Datashare 93

Solving a tuff problem: Defining a chronostratigraphic framework for Middle to Upper Jurassic nonmarine strata in eastern Australia using uranium–lead chemical abrasion–thermal ionization mass spectrometry zircon dates

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APPENDIX 1. LASER ABLATION–INDUCTIVELY COUPLED PLASMA MASS SPECTROMETRY METHODS

Zircon from 11 samples was analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS). Zircon grains were separated using standard techniques, annealed at 900°C for 60 hr in a muffle furnace, mounted in epoxy, and polished until their centers were exposed. In two samples, sharply faceted and round grains were mounted separately. Cathodoluminescence (CL) images were obtained with a JEOL JSM-1300 scanning electron microscope and Gatan MiniCL. Zircon was analyzed by LA-ICPMS using a ThermoElectron X-Series II quadrupole ICPMS and the New Wave Research UP-213 Nd:YAG UV (213 nm) laser ablation system. In-house analytical protocols, standard materials, and data reduction software were used for acquisition and calibration of U-Pb dates and a suite of high-field strength elements (HFSEs) and rare-earth elements (REEs). Zircon was ablated with a 25-µm-wide laser spot using fluence and pulse rates of 5 J/cm^2 and 10 Hz, respectively, during a 45-s analysis (15-s gas blank, 30-s ablation) that excavated a pit approximately 25 µm deep. Ablated material was carried by a 1.2 L/min He gas stream to the nebulizer flow of the plasma. Dwell times were 5 ms for Si and Zr, 200 ms for ^{49}Ti and ^{207}Pb, 80 ms for ^{206}Pb, 40 ms for ^{202}Hg, ^{204}Pb, ^{208}Pb, ^{232}Th, and ^{238}U and 10 ms for all other HFSEs and REEs. Background count rates for each analyte were obtained prior to each spot analysis and subtracted from the raw count rate for each analyte. Ablations pits that appear to have intersected glass or mineral inclusions were identified based on Ti and P. The U-Pb dates from these analyses are considered valid if the U-Pb ratios appear to have been unaffected by the inclusions. Analyses that appear contaminated by common Pb were rejected based on mass 204 being above baseline. For concentration calculations, background-subtracted count rates for each analyte were internally normalized to ^{29}Si and calibrated with respect to National Institute of Standards and Technology SRM-610 and -612 glasses as the primary standards. Temperature was calculated from the Ti-in-zircon thermometer (Watson et al., 2006). Because there are no constraints on the activity of TiO_2, an average value in crustal rocks of 0.8 was used.

Data were collected in six sessions from February 2015 to March 2018 (Table S1). For U-Pb and ^{207}Pb/^{206}Pb dates, instrumental fractionation of the background-subtracted ratios was corrected and dates were calibrated with respect to interspersed measurements of zircon standards and reference materials. The primary standard Plešovice zircon (Sláma et al., 2008) was used to monitor time-dependent instrumental fractionation based on 2 analyses for every 10 analyses of unknown zircon. A secondary correction to the ^{206}Pb/^{238}U dates was made based on results from the zircon standards Seiland (530 Ma, J. L. Crowley, unpublished data, Boise State University) and Zirconia (327 Ma, J. L. Crowley, unpublished data, Boise State University), which were treated as unknowns and measured once for every 10 analyses of unknown zircon. These results showed a linear age bias of up to 2% that is related to the ^{206}Pb count rate. The secondary correction is thought to mitigate matrix-dependent variations due to contrasting compositions and ablation characteristics between the Plešovice zircon and other standards (and unknowns).

Radiogenic isotope ratio and age error propagation for all analyses include uncertainty contributions from counting statistics and background subtraction. Weighted-mean ^{206}Pb/^{238}U dates are calculated from equivalent dates (i.e., probability of fit >0.05) that are at the young end of age spectra. A weighted-mean date is first calculated using Isoplot 3.0 (Ludwig, 2003) using errors on individual dates that do not include a standard calibration uncertainty, and then a standard calibration uncertainty is propagated into the error on the weighted-mean date. This uncertainty is the local standard deviation of the polynomial fit to the interspersed primary standard measurements versus time for the time-dependent, relatively larger U/Pb fractionation factor, and the standard error of the mean of the consistently time-invariant and smaller ^{207}Pb/^{206}Pb fractionation factor. These uncertainties are 1.1%–2.2% (2σ) for ^{206}Pb/^{238}U and 0.3–1.5% (2σ) for ^{207}Pb/^{206}Pb. Age interpretations are based on ^{207}Pb/^{206}Pb dates for greater than 1000 Ma zircon. The ^{206}Pb/^{238}U dates are used for less than 1000 Ma zircon. Errors on the ^{207}Pb/^{206}Pb and ^{206}Pb/^{238}U dates from individual analyses are given at 2σ, as are the errors on the weighted-mean dates.

APPENDIX 2. CHEMICAL ABRASION–THERMAL IONIZATION MASS SPECTROMETRY METHODS

The U-Pb dates were obtained by the chemical abrasion–-thermal ionization mass spectrometry (CA-TIMS) method from analyses composed of single-zircon grains (Table 3), modified after Mattinson (2005). Zircon was separated from 33 tuff samples using standard techniques and annealed including two previously dated by Wainman et al. (2015). Only sharply faceted grains were selected for CA-TIMS dating. Grains were large enough in 21 samples to be mounted in epoxy and imaged with CL as described in the previous section. Zircon in 11 samples was analyzed by LA-ICPMS. Nine were removed from the epoxy mounts for CA-TIMS dating based on the LA-ICPMS dates. For the samples without LA-ICPMS data, the grains were removed from the epoxy mounts for CA-TIMS dating-based CL images. Grains with homogeneous CL images from a dominant population were preferentially selected. For the 10 samples without CL images, sharply faceted grains were randomly selected.

