Supplemental Information

An expanded Supplemental Information section is provided here as a reference for: **(1)** methodologies used during geochemical analyses; **(2)** results for individual zircon grain analyses; **(3)** expanded interpretation of bentonite intervals as individual events of primary ashfall (vs. reworked detrital zircon grains in volcaniclastic sediment); **(4)** references cited herein. We also provide a figure showing photographs of individual zircon grains analyzed and five data tables showing: **(1.1)** stratigraphic correlation of collected paleontological specimens; **(1.2)** stratigraphic correlation of collected bentonites; **(1.3)** stratigraphic correlation of collected geochemical samples; **(2)** single grain U-Pb isotope data for samples analyzed at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Canada (i.e., Table 2.1) and the Massachusetts Institute of Technology (MIT), Cambridge MA (i.e., Table 2.2); **(3)** trace element concentration data for zircon grains (sample 2017GC3.8); **(4)** chondrite normalized rare earth elements, selected trace element concentrations, and Ti-in-zircon temperatures for zircons (sample 2017GC3.8); and **(5)** LA-ICPMS and CA-ID-TIMS U-Pb age comparison data for all bentonite samples in this study.

1. Expanded Methodology

We collected 70 samples for carbon isotope analysis and 30 samples for conodont analysis. We collected float and *in situ* macrofossils (ammonoids, bivalves, and hydrozoans) from 51 fossil horizons that yielded 103 specimens and sampled 4 ash beds for U-Pb CA-ID TIMS analysis. Geochemical samples were analyzed for organic carbon isotope composition ($\delta^{13}C_{org}$) and whole-rock total organic carbon (TOC_{wr}) content at Durham University, England; conodont samples were processed at the Geological Survey of Canada (Vancouver); ammonoids and hydrozoans were identified at Western Michigan University, USA; bivalves were identified at the Museum für Naturkunde (Berlin, Germany) and SUNY Cortland (New York); and U-Pb CA-ID TIMS analysis took place at PCIGR and MIT. All fossils and geochemical samples were collected under National Parks Service collection and research permits (WRST-2018-SC1-0004 and WRST-2018-SCI-0005) and paleontological specimens curated with the Wrangell-St Elias National Park Museum. Geochemical residues are curated and stored at the respective institutions.

Carbon-isotope analysis

Organic $\delta^{13}C$ data were obtained following the methods described by Skrzypek and Debajyoti (2006) and Gröcke et al. (2009). Approximately 200 mg of sediment was decalcified using 3M HCl, left overnight at room temperature. Samples were then neutralized using deionized water and dried in an oven at 55 °C. $\delta^{13}C_{org}$ data were acquired using a Costech Elemental Analyzer (ECS 4010) coupled to a ThermoFinnigan Delta V Advantage mass spectrometer. Carbon-isotope ratios were corrected for ^{17}O contribution and reported in standard delta (δ) notation in per mil (‰) relative to the VPDB scale. Data accuracy was monitored through routine analyses of in-house standards, which are calibrated against international standards (USGS 40, USGS 24, IAEA 600, IAEA CH6): this provides a linear range in $\delta^{13}C$ between +2‰ and −47‰. Analytical uncertainty for $\delta^{13}Corg$ is typically ±0.1‰ for replicate analyses of the international standards and typically <0.2‰ on replicate sample analysis.

CA-ID-TIMS analysis

High precision U-Pb zircon analyses were carried out at the University of British Columbia (UBC) and the Massachusetts Institute of Technology (MIT). All analyses were single grain chemical abrasion isotope dilution thermal ionization spectrometry (CA-ID-TIMS) analyses. The MIT analyses followed the procedures outlined in Rioux et al. (2012) and data reduction was done using the ET Redux software package (Bowring et al., 2011; McLean et al., 2011). The UBC analyses followed procedures modified from Mundil et al. (2004), Mattinson (2005), and Scoates and Friedman (2008), and are detailed below.

