Supplemental Material – Data and Detailed Methods: Pace, magnitude, and nature of terrestrial climate change through the End Permian Extinction in southeastern Gondwana

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Materials

This study focuses on samples from seven drillcores containing conformable records across the Permian-Triassic boundary in the Bowen-Gunnedah-Sydney Basin System of eastern Australia (Fig. DR1). Four cores from the Bowen Basin, Queensland, Geological Survey of Queensland (GSQ), GSQ Emerald New Series 7 (ENS7), GSQ Springsure 19 (SS19), and GSQ Taroom 10 (T10) and one industry core, Origin Meeleebee 5 (MEE5), were described and sampled at the Queensland Department of Natural Resources, Mines and Energy Exploration Data Centre in Zillmere, Queensland. Wancol Lithgow DDH16 (WL16), Pacific Power Hawkesbury Bunnerong DDH1 (PHKB1), and Pacific Power Hawkesbury Eveleigh DDH1 (PHKE1), from the Sydney Basin, New South Wales, were described and sampled at the W.B. Clarke Geoscience Information Center in Londonderry, New South Wales.

Figure DR1. Map of eastern Australia showing the present-day locations of drillcores GSQ Emerald 7 (ENS7; 23.365079°S, 148.293907°E), Springsure 19 (SS19; 24.6838°S, 148.15138°E), GSQ Taroom 10 (T10; 25.21838°S, 148.80478°E), Origin Meeleebee 5 (MEE5; 26.228144°S, 149.208663°E), Wancol Lithgow DDH16 (WL16; 33.41648°S, 150.2603°E), Pacific Power Hawkesbury Bunnerong DDH1 (PHKB1; 33.970225°S, 151.230056°E), and Pacific Hawkesbury Eveleigh DDH1 (PHKE1; 33.8959°S, 151.1939°E).

ENS7, SS19, T10, and MEE5 provide a north-to-south transect through the Bowen Basin (Fig. DR1). T10 contains an expanded section, as it was drilled into the Taroom Trough, a depocenter of the basin. MEE5, located on the Roma Shelf along on the western edge of the Taroom Trough, contains a condensed section but provides a geochronological reference section for the basin (Metcalf et al., 2015). In the Sydney Basin, WL16 is located at the western cratonic margin, while PHKB1 and PHKE1 were drilled along the foredeep basin axis (Fig. DR1). In general, Sydney Basin cores are located closer to the paleo-orogenic front than cores in the Bowen Basin, which were located more proximal to the craton. Throughout the study area, the EPE is manifest as the abrupt disappearance of Permian forest-mire communities and the end of peat deposition (Michaelsen, 2002; Fielding et al., 2019; Vajda et al., 2020; McLoughlin et al., 2021), which, in combination with the spore-pollen biostratigraphy (McKellar, 1977; Mays et al., 2020), provides a datum for regional correlation. The position of the Permo-Triassic boundary, which lies some meters above the EPE, is not as well-constrained. A full discussion of the geochronological framework for the Permo-Triassic transition in the BGSBS is provided in Fielding et al. (2021).

GEOCHEMISTRY

Analytical Methods

Elemental Analysis of Mudrocks

Elemental concentrations in mudrock were determined using a Bruker Tracer 5i portable x-ray fluorescence (XRF) analyzer calibrated with a series of mudrock standards including USGS shale standards SBC-1 and SCO-2, a suite of mudrock reference materials characterized by Rowe et al. (2012), and nine in-house reference materials from Permo-Triassic mudrocks in PHKB1 described by Fielding et al. (2019). Compositions of in-house reference materials were determined by American Assay in Sparks, NV, USA, with major element concentrations measured by XRF wavelength dispersive analysis of lithium borate-fused disks and trace element concentrations determined by ICP-OES. Both standards and samples collected for the present study were analyzed four times using a Bruker Tracer 5i in the Sedimentary Geochemistry Laboratory at the University of Nebraska-Lincoln, twice under low-energy and twice under high-energy conditions with different filters, to target a series of overlapping $K\alpha$ ranges and enable precise analysis of relatively light and heavy elements. The elements Na to Fe on the periodic table were analyzed with no filter at 15 kV and 15 μ A and a count time of 30 s. Concentrations of Na and Mg were also measured under a helium flush to negate atmospheric interference. High-energy analyses were undertaken at 50 kV and 35 μ A and a count time of 30 s, with a Cu 75 μ m:Ti 25 μ m:Al 200 μ m filter for the elements Ca to Kr and a Cu 100 μ m:Ti 25 μ m:Al 200 μ m filter for the so-called volcanic elements (Co and higher on the periodic table). In general, for the instrument used in the present study, the raw count rate per second (rcps) signals lay between 20,000 and 100,000 rcps. Data are provided in Table DR1.