Single grains were transferred to 3-ml Teflon perfluoroalkoxy (PFA) beakers and loaded into 300-µl Teflon PFA microcapsules. Fifteen microcapsules were placed in a large-capacity Parr vessel and the grains partially dissolved in 120 µl of 29 M hydrofluoric acid (HF) for 12 hr at 180°C. The contents of the microcapsules were returned to 3-ml Teflon PFA beakers, HF removed, and the residual grains immersed in 3.5 M HNO_3, ultrasonically cleaned for 1 hr, and fluxed on a hotplate at 80°C for 1 hr. The HNO_3 was removed and grains were rinsed twice in ultrapure H_2O before being reloaded into the 300-µl Teflon PFA microcapsules (rinsed and fluxed in 6 M HCl during sonication and washing of the grains) and spiked with the Earthtime-mixed ^{233}U-^{235}U-^{205}Pb tracer solution. Zircon was dissolved in Parr vessels in 120 µl of 29 M HF with a trace of 3.5 M HNO_3 at 220°C for 48 hr, dried to fluorides, and redissolved in 6 M HCl at 180°C overnight. The U and Pb were separated from the zircon matrix using an HCl-based anion-exchange chromatographic procedure (Krogh, 1973) eluted together and dried with 2 µl of 0.05 N H_3PO_4.

The Pb and U were loaded on a single-outgassed Re filament in 5 µl of a silica-gel and phosphoric acid mixture (Gerstenberger and Haase, 1997); U and Pb isotopic measurements were made on a GV Isoprobe-T multicollector thermal ionization mass spectrometer equipped with an ion-counting Daly detector. The Pb isotopes were measured by peak-jumping all isotopes on the Daly detector for 160 cycles, and corrected for 0.16% ± 0.03%/atomic mass unit (1σ error) mass fractionation. Transitory isobaric interferences due to high-molecular-weight organics, particularly on ^{204}Pb and ^{207}Pb, disappeared within approximately 30 cycles, whereas ionization efficiency averaged 10^4 centipoise/picogram of each Pb isotope. Linearity (to $\geq 1.4 \times 10^6$ counts per s) and the associated deadtime correction of the Daly detector were monitored by repeated analyses of NBS982, and have been constant since installation. The U was analyzed as UO_2^+ ions in static Faraday mode on 10^{12} ohm resistors for 300 cycles and corrected for isobaric interference of $^{233}U^{18}O^{16}O$ on $^{235}U^{16}O^{16}O$ with an $^{18}O/^{16}O$ of 0.00206. Ionization efficiency averaged 20 mV/ng of each U isotope. The U mass fractionation was corrected using the known $^{233}U/^{235}U$ ratio of the EARTHTIME tracer solution.

The CA-TIMS U-Pb dates and uncertainties were calculated using the algorithms of Schmitz and Schoene (2007), Earthtime ET535 tracer solution with calibration of $^{235}U/^{205}Pb = 100.233$, $^{233}U/^{235}U = 0.99506$, and $^{205}Pb/^{204}Pb = 11268$, and U decay constants recommended by Jaffey et al. (1971). The $^{206}Pb/^{238}U$ ratios and dates were corrected for initial ^{230}Th disequilibrium using a Th/U[magma] = 3.0 ± 0.3 using the algorithms of Crowley et al. (2007), resulting in an increase in the $^{206}Pb/^{238}U$ dates of approximately 0.09 Ma. All common Pb in analyses was attributed to laboratory blank and subtracted based on the measured laboratory Pb isotopic composition and associated uncertainty. The U blanks are estimated at 0.02 pg.

An average of 7.8 grains per tuff were analyzed, with the age of tuff deposition being interpreted from an average of 5.0 grains per sample. In 8 of the 31 tuffs, all analyzed grains yielded equivalent dates (i.e., probability of fit >0.05). For these samples, weighted-mean $^{206}Pb/^{238}U$ dates were calculated from all dates using Isoplot 3.0 (Ludwig, 2003) and interpreted as the ages of tuff deposition. For 22 of the other 23 samples, ages of tuff deposition are interpreted from weighted-mean $^{206}Pb/^{238}U$ dates from equivalent dates (i.e., probability of fit >0.05) that are at the young end of age spectra. The older dates are interpreted as being from detrital grains that were incorporated into the tuff after deposition or grains with extended residence histories in the magma chamber or were inherited in the magma chamber. For the one sample in which there are no equivalent dates, no age interpretation could be made.

Errors on the weighted-mean dates are given as ± *x*/*y*/*z*, where *x* is the internal error based on analytical uncertainties only, including counting statistics, subtraction of tracer solution, and blank and initial common Pb subtraction, *y* includes the tracer calibration uncertainty propagated in quadrature, and *z* includes the ^{238}U decay constant uncertainty propagated in quadrature. Internal errors should be considered when comparing our dates with $^{206}Pb/^{238}U$ dates from other laboratories that used the same Earthtime tracer solution or a tracer solution that was cross-calibrated using Earthtime gravimetric standards. Errors including the uncertainty in the tracer calibration should be considered when comparing our dates with those derived from other geochronological methods using the U-Pb decay scheme (e.g., LA-ICPMS). Errors including uncertainties in the tracer calibration and ^{238}U decay constant (Jaffey et al., 1971) should be considered when comparing our dates with those derived from other decay schemes (e.g., $^{40}Ar/^{39}Ar$, ^{187}Re-^{187}Os). Errors for weighted-mean dates and dates from individual grains are given at 2σ.

