Supplementary Materials for

A Lagerstätte from Australia provides insight into the nature of Miocene mesic ecosystems

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The PDF file includes:

Supplementary Methods
Figs. S1 to S6
Tables S1, S3, S4, and S5

Other supplementary material for this manuscript includes the following:

Table S2
Supplementary methods

XRD analysis

Three samples of matrix and fossil from McGraths Flat (Table S1) were analyzed using a Panalytical X’Pert Pro X-ray diffractometer with vertical theta-theta goniometer, proportional counter, graphite monochromator, and copper anode X-ray source. Scans were performed at 45 kV and 40 mA, with a 0.5-degree divergence slit and 1-degree anti-scatter slit, counting for 1 second per 0.02-degree step from 5 to 75 degrees of two-theta. Scans were processed with Panalytical HighScore Plus software and peak patterns were matched with the PDF-4/Minerals 2019 database. Peak matches indicated almost pure goethite, FeO(OH), with a small amount of quartz in some samples. Some goethite peak matches were possibly closer to a slightly aluminous goethite, but additional chemical data are required to confirm the presence of aluminium.

$^{40}$Ar/$^{39}$Ar dating

_flux monitor:_ GA 1550 @ 98.5 ±0.8 Ma (29).

\[
\begin{align*}
(\overset{36}{37}\text{Ar}/\overset{39}{37}\text{Ar})_\text{Ca} & \text{ correction factor} \quad 1.289^{-4} \\
(\overset{39}{37}\text{Ar}/\overset{37}{39}\text{Ar})_\text{Ca} & \text{ correction factor} \quad 8.281^{-4} \\
(\overset{40}{39}\text{Ar}/\overset{39}{37}\text{Ar})_\text{K} & \text{ correction factor} \quad 8.342^{-2} \\
(\overset{38}{39}\text{Ar}/\overset{39}{37}\text{Ar})_\text{K} & \text{ correction factor} \quad 1.172^{-2} \\
(\overset{38}{39}\text{Ar})_\text{Cl}/(\overset{39}{37}\text{Ar})_\text{K} & \text{ correction factor} \quad 8.065^{-2} \\
\text{Ca/K conversion factor} & \quad 1.9 \\
\text{Lambda} & \quad 5.543^{-10}
\end{align*}
\]

Mineral separation and characterization

Samples were crushed and separated at the Research School of Earth Science, The Australian National University, Canberra, Australia, using normal mineral separation techniques. The most pristine sections of the basalt were cut from the rock, crushed, and sieved to 250-µm grain size, de-slimed, dried, and washed. Grains were again cleaned in de-ionized water and wrapped in aluminum foil in preparation for irradiation.

Sample irradiation details

Aluminum-wrapped sample packets were placed into a quartz irradiation canister together with aliquots of the flux monitor GA1550 (29). The GA1550 standards are dispersed
throughout the irradiated cannister, between the unknown age samples. Approximately 30 of
the GA1550 standards were analyzed, a linear best fit method was then used for the
calculation of the J-factor and J-factor uncertainty. Packets containing K$_2$SO$_4$ and CaF$_2$ were
placed in the middle of the canister to monitor $^{40}$Ar production from potassium and calculate
necessary correction factors.

Irradiation of samples for $^{40}$Ar/$^{39}$Ar analysis was undertaken at the University of California
Davis’ McClellan Nuclear Research Center, CA, USA, prior to analysis. Irradiated samples
were unwrapped on their return to the Australian National University, and then rewrapped in
tinfoil ready for analysis.

$^{40}$Ar/$^{39}$Ar procedures:

Samples and standards were analyzed in the Argon Laboratory at the Research School of
Earth Science, The Australian National University, Canberra, Australia.