Paleoweathering Indices

The Chemical Index of Alteration (CIA) of Nesbitt and Young (1982) is a widely used proxy that provides a means of tracking the conversion of feldspar minerals to clay minerals via hydration during the weathering of fine-grained siliciclastics (Sheldon and Tabor, 2009). Whereas fresh crystalline rocks are characterized by relatively low CIA values (45–55), leaching of mobile oxides and concentration of Al_2O_3 during chemical weathering causes CIA values to approach 100. The CIA is calculated using the following equation:

$$CIA = 100 \times \frac{Al_2O_3}{Al_2O_3 + CaO^* + K_2O + Na_2O},$$

in which all oxides are in molar units and CaO^* represents the CaO in the silicate fraction following the method of McLennan (1993). Previous work has shown that enrichment of K_2O via metasomatism can

artificially lower CIA values, making samples appear to be less weathered than they actually are. The A-CN-K diagram, a ternary plot with apices represented by Al_2O_3 , $\text{Na}_2\text{O}+\text{CaO}^*$, and K_2O , provides a means of assessing diagenetic enrichment of K_2O in mudrocks and the degree to which samples follow expected compositional changes due to weathering (Fedo et al., 1995). Examination of the correlation between the CIA and the Chemical Index of Weathering (CIW), proposed by Harnois (1988), provides another test (Cao et al., 2019). The CIW is calculated as follows:

$$\text{CIW} = 100 \times \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O}}$$

As with the CIA, the CIW calculation uses oxides in molar units and CaO^* represents silicate-bound CaO (McLennan, 1993). The absence of K_2O from the CIW equation is intended to remove concerns related to K metasomatism. In cases where these methods show that samples are affected by metasomatism, pre-alteration K_2O concentrations are calculated as outlined in Panahi et al. (2000):

$$\text{K}_2\text{O}_{\text{corr}} = \frac{[\text{mAl}_2\text{O}_3 + \text{m}(\text{CaO}^* + \text{Na}_2\text{O})]}{1 - \text{m}}, \text{ where}$$

$$\text{m} = \frac{\text{K}_2\text{O}}{\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O}}$$

of the parent material, in this case estimated using the composition of the Lachlan Fold Belt granitoids (White and Chappell, 1983; Chappell and White, 1992). This correction recalculates K_2O values such that they fall along the predicted weathering trend. The “corrected” CIA (CIA_{corr}) may then be calculated by substituting the $\text{K}_2\text{O}_{\text{corr}}$ value for K_2O in the CIA equation noted above with the understanding that where $\text{CIA}_{\text{corr}} < \text{CIA}$, the CIA is considered to provide a more accurate reflection of weathering intensity.

An underlying assumption of the CIA and CIW proxies is that the materials being weathered are silicates. In this regard, the presence of carbonate minerals, either primary or diagenetic, can produce artificially low CIA values. Although the approach of McLennan (1993) goes some way toward correcting for the presence of carbonate, the correction assumes that carbonate concentrations are low. To account for the effects of diagenetic carbonate minerals, Garzanti et al. (2014) developed the CIX proxy, which removes CaO from the CIA equation of Nesbitt and Young (1982). Statistical tests to investigate the significance of correlation between the CIA and CIX indices are used here to screen for contamination by CaCO_3 .

Changes in sediment provenance and attendant changes in sediment composition can produce variations in the CIA that are unrelated to paleoweathering (McClennan, 1993). To assess the potential for temporal changes in sediment source, thin sections were prepared from six sandstone samples spanning the stratigraphic interval of interest PHKB1, which is situated in the depocenter of the Sydney Basin (Fielding et al., 2019). Thin sections were analyzed for mineralogy, sedimentary textures, and diagenesis using transmitted light microscopy. Point counting of framework grains was conducted on each sample using a standard petrographic microscope as outlined by Harwood (1988). Quartz, feldspar and lithic grain abundances in each sample were used to determine sandstone type (Folk, 1980) and assess provenance (Dickinson et al., 1983). In these analyses, quartz refers to monocrystalline quartz, whereas chert and polycrystalline quartz grains are counted as lithic fragments. Additional screening for spatiotemporal changes in source is provided through examination of weight-percent ratios of Ti/Al . Ti is considered a useful tracer for discriminating among sediment sources because it resides in minerals that are chemically stable and largely unaffected by diagenesis and weathering (Craigie, 2018).