APPENDIX 3. URANIUM–LEAD GEOCHRONOLOGY RESULTS

Data are presented by well and location, from east to west. Zircon from all samples were mounted for CL imaging

(Figures S1–S24), except where it is noted that the grains were too small for mounting. Plots of $^{206}Pb/^{238}U$ CA-TIMS dates are shown in Figure 6 of the paper.

Mt. Lindesay 1

Six zircon grains from a tuff at 151.23–151.30 m (496.16–496.39 ft) (Geoscience Australia sample number [GA] 2389974) were analyzed. The five youngest yielded equivalent CA-TIMS dates with a weighted mean of 155.38 ± 0.07/0.11/0.20 Ma (mean square of the weighted deviates [MSWD] = 1.4, probability of fit = 0.23). This is the interpreted age of ash deposition. An older date is 155.88 ± 0.16 Ma.

Kalbar 1

Ten zircon grains from a tuff at 400.50–400.67 m (1313.97–1314.53 ft) (GA 2233282) were analyzed. Grains were too small for mounting and CL imaging. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 167.56 ± 0.06/0.10/0.21 Ma (MSWD = 2.2, probability of fit = 0.08). This is the interpreted age of ash deposition. Older dates are 167.84 ± 0.14 Ma to 168.28 ± 0.15 Ma.

Turallin 1

Six zircon grains from a tuff at 185.37–185.66 m (608.17–609.12 ft) (GA 2254136) yielded equivalent CA-TIMS dates with a weighted mean of 164.74 ± 0.04/0.09/0.20 Ma (MSWD = 0.3, probability of fit = 0.91). This is the interpreted age of ash deposition.

Stratheden 4

Seven zircon grains from a tuff at 396.41–396.46 m (1211.97–1212.14 ft) (GA 2180600) were analyzed by Wainman et al. (2015). The seven youngest yielded equivalent CA-TIMS dates with a weighted mean of 162.54 ± 0.05/0.09/0.20 Ma (MSWD = 0.6, probability of fit = 0.74). This is the interpreted age of ash deposition. Older dates are 162.81 ± 0.14 Ma to 171.18 ± 0.21 Ma. Thirty-two zircon grains were analyzed by LA-ICPMS. The youngest 24 analyses yielded equivalent dates with a weighted mean of 160.8 ± 4.3 Ma (MSWD = 0.7, probability of fit = 0.90). Older dates are 171.5 ± 16.8 Ma to 182.2 ± 13.1 Ma.

Six zircon grains from a tuff at 209.62–209.87 m (687.73–688.55 ft) (GA 2231585) yielded equivalent CA-TIMS dates with a weighted mean of 159.69 ± 0.04/0.09/0.19 Ma (MSWD = 1.0, probability of fit = 0.41). This is the interpreted age of ash deposition.

Six zircon grains from a tuff at 182.84–183.04 m (599.57–600.52 ft) (GA 2180601) were analyzed by Wainman et al. (2015). All grains yielded equivalent CA-TIMS dates with a weighted mean of 158.86 ± 0.04/0.09/0.19 Ma (MSWD = 1.5, probability of fit = 0.18). This is the interpreted age of ash deposition. Twenty-seven zircon grains were analyzed by LA-ICPMS. The youngest 18 analyses yielded equivalent dates with a weighted mean of 163.0 ± 4.7 Ma (MSWD = 0.6, probability of fit = 0.93). Older dates are 173.0 ± 14.3 Ma to 183.8 ± 17.5 Ma.

Stratheden 60

Twelve zircon grains from a tuff at 477.64–477.70 m (1567.10–1567.26 ft) (GA 2231590) were analyzed. The three youngest yielded equivalent CA-TIMS dates with a weighted mean of 168.07 ± 0.07/0.11/0.21 Ma (MSWD = 1.7, probability of fit = 0.18). This is the interpreted age of ash deposition. Older dates are 168.32 ± 0.14 Ma to 172.97 ± 0.12 Ma. Twenty-eight zircon grains were analyzed by LA-ICPMS. The youngest 15 analyses yielded equivalent dates with a weighted mean of 171.1 ± 3.4 Ma (MSWD = 1.3, probability of fit = 0.21). Older dates are 185.8 ± 9.0 Ma to 3392 ± 21 Ma.

Nine zircon grains from a tuff at 324.24–324.31 m (1063.78–1064.00 ft) (GA 2231589) were analyzed. The five youngest yielded equivalent CA-TIMS dates with a weighted mean of 162.18 ± 0.06/0.10/0.20 Ma (MSWD = 1.1, probability of fit = 0.37). This is the interpreted age of ash deposition. Older dates are 162.43 ± 0.12 Ma to 162.69 ± 0.13 Ma. Forty-six zircon grains were analyzed by LA-ICPMS. The youngest 44 analyses yielded equivalent dates with a weighted mean of 161.4 ± 2.9 Ma (MSWD = 0.9, probability of fit = 0.56). Older dates are 177.6 ± 11.7 Ma and 183.1 ± 12.1 Ma.

Nine zircon grains from a tuff at 247.61–247.66 m (812.37–812.53 ft) (GA 2231588) were analyzed. Grains were too small for mounting and CL imaging. The two youngest yielded equivalent CA-TIMS dates with a weighted mean of 160.54 ± 0.12/0.14/0.22 Ma (MSWD = 1.3, probability of fit = 0.25). This is the interpreted age of ash deposition. Older dates are 161.03 ± 0.19 Ma to 343.27 ± 6.05 Ma.

