GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45915.1

Manuscript received 10 August 2018
Revised manuscript received 12 December 2018
Manuscript accepted 13 March 2019

Long-lived transcontinental sediment transport pathways of East Gondwana

Sara Morón[1,2], Peter A. Cawood[3], Peter W. Haines[4], Stephen J. Gallagher[1], Sabin Zahirovic[2], Christopher J. Lewis[5], and Louis Moresi[1]
[1]School of Earth Sciences, University of Melbourne, Parkville, Victoria 3010, Australia
[2]EarthByte Group, School of Geosciences, University of Sydney, New South Wales 2006, Australia
[3]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria 3800, Australia
[4]Geological Survey of Western Australia, 100 Plain Street, East Perth, Western Australia 6004, Australia
[5]Geoscience Australia, GPO Box 378, Canberra, Australian Capital Territory 2601, Australia

ABSTRACT

Few modern sediment dispersal pathways predate the breakup of Pangea. This suggests that river lifespan can be controlled by continental assembly and dispersal cycles, with the longest-lived river systems present during supercontinent regimes. Based on the strikingly similar age spectra and Hf isotopic array extracted from Paleozoic to early Mesozoic sedimentary sequences from the Paleo-Tethyan margin basins, we argue that a long-lived supercontinental-scale system, with headwaters originating in Antarctica, flowed northward to finally debouch on the margin with the Paleo-Tethys Ocean. Channel-belt thickness scaling relationships, which provide an estimate of drainage area, support the notion that this was a supercontinental-scale system. Sediments were eroded from Proterozoic orogenic belts and flanked resistant kernels of Archean cratons. Remnants of this system, which can still be traced today as topographic lows, controlled post-breakup drainage patterns in Gondwanan fragments in Western Australia. We conclude that supercontinental regimes allow sediment dispersal systems to be long-lived, as they provide both an abundant sediment supply, due to erosion of large-scale, collision-related internal mountain systems, and a stable, large-scale configuration that lasts until breakup.

INTRODUCTION

Sediment dispersal pathways are ubiquitous systems that transverse continental domains, and as such, their evolution and longevity are likely associated with the Wilson cycle (Potter and Hambling, 2006; Gibling, 2017). For instance, the origin of large-scale drainage systems such as the Niger (West Africa), Orange (southern Africa), and Paraná (eastern South America) date back to the breakup of Pangea (Reijers et al., 1997; Dingle and Hendry, 1984). This observation poses the questions: what happens to sediment transport pathways during supercontinental regimes, and what, if any, is the relationship between pre- and post-breakup sediment dispersal patterns?

To explore the scale and lifespan of sediment transport pathways during supercontinental regimes and the controls involved, we investigate the sediment dispersal patterns of Ordovician–Triassic sequences that were deposited on the Paleo-Tethyan Gondwanan margin. These sequences were deposited during Gondwanan and Pangean regimes, and therefore the sediment sources and depocenters remained part of the same continental mass during the investigated time interval. Detrital zircon age spectra and Lu-Hf isotopes from these sequences document a long-lived transcontinental sediment dispersal system with its headwaters in Antarctica, draining through central Australia to final debouch off northwestern Australia. Additionally, we use channel-belt thickness scaling relationships to provide an independent estimate of drainage area of this river system during the Triassic. After the breakup of Gondwana, the ancestral river pathways of this system created a template for Cenozoic fluvial networks of Western Australia, in which low-lying topographic paleovalleys can be traced.