A furnace step-heating technique was used to extract argon from the samples to ensure 100% release of $^{39}$Ar (30), while the flux monitors crystals (GA1550 biotite) were fused using a
CO$_2$ continuous-wave laser; gases extracted from both samples and standards were analyzed in
the Argus VI mass spectrometer. Samples were analyzed in 30 steps and with temperatures of
the overall schedule rising from 450 to 1450 °C (31). Backgrounds were measured prior to
each step analysis and subtracted from each step analysis. The furnace cleaning procedure
entailed heating and degassing four times at 1450 °C for 15 minutes and the gas pumped
away prior to the loading of the subsequent sample. Gas released from flux monitors and each
step of sample analyses was exposed to three different Zr-Al getters to remove active gases
for 10 minutes, and the purified gas was then isotopically analyzed in the mass spectrometer.
$^{40}$K abundances and decay constants are those of Steiger and Jäger (1977) (32). Stated
precisions for $^{40}$Ar/$^{39}$Ar ages include all uncertainties in the measurement of isotope ratios
and are quoted at the one sigma level and exclude errors in the age of the fluence monitor
GA1550 (98.5 ±0.8 Ma) (29). The reported data have been corrected for system backgrounds,
mass discrimination, fluence gradients, and atmospheric contamination. The $^{40}$Ar/$^{39}$Ar dating
technique is described in detail by MacDougall and Harrison (1999) (33) and adapted as in
Forster and Lister (2009) (30).

$^{40}$Ar/$^{39}$Ar sample information

Sample name: 435839350
J-factor: 1.1815E-3
± % J: 0.2419
Mineral: basalt (whole rock)
Measurement date: 17/01/2020
The background levels within the mass spectrometer were measured prior to every step of the analysis and subtracted from the isotope intensities for $^{40}$Ar, $^{39}$Ar, $^{38}$Ar, $^{37}$Ar, and $^{36}$Ar. The interfering nuclear reactions and correction factor ratios for the isotopes listed above were calculated. These are measured for the reactions and uncertainties of $^{40}$Ar/$^{39}$Ar$\kappa$, $^{39}$Ar/$^{37}$Ar$\kappa$, $^{38}$Ar/$^{39}$Ar$\kappa$, and $^{38}$Ar/$^{39}$Ar$\kappa$, and were calculated prior to sample analysis.

Data reduction was done with an adapted version of Noble Software (written and adapted by the Australian National University Argon Laboratory). The data reduction was based on optimizing MSWD (the mean square of weighted deviates) of isotope intensities with an exponential best fit methodology. The discrimination factor was calculated by analyzing Air Shots analysis on either side of sample analysis, based on the $^{40}$Ar/$^{36}$Ar ratio (298.57), and the calculation of the 1 amu was used for the discrimination factor.

$^{40}$Ar/$^{39}$Ar results are supplied in Supplemental Table S2.

**Detrital zircon analysis**

Three rock samples were received by Geoscience Australia and assigned GA numbers (3081571, 3081572, and 3081573) before being processed for the isolation of zircons. Samples 3081571 and 3081572 were fossiliferous limonitic fine-grained sandstone representing sandy layers at the base of the fossil deposit. Sample 3081573 was an iron-rich quartz pebble conglomerate representing the lag deposit found bellow the fossil deposit. Samples 3081571 and 3081572 yielded typically rounded and equant detrital zircons, and a sub-population of large, relatively unrounded elongated grains. These elongated grains were mounted alongside the unpicked separates.

All samples were analyzed on a SHRIMP IIe using standard U-Th-Pb methodology (34). Samples were normalized to a Temora 2 zircon with an age of 416.8 Ma (35). The error of the mean of 61 Temora 2 analyses was 0.1%. An excess spot to spot error of 0.5% was sufficient to explain all dispersion in the reference material data.

Sample 3081571 had 108 detrital zircon analyses, including 14 analyses of elongated grains. Sample 3081572 had 105 analyses, including 13 of elongated grains. Sample 3081573 had 109 zircons analyzed. Of these 108 grains analyzed for sample GA3081571, 11 were discordant beyond the uncertainty envelope. The remaining 97 zircon ages ranged from Cretaceous to Paleoarchean. The youngest three zircons ranged from 133 to 147 Ma, but do not form a single group within uncertainty of each other.