Following standard mineral separation procedures, zircons were handpicked in alcohol. The clearest, crack- and inclusion-free grains are selected, photographed, and then annealed in quartz glass crucibles at 900 °C for 60 hours. Annealed grains were transferred into 3.5 mL PFA screwtop beakers, ultrapure HF (up to 50% strength, 500 mL) and HNO_3 (up to 14N, 50 mL) were added and caps were closed finger tight. The beakers were placed in 125 mL PTFE liners (up to four per liner) and ~2 mL HF and 0.2 mL HNO_3 of the same strength as acid within beakers was added to the liners. The liners were then slid into stainless steel Parr™ high-pressure dissolution devices, which were sealed and brought up to a maximum of 200 °C for 8–16 hours (typically 175 °C for 12 hours). Beakers were removed from liners and zircon separated from leachate. Zircons were rinsed with >18 MΩ.cm water and subboiled acetone. Then 2 mL of subboiled 6N HCl was added and beakers were set on a hotplate at 80–130 °C for 30 minutes and again rinsed with water and acetone. Masses were estimated from the dimensions (volumes) of grains. Single grains were transferred into clean 300 mL PFA microcapsules (crucibles), and 50 mL 50% HF and 5 mL 14N was added. Each grain was spiked with a $^{233\text{-}235}$U-^{205}Pb tracer solution (EARTHTIME ET535), capped, and again placed in a Parr liner (8–15 microcapsules per liner). HF and nitric acids in a 10:1 ratio, respectively, were added to the liner, which was then placed in Parr high-pressure device and dissolution was achieved at 240 °C for 40 hours. The resulting solutions were dried on a hotplate at 130 °C, 50 mL 6N. HCl was then added to the microcapsules, and fluorides were dissolved in high-pressure Parr devices for 12 hours at 210 °C. HCl solutions were transferred into clean 7 mL PFA beakers and dried with 2 mL of 0.5N H_3PO_4. Samples were then loaded onto degassed, zone-refined Re filaments in 2 mL of silicic acid emitter (Gerstenberger and Haase, 1997).

Isotopic ratios were measured using a modified single collector VG-54R or 354S (with Sector 54 electronics) thermal ionization mass spectrometer equipped with analog Daly photomultipliers. Measurements were done in peak-switching mode on the Daly detector. Estimated U analytical blanks are 0.2 pg and common Pb ranged from 0.15–0.57 pg per grain in this study. U fractionation was determined directly on individual runs using the $^{233\text{-}235}$U tracer, and Pb isotopic ratios were corrected for fractionation of 0.23%/amu, based on replicate analyses of the NBS-982 Pb reference material and the values recommended by Thirlwall (2000). Data reduction employed the excel-based program of Schmitz and Schoene (2007). Standard concordia diagrams were constructed and regression intercepts, weighted averages were calculated with Isoplot (Ludwig, 2003). Unless otherwise noted, all errors are quoted at the 2 sigma or 95% level of confidence. Isotopic dates were calculated the decay constants λ_{238}=1.55125E-10 and λ_{235}=9.8485E-10 (Jaffey et al. 1971). EARTHTIME U-Pb synthetic solutions are analyzed on an ongoing basis in the UBC lab to monitor the accuracy of results.

Sample preparation and zircon trace element LA-ICP-MS analysis

After rock samples have undergone standard mineral separation procedures, zircons were handpicked in alcohol and mounted in epoxy, along with reference materials. Grain mounts were then wet ground with carbide abrasive paper and polished with diamond paste. Next, cathodoluminescence (CL) imaging was carried out on a Philips XL-30 scanning electron microscope (SEM) equipped with a Bruker Quanta 200 energy-dispersion X-ray microanalysis system at the Electron Microbeam/X-Ray Diffraction Facility (EMXDF) at the University of British Columbia. An operating voltage of 15 kV was used, with a spot diameter of 6 µm and peak count time of 30 seconds. After removal of the carbon coat the grain mount surface was washed with mild soap and rinsed with high purity water. Prior to analysis the grain mount surface was cleaned with 3N HNO_3 acid and again rinsed with high purity water to remove any surficial Pb contamination that could interfere with the early portions of the spot analyses.

Analyses were conducted using a Resonetics RESOlution M-50-LR, which contains a Class I laser device equipped with a UV excimer laser source (Coherent COMPex Pro 110, 193 nm, pulse width of 4 ns) and a two-volume cell designed and developed by Laurin Technic Pty. Ltd. (Australia). This sample chamber allowed for the investigation of several grain mounts within one analytical session. The laser path was fluxed by N$_2$ to ensure better stability. Ablation was carried out in a cell with a volume of approximately 20 cm^3 and a He gas stream that ensured better signal stability (Eggins et al., 1998). The laser cell was connected via a Teflon squid to an Agilent 7700x quadrupole ICP-MS housed at PCIGR. A pre-ablation shot was used to ensure that the spot area on the grain surface was contamination-free. Samples and reference materials were analyzed for up to 34 isotopes, including: ^{7}Li, ^{29}Si, ^{43}Ca, ^{49}Ti, ^{85}Rb, ^{88}Sr, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{139}La, ^{140}Ce, ^{141}Pr, ^{146}Nd, ^{147}Sm, ^{153}Eu, ^{157}Gd, ^{159}Tb, ^{163}Dy, ^{165}Ho, ^{166}Er, ^{169}Tm, ^{172}Yb, ^{175}Lu, ^{177}Hf, ^{188}Ta, ^{202}Hg, Pb (^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb), ^{232}Th, and U (^{235}U and ^{238}U) with a dwell time of 0.02 seconds for each isotope. These isotopes were selected based on their relatively high natural abundances and absence of interferences. The settings for the laser were: spot size of 34 µm with a total ablation time of 30 seconds, frequency of 5 Hz, fluence of 5 J/cm^2, power of 7.8 mJ after attenuation, pit depths of approximately 15 µm, He flow rate of 800 mL/min, N$_2$ flow rate of 2 mL/min, and a carrier gas (Ar) flow rate of 0.57 L/min.