Paleotemperature Estimates

Land surface temperatures (LSTs) were estimated using the approach of Yang et al. (2014), who showed that CIA values of suspended sediment carried by modern large river estuaries vary linearly on a global scale with LST. This relationship is represented by the following equation:

$$T = 0.56 \times CIA - 25.7 (r^2 = 0.50),$$

where T is temperature in degrees Celsius. With an uncertainty of c. ± 5 °C, the relationship is robust over a CIA range of c. 50–90, which corresponds to a temperature range of 3–25 °C. The equation is derived from a dataset compiled by Li and Yang (2010), who demonstrated that CIA values of suspended sediment in large rivers is more sensitive to temperature and latitude at the river mouth than factor such as drainage area, precipitation, average elevation and runoff.

Results and Interpretation

CIA, CIA_{corr}, CIW, CIX values range between 60 and 95 and show similar stratigraphic trends (Fig. DR2). CIA values in pre-End Permian Extinction (EPE) strata average 70 to 80, whereas post-EPE samples are characterized by values of 80–90. Other indices tend to have higher values, but show similar temporal trends.

To assess the potential effects of K metasomatism on CIA values, the molar A-CN-K ternary diagram developed by Fedo et al. (1995) is applied. When plotted on the A-CN-K diagram, most samples from the present study correspond to the expected weathering trend from regional source rocks, Lachlan Fold Belt Granites with CIA values of 50–55 (Fig. DR3). A subset of samples, dominantly from Permian strata, deviate from the predicted trend and show evidence for possible secondary enrichment in K₂O.

Correlation coefficients (R) for CIA vs CIW and CIA vs CIX exceed 0.7 in all cores, indicating strong positive linear relationships between the variables (Fig. DR4). The very strong, 1:1 linear relationship between CIA and CIX values, in particular, indicates that CIA values have not been strongly impacted by the presence of CaCO₃. Lower R values for CIA vs CIW reflect excess K in some samples (Fig. DR3). Substituting a CIA_{corr} value for samples in which CIA – CIA_{corr} < 0 and the absolute difference is >1, indicating significant introduction of secondary K, yields significant increase in the correlation coefficient at all sites.

Temporal changes in sediment provenance may impart changes in sediment composition that can cause shifts in CIA profiles that are not related to paleoweathering. Uniformity in ratios of Ti/Al (0.06 ± 0.02 ; n= 457) through all stratigraphic sections indicate that temporal shifts in weathering indices cannot be attributed to changes in sediment provenance (Table DR1). Point counting sandstone framework grains reveals that despite variation in grain size from very fine to medium-grained sand and sorting (poorly to well sorted), all sandstones in PHKB1 are quartz-poor litharenites (Table DR2). Framework grains are dominated by lithoclasts ($85.5 \pm 9.4\%$), with some quartz ($10.3 \pm 8.0\%$) and minor feldspar ($4.2 \pm 2.9\%$). Lithoclasts are mainly sedimentary rock fragments ($76.2 \pm 7.3\%$) including mudrock, limestone, and chert, along with lesser amounts of igneous ($9 \pm 7.5\%$) clasts. A significant proportion of the quartz framework grains have characteristics consistent with a nearby volcanic origin, including embayments, preserved crystal shapes, and a lack of inclusions. Although no samples are quartz-rich, upper Permian sandstones tend to contain slightly less quartz than do Triassic counterparts (Table DR 2). Results correspond to those of previous investigations of these stratigraphic units (Loughnan, 1963, 1966; Retallack, 1999), which used various proxies to conclude that sediment provenance remained uniform across the Permo-Triassic transition. These results are also consistent with paleocurrent data, which show that sediment dispersal directions remained unchanged through the upper Permian-Lower Triassic (Fielding et al., 2021)

Considered as a whole, the results indicate that although some (mainly pre-EPE) samples show evidence of secondary addition of K through metasomatism, CIA profiles were not affected by either carbonate concentrations or shifts in sediment provenance. CIA_{corr} values calculated for samples in which CIA – CIA_{corr} < 0 and the absolute difference is >1 provide a means of correcting for the effects of K metasomatism on affected samples. Thus, we feel confident that CIA + CIA_{corr} profiles provide reliable records of temporal changes in chemical weathering intensity and paleotemperatures in the study area.