The most common age in GA3081571—with just under half the zircons—is in the Cambrian to Ediacaran “Pacific Gondwanan” population related to the assembly of Gondwana (36). These peaks are at 490 Ma, 525 Ma, and ~560 Ma. Another prominent peak is at 430 Ma, the age of widespread S-type plutonism and volcanism in New South Wales. There are also several ~180 to 230-Ma, ~950 to 1150-Ma, and 640 to 680-Ma grains, with scattered older Paleoproterozoic and Archean grains.
Sample GA3081572 had 105 analyses including 13 of the elongated grains. Of these, eight were discordant, leaving a sample of 97 grains. Their ages were broadly similar to sample GA3081571, with ages ranging from Jurassic to Neoarchean. The youngest three zircons ranged from 189 to 215 Ma, but do not form a single group within uncertainty of each other.

The most common age of GA3081572 is Pacific Gondwanan, with peaks at 522 Ma and a broad 550 to 565-Ma peak. These grains account for just under half of the total zircons. There are smaller populations at 360 and 430 Ma, and scattered grains from 800 to 1050 and 180 to 300 Ma. There is only one Archean grain, and only four grains from the Paleoproterozoic.

One hundred and nine zircons were analyzed from sample GA3081573. Eighteen of these analyses were discordant. Of the remaining 91 grains, the youngest three are not within error of each other, and range from 220 to 243 Ma. The age distribution of the Paleozoic and Proterozoic grains is quite different to the other two samples, however. The most prominent peaks are ~430 Ma and ~390 Ma, and these account for just over a third of the zircons. Pan-African zircons were present but made up only one quarter of the total zircon population. The main peaks are at 485 Ma, 515 Ma, and 560 Ma. There are also broad distributions in the 220 to 320 and 880 to 1180 Ma range. There are four Paleoproterozoic and three Neoarchean grains.

As samples 3081571 and 3081572 contain Miocene fossils, the zircon data give no meaningful constraints on the depositional age. For sample GA3081573 the deposition age must be younger than the Triassic youngest zircons in this sediment, as discussed below. The interpretation of the Permian-to-Mesozoic zircon data is difficult. Detrital zircon age interpretation generally relies on the population statistics of the zircons. However, with the exception of the three ~180-Ma zircons in sample GA3081571, none of the zircons younger than ~330 Ma form groups of three or more zircons. This is unusual; however, as no other Triassic samples were analyzed in months prior to this analysis, the result is not likely a consequence of sample contamination.

Due to the young age of these zircons, it is possible that this spread is caused by variable Pb loss subparallel to concordia, as the $^{207}$Pb precision may not be sufficient to distinguish this sort of Pb loss in the Mesozoic. This is unlikely for samples GA3081571 and GA3081572. In sample GA3081571, all of the grains younger than 300 Ma are low in uranium (<500 ppm) and have less than 1% common $^{206}$Pb, so are unlikely to have been disturbed. In sample GA3081572, the U contents are up to 1100 ppm, but the same is generally the case. This cannot be said for sample GA3081573.