NIST 612 glass was used for both drift correction and trace element calibration with sample spacing between every five to eight unknowns and ^{90}Zr was used as the internal standard assuming stoichiometric values for zircon. NIST 610 glass was analyzed after each NIST 612 analysis and used as a monitor reference material for trace elements. Raw data were reduced using the Iolite 3.4 extension (Paton et al., 2011) for Igor Pro™ yielding concentration values and propagated uncertainties.

2. Expanded Results

Sample 2017GC3.8

Zircons from sample 2017GC3.8 (collected at 0 m in the Grotto Creek section) comprise a homogenous population of elongate, euhedral to subhedral prisms 200–500 µm in length; containing elongate inclusions up to 300 µm in length that are aligned with their long dimensions roughly parallel to the length of grains (SI Fig. 1A). Eighteen grains from the sample were mounted, sectioned, and polished for cathodoluminescence (CL) imaging (SI Fig. 1C); showing weak oscillatory zoning in most grains, often overprinted by broad simple tabular and sector zoning. Inclusions are mantled by material that is unzoned or has a mottled, disrupted appearance and cross-cuts oscillatory, tabular, and sector zoning. Zircons from 2017GC3.8 are interpreted as magmatic grains with minor inclusions and well-developed zoning patterns. The elongate euhedral to subhedral crystal shape in conjunction with the tight age cluster of analyzed grains is indicative of a primary magmatic age with no sedimentary evidence for reworking or abrasion of zircon grains. Large inclusions are interpreted as late-magmatic, resorption-related features that likely formed via melt inclusions. Laser ablation ICP-MS trace element data were acquired for some of the mounted zircon grains (SI Fig. 1D; Tables 2, 3, 5). A plot of normalized rare earth elements (REE) shows the consistency of analyses with relative light REE depletion, Ce and Eu anomalies, and heavy REE enrichment (SI Fig 1D).

Sample 2017GC14.9

Zircons separated from ash 2017GC14.9 (collected at 11.07 m in the Grotto Creek section) are shown in photomicrograph (SI Fig. 1B). Grains are elongate, euhedral to subhedral in shape measuring 100–300 µm in length, with some grains presenting a broken and stubby appearance. Rare inclusions are similar in appearance to those in sample 2017GC3.8. Due to the modest number of grains recovered zircons were not mounted.

Sample Grot-124

Eleven single-grain analyses from sample Grot-124 yielded overlapping Th-corrected ^{206}Pb/^{238}U dates from 210.10 ± 0.16 to 209.73 ± 0.25 Ma, with a weighted mean of 209.92 ± 0.043 Ma (MSWD = 1.6). Many of the analyzed grains were acicular—with some containing apparent melt inclusions parallel to the c-axis—consistent with a volcanic origin. We interpret the weighted mean date as the eruption age of this sample.

Sample Grot-1

Ten single-grain analyses from sample Grot-1 yielded a range of Th-corrected ^{206}Pb/^{238}U dates from 245.8 ± 2.0 to 213.2 ± 1.6 Ma (excluding a single low precision analysis, z27). The analyzed zircons from this sample were small, equant, and had relatively low U and Pb contents, leading to less precise results. Eight of the 10 analyses overlap within uncertainty with a Th-corrected weighted mean ^{206}Pb/^{238}U date of 214.36 ± 0.19 Ma (MSWD = 1.2). The weighted mean is controlled by four higher-precision analyses that yield overlapping dates of 214.98 ± 0.65 to

214.28 ± 0.25 Ma, with a weighted mean of 214.39 ± 0.19 Ma (MSWD = 1.7), in close agreement with the mean of the larger population. We interpret the weighted mean date of the eight overlapping analyses as the eruption age of the sample, while the two older grains (245.8–221.3 Ma) are likely inherited xenocrysts. The mean square of the weighted deviates (MSWD) of the weighted means for Grot-124 and Grot-50 are within the 95% confidence interval of the expected value Wendt and Carl (1991).