Nine zircon grains from a tuff at 212.50–212.55 m (697.18–697.34 ft) (GA 2254143) were analyzed. The seven youngest yielded equivalent CA-TIMS dates with a weighted mean of 160.45 ± 0.05/0.09/0.19 Ma (MSWD = 1.5, probability of fit = 0.18). This is the interpreted age of ash deposition. Older dates are 160.65 ± 0.13 Ma and 160.90 ± 0.11 Ma.

Six zircon grains from a tuff at 135.86–136.11 m (455.73–446.56 ft) (GA 2254141) yielded equivalent CA-TIMS dates with a weighted mean of 159.02 ± 0.04/0.09/0.19 Ma (MSWD = 1.8, probability of fit = 0.10). This is the interpreted age of ash deposition.

Wyalla 3

Ten zircon grains from a tuff at 345.54–345.60 m (1133.66–1133.85 ft) (GA 2254151) were analyzed. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 163.16 ± 0.06/0.10/0.20 Ma (MSWD = 0.4, probability of fit = 0.72). This is the interpreted age of ash deposition. Older dates are 163.38 ± 0.10 Ma to 166.13 ± 0.18 Ma.

Six zircon grains from a tuff at 127.30–127.40 m (417.65–417.98 ft) (GA 2254147) yielded equivalent CA-TIMS dates with a weighted mean of 159.67 ± 0.04/0.09/0.19 Ma (MSWD = 2.2, probability of fit = 0.05). This is the interpreted age of ash deposition.

Alderley 1

Nine zircon grains from a tuff at 402.68–402.76 m (1321.13–1321.39 ft) (GA 2254165) were analyzed. The six youngest yielded equivalent CA-TIMS dates with a weighted mean of 163.08 ± 0.05/0.09/0.20 Ma (MSWD = 0.5, probability of fit = 0.78). This is the interpreted age of ash deposition. Older dates are 163.44 ± 0.11 Ma to 163.52 ± 0.13 Ma.

Ten zircon grains from a tuff at 156.13–156.17 m (512.24–512.36 ft) (GA 2254160) were analyzed. The five youngest yielded equivalent CA-TIMS dates with a weighted mean of 157.55 ± 0.05/0.09/0.19 Ma (MSWD = 1.8, probability of fit = 0.13). This is the interpreted age of ash deposition. Older dates are 157.71 ± 0.14 Ma to 160.02 ± 0.25 Ma. Thirty zircon grains were analyzed by LA-ICPMS. The youngest 25 analyses yielded equivalent dates with a weighted mean of 154.9 ± 3.2 Ma (MSWD = 1.2, probability of fit = 0.24). Older dates are 164.0 ± 8.4 Ma to 167.8 ± 9.2 Ma.

Ten zircon grains from a tuff at 135.24–135.29 m (443.70–443.86 ft) (GA 2254159) were analyzed. The three youngest yielded equivalent CA-TIMS dates with a weighted mean of 152.99 ± 0.06/0.10/0.19 Ma (MSWD = 0.6, probability of fit = 0.55). This is the interpreted age of ash deposition. Older dates are 154.04 ± 0.11 Ma to 181.35 ± 0.12 Ma. Forty-two zircon grains were analyzed by LA-ICPMS. The youngest 15 analyses yielded equivalent dates with a weighted mean of 150.9 ± 2.1 Ma (MSWD = 1.1, probability of fit = 0.32). Older dates are 156.1 ± 4.8 Ma to 285.0 ± 6.7 Ma.

Guluguba 2

Nine zircon grains from a tuff at 509.40–509.43 m (1671.25–1671.36 ft) (GA 2233310) were analyzed. The six youngest yielded equivalent CA-TIMS dates with a weighted mean of 165.93 ± 0.05/0.09/0.20 Ma (MSWD = 1.6, probability of fit = 0.17). This is the interpreted age of ash deposition. Older dates are 169.40 ± 0.12 Ma to 519.20 ± 1.55 Ma.

Six zircon grains from a tuff at 428.51–428.57 m (1405.67–1406.07 ft) (GA 2233308) were analyzed. The five youngest yielded equivalent CA-TIMS dates with a weighted mean of 163.05 ± 0.05/0.09/0.20 Ma (MSWD = 0.9, probability of fit = 0.46). This is the interpreted age of ash deposition. An older date is 163.37 ± 0.11 Ma.

Eight zircon grains from a tuff at 404.16–404.23 m (1325.98–1326.21 ft) (GA 2233302) were analyzed. Grains were too small for mounting and CL imaging. The six youngest yielded equivalent CA-TIMS dates with a weighted mean of 162.40 ± 0.04/0.09/0.20 Ma (MSWD = 1.5, probability of fit = 0.19). This is the interpreted age of ash deposition. Older dates are 162.71 ± 0.12 Ma to 162.86 ± 0.12 Ma.

Seven zircon grains from a tuff at 279.11–279.15 m (915.72–915.84 ft) (GA 2233298) were analyzed. Grains were too small for mounting and CL imaging. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 159.92 ± 0.06/0.10/0.20 Ma (MSWD = 1.4, probability of fit = 0.23). This is the interpreted age of ash deposition. Older dates are 160.09 ± 0.12 Ma to 160.15 ± 0.11 Ma.

Thirteen zircon grains from a tuff at 162.03–162.10 m (531.59–531.84 ft) (GA 2233290) were analyzed. Grains were too small for mounting and CL imaging. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 157.97 ± 0.08/0.11/0.20 Ma (MSWD = 2.1, probability of fit = 0.10). This is the interpreted age of ash deposition. Older dates are 158.30 ± 0.12 Ma to 678.64 ± 2.45 Ma.