The youngest grain in sample GA3081573 has more than 2% common $^{206}$Pb, and the U content is well over 1000 ppm. So, it is conceivable that this zircon is as old or older than the 236 Ma next-youngest concordant grain and has lost Pb to appear younger. Thus, the maximum depositional age for this sample is approximately 236 Ma, based on two zircon grains that are within uncertainty of each other. The presence of an older well-behaved Triassic grain further supports the interpretation that the matrix is Mesozoic (or younger) sediment. The results of this analysis are presented in Fig. S4.
**Fig. S1. XRF results.** Graph of XRF spectra from a sample of fossil and matrix from McGraths Flat. The matrix and fossil primarily contain iron hydroxides, with small concentrations of Mn, Cr, Ti, S, Si, and Al.
**Fig. S2. XRF images.** (A) black and white image of the fossil; (B) distribution of aluminum (Al); (C) distribution of silicon (Si); (D) distribution of titanium (Ti); (E) distribution of manganese (Mn); and (F) distribution of iron (Fe). Scale bars, 10 mm.
Fig. S3. Stratigraphic cross section at McGraths Flat. Stratigraphic East–West cross-section through the McGraths Flat site. The position of the McGraths Flat bed (Mf) is depicted in relation to surrounding stratigraphic units. Field photographs are provided to show examples of the rock types and units discussed. Scale of photographs is provided by geological hammers.
Fig. S4. Zircon dating results. Probability density plots for the Neoproterozoic-to-Cretaceous portions of the detrital zircon spectra for the samples. Sample GA3081573 had zircons with different provenance to the other two samples. GA3081571 is red, GA3081572 is green, and GA3081573 is blue.
Fig. S5. Two thin-sections through fossiliferous layers from McGraths Flat. The matrix contains little silica, but when grains are present, the goethite forms thinly bedded layers around the grains. Scale bars, 50 µm (A) and 200 µm (B).
Fig. S6. Biostratigraphically informative spores and pollen. (A) *Rugulatisporites trophus* Stover & Partridge (AM F.145717-P33); (B) *Rugulatisporites cowrensis* (Martin) Mildenhall & Pocknall (AM F.146023-P30); (C) *Foveotriletes balteus* Stover & Partridge (AM F.146164-P19); (D) *Proteacidites pachypolus* Cookson & Pike (AM F.146088-P25); (E) *Cingulasporites ornatus* Martin (AM F.146156-P42); (F) *Polypodiisporites usmensis* (van der Hammen) Khan & Martin (AM F.146159-P26); (G) *Lygistepollenites florinii* (Cookson & Pike) Stover & Evans (AM F.146023-P14); (H and I) *Imyrtaceidites* ssp. (AM F.146023-P20 and AM F.146157-P17, respectively); (J and K) *Cupanieidites* ssp. (AM F.146160-P27 and AM F.146088-P42, respectively); (L) *Margocolporites vanwijhei* Germeraad et al. (AM F.146163-P23); (M) *Nothofagidites emarcidus-heterus* (Cookson) Harris (AM F.146023-P27); (N) *Nothofagidites asperus* Romero (AM F.146026-P5); and (O) *Haloragacidites harrisii* (Couper) Harris (AM F.145848-P5). Scale bars, 10 μm.
| XRD scan         | AM F.145277 (fossil)* | AM F.145277 (matrix)* | AM F.145330 (matrix) |
|------------------|-----------------------|-----------------------|----------------------|
| X2019062         | Goethite              |                       |                      |
| X2019063         |                       |                       | Goethite             |
| X2019064         |                       |                       | Goethite, very minor quartz |
| X2019065         |                       |                       | Goethite, very minor quartz |
| X2019066         |                       |                       | Goethite             |
| X2019067         |                       |                       | Goethite             |
| X2019068         |                       |                       | Goethite             |

*Two samples (representing matrix and fossil) were taken from the same specimen.*
Table S3. Macroflora and palynomorphs

| Fungi                   |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Dactylaria*            |                         |                         |
| *Dicellaesporites* sp.  |                         |                         |
| *Dyadosporites* sp.     |                         |                         |

| Bryophyta               |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Hepaticae*             |                         |                         |
| *Cingulatisporites ornatus* Martin 1973 |                         |                         |
| Sphagnaceae             |                         |                         |
| *Stereisporites* spp.   |                         |                         |

| Lycophyta               |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Sellaginellaceae*      |                         |                         |
| *Densoisporites* sp.    |                         |                         |
| *Foveotriletes balteus* Partriaje 1973 |                         |                         |