3. Zircon ages: primary airfall ash vs reworked detrital grains

The bentonite beds that were sampled in the Grotto Creek section represent four separate volcanic events and associated settling of volcanic ash through the water column onto the seafloor below storm wave-base under low oxygen to anoxic conditions. In such an environment, primary ash layers often reside on the seafloor for extended periods of time with no/little reworking. Low sedimentation rate(s) may lead to amalgamation of multiple ash-fall events or mixing of ash with detrital sediments (e.g., ver Straeten, 2004).

The former (i.e., settling of volcanic ash through the water column) is most likely the case at Grotto Creek. This is due to a number of sedimentological and morphological factors including: (i) the sampled lithology is a thin light gray to yellow-weathering sticky claystone lacking induration or coarser clasts, consistent with diagenetically altered smectite clays derived from devitrified ash—more difficult to rework (e.g., ver Straeten, 2004); (ii) the dominance of needle-shaped zircons in samples 2017GC3.8, 2017GC14.9 and Grot-124 is indicative of a volcanic origin, rather than detrital grain morphologies indicative of recycling from nonvolcanic sources; (iii) the euhedral morphology of the sampled zircons, some pristine (i.e., not abraded subrounded to rounded zircon morphologies), is inconsistent with reworking or contamination by older detrital zircons; (iv) no sedimentary evidence for sediment reworking (i.e., no sedimentary structures, such as cross-stratification, early post-depositional soft sediment deformation, contorted/convolute laminae, ball/pillow structures, trace fossils, etc.); (v) no multiple graded layers or fossiliferous zones within the sampled bentonite horizons indicative of complex depositional histories that could mix ash with older/younger detritus; (vi) no glauconite or scattered phosphatic pebbles (hardgrounds) directly upon or within the sampled bentonites indicative of significant sediment starvation and condensation that might promote mixing of the ash with younger sediments containing older detrital zircons; and (vii) only minor variation in zircon ages recorded throughout the section (i.e., Fig. 7).

To expand on point (vii), there is no geochronologic evidence of pre-Triassic detrital ages in this study (i.e., Fig. 7, SI Table 2). All zircon ages cluster within Late Triassic and younger (upsection) rocks and are consistent with biostratigraphy. To better emphasize this point, age comparison data for all bentonite samples in the Grotto Creek section were generated for LA-ICPMS and CA-ID-TIMS U-Pb analyses. Data presented in Figure 7B show $^{206}Pb/^{238}U$ age distributions that are in-line with crystals from a primary ash bed rather than a volcaniclastic sandstone containing population(s) of significantly older zircon grains.

4. References (Supplemental Information)

Bowring, J. F., N. M. McLean, and S. A. Bowring (2011), Engineering Cyber Infrastructure for U-Pb Geochronology: Tripoli and U-Pb_Redux, *Geochemistry*, *Geophysics*, *Geosystems*, doi: 10.1029/2010GC003479.

Eggins S.M., Kinsley L. and Shelley J., 1998. Deposition and element fractionation processes during atmospheric pressure laser sampling for analysis by ICP-MS. Appl. Surf. Sci. 127-129, 278–286.

Gerstenberger, H., and Haase, G., 1997. A highly effective emitter substance for mass spectrometric Pb isotope ratio determinations. Chem. Geol. 136, 309–312.

Gröcke, D.R., Rimmer, S.M., Yoksoulian, L.E., Cairncross, B., Tsikos, H., and van Hunen, J., 2009. No evidence for thermogenic methane release in coal from the Karoo–Ferrar large igneous province: Earth and Planetary Science Letters, v. 277, p. 204–212.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. Phys. Rev. C4, 1889–1906.

Ludwig K.R., 2003. Isoplot 3.00, A Geochronological Toolkit for Microsoft Excel. University of California at Berkeley, kludwig@bgc.org.

Mattinson, J.M., 2005. Zircon U-Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology, v. 220, p. 47–66.

McLean, N. M., J. F. Bowring, and S. A. Bowring (2011), An algorithm for U-Pb isotope dilution data reduction and uncertainty propagation, *Geochemistry*, *Geophysics*, *Geosystems*, doi: 10.1029/2010GC003478.

McDonough, W.F and Sun, S.-s., 1995. The composition of the earth. Chemical Geology, 120, 223-253.