Cameron 1

Five zircon grains from a tuff at 221.30–221.40 m (726.00–726.38 ft) (GA 2389991) yielded equivalent CA-TIMS dates with a weighted mean of 157.70 ± 0.05/0.09/0.19 Ma (MSWD = 0.3, probability of fit = 0.88). This is the interpreted age of ash deposition.

Five zircon grains from a tuff at 415.19–415.32 m (1362.17–1362.60 ft) (GA 2389997) were analyzed by LA-ICPMS. Dates are 213.7 ± 11.8 Ma to 762.4 ± 47.2 Ma.

Pleasant Hills 25

Five zircon grains from a tuff at 512.07–512.20 m (1680.02–1680.45 ft) (GA 2390012) were analyzed. Grains were too small for mounting and CL imaging. The CA-TIMS dates are 151.39 ± 0.12 Ma to 197.89 ± 0.34 Ma and none equivalent. The youngest date is not interpreted as a maximum depositional age because it is just a single analysis; it cannot be ruled out that it domains with Pb loss remained after undergoing chemical abrasion. The next youngest grain is 162.05 ± 0.15 Ma, which overlaps in age with the interpreted age of deposition for sample GA 2390011 that is approximately 0.7 m (2.29 ft) above.

Six zircon grains from a tuff at 511.37–511.51 m (1677.72–1678.18 ft) (GA 2390011) were analyzed. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 162.21 ± 0.08/0.11/0.21 Ma (MSWD = 1.5, probability of fit = 0.22). This is the interpreted age of ash deposition. Older dates are 162.59 ± 0.22 and 162.66 ± 0.20 Ma. Twenty zircon grains were analyzed by LA-ICPMS. The 14 youngest yielded equivalent dates with a weighted mean of 159.7 ± 3.0 Ma (MSWD = 1.3, probability of fit = 0.20). Older dates are 173.8 ± 10.5 Ma to 967.3 ± 31.4 Ma.

Eight zircon grains from a tuff at 335.00–335.08 m (1099.08–1099.34 ft) (GA 2390007) were analyzed. The seven youngest yielded equivalent CA-TIMS dates with a weighted mean of 150.77 ± 0.06/0.10/0.19 Ma (MSWD = 2.0, probability of fit = 0.06). This is the interpreted age of ash deposition. An older date is 151.10 ± 0.15 Ma.

Fourteen zircon grains from a tuff at 299.11–299.15 m (981.33–981.46 ft) (GA 2390002) were analyzed by LA-ICPMS. Dates are 139.9 ± 9.1 Ma to 549.7 ± 23.5 Ma.

Indy 4

Six zircon grains from a tuff at 201.59–202.00 m (661′38″–662.73 ft) (GA 2233272) were analyzed. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 152.90 ± 0.07/0.10/0.19 Ma (MSWD = 1.8, probability of fit = 0.14). This is the interpreted age of ash deposition. Older dates are 157.38 ± 0.41 Ma to 188.06 ± 0.16 Ma.

Indy 3

Five zircon grains from a tuff at 159.57–159.76 m (524.15–525.52 ft) (GA 2254172) yielded equivalent CA-TIMS dates with a weighted mean of 150.11 ± 0.04/0.09/0.18 Ma (MSWD = 1.2, probability of fit = 0.31). This is the interpreted age of ash deposition.

Eight zircon grains from a tuff at 139.97–140.38 m (459.22–460.57 ft) (GA 2254170) were analyzed. Grains were too small for mounting and CL imaging. The seven youngest yielded equivalent CA-TIMS dates with a weighted mean of 149.78 ± 0.06/0.10/0.19 Ma (MSWD = 1.0, probability of fit = 0.41). This is the interpreted age of ash deposition. Older dates are 160.83 ± 0.39 Ma and 190.05 ± 0.43 Ma.

Six zircon grains from a tuff at 104.40–140.62 m (342.52–343.24 ft) (GA 2254169) yielded equivalent CA-TIMS dates with a weighted mean of 149.08 ± 0.06/0.09/0.18 Ma (MSWD = 1.1, probability of fit = 0.36). This is the interpreted age of ash deposition.

Zeus 7

Seven zircon grains from a volcanogenic sandstone at 1677.31–1677.51 m (5502.98–5503.64 ft) (GA 2550367) were analyzed. The three youngest yielded equivalent CA-TIMS dates with a weighted mean of 162.39 ± 0.06/0.10/0.20 Ma (MSWD = 2.5, probability of fit = 0.08). This is the interpreted age of sandstone deposition. Older dates are 162.57 ± 0.10 Ma to 169.83 ± 0.11 Ma. Fifty-seven zircon grains were analyzed by LA-ICPMS. Thirty-one grains are sharply faceted and others are round. Ten of the youngest 11 analyses are from sharply faceted grains. These 11 analyses yielded equivalent dates with a weighted mean of 163.8 ± 2.2 Ma (MSWD = 1.5, probability of fit = 0.12). Older dates are 178.0 ± 7.3 Ma to 2769 ± 29 Ma.