| Filicopsida             |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Incertae sedis*        |                         |                         |
| *Verrucosisporites* sp. (fern spore) |                         |                         |
| *Laevigatosporites* sp. (numerous monolet-producing ferns including Blechnaceae) |                         |                         |
| *Cyathidites* spp.      |                         |                         |
| *Matonisporites* sp.    |                         |                         |

| Cyatheaceae             |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Cyathidites palaeospora* (Martin) Alley & Broadbridge 1992 |                         |                         |

| Schizeaceae             |                         |                         |
|-------------------------|-------------------------|-------------------------|
| *Lygodiaceae*           |                         |                         |
| *Lygodium* sp.          |                         |                         |
| *Cyathidites splendens* Harris 1965 |                         |                         |

| Lophosoriaceae          |                         |                         |
Cyatheacidites annulatus Cookson 1947

Dicksoniaceae/Gleicheniaceae

Dictyophyllidites spp.

Gleicheniaceae

Gleichenia sp.

Gleicheniidites sp.

Osmundaceae

Osmundacidites sp.

Blechnaceae

cf. Stenochlaena

Polypodiisporites usmensis (Van der Hammen) Khan & Martin 1971

Thrysopteridaceae

Calochlaena-Calcula

Rugulatisporites cowrensis (Martin) Mildenhall & Pocknall 1989

Rugulatisporites mallatus Stover & Partridge 1973

Rugulatisporites trophus Stover & Partridge 1973

Hymenophyllaceae

Hymenophyllum sp.

Pteridospermaphyta

Alisporites sp. (probably recycled from underlying Mesozoic sediments)

Coniferophyta

Araucariaceae

Araucaria

Araucariacites australis Cookson 1947

Dilwynites sp.

Agathis sp.

Podocarpaceae

Lygistepollenites florinii (Cookson & Pike) Stover & Evans 1973

Podocarpidites ellipticus Cookson 1947
Phyllocladidites mawsonii Cookson. 1947
Podocarpus sp.
Dacrydium sp.

Monocotyledonae

Incertae sedis
Monocot leaves

Sparganiaceae
Aglaoreidia sp.

Poaceae
Graminidites sp.

Restionaceae
Milfordia spp.

Dicotyledonae

Anarcardiaceae
Ailanthipites paenestriatus (Stover & Partridge) Milne 1988

Chenopodiaceae
Chenopodipollis cf. chenopodiaceoides (Martin) Truswell 1985

Sapindaceae
Cupanieae
Cupanieidites orthoteichus Cookson & Pike 1954
Cupanieidites spp.

Casuarinaceae
Haloragacidites harrisii (Couper) Harris 1971
Gymnostoma sp.

Nothofagaceae
Nothofagus sp.
Nothofagus sp.

Lophozonia
Nothofagidites asperus Romero 1973
Brassospora

*Nothofagidites deminutus* (Cookson) Stover & Evans 1973

*Nothofagidites emarcidus/heterus* (Cookson) Harris 1965

Malvaceae

*Brachychiton* sp.

Euphorbiaceae

*Malvacipollis* spp.

Caesalpiniaceae

*Margocolporites vanwijhei* Germeraad, Hopping & Muller 1968

Myrtaceae

*Myrtaceidites* spp.

Trimeniaceae

*Periporopollenites demarcatus* Stover & Partridge 1973

Proteaceae

*Propyliopolis* sp.

*Proteacidites pachypolus* Cookson & Pike 1954

*Proteacidites pseudomoides* Stover & Partridge 1973

*Proteacidites* spp.

*Banksia* sp.

Paracryphiaceae

*Quintinia*

*Quintiniapollis* cf. *psilatispora* (Martin) Mildenhall & Pocknall 1989

Santalaceae

*Santalum*

*Santalumidites* sp.

Lauraceae

*Laurophyllum* sp.