Figure DR2. Comparison of CIA, CIA_{corr}, CIW, and CIX profiles in drillcores GSQ Emerald New Series 7, Springsure 19, GSQ Taroom 10, Origin Meeleebee 5, Wancoal Lithgow DDH16, Pacific Hawkesbury Bunnerong DDH1, and Pacific Hawkesbury Eveleigh DDH1. Refer to Figure DR1 for drillcore locations. Datum is the top of the uppermost coal in the Permian section, which coincides with the loss of glossopterid macroflora. Vertical grey dashed line at index value of 70 enhances visual comparison between sites.

Figure DR3. Molar A-CN-K plot (after Fedo et al., 1995) showing compositions of Permian (P) and Triassic (Tr) mudrocks in drillcores GSQ Emerald New Series 7, Springsure 19, GSQ Taroom 10, Origin Meeleebbee 5, Wancoal Lithgow DDH16, Pacific Hawkesbury Bunnerong DDH1, and Pacific Hawkesbury Eveleigh DDH1. Refer to Figure DR1 for drillcore locations. White triangles and square mark the compositions of local sediment sources, granites from the Lachlan Foldbelt (White and Chappell, 1983; Chappell and White, 1992), and Post-Archean Average Australian Shale, representative of average upper crust composition (Taylor and McLennan, 1985), respectively. Red arrow indicates the predicted weathering trend of sediments derived from local granites. Dashed black arrow indicates the expected trend for samples affected by K-metasomatism.

Figure DR4. Binary plots of (top) CIW vs CIA and (bottom) CIX vs CIA values for pre- and post-EPE mudrocks in drillcores GSQ Springsure 19, GSQ Taroom 10, Wancoal Lithgow DDH16, and Pacific Hawkesbury Eveleigh DDH1. Refer to Figure DR1 for drillcore locations. R values in legend represent the correlation coefficient between CIA and CIW and CIX values of Permo-Triassic mudrock samples in each drillcore.

Table DR2: Normalized concentrations of quartz, feldspar, and lithic framework grains in Permo-Triassic sandstones in PHKB1, Sydney Basin, Australia, based on point counting in thin section.

Depth (m)	Age	Quartz (%)	Feldspar (%)	Rock Fragments (%)	Lithology
723.58	Triassic	15	3	82	Litharenite
767.10	Triassic	19	9	72	Litharenite
799.97	Triassic	11	4	85	Litharenite
953.90	Permian	16	2	82	Litharenite
1171.81	Permian	0	1	99	Litharenite
1198.64	Permian	1	6	93	Litharenite

CLIMATE SIMULATIONS

The climate transition across the End-Permian Extinction (EPE) was simulated using the global Community Climate System Model version 3 (CCSM3; Collins et al., 2006) through cooperation with the Computational and Information Systems Laboratory (2019). The boundary conditions consist of a paleoinsolation of 1338 W/m^2 (which is $\sim 2.1\%$ lower than the present value), paleo-orbital settings (eccentricity of 0° , obliquity of 23.5°), paleogeography, and paleoland surface conditions. For a baseline scenario for the time prior to the EPE, greenhouse gas levels of four times the pre-industrial level of 280 ppmv ($4\times \text{CO}_2$) were used. Early Triassic hothouse climate experiments assumed elevated atmospheric greenhouse levels of $12.7\times \text{CO}_2$ and were performed both with and without a reduced cloud optical thickness in response to changes in the cloud droplet radii and concentration (Kump and Pollard, 2008; Winguth et al., 2015). All simulations were equilibrated into quasi-steady state with $\sim 5500\text{--}8000$ years of integration.

Cloud cover is of importance for the radiative transfer. Increase in total cloud enhances the planetary albedo and reduces the downward shortwave radiation below the clouds. Clouds also contribute to the greenhouse effect by influencing the long wave radiation. The difference of reduced total cloud cover, in particular low cloud cover, of the $12\times \text{CO}_2$ scenario with low optical depth and $4\times \text{CO}_2$ scenario suggest a warming over the ocean east of the southeastern Pangean coast at $\sim 40^\circ\text{S}\text{--}50^\circ\text{S}$ that simulates convective precipitation. Overall simulated rise and increase in the latitudinal gradient of high cloud cover from the Permian to the Triassic may contribute to warming over southeastern Pangea and the adjacent sea surface.