Eight zircon grains from a volcanogenic sandstone at 1659.03–1659.31 m (5443.00–5443.93 ft) (GA 2550364) were analyzed. The four youngest yielded equivalent CA-TIMS dates with a weighted mean of 161.11 ± 0.05/0.10/0.20 Ma (MSWD = 0.8, probability of fit = 0.47). This is the interpreted age of sandstone deposition. Older dates are 162.23 ± 0.09 Ma to 166.36 ± 0.13 Ma. Fifty-eight zircon grains were analyzed by LA-ICPMS. Thirty-five grains are sharply faceted and others are round. Fourteen of the youngest 15 analyses are from sharply faceted grains. These 15 analyses yielded equivalent dates with a weighted mean of 160.7 ± 1.8 Ma (MSWD = 0.8, probability of fit = 0.73). Older dates are 174.1 ± 8.5 Ma to 2692 ± 28 Ma.

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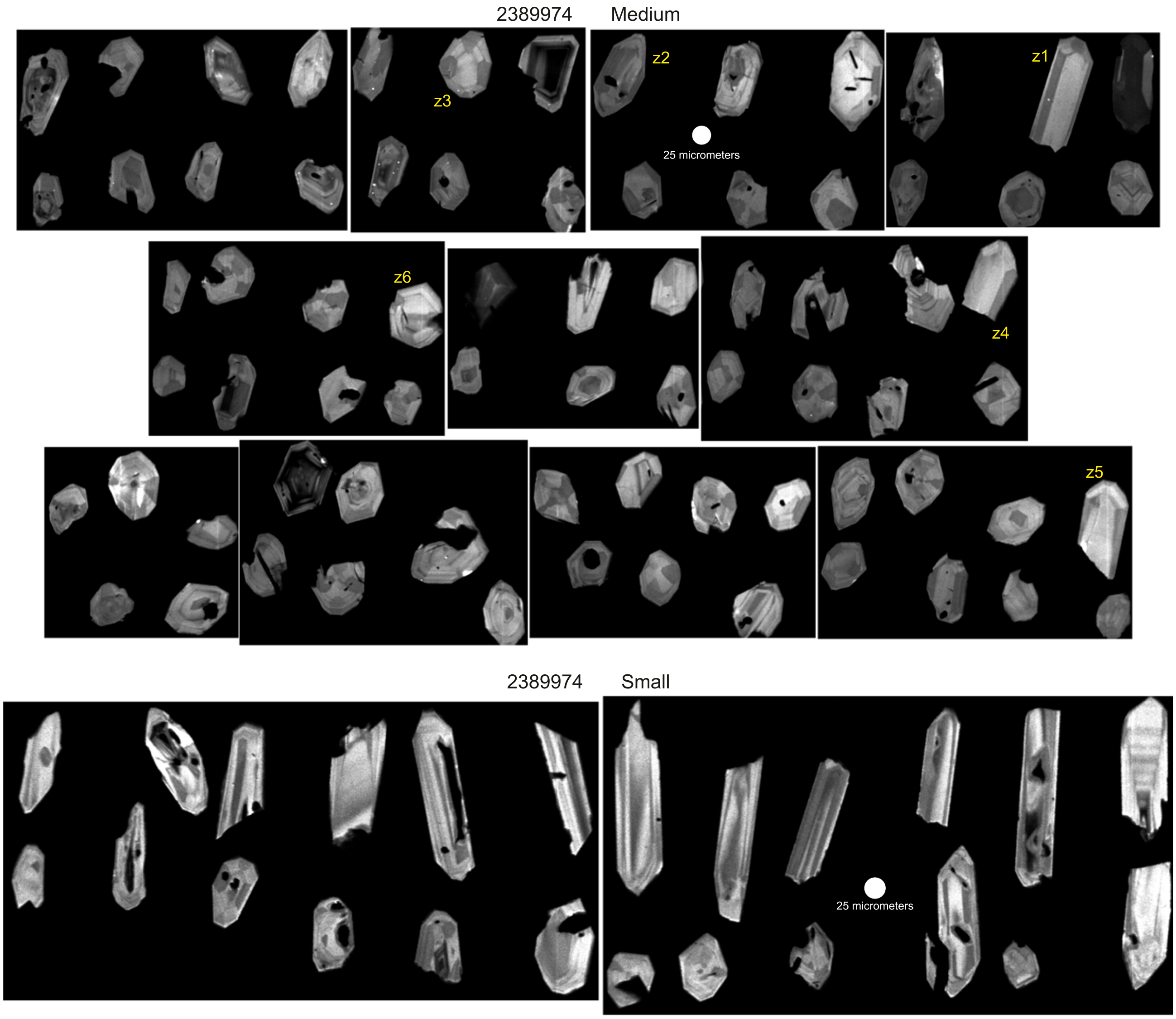


Figure S1. Cathodoluminescence images of selected zircons extracted from the Mt. Lindesay 1 well, 151.30 m (496.39 ft) (Geoscience Australia sample number 2389974). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