*Cinamonum* sp.
**Table S4. Fauna**

The number of specimens of each taxon collected to date are provided in brackets.

| Insecta          |                                                                 |
|------------------|------------------------------------------------------------------|
| Odonata          |                                                                 |
|                  | Corduliidae indet. (3)                                           |
|                  | Gomphidae                                                       |
|                  | *Austrogomphus* sp. (13)                                        |
| Ephemeroptera    |                                                                 |
|                  | Baetidae                                                        |
|                  | *cf. Platybaetis* sp. (22)                                      |
|                  | Ichthybotidae or Coloburiscidae indet. (1)                      |
|                  | *gen. sp. nov.* (23)                                            |
| Hemiptera        |                                                                 |
|                  | Fulgoridae                                                      |
|                  | *gen. sp. nov.* (1)                                             |
|                  | Reduviidae                                                      |
|                  | *gen. sp. nov.* (3)                                             |
|                  | Cicadidae                                                       |
|                  | *cf. Psaltoda* sp. (5)                                          |
| Blattodea        |                                                                 |
|                  | Mastotermitidae                                                 |
|                  | *gen. sp. nov.* (2)                                             |
| Megaloptera      |                                                                 |
|                  | Sialidae                                                        |
|                  | *gen. sp. nov.* (12)                                            |
| Coleoptera       |                                                                 |
|                  | Chrysomeloidea indet. (14)                                      |
|                  | Dytiscidae                                                      |
|                  | *gen. sp. nov.* (1)                                             |
Archostemata
    gen. sp. nov. (2)
Curculionidae
    gen. sp. nov. (1)

Diptera

Limoniidae
    Limnophilinae
        cf. Tonnoirella gen. sp. nov (1)
indet (1)

Chironomidae
    Riethia sp. (>115)
Orthocladiinae indet. (5)
Podonominae indet. (3)
Ceratopogonidae indet. (3)
Chaoboridae
    Chaoborus sp. nov. (>180)

Hymenoptera

    Tenthredinoidea
        gen. sp. nov. (1)
    Formicidae indet. (5)
        indet. (2)

Trichoptera

    Polycentropodidae indet. (33)

**Arachnida**

Araneae

    Theridiidae indet. (6)
    Mygalomorphae indet. (1)
        indet. (6)
Bivalvia

Unionida indet. (1)

Aves indet.

Aves indet. (1)

Actinopterygii

Osmeriformes

cf. Retropinnidae

gen. sp. nov. (25)

Perciformes indet (1)
Table S5. CLAMP physiognomic scores for the flora from McGrath Flat.

| Feature               | Score      |
|-----------------------|------------|
| Lobed                 | 4.081633   |
| No Teeth              | 58.333333  |
| Regular teeth         | 41.66667   |
| Close teeth           | 6.25       |
| Round teeth           | 35.41667   |
| Acute teeth           | 6.25       |
| Compound teeth        | 0          |
| Nanophyll             | 2.564103   |
| Leptophyll 1         | 0          |
| Leptophyll 2         | 0          |
| Microphyll 1          | 7.692308   |
| Microphyll 2          | 7.692308   |
| Microphyll 3          | 33.33333   |
| Mesophyll 1           | 35.89744   |
| Mesophyll 2           | 10.25641   |
| Mesophyll 3           | 2.564103   |
| Emarginate apex       | 0          |
| Round apex            | 9.090909   |
| Acute apex            | 59.09091   |
| Attenuate apex        | 31.81818   |
| Cordate base          | 0          |
| Round base            | 21.42857   |
| Acute base            | 78.57143   |
| L:W <1:1              | 0          |
| L:W 1-2:1             | 18.91892   |
| L:W 2-3:1             | 27.02703   |
| L:W 3-4:1             | 37.83784   |
| L:W >4:1              | 16.21622   |
| Obovate               | 3.947368   |
| Elliptic              | 78.94737   |
| Ovate                 | 17.10526   |