Figure DR6. Difference in cloud cover (in %) between the $12.7\times\text{CO}_2\text{_WC}$ experiment and the $4\times\text{CO}_2$ experiment; A) Total cloud cover, B) low cloud cover, and C) high cloud cover.

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References Cited

- Cao, Y., Song, H., Algeo, T.J., Chu, D., Du, Y., Tian, L., Wang, Y., and Tong, J., 2019, Intensified chemical weathering during the Permian-Triassic transition recorded in terrestrial and marine successions: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 519, p. 166–177. <https://doi.org/10.1016/j.palaeo.2018.06.012>
- Chappell, B.W., and White, A.J.R., 1992, I- and S-type granites in the Lachlan Fold Belt. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 83, p. 1–26. <https://doi.org/10.1017/S0263593300007720>
- Collins, W.D., Bitz, C.M., Blackmon, M.L., Bonan, G.B., Bretherton, C.S., Carton, J.A., Chang, P., Doney, S.C., Hack, J.J., Henderson, T.B., Kiehl, J.T., Large, W.G., McKenna, D.S., Santer, B.D., and Smith, R.D., 2006, The Community Climate System Model Version 3 (CCSM3): *Journal of Climate*, v. 19, p. 2122–2143. <https://doi.org/10.1175/JCLI3761.1>
- Computational and Information Systems Laboratory, 2019, Cheyenne: HPE/SGI ICE XA System (University Community Computing). Boulder, CO: National Center for Atmospheric Research. doi:10.5065/D6RX99HX.
- Craigie, N., 2018, *Principles of Elemental Chemostratigraphy: A Practical User's Guide*: Springer International, Switzerland, 189 p.
- Dickinson, W.R., 1983, Interpreting provenance relationships from detrital modes of sandstones. In: Zuffa, G.G., *Provenance of Arenites*, NATO ASI Series, v. 148, p. 333–361.
- Fedo, C.M., Nesbitt, H.W., and Young, G.M., 1995, Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. *Geology*, v. 23, p. 921–924. [https://doi.org/10.1130/0091-7613\(1995\)023<0921:UTEOPM>2.3.CO;2](https://doi.org/10.1130/0091-7613(1995)023<0921:UTEOPM>2.3.CO;2)
- Fielding, C.R., Frank, T.D., McLoughlin, S., Vajda, V., Mays, C., Tevyaw, A., Winguth, A., Winguth, C., Nicoll, R., Bocking, M., and Crowley, J., 2019, Age and pattern of the southern high-latitude continental end-Permian extinction constrained by multiproxy analysis. *Nature Communications*, v. 10, article # 385, <https://doi.org/10.1038/s41467-018-07934-z>.
- Fielding, C.R., Frank, T.D., Tevyaw, A.P., Savatic, K., Vajda, V., McLoughlin, S., Mays, C., Nicoll, R.S., Bocking, M., and Crowley, J.L., 2021, Sedimentology of the continental end-Permian extinction event in the Sydney Basin, eastern Australia: *Sedimentology*, v. 68, p. 30–62. <https://doi.org/10.1111/sed.12782>
- Folk, R. L., 1980, *Petrology of sedimentary rocks*. Austin, Tex.: Hemphill Pub. Co., 184 pp.
- Garzanti, E., Padoan, M., Setti, M., López-Galindo, A., and Villa, I.M., 2014, Provenance versus weathering control on the composition of tropical river mud (southern Africa). *Chemical Geology*, v. 366, p. 61–74.
- Harnois, L. (1988) The CIW Index: A New Chemical Index of Weathering: *Sedimentary Geology*, v. 55, p. 319–322.
- Harwood, G., 1988, Microscopical techniques: II. Principles of sedimentary petrography, in, Tucker, R.M., ed., *Techniques in Sedimentology*, p. 108–173.
- Kump, L. R., and Pollard, D., 2008, Amplification of Cretaceous warmth by biological cloud feedbacks: *Science*, v. 320, article 195. DOI: 10.1126/science.1153883
- Li, C., and Yang, S., 2010, Is chemical index of alteration (CIA) a reliable proxy for chemical weathering in global drainage basins? *American Journal of Science*, v. 310, p. 111–127. DOI: [10.2475/02.2010.03](https://doi.org/10.2475/02.2010.03).