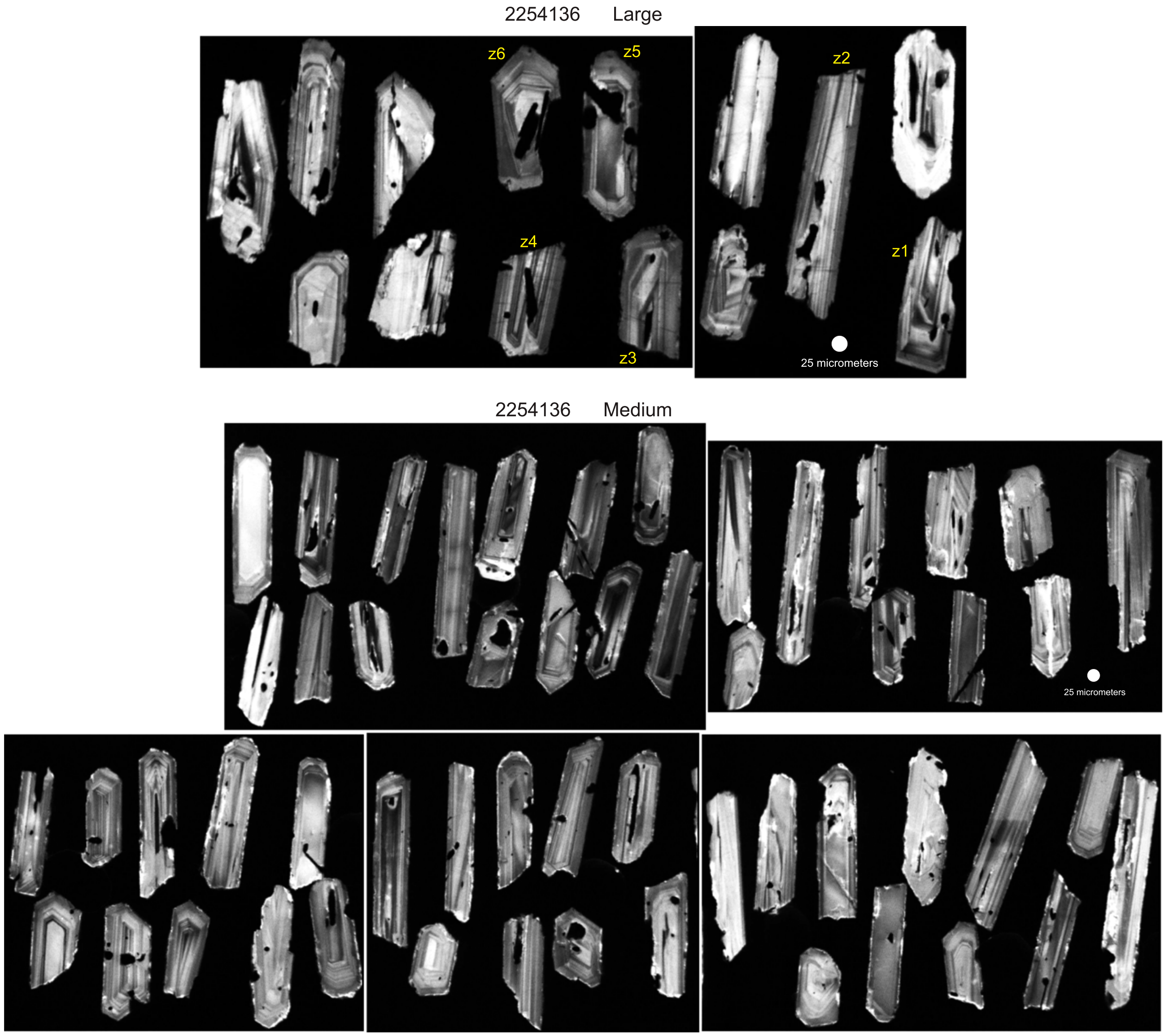


Figure S2. Cathodoluminescence images of selected zircons extracted from the Turallin 1 well, 185.37 m (608.17 ft) (Geoscience Australia sample number 2254136). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

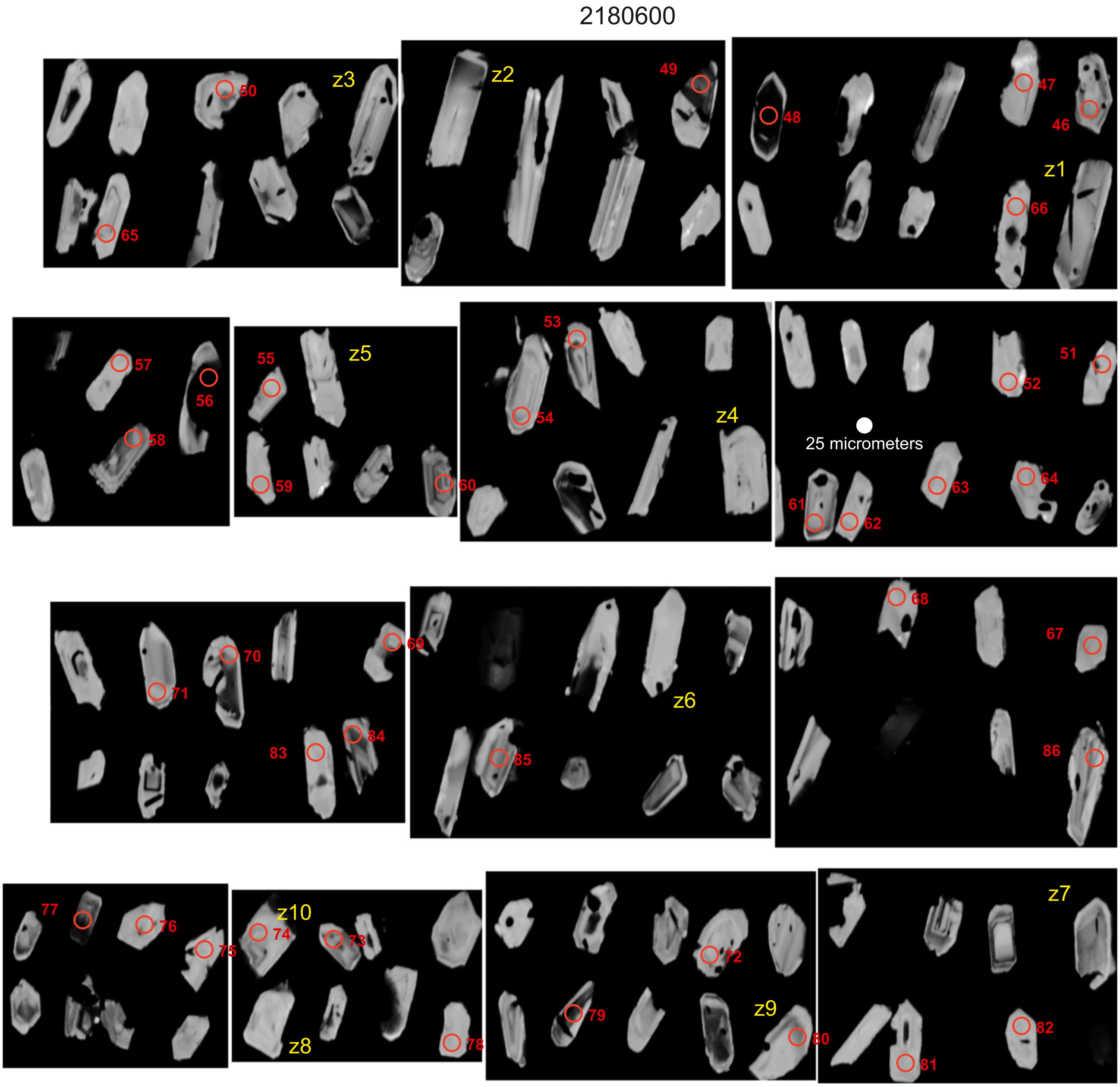


Figure S3. Cathodoluminescence images of selected zircons extracted from the Stratheden 4 well, 396.46 m (1300.72 ft) (Geoscience Australia sample number 2180600). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

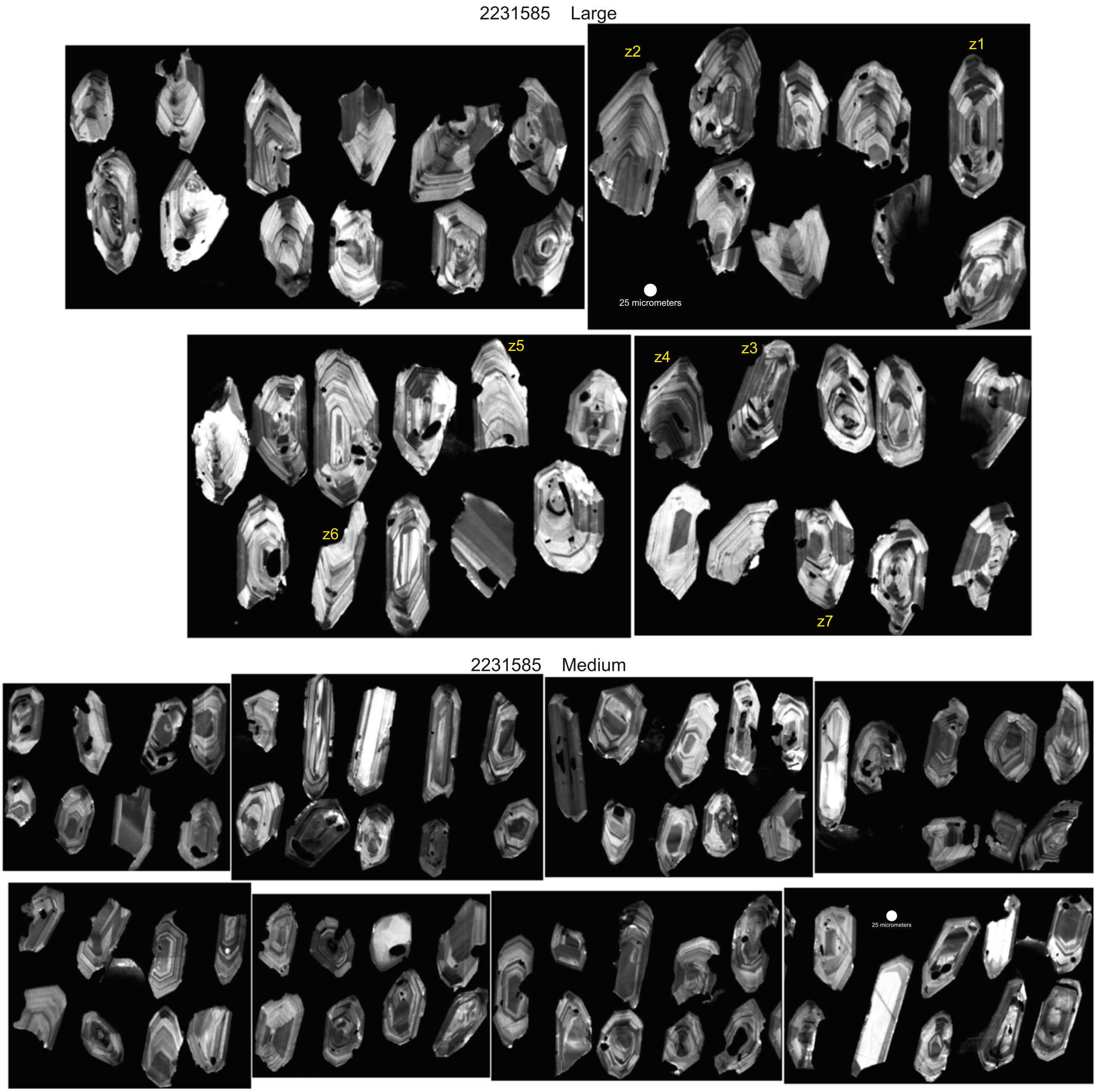


Figure S4. Cathodoluminescence images of selected zircons extracted from the Stