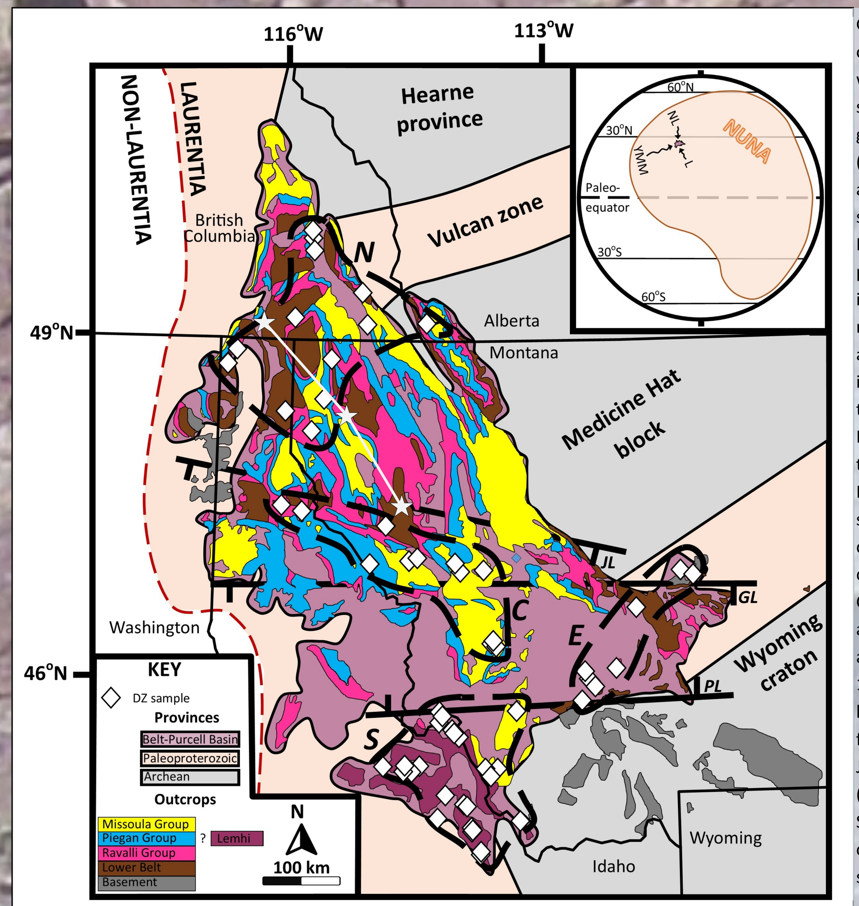
Introduction

The paradigm of plate tectonics is the template for conceptual models in geology. The provocative work of Warren Hamilton challenges our understanding of the Earth by proposing that subduction and modern-style plate tectonics are a relatively new phenomena (Hamilton, 2019). The Belt and Purcell Supergroups offer critical constraints on the tectonics effecting the Mesoproterozoic Nuna supercontinent. Interpretations commonly fit the basin within the modern plate tectonic framework, classifying the basin as a failed rift (eg. Price 1964; McMechan 1981; Cressman 1989; Whipple 1989; Ross et al. 1989; Sears et al. 1998; Ross and Villeneuve, 2003; Sears et al., 2006; Stewart et al., 2010; Medig et al., 2014; Jones et al., 2015; Mulder et al., 2015). Alternatively, the basin may be interpreted as intracratonic, reflecting long-term stability within a prolonged period of tectonic quiescence and an absence of subduction, termed the "Boring Billion" (Brasier, 2012; Roberts, 2013).

In this contribution, we honor the legacy of Warren Hamilton by investigating the tectonics of the western Laurentian boundary of the Mesoproterozoic Nuna supercontinent as recorded within strata of the Belt Basin. The conventional failed-rift model cites removal of detrital zircon dates falling within the North American Magmatic Gap (NAMG; 1490 -1610 Ma) as evidence of rifting away of an adjacent Non-Laurentian source terrane. This model fundamentally assumes that detrital zircon populations are evenly distributed in space but not time, so that stratigraphic units have characteristic signatures that reflect the tectonic state of the greater basin. We test this fundamental assumption by cataloguing 72 detrital zircon datasets and quantifying dissimilarity between the samples as a function of space and time. We interpret these spatial and temporal trends in provenance through the context of available stratigraphic and sedimentologic models for the basin. We offer key conclusions for constraints that must be satisfied by any viable tectonic models that are consistent with the modern plate tectonic framework or with the Boring Billion hypothesis.



Generalized geologic map of the Belt-Purcell Basin with outcrop pattern shown in bright colors, generalized Provinces (adapted from Whitmeyer and Karlstrom, 2007) shown in subdued colors. Inset shows generalized position of the basin within the Nuna supercontinent at ~ 1.27 Ga (Evans and Mitchell, 2011), with inferred sediment transport from Non-Laurentian (NL); Laurentian (L); and Yavapai/Mazatzal/Mojave (YMM) source terranes. Spatial domains of the dataset are denoted: Northern (N); Central (C); Eastern (E); and Southern (S). Structural lineaments (Winston, 1986) are shown as bold lines, with dashes on inferred down-dropped side: Jocko Line (JL); Garnet Line (GL); and Perry line (PL). Stars denote location of correlated stratigraphic sections shown below.

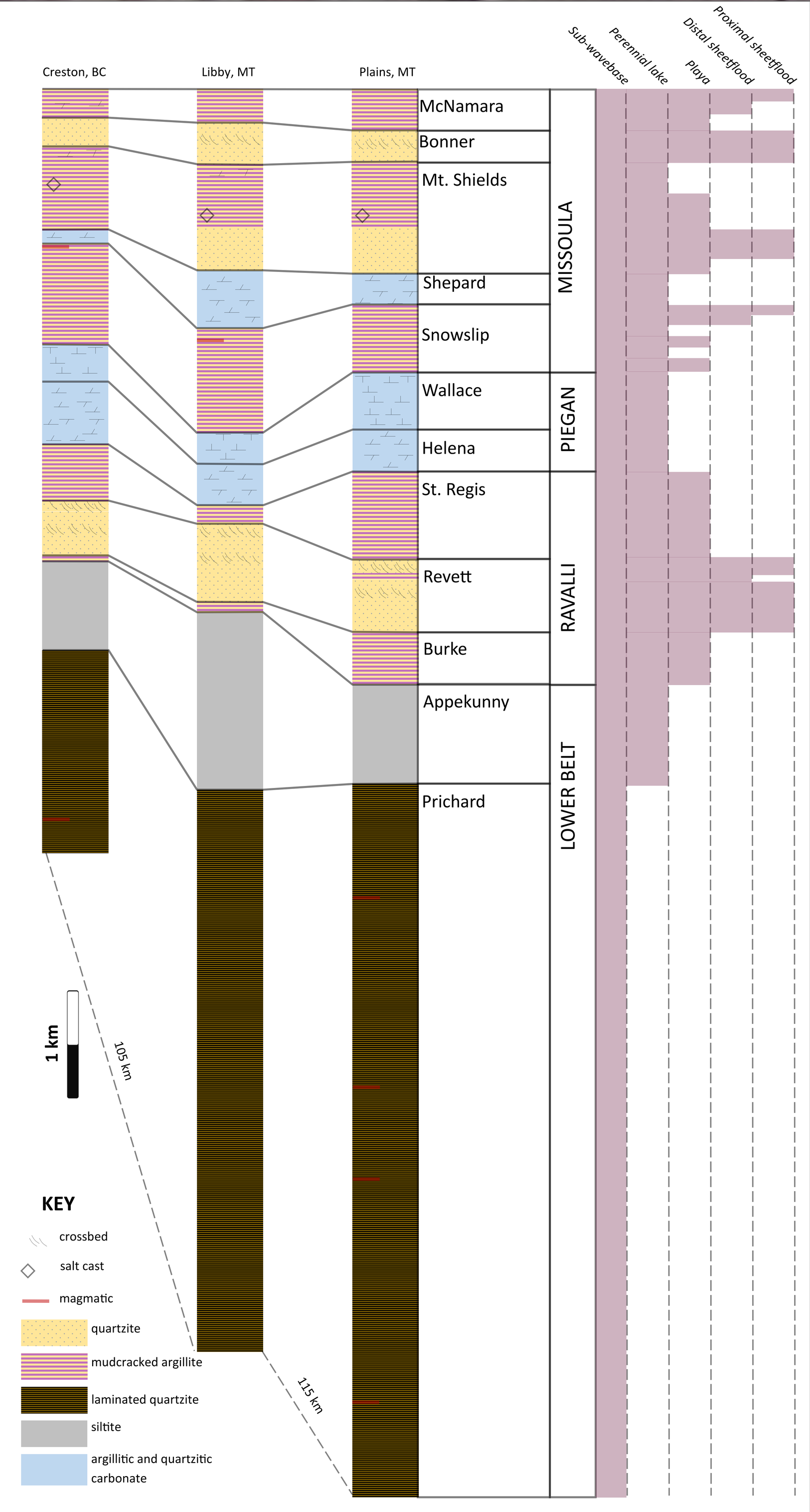
Detrital Zircon Source Terranes

1.75-1.90 Ga: Dispersed Laurentian signature from the east

1.49-1.61 Ga: NAMG signature, Non-Laurentian sources to the west

>2.00 Ga: Local cratonic signatures of the Wyoming,Medicine Hat, and Hearne Province

1.65-1.80 Ga: Yavapai-Mazatzal-Mojave signature from the south



Correlated stratigraphic sections across the northern part of the Belt-Purcell Basin (see stars on map for measured section locations). Right column shows correlative Formation and Group. Shaded histogram on right shows interpreted depositional environments. Measured sections in part from; Cressman, 1982; Cressman, 1985; Höy, 1993.

Conventional rift model

(eg. Price 1964; McMechan 1981; Cressman 1989; Whipple 1989; Ross et al. 1989; Sears et al. 1998; Ross and Villeneuve, 2003; Sears et al., 2006; Stewart et al., 2010; Medig et al., 2014; Jones et al., 2015; Mulder et al., 2015)

Assumption

- Detrital zircons are evenly distributed in space, but not time. So that a sample from a given stratigraphic package is representative of the basin as a whole and therefore reflects the tectonic regime

Observations

- NAMG signature is present below the Missoula Group and equivalent strata, but absent within the Missoula Group and equivalent strata
- Yavapai-Mazatzal-Mojave signature dominates Missoula Group and equivalent strata

Interpretations

- Rifting of Nuna at 1.45 Ga removes NAMG source terranes west of Laurentia
- Exhumation associated with orogenesis to the south provides the Yavapai-Mazatzal-Mojave signature

Prediction

- The shift from a NAMG to Yavapai-Mazatzal-Mojave signature is sudden, occurring at 1.45 Ga
- The shift from a NAMG to Yavapai-Mazatzal-Mojave signature is widespread, occurring throughout the basin

Sedimentology and Stratigraphy

The Belt-Purcell basin is extraordinary in its thickness and continuity. The following are the key attributes of the Belt-Purcell basin.

Observation

-Laterally continuous, graded event beds

-Predominantly shallow water facies

-No unconformities and negligible incision

-Lithostratigraphy can be correlated over great distances

-Discrete sediment packages enter the basin from all sides

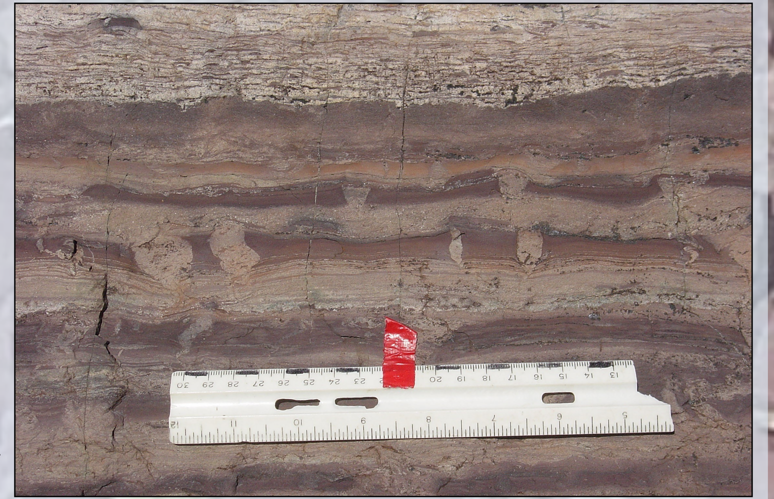
Interpretation

-Sediment transport occurred at grade, in unconfined sheetfloods

-Profound absence of topography

-Gently rising and falling water level

-Continuous deposition



Mud-cracked silt to clay couplets assigned to a playa setting.

Tabular, flat-laminated quartzite with climbing ripples showing decelerating and shallowing flow, assigned to a proximal sheetflood setting.

Visualizing Stratigraphic trends

Methods

Reported best U/Pb detrital zircon dates and corresponding uncertainties were listed in series for 72 individual samples with sample sizes ranging from 18 to 190 grains (Aleinikoff et al., 2012; Aleinikoff et al., 2015; Gardner, 2006; Hendrix et al., Unpublished; Ross and Villeneuve, 2003; Lewis et al., 2007; Lewis et al., 2010; Link et al., 2007; Link et al., 2016; Mueller et al., 2016; Stewart et al., 2010).

Two-dimensional metric MDS

1) Quantify dissimilarity for all comparisons using Kolmogorov–Smirnov (KS) statistics.

2) Create Symmetrical matrix of all dissimilarity (D) values. [Complete dissimilarity when D=1.0, and complete similarity when D=0.0. Statistically indistinguishable within 95% confidence when D<.03 (Satkoski et al., 2013).]

3) Perform MDS. [Each date series is a single point plotted in an arbitrary two-dimensional space. Distances between points approximate the similarities (D values) between series. Kruskal's stress (S) values quantify the misfit of the model (the discrepancy between the measured dissimilarity and the plotted distance). Model fit is "poor" when S >0.2 and "perfect" when S=0 Kruskal (1964).

4) Connect nearest neighbors with solid lines

Results

Individual samples

-D range from 0.05 to 0.98

-Average D of 0.5 (n=2,556), slight bimodal distribution

-Internal consistency = 30% (N=72, n=2,556).

-Low D values are less abundant for increasing stratigraphic

-Internal consistencies decrease with increasing stratigraphic separation.

-Trends are dampened in Missoula Group data

Stratigraphically equivalent samples

-Dates are mostly <2.0 Ga, with the exception of the LaHood

-Low internal consistencies, averaging 60%.

-Yavapai-Mazatzal-Mojave dates (1.65-1.80 Ga) most common population at all stratigraphic levels

-Yavapai-Mazatzal-Mojave dates are more common upsection

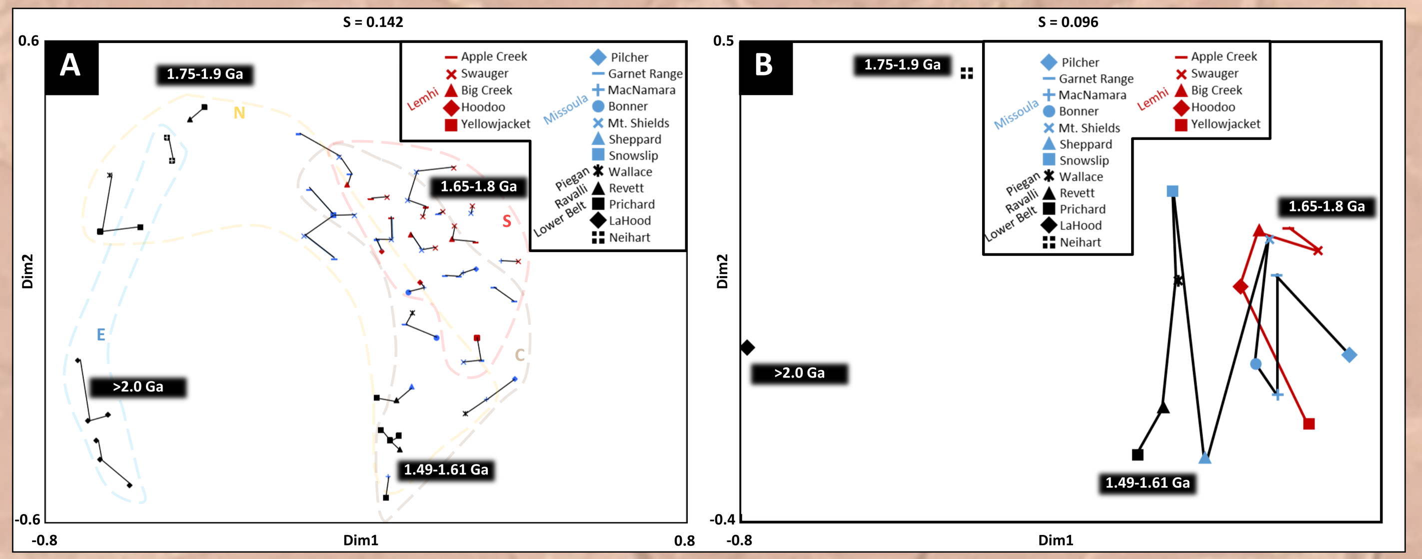
-NAMG dates (1.49-1.61 Ga) are rare, but are only entirely absent in the Neihart equivalent strata.

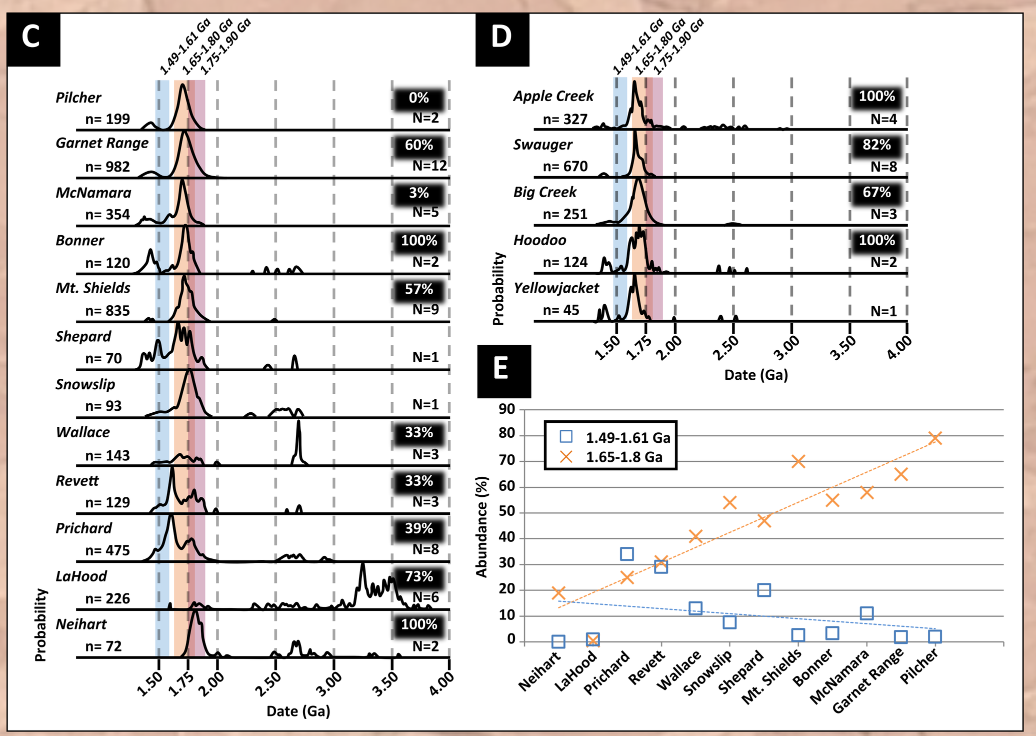
-NAMG dates are less common upsection (with no break in trend)

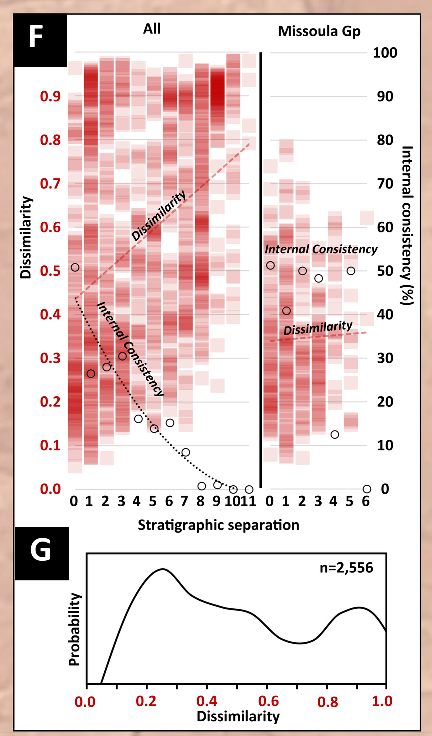
-Complex mixing between the four identified source terrane endmembers

-Nearest neighbors are rarely from the same stratigraphic level.

-Stratigraphic position does not predict position in MDS space.







Multi-dimensional scaling of **A)** individual samples and **B)** equivalent stratigraphic samples. Both axes show dimensionless measure of dissimilarity (see methods). Key date populations are shown in black boxes near their idealized positions. Spatial domains are circled in a). Lines denote a) nearest neighbors and b) stratigraphic order respectively. S denotes the kruskal stress value for each model (see methods). **(C-D)** Stacked probability curves of reported (see methods for data sources) U/Pb dates from detrital zircon within stratigraphic equivalents of the **C)** Belt/Purcell Supergroup and **D)** Lemhi subbasin. Colored boxes denote prominent date populations, see text for description. Internal consistencies (see definition of terms) are shown in the right column. N denotes the number of samples, n denotes the total number of analyses. **E)** Abundance of dates falling within specified populations for various stratigraphic equivalents of the Belt/Purcell Supergroup. Linear best fit lines shown. **F)** Dissimilarity (red boxes) and internal consistency (hollow circles) plotted against stratigraphic separation, for all samples and for only Missoula Group samples. Best fit lines shown. **G)** Probability density curve for all calculated dissimilarity values. Note bimodal distribution.

Quantifying spatial trends

Results

-Dates homogenize towards the southern end of the basin,

-Unique Archean date populations in the east

-NAMG dates are biased to the north and west.

-Dissimilarity is positively correlated with distance between sample locations.

-Average D value exceeds 0.3 at ~200 km.

-Internal consistency decreases with increasing distance between samples.

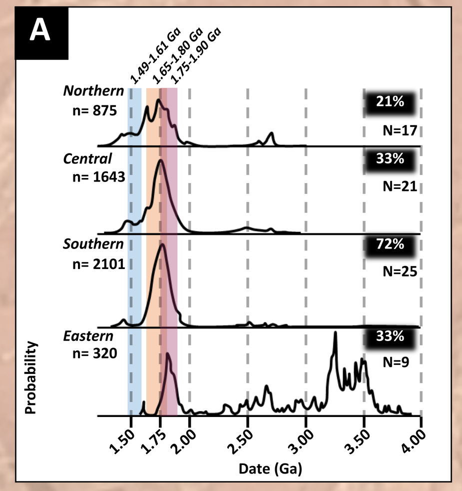
-Trends are dampened in Missoula Group samples.

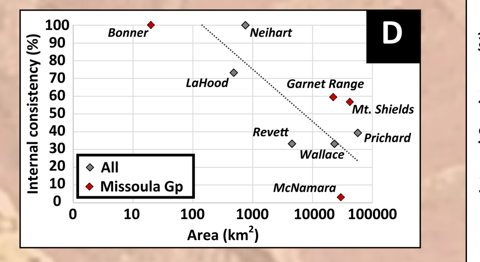
- Yavapai-Mazatzal-Mojave dates (1.65-1.80 Ga) increase to the south (with a break occurring at the Garnet Line)

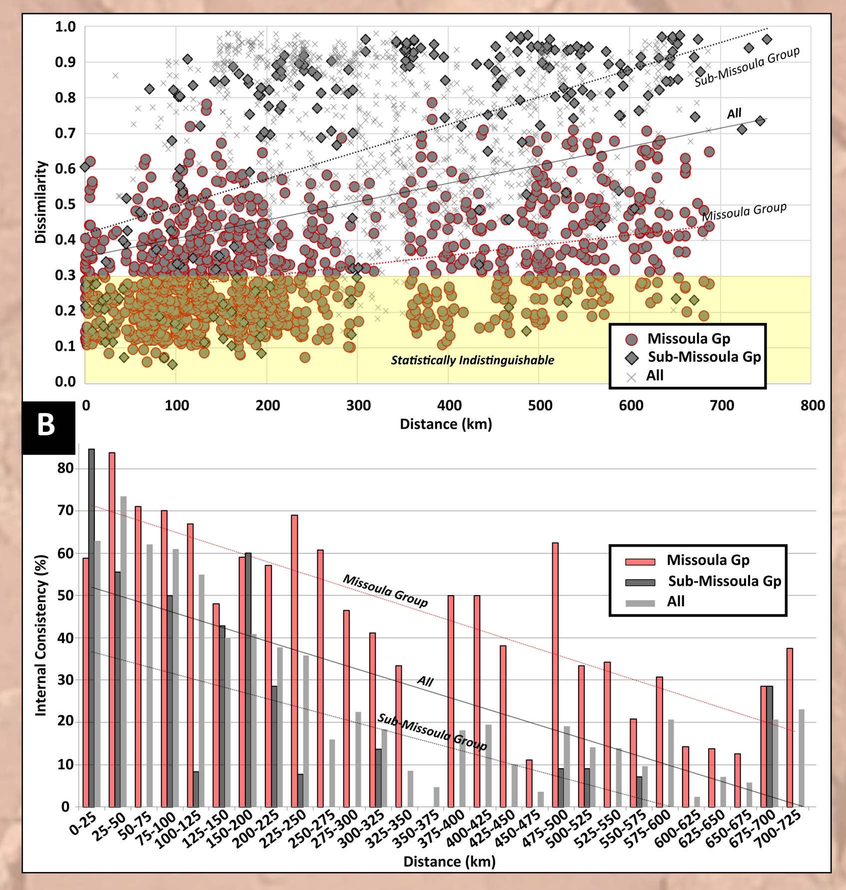
-NAMG dates (1.49-1.61 Ga) are only dominant near (<200 km) the Priest River block.

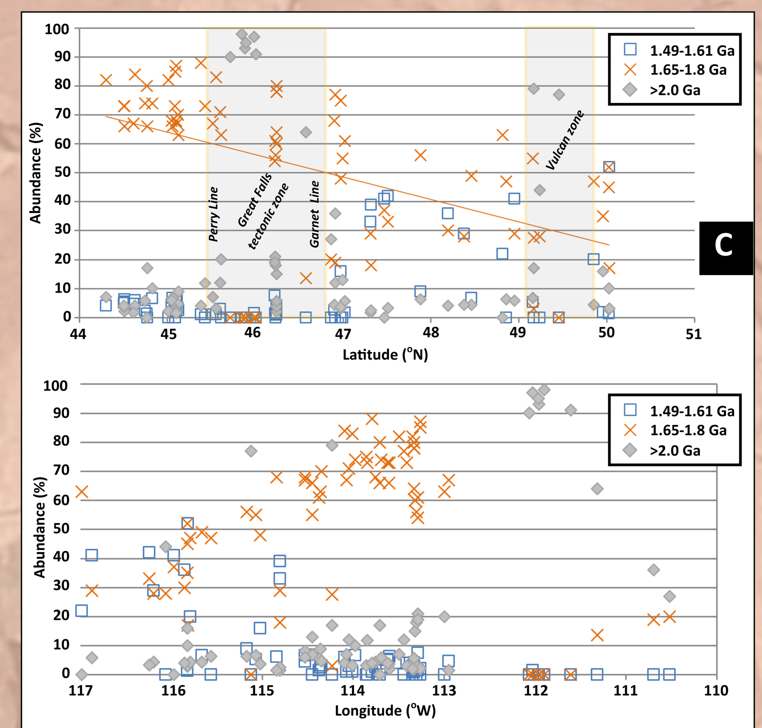
-NAMG dates are nearly absent south of the Garnet line.

-Dates >2.0 Ga, attributed to cratonic crust in the Wyoming, Medicine Hat, and Hearne blocks, are only abundant where the Great Falls Tectonic and Vulcan Zones intersect the basin.









Stacked probability curves of reported (see methods for data sources) U/Pb dates from detrital zircons from **A)** spatial areas. Colored boxes denote prominent date populations, see text for description. Internal consistencies (see definition of terms) are shown in the right column. N denotes the number of samples, n denotes the total number of analyses. **B)** Dissimilarity and internal consistency plotted against distance between sample locations. Linear best fit lines shown for comparisons of only Missoula Group samples, all samples, and sub-Missoula Group samples. **C)** Abundance of key date populations plotted against geographic position. Overlay in upper plot shows general position of structural lineaments bounding Paleoproterozoic provinces. Solid line denotes linear best fit of the 1.65-1.80 Ga dataset. **D)** Internal consistency as a function of the area measured (see methods) for equivalent stratigraphic samples. Logarithmic best fit line shown.

Assessment of the rift model

Assumptions

- Sheetflood deposition resulted in detrital zircons that are NOT evenly distributed in space or time
- Detrital zircon signatures are only diagnostic for a stratigraphic package when samples are within ~200 km of each other

Observations

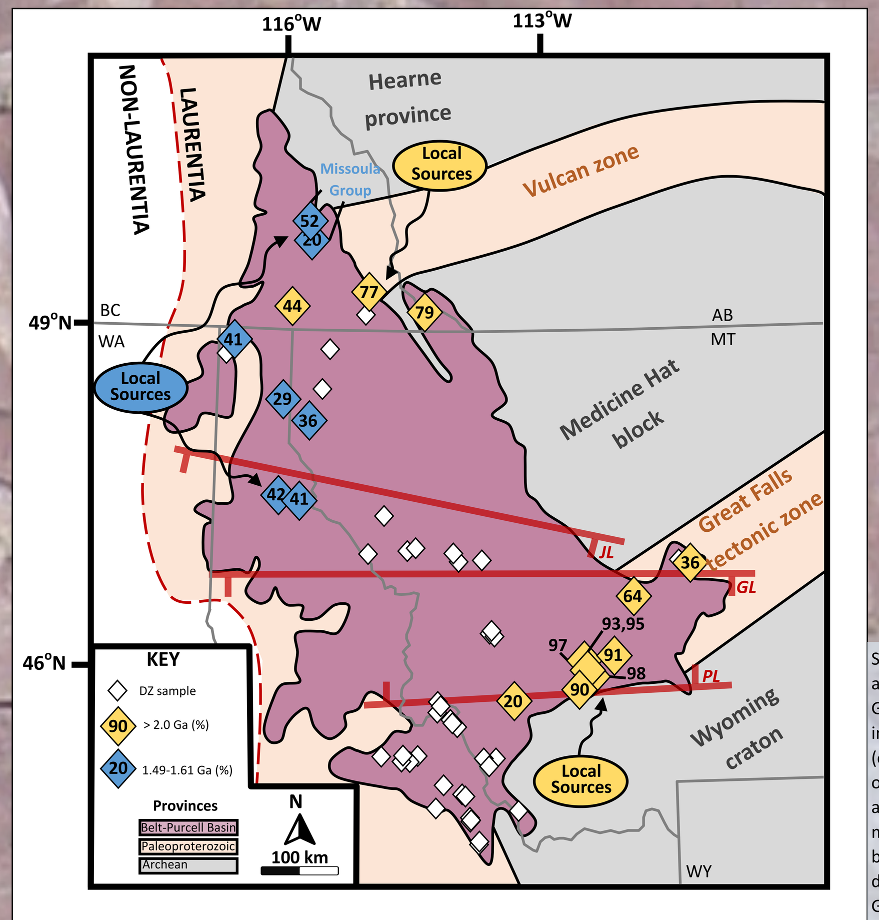
- The NAMG signature is spatially biased, only dominating when samples are near the Priest River block
- The strength of the NAMG signature may diminish upsection, but the apparent loss occurring at the Missoula Group is due to spatial bias
- Yavapai-Mazatzal-Mojave signature gradually becomes more abundant upsection and to the south

Interpretations

- Source terranes remained in communication with the Belt-Purcell basin throughout deposition
- Sheetflood deposition resulted in poor mixing and limited transport of sediment packages
- Gradual changes in the detrital zircon signature through time do NOT require a major basin reorganization
- Slow and gradual denudation of a widespread pediment satisfies the observations

Prediction

- Missoula Group and equivalent strata in the north and western part of the basin, within ~200 km of the Priest River block, should contain a NAMG signature



Spatial distribution of samples with high abundances of NAMG (blue) and >2.0 Ga date populations (yellow). Numbers indicate abundance, as a percentage (only values >20% are shown). Position of inferred long-lived source terranes are shown as ovals. Structural lineaments (Winston, 1986) are shown as bold lines, with dashes on inferred down-dropped side: Jocko Line (JL); Garnet Line (GL); and Perry line (PL).

Constraints for viable tectonic models

- Long-lived deposition, with stable baselevel conditions
- Minor to absent magmatism
- Lack of angular unconformities
- Thickness changes across structural liniments
- Source terranes remained in communication throughout the life of the basin
- Limited exhumation of surrounding Archean cratonic blocks
- Gradual decrease in NAMG abundance (derived from the west) upsection
- Gradual increase in Yavapai-Mazatzal-Mojave abundance (derived from south) upsection
- Upper unconformity (mostly the Sauk sequence boundary) cuts upsection towards the center of the basin

Conclusions

- Stratigraphic position alone does not predict detrital zircon signature
- Detrital zircon signatures have low internal consistencies and carry less than ~200 km
- North American Magmatic Gap dates (1.49-1.61 Ga) are only dominant within 200 km of the Priest River block and remain present throughout deposition
- Earliest Paleoproterozoic and Archean dates (> 2.0 Ga) are localized near the Perry and Vulcan Lines
- The fundamental assumption and foremost prediction of the conventional rift model are inconsistent with the cataloged detrital zircon data
- Deposition occurred at grade in a low-relief landscape without fault block rotation, sudden removal of source terrains, or significant exhumation of the surrounding Archean blocks
- kilometers of vertical accommodation space were filled in the absence of significant horizontal extension of the upper crust, consistent with the hypothesis that vertical motions dominated the "boring billion"

References

Special thanks to Marc Hendrix and Shibu Arens for sharing their unpublished datasets.

Aleinikoff, J.N., Lund, K. and Fanning, C.M., 2015. SHRIMP U–Pb and REE data pertaining to the origins of xenotime in Belt Supergroup rocks: evidence for ages of deposition, hydrothermal alteration, and metamorphism. Canadian Journal of Earth Sciences, 52(9), pp.722-745.
Aleinikoff, J.N., Slack, J.F., Lund, K., Evans, K.V., Fanning, C.M., Mazdab, F.K., Wooden, J.L. and Pillers, R.M., 2012. Constraints on the timing of Co-Cu±Au mineralization in the Blackbird district, Idaho, using SHRIMP U-Pb ages of monazite and xenotime plus zircon ages of related Mesoproterozoic orthogneisses and metasedimentary rocks. Economic Geology, 107(6), pp.1143-1175.
Brasier, M., 2012. Secret chambers: the inside story of cells and complex life. OUP Oxford.
Cressman, E.R., 1989. Reconnaissance stratigraphy of the Prichard Formation (Middle Proterozoic) and the early development of the Belt Basin, Washington, Idaho, and Montana. United States Geological Survey, Professional Paper;(USA), 1490.
Cressman, E.R., 1982. Generalized Stratigraphic Section of the Prichard Formation, Basal Belt Supergroup, Proterozoic Y, Near Plains, Montana (No. 82-495).
Cressman, E.R., 1985. Prichard Formation of the lower part of the Belt Supergroup (middle Proterozoic), near Plains, Sanders County, Montana.
Evans, D.A. and Mitchell, R.N., 2011. Assembly and breakup of the core of Paleoproterozoic–Mesoproterozoic supercontinent Nuna. Geology, 39(5), pp.443-446.
Gardner, D.W., 2008. Sedimentology, stratigraphy, and provenance of the upper Purcell Supergroup, southeastern British Columbia, Canada: implications for syn-depositional tectonism, basin models, and paleogeographic reconstructions (Doctoral dissertation, University of Victoria).
Hamilton, W.B., 2019. Toward a myth-free geodynamic history of Earth and its neighbors. Earth-Science Reviews, p.102905.
Höy, T., 1993. Geology of the Purcell Supergroup in the Fernie west-half map area, southeastern British Columbia (Vol. 84). Province of British Columbia, Ministry of Energy, Mines and Petroleum Resources.
Jones III, J.V., Daniel, C.G. and Doe, M.F., 2015. Tectonic and sedimentary linkages between the Belt-Purcell basin and southwestern Laurentia during the Mesoproterozoic, ca. 1.60–1.40 Ga. Lithosphere, 7(4), pp.465-472.
Lewis, R.S., Vervoort, J.D., Burmester, R.F. and Oswald, P.J., 2010. Detrital zircon analysis of Mesoproterozoic and Neoproterozoic metasedimentary rocks of north-central Idaho: implications for development of the Belt Purcell basin. Canadian Journal of Earth Sciences, 4 (11), pp.1383-1404.
Lewis, R.S., Vervoort, J.D., Burmester, R.F., McClelland, W.C. and Chang, Z., 2007. Geochronological constraints on Mesoproterozoic and Neoproterozoic (?) high-grade metasedimentary rocks of north-central Idaho, USA. In SEPM Special Publication (Vol. 86, pp. 37-53). Society for Sedimentary Geology.
Link, P.K., Fanning, C.M., Lund, K.I. and Aleinikoff, J.N., 2007. Detrital zircons, correlation and provenance of Mesoproterozoic Belt Supergroup and correlative strata of east-central Idaho and southwest Montana. Proterozoic Geology of western North America and Siberia. Edited by PK Link and RS Lewis. SEPM Special Publication, 86, pp.101-128.
Link, P.K., Stewart, E.D., Steel, T., Sherwin, J.A., Hess, L.T. and McDonald, C., 2016. Detrital zircons in the Mesoproterozoic upper Belt Supergroup in the Pioneer, Beaverhead, and Lemhi Ranges, Montana and Idaho: The Big White arc. Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper, 522.
McMechan, M.E., 1981. The Middle Proterozoic Purcell Supergroup in the southwestern Rocky and southeastern Purcell Mountains, British Columbia and the initiation of the Cordilleran miogeocline, southern Canada and adjacent United States. Bulletin of Canadian Petroleum Geology, 29(4), pp.583-621.
Medig, K.P.R., Thorkelson, D.J., Davis, W.J., Rainbird, R.H., Gibson, H.D., Turner, E.C. and Marshall, D.D., 2014. Pinning northeastern Australia to northwestern Laurentia in the Mesoproterozoic. Precambrian Research, 249, pp.88-99.
Mueller, P., Mogk, D., Wooden, J. and Spake, D., 2016. U-Pb ages of zircons from the Lower Belt Supergroup and proximal crystalline basement: Implications for the early evolution of the Belt Basin. Geological Society of America Special Papers, 522, pp.SPE522-11.
Mulder, J.A., Halpin, J.A. and Daczko, N.R., 2015. Mesoproterozoic Tasmania: witness to the east Antarctica–Laurentia connection within Nuna. Geology, 43(9), pp.759-762.
Price, R.A., 1964. The Precambrian Purcell System in the Rocky Mountains of southern Alberta and British Columbia. Bulletin of Canadian Petroleum Geology, 12(2), pp.399-426.
Roberts, N.M., 2013. The boring billion?–Lid tectonics, continental growth and environmental change associated with the Columbia supercontinent. Geoscience Frontiers, 4(6), pp.681-691.
Ross, G.M. and Villeneuve, M., 2003. Provenance of the Mesoproterozoic (1.45 Ga) Belt basin (western North America): Another piece in the pre-Rodinia paleogeographic puzzle. Geological Society of America Bulletin, 115(10), pp.1191-1217.
Satkoski, A.M., Wilkinson, B.H., Hietpas, J. and Samson, S.D., 2013. Likeness among detrital zircon populations—An approach to the comparison of age frequency data in time and space. Bulletin, 125(11-12), pp.1783-1799.
Sears, J.W., Chamberlain, K.R. and Buckley, S.N., 1998. Structural and U-Pb geochronological evidence for 1.47 Ga rifting in the Belt basin, western Montana. Canadian Journal of Earth Sciences, 35(4), pp.467-475.
Sears, J.W., Link, P.K. and Lewis, R.S., 2006. Rift destabilization of a Proterozoic epicontinental pediment: A model for the Belt-Purcell basin, North America. SPECIAL PUBLICATION-SEPM, 86, p.55.
Stewart, E.D., Link, P.K., Fanning, C.M., Frost, C.D. and McCurry, M., 2010. Paleogeographic implications of non-North American sediment in the Mesoproterozoic upper Belt Supergroup and Lemhi Group, Idaho and Montana, USA. Geology, 38(10), pp.927-930.
Whitmeyer, S.J. and Karlstrom, K.E., 2007. Tectonic model for the Proterozoic growth of North America. Geosphere, 3(4), pp.220-259.
Winston, D., 1986. Sedimentation and Tectonics of the Middle Proterozoic Belt Basin and Their Influence on Phanerozoic Compression and Extension in Western Montana and Northern Idaho: Part II. Northern Rocky Mountains.