- Loughnan, F.C., 1963, A petrological study of a vertical section of the Narrabeen Group at Helensburgh, New South Wales: *Geological Society of Australia Journal*, v. 10, p. 177–192. <https://doi.org/10.1080/00167616308728539>
- Loughnan, F.C., 1966, A comparative study of the Newcastle and Illawarra Coal Measure sediments of the Sydney Basin, New South Wales: *Journal of Sedimentary Petrology*, v. 36, p. 1016–1025. <https://doi.org/10.1306/74D715E6-2B21-11D7-8648000102C1865D>
- Mays, C., Vajda, V., Frank, T.D., Fielding, C.R., Nicoll, R.S., Tevyaw, A.P., and McLoughlin, S., 2020, Refined Permian–Triassic floristic timeline reveals early collapse and delayed recovery of south polar terrestrial ecosystems: *Geological Society of America Bulletin*, v. 131, p. 1489–1513. <https://doi.org/10.1130/B35355.1>.
- McLennan, S.M., 1993, Weathering and global denudation: *Journal of Geology*, v. 101, p. 295–303. <https://doi.org/10.1086/648222>
- McLoughlin, S., Nicoll, R.S., Crowley, J.L., Vajda, V., Mays, C., Fielding, C.R., Frank, T.D., Wheeler, A., Bocking, M., 2021. Age and paleoenvironmental significance of the Frazer Beach Member—A new lithostratigraphic unit overlying the end-Permian extinction horizon in the Sydney Basin, Australia. *Frontiers in Earth Science*, 8: 31 pp. <https://doi.org/10.3389/feart.2020.600976>
- Nesbitt, H.W., Young, G.M., 1982, Early Proterozoic climates and plate motion inferred from major element chemistry of lutites: *Nature*, v. 299, p. 715–717. <https://doi.org/10.1038/299715a0>
- Panahi, A., Young, G.M., and Rainbird, R.H., 2000, Behavior of major and trace elements (including REE) during Paleoproterozoic pedogenesis and diagenetic alteration of an Archean granite near Ville Marie, Québec, Canada: *Geochimica et Cosmochimica Acta*, v. 64, p. 2199–2220.
- Retallack, G.J., 2009, Postapocalyptic greenhouse paleoclimate revealed by earliest Triassic paleosols in the Sydney Basin, Australia: *Geological Society of America Bulletin*, v. 111, p. 52–70. [https://doi.org/10.1130/0016-7606\(1999\)111<0052:PGPRBE>2.3.CO;2](https://doi.org/10.1130/0016-7606(1999)111<0052:PGPRBE>2.3.CO;2)
- Rowe, H., Hughes, N., and Robinson, K., 2012, The quantification and application of handheld energy-dispersive x-ray fluorescence (ED-XRF) in mudrock chemostratigraphy and geochemistry. *Chemical Geology*, v. 234–235, p. 122–131. <https://doi.org/10.1016/j.chemgeo.2011.12.023>
- Sheldon, N.D., and Tabor, N.J., 2009, Quantitative paleoenvironmental and paleoclimatic reconstructions using paleosols. *Earth-Science Reviews*, v. 95, p. 1–52. <https://doi.org/10.1016/j.earscirev.2009.03.004>
- Taylor, S.R., and McLennan, S.M., 1985, *The Continental Crust: its Composition and Evolution*, Blackwell, Oxford, 312 pp.
- Vajda, V., McLoughlin, S., Mays, C., Frank, T.D., Fielding, C.R., Tevyaw, A., Lehsten, V., Bocking, M., and Nicoll, R., 2020, End-Permian (252 Mya) deforestation, wildfires and flooding—An ancient biotic crisis with lessons for the present: *Earth and Planetary Science Letters*, v. 529, Article 115875, <https://doi.org/10.1016/j.epsl.2019.115875>.
- White, A.J.R., and Chappell, B.W., 1983, Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia, in *Circum-Pacific Plutonic Terranes*, Roddick, J.A., ed., *Geological Society of America Memoir*, v. 159, p. 21–34. <https://doi.org/10.1130/MEM159-p21>
- Winguth, A. M. E., Shields, C., and Winguth, C., 2015, Transition into a hothouse world at the Permian–Triassic boundary - A model study: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 440, p. 316–327. <https://doi.org/10.1016/j.palaeo.2015.09.008>

Yang, J.H., Cawood, P.A., Du, Y.S., Feng, B., and Yan, J., 2014, Global continental weathering trends across the Early Permian glacial to postglacial transition: correlating high- and low-paleolatitude sedimentary records: *Geology*, v. 42, p. 835–838.