METHODS, DATA, AND PROVENANCE FROM NORTHEASTERN GONDWANA

Previously dated detrital zircons from drill-core samples of Triassic rocks from the Northern Carnarvon Basin, Western Australia (Fig. 1), were analyzed for Lu-Hf isotopes by inductively coupled plasma–mass spectrometry (ICP-MS) (see the GSA Data Repository[1]). Results were compared with data from Paleozoic basins in Western Australia (Haines et al., 2013), Antarctica (Veevers, 2018), and Tibet (Li et al., 2010; Zhu et al., 2011) as well as with data from crystalline rocks in Antarctica (Morrissey et al., 2017) and central (Smithies et al., 2011; Hollis et al., 2013; Kirkland et al., 2013) and southwestern Australia (Smits et al., 2014). Comparison of detrital zircon age spectra from the Northern Carnarvon, Canning, and Officer Basins and Tibet (see locations in Figure 1, and in Figure DR1 in the Data Repository) show strikingly consistent threefold peaks in the ranges 1800–1500 Ma, 1250–1000 Ma, and 700–500 Ma (Figs. 2D–2L), suggesting derivation from similar sources throughout most of the Paleozoic. We are aware that age populations spanning these age ranges are related to major global orogenic events (Lawton, 2014); however, it is the distribution of these age populations in our sample set, as well as comparisons with other regions, that allow us to limit potential source areas. For example, other Paleozoic and Mesozoic basins in Australia contain only certain components of this threefold age assemblage (Figs. DR4F–DR4G, DR5A) despite being also part of East Gondwana, and in other cases none of the age assemblages are present (Fig. DR5B); thus we consider that this is a diagnostic

---

[1] GSA Data Repository item 2019188, the data presented in the paper, as well as a detailed description of the analytical and statistical methods performed to analyze the data, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

CITATION: Morón, S., et al., 2019, Long-lived transcontinental sediment transport pathways of East Gondwana: Geology, v. 47, p. 513–516, https://doi.org/10.1130/G45915.1

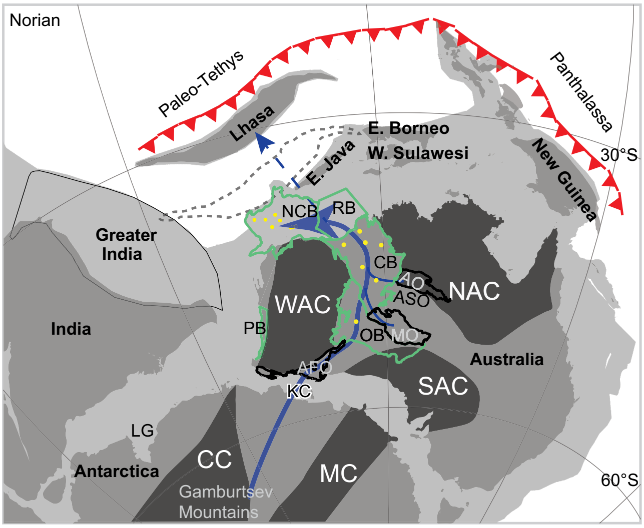

Figure 1. Continental configuration of East Gondwana at ca. 215 Ma (Norian), with continental outlines (light gray), reconstructed present-day coastlines (medium gray), cratons (dark gray), western Australian continental basins (green), and sample locations (yellow). Dashed gray line represents the outline of Lhasa in the position where it drifted from the Gondwanan margin in the Late Triassic. Blue solid lines show inferred main sediment dispersal pathways that were active before and during Norian, and dashed blue line shows how the sediment pathway would have changed as the Lhasa terrain drifted, based on zircon chronology and Hf data (see Fig. 2). Tectonic reconstructions were made in open-source and cross-platform GPlates software (https://www.gplates.org). AFO—Albany-Fraser orogen; AO—Arunta orogen; ASO— Alice Springs orogen; CB—Canning Basin; CC—Crohn craton; KC—Knox Coast; LG—Lambert graben; MC—Mawson craton; MO—Musgrave orogen; NAC—North Australian craton; NCB—Northern Carnarvon Basin; OB— Officer Basin; PB—Perth Basin; RB—Roebuck Basin; SAC—South Australian craton; WAC—West Australian craton.

ensemble of ages. We acknowledge that there are small age modes that vary with depositional age (Figs. 2D–2L) and that it is not possible to determine whether they are the result of genuine differences in provenance, intra-sample sorting during transport, or the moderate sample size ($n \approx 100$). However, even if these small variations in age modes are genuine, they would be associated with changes in minor sediment transport pathways, not the large-scale dispersal patterns that are the focus of this study. Results of the Kolmogorov-Smirnov (KS) dissimilarity, described as the fractional difference between two distributions, show that in all possible age permutations, the dissimilarity between any two given spectra never exceeds 50% (Fig. DR7). Despite the fact that it has been argued that this non-parametric statistic is sensitive to sample size (Vermeesch, 2018), the difference between bootstrapped mean KS dissimilarities and the original ones are <4% (Fig. DR8), suggesting that in this case the KS dissimilarity provides a reliable indication of the similarities between the age spectra presented here.

Lutetium-hafnium (Lu-Hf) analysis of dated zircon grains allowed us to refine the criteria to discriminate source areas of similar age. The threefold age assemblage displays distinctive initial Hf isotopic ratios (Figs. 2A and 2B). Integration of U-Pb and Hf detrital zircon isotopic data for Western Australian basins can be closely linked to crystalline source regions in Australia and Antarctica within Gondwana. Zircons in the range 1800–1500 Ma have similar ages and Hf-isotopic values (^{176}Hf/^{177}Hf = 0.2815–0.2820) as igneous zircons from the Albany-Fraser and Arunta orogens (Western Australia; Fig. 2A; Hollis et al., 2013; Smits et al., 2014). Detrital zircons spanning 1300–1000 Ma correspond in age range and Hf-isotopic values (^{176}Hf/^{177}Hf = 0.2817–0.2822) with the Albany-Fraser orogen (Smits et al., 2014), the Musgrave orogen (central Australia; Smithies et al., 2011; Kirkland et al., 2013), and magmatic rocks from East Antarctica (Windmill Islands; Morrissey et al., 2017). Ages between 700 and 500 Ma show the largest spread in the Hf-isotopic signal, with ^{176}Hf/^{177}Hf ratios ranging from 0.2813 to 0.2827. The origin of this detritus is controversial. One hypothesis is that the Paterson orogen (Western Australia; Fig. DR1), which contains granites dated at 650–630 Ma (Martin et al., 2017), is a possible source for some of this detritus; however, the Hf-isotopic array extracted from the zircons presented here is lower than ^{176}Hf/^{177}Hf = 0.2820 (Fig. DR10), arguing against it acting as a significant sedimentary source. Another hypothesis suggests that the 700–500 Ma population is originally from Antarctica and entered via eastern Australia but underwent several phases of sediment recycling in Neoproterozoic–late Paleozoic basins in central Australia (cf. Haines et al., 2013). An alternative hypothesis is that the 700–500 Ma zircon population is directly derived from Antarctica (Cawood and Nemchin, 2000; Veevers, 2018). A comparison of the Hf-isotopic array for similar-age detrital zircons in Permian–Triassic sandstones (Veevers, 2018) in the Prince Charles Mountains and offshore Prydz Bay (Antarctica) supports this conclusion (Fig. 2A). The lack of 700–500 Ma ages (Fig. DR4) in sedimentary units deposited after the breakup from Antarctica in Western Australia substantiates this idea.

The common provenance record for the Paleozoic–Mesozoic strata in Western Australia argue for a long-lived and stable sediment dispersal system. Furthermore, there is no change in provenance associated with the end-Carboniferous to early Permian glaciations (Gzhelian–Sakmarian, ca. 305–285 Ma; Mory et al., 2008), suggesting that sediment transport pathways were not significantly affected by glacial activity.

Our data indicate that detritus in the basins along the Paleo-Tethyan margin of northern Gondwana were fed by two main sediment transport pathways: a south-to-north system with headwaters in mountains in East Antarctica (cf. Cawood and Nemchin, 2000; Veevers, 2018), and a subsidiary network starting in central Australia. Previously published isopach maps from Paleozoic sequences (Mory and Haines, 2013; Fig. DR11), paleocurrent data from onshore Permo-Carboniferous units (Martin, 2008; Fig. DR11B), and 700 seismically mapped Triassic channel belts (Martin et al., 2018; Fig. DR11A) from offshore Western Australia provide additional physical evidence for sediment transport pathways. Our interpretation refutes the idea that basins along the Paleo-Tethyan margin of northern Gondwana were fed by only Australia-wide sediment dispersal systems, derived from eastern Australia (Wang et al., 2016). The euhedral nature of the Triassic zircons (see the Triassic zircon population in Figs. 2D and 2E; Fig DR12), which requires derivation from local sources, and the lack of Permian ages (e.g., Shaanan and Rosenbaum, 2018) argue against eastern Australian sources. Furthermore, channel-belt thickness scaling relationships, which provide an estimate of drainage area, suggest a continental-scale system, at least during the Triassic (Fig. 3). Channel-belt thickness may be used as a proxy for paleo-flow depth, which scales to the contributing drainage area. Channel-belt thickness data of Triassic sedimentary sequences in the Northern Carnarvon Basin (Martin et al., 2018) and the scaling relationship of Milliken et al. (2018) provide a first-order estimate for the scale of the paleo-catchment area (see the Data Repository for details). Although a lack of data prevents us from applying this approach to older parts of the successions onshore, the common provenance record throughout is consistent with a similar continental-scale drainage system existing since the Ordovician, while rates of sediment supply may have varied over time.

THE ROLE OF SUPERCONTINENTAL-SCALE TECTONICS IN CONTROLLING TRANSCONTINENTAL SEDIMENT TRANSPORT PATHWAYS

We suggest that the scale and duration of the sediment transport pathways supplying detritus to the Western Australian basins require both a large sediment supply and a stable plate-tectonic configuration. Thermochronology data support

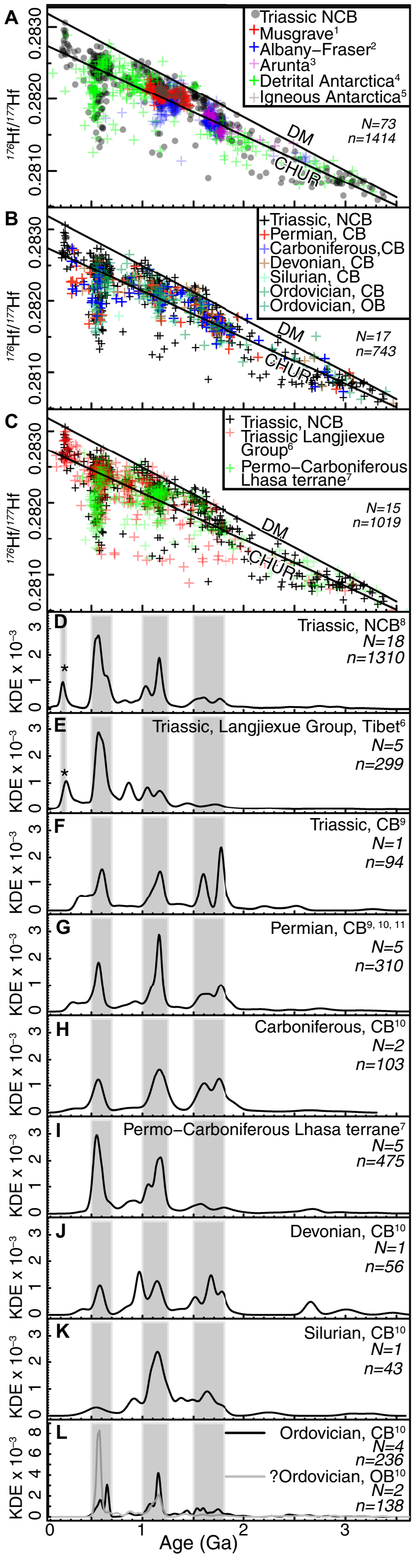

Figure 2. Hafnium evolution plots (with isotopic values calculated at grain crystallization age) of detrital zircons from sedimentary deposits on Paleo-Tethyan margin of northern Gondwana. *N*—number of samples, *n*—number of grains. A: Comparison against data sets extracted from likely potential sediment sources. B: Comparison with Paleozoic units from central and western Australia. C: Comparison with detrital zircons from Triassic and Permian–Carboniferous sequences from Tibet. D–L: Kernel density estimation (KDE) plots of U-Pb age data from detrital zircons. Consistency in three major peaks in age spectra (gray shades) and Hf isotopic signal through time suggest existence of a continental-scale long-lived fluvial system that existed during entire Paleozoic and the Triassic. A detailed list of sample IDs and present-day locations for the entire dataset are provided in the Data Repository (see footnote 1). Plot is constructed using the statistical package "provenance" (Vermeesch, et al., 2016). NCB—Northern Carnarvon Basin; CB—Canning Basin; OB—Officer Basin; CHUR—chondrite universal reservoir (Bouvier et al., 2008); DM—depleted mantle (Vervoort and Blichert-Toft, 1999). *Rhyolite, K/Ar age 213 ± 3 Ma (von Stackelberg et al., 1980). Data sources: 1—Smithies et al. (2011); Kirkland et al. (2013); 2—Smits et al. (2014); 3—Hollis et al. (2013); 4—Veevers (2018); 5—Morrissey et al. (2017); 6—Li et al. (2010); 7—Zhu et al. (2011); 8—Lewis and Sircombe (2013); 9—http://www.ga.gov.au/geochron-sapub-web/geochronology/shrimp/search.htm; 10—Haines et al. (2013); 11—Martin (2008).

the notion that East Antarctic terrains within Gondwana may have delivered a significant volume of sediments to generate and maintain large sediment dispersal systems. Apatite fission-track data from the northern Prince Charles Mountains and the Mawson Escarpment in Antarctica indicate that as much as 5 km of denudation took place from the Carboniferous until the Jurassic (Lisker et al., 2003). Additionally, models based on radar, gravity, and magnetic data support the idea that significant uplift took place in the Gamburtsev Mountains, East Antarctica (Fig. 1), during the Permian. Modeling of these geophysical data sets suggests that uplift was due to the combination of rift-flank uplift, root buoyancy, and the isostatic response to fluvial and glacial erosion, and these would have provided sufficient relief to account for significant amounts of denudation (Ferraccioli et al., 2011). Furthermore, the intra-continental deformation event associated with the Alice Springs orogeny (ca. 450–300 Ma; Fig. 1; Haines et al., 2013) in central Australia generated an additional source of sediments, which then fed into the main south-to-north sediment transport pathway. Large volumes of sediment being transported over great distances during supercontinent regimes have also been inferred based on zircon chronology of Cambrian to Ordovician sedimentary sequences from the Tethyan Himalaya (Myrow et al., 2010).

Our data show that the sediment transport system presented here developed in an intercontinental setting (Fig. 1), similar to modern large-scale drainage systems (e.g., Amazon [South America] and Mississippi [USA] rivers; Fig. 3). The intercontinental setting and the supercontinent regime in which these sediment transport pathways developed were likely key factors for controlling the longevity of this system (Fig. 1). Furthermore, this sediment transport system developed in a setting flanked by resistant cratons (Fig. 1), establishing a stable configuration that allowed the pathways to be entrenched in adjoining Proterozoic orogens and resilient to change.

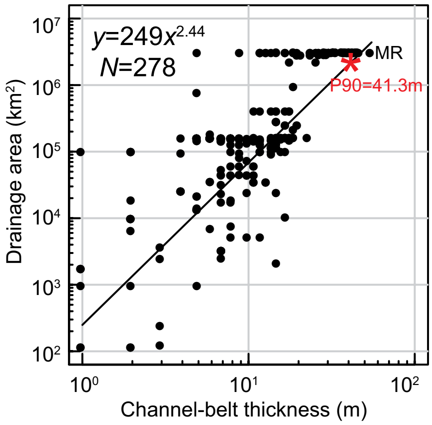

Figure 3. Relationship between channel-belt thickness and drainage basin area, which is indicative of paleoflow and discharge-drainage area. Both global Quaternary channel-belt database and best-fit line are from Milliken et al. (2018). Scaling relationship is from Milliken et al. (2018). 90th percentile (P90) channel-belt thickness for Triassic Mungaroo Formation (North West Shelf, Australia; red asterisk) is from Martin et al. (2018). P90 thickness value approximates bankfull discharge of trunk channel and thus provides an appropriate estimate of the drainage area; see details about the method and dataset in Data Repository (see footnote 1). Results of scaling analysis provide independent line of evidence that supports our claim that sediment dispersal system presented here has continental scale. MR—Mississippi River (USA).

The lack of post-Hauterivian (ca. <130 Ma) clastic deposits (Lewis and Sircombe, 2013) in the Northern Carnarvon Basin indicates that this system ceased delivering sediments from Antarctica to the North West Shelf of Australia after the breakup of Gondwana. However, while this system decreased in scale and was no longer active, it created a template for some of the Cenozoic drainage systems in Western Australia, whose paleo-valleys have been preserved (e.g., Magee, 2009). This study showcases how supercontinent regimes allow sediment transport pathways to be long-lived and at a scale proportional to continental area. This means that supercontinents supply both sufficient sediment volume, through the generation of large-scale internal mountain systems associated with their collisional assembly, and a stable, large-scale configuration that lasts until breakup. This suggests that despite the fact that most modern drainage systems postdate the breakup of Pangea (Potter and Hamblin, 2006; Gibling, 2017), ancestral sediment transport pathways can still be traced to origins within the Gondwanan supercontinent cycle.

ACKNOWLEDGMENTS

This research was supported by Australian Research Council's Industrial Transformation Research Hubs project IH130200012 and grant FL160100168. Morón acknowledges support from the University of Melbourne Early Career Researcher grant. We thank Geoscience Australia for providing access to the zircons used for further Hf analyses, and J.D. Woodhead and R. Maas for their help with the Hf isotopic analysis. Morón thanks M.R. Gibling for his helpful discussions about the longevity of sediment dispersal systems and M. Blum for his comments about the scaling analysis. We thank three anonymous reviewers for their constructive comments on earlier versions of this manuscript. Haines publishes with the permission of the Executive Director of the Geological Survey of Western Australia. Lewis publishes with the permission of the Chief Executive Officer of Geoscience Australia.

REFERENCES CITED

Bouvier, A., Vervoort, J.D., and Patchett, P.J., 2008, The Lu-Hf and Sm-Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets: Earth and Planetary Science Letters, v. 273, p. 48–57, https://doi.org/10.1016/j.epsl.2008.06.010.

Cawood, P.A., and Nemchin, A.A., 2000, Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia: Sedimentary Geology, v. 134, p. 209–234, https://doi.org/10.1016/S0037-0738(00)00044-0.

Dingle, R.V., and Hendry, Q.B., 1984, Late Mesozoic and Tertiary sediment supply to the eastern Cape Basin (SE Atlantic) and palaeo-drainage systems in Southwestern Africa: Marine Geology, v. 56, p. 13–26, https://doi.org/10.1016/0025-3227(84)90003-3.

Ferraccioli, F., Finn, C.A., Jordan, T.A., Bell, R.E., Anderson, L.M., and Damaske, D., 2011, East Antarctic rifting triggers uplift of the Gamburtsev Mountains: Nature, v. 479, p. 388–392, https://doi.org/10.1038/nature10566.

Gibling, M.R., 2017, River history and longevity through geological time: An update, *in* Hubbard, S.M., et al., eds., Conference Programme and Abstracts Volume, 11th International Conference on Fluvial Sedimentology, 17–21 July, Calgary, Canada: Calgary, International Association of Sedimentologists, p. 61.

Haines, P.W., Wingate, M.T.D., and Kirkland, C.L., 2013, Detrital zircon U-Pb ages from the Paleozoic of the Canning and Officer Basins, Western Australia: Implications for provenance and interbasin connections, *in* Keep, M., and Moss, S.J., The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, Western Australia: Perth, Petroleum Exploration Society of Australia, 19 p.

Hollis, J.A., Kirkland, C.L., Spaggiari, C.V., Tyler, I.M., Haines, P.W., Wingate, M.T.D., Belousova, E.A., and Murphy, R.C., 2013, Zircon U–Pb–Hf isotope evidence for links between the Warumpi and Aileron provinces, west Arunta region: Geological Survey of Western Australia, Record 2013/9, 30 p.

Kirkland, C.L., Smithies, R.H., Woodhouse, A.J., Howard, H.M., Wingate, M.T.D., Belousova, E.A., Cliff, J.B., Murphy, R.C., and Spaggiari, C.V., 2013, Constraints and deception in the isotopic record: The crustal evolution of the west Musgrave Province, central Australia: Gondwana Research, v. 23, p. 759–781, https://doi.org/10.1016/j.gr.2012.06.001.

Lawton, T.F., 2014, Small grains, big rivers, continental concepts: Geology, v. 42, p. 639–640, https://doi.org/10.1130/focus072014.1.

Lewis, C.J., and Sircombe, K.N., 2013, Use of U-Pb geochronology to delineate provenance of North West Shelf sediments, Australia, *in* Keep, M., and Moss, S.J., The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, Western Australia: Perth, Western Australia: Perth, Petroleum Exploration Society of Australia, 27 p.

Li, G., Liu, X., Pullen, A., Wei, L., Liu, X., Huang, F., and Zhou, X., 2010, In-situ detrital zircon geochronology and Hf isotopic analyses from Upper Triassic Tethys sequence strata: Earth and Planetary Science Letters, v. 297, p. 461–470, https://doi.org/10.1016/j.epsl.2010.06.050.

Lisker, F., Brown, R., and Fabel, D., 2003, Denudational and thermal history along a transect across the Lambert Graben, northern Prince Charles Mountains, Antarctica, derived from apatite fission track thermochronology: Tectonics, v. 22, 1055, https://doi.org/10.1029/2002TC001477.

Magee, J.W., 2009, Palaeovalley groundwater resources in arid and semi-arid Australia—A literature review: Geoscience Australia Record 2009/03, 224 p.

Martin, E.L., Collins, W.J., and Kirkland, C.L., 2017, An Australian source for Pacific-Gondwanan zircons: Implications for the assembly of northeastern Gondwana: Geology, v. 45, p. 699–702, https://doi.org/10.1130/G39152.1.

Martin, J., 2008, Sedimentology, provenance and icesheet dynamics of the Late Palaeozoic glaciation in Oman and the Canning Basin (West Australia): An integrated outcrop and subsurface study of the Permo-Carboniferous glaciogenic suites of Arabia and Western Australia [Ph.D. thesis]: Manchester, UK, University of Manchester, 274 p.

Martin, J., Fernandes, A.M., Pickering, J., Howes, N., Mann, S., and McNeil, K., 2018, The stratigraphically preserved signature of persistent backwater dynamics in a large paleodelta system: The Mungaroo Formation, North West Shelf, Australia: Journal of Sedimentary Research, v. 88, p. 850–872, https://doi.org/10.2110/jsr.2018.38.

Milliken, K.T., Blum, M.D., Snedden, J.W., and Galloway, W.E., 2018, Application of fluvial scaling relationships to reconstruct drainage-basin evolution and sediment routing for the Cretaceous and Paleocene of the Gulf of Mexico: Geosphere, v. 14, p. 749–767, https://doi.org/10.1130/GES01374.1.

Morrissey, L.J., Payne, J.L., Hand, M., Clark, C., Taylor, R., Kirkland, C.L., and Kylander-Clark, A., 2017, Linking the Windmill Islands, east Antarctica and the Albany–Fraser Orogen: Insights from U-Pb zircon geochronology and Hf isotopes: Precambrian Research, v. 293, p. 131–149, https://doi.org/10.1016/j.precamres.2017.03.005.

Mory, A.J., and Haines, P.W., 2013, A Paleozoic perspective of Western Australia, *in* Keep, M., and Moss, S.J., eds., The Sedimentary Basins of Western Australia IV: Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, Western Australia: Perth, Petroleum Exploration Society of Australia, 27 p.

Mory, A.J., Redfern, J., and Martin, J.R., 2008, A review of Permian–Carboniferous glacial deposits in Western Australia, *in* Fielding, C.R., et al., eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Papers, v. 441, p. 29–40, https://doi.org/10.1130/2008.2441(02).

Myrow, P.M., Hughes, N.C., Goodge, J.W., Fanning, C.M., Williams, I.S., Peng, S., Bhargava, O.N., Parcha, S.K., and Pogue, K.R., 2010, Extraordinary transport and mixing of sediment across Himalayan central Gondwana during the Cambrian–Ordovician: Geological Society of America Bulletin, v. 122, p. 1660–1670, https://doi.org/10.1130/B30123.1.

Potter, P.E., and Hamblin, W.K., 2006, Big rivers worldwide: Brigham Young University Geology Studies 48, 78 p.

Reijers, T.J.A., Petters, S.W., and Nwajide, C.S., 1997, The Niger Delta basin, *in* Selley, R.C., ed., Sedimentary Basins of the World, Volume 3: African Basins: Amsterdam, Elsevier, p. 151–172.

Shaanan, U., and Rosenbaum, G., 2018, Detrital zircons as palaeodrainage indicators: Insights into southeastern Gondwana from Permian basins in eastern Australia: Basin Research, v. 30, no. S1, p. 36–47, https://doi.org/10.1111/bre.12204.

Smithies, R.H., Howard, H.M., Evins, P.M., Kirkland, C.L., Kelsey, D.E., Hand, M., Wingate, M.T.D., Collins, A.S., and Belousova, E., 2011, High-temperature granite magmatism, crust-mantle interaction and the Mesoproterozoic intracontinental evolution of the Musgrave Province, Central Australia: Journal of Petrology, v. 52, p. 931–958, https://doi.org/10.1093/petrology/egr010.

Smits, R.G., Collins, W.J., Hand, M., Dutch, R., and Payne, J., 2014, A Proterozoic Wilson cycle identified by Hf isotopes in central Australia: Implications for the assembly of Proterozoic Australia and Rodinia: Geology, v. 42, p. 231–234, https://doi.org/10.1130/G35112.1.

Veevers, J.J., 2018, Gamburtsev Subglacial Mountains: Age and composition from morainal clasts and U-Pb and Hf-isotopic analysis of detrital zircons in the Lambert Rift, and potential provenance of East Gondwanaland sediments: Earth-Science Reviews, v. 180, p. 206–257, https://doi.org/10.1016/j.earscirev.2018.03.002.

Vermeesch, P., 2018, Dissimilarity measures in detrital geochronology: Earth-Science Reviews, v. 178, p. 310–321, https://doi.org/10.1016/j.earscirev.2017.11.027.

Vermeesch, P., Resentini, A., and Garzanti, E., 2016, An R package for statistical provenance analysis: Sedimentary Geology, v. 336, p. 14–25, https://doi.org/10.1016/j.sedgeo.2016.01.009.

Vervoort, J.D., and Blichert-Toft, J., 1999, Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time: Geochimica et Cosmochimica Acta, v. 63, p. 533–556, https://doi.org/10.1016/S0016-7037(98)00274-9.

von Stackelberg, U., Exon, N.F., von Rad, U., Quilty, P., Shafik, S., Beiersdorf, H., Seibertz, E., and Veevers, J.J., 1980, Geology of the Exmouth and Wallaby Plateaus off northwest Australia: Sampling of seismic sequences: Journal of Australian Geology & Geophysics, v. 5, p. 113–140.

Wang, J.-G., Wu, F.-Y., Garzanti, E., Hu, X., Ji, W.-Q., Liu, Z.-C., and Liu, X.-C., 2016, Upper Triassic turbidites of the northern Tethyan Himalaya (Langjiexue Group): The terminal of a sediment-routing system sourced in the Gondwanide Orogen: Gondwana Research, v. 34, p. 84–98, https://doi.org/10.1016/j.gr.2016.03.005.

Zhu, D.-C., Zhao, Z.-D., Niu, Y., Dilek, Y., and Mo, X.-X., 2011, Lhasa terrane in southern Tibet came from Australia: Geology, v. 39, p. 727–730, https://doi.org/10.1130/G31895.1.

Printed in USA