Mundil, R. Ludwig, K. R., Metcalfe, I, and Renne, P.R., 2004. Age and Timing of the Permian Mass Extinctions: U/Pb Dating of Closed-System Zircons. Science, v 305, p 1760-1763.

Paton C., Hellstrom J., Paul B., Woodhead J. and Hergt J., 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. J. Anal. Atom. Spectrom. 26, 2508–2518.

Rioux, M., S. A. Bowring, P. B. Kelemen, S. Gordon, F. Dudás, and R. Miller, 2012. Rapid crustal accretion and magma assimilation in the Oman-U.A.E. ophiolite: High precision U-Pb zircon geochronology of the gabbroic crust. Journal of Geophysical Research, *117*.

Scoates, J.S. and Friedman, R.M., 2008. Precise age of the platiniferous Merensky Reef, Bushveld Complex, South Africa, by the U-Pb zircon chemical abrasion ID-TIMS technique, Economic Geology, v. 103, p 465-471.

Schmitz, M. D., and Schoene, B., 2007. Derivation of isotope ratios, errors, and error correlations for U-Pb geochronology using 205Pb-235U-(233U)-spiked isotope dilution thermal ionization mass spectrometric data, Geochem. Geophys. Geosyst., 8, Q08006, doi:10.1029/2006GC001492.

Skrzypek, G., and Debajyoti, P., 2006. δ^{13}C analyses of calcium carbonate: comparison between the GasBench and elemental analyzer techniques. Rapid Communications in Mass Spectrometry, v. 20, p. 2915–2920.

Stacey, J.S., and Kramers, J.D., 1975. Approximation of terrestrial lead isotopic evolution by a two-stage model. Earth and Planetary Science Letters, 26: 207–221.

Thirlwall, M.F., 2000. Inter-laboratory and other errors in Pb isotope analyses investigated using a ^{207}Pb–^{204}Pb double spike. Chemical Geology, 163 p. 299–322.

Thirlwall, M.F., 2000. Inter-laboratory and other errors in Pb isotope analyses investigated using a ^{207}Pb–^{204}Pb double spike. Chemical Geology, 163 p. 299–322.

Wendt, I., and C. Carl, 1991. The statistical distribution of the mean squared weighted deviation. Chemical Geology, 86(4), 275-285.

Witmer, J.W., 2007. Sedimentology and Stratigraphy of the Upper Triassic - Lower Jurassic McCarthy Formation, Wrangell Mountains, South-Central Alaska. Unpublished BSc Thesis, Bucknell University.

Wotzlaw, J.F., Guex, J., Bartolini, A., Gallet, Y., Krystyn, L., McRoberts, C.A., Taylor, D., Schoene, B., Schaltegger, U., 2014. Towards accurate numerical calibration of the Late Triassic: high-precision U–Pb geochronology constraints on the duration of the Rhaetian. Geology 42, 571–574. http://dx.doi.org/10.1130/g35612.1.

Captions (Supplemental Information)

Table 1: Correlation tables for samples and specimens collected from the Grotto Creek section presented on figure 3 (main text). **(I)** paleontological specimens. **(II)** bentonite samples for (CA-ID) TIMS analysis. **(III)** samples for geochemical (i.e., organic carbon isotope and total organic carbon) analyses.

Table 2: Single grain U-Pb isotope data for samples analyzed at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, Canada (i.e., table 2.1) and the Massachusetts Institute of Technology (MIT), Cambridge MA (i.e., table 2.2).

Table 3: Trace element concentration data for zircons from ash sample 2017GC3.8.

Table 4: Chondrite normalized rare earth elements, selected trace element concentrations, and Ti-in-zircon temperatures for zircons from ash sample 2017GC3.8.

Table 5: LA-ICPMS and CA-ID-TIMS U-Pb age comparison data for all bentonite samples presented in this study.

Figure 1: Images for analyzed zircon grain analysis from the Grotto Creek Section. **(A)** Photomicrograph of zircons from ash sample 2017GC3.8 in plane-polarized light. **(B)** Photomicrograph of zircons from ash sample 2017GC14.9 in plane-polarized light. Grain IDs correspond to those that appear in CA-ID-TIMS U-Pb analytical data table. All 5 grains were processed for CA-ID-TIMS with grains D and E lost in processing.

Laser Ablation techniques are listed in SI methodology (above). **(C)** Cathodoluminescence (CL) images of zircons from ash sample 2017GC3.8. Grain IDs correspond to those in tables 2-5 and CA-ID-TIMS U-Pb analytical data table. **(D)** Plot of chondrite normalized rare earth elements for 2017GC3.8 zircons normalized to chondrite values of McDonough and Sun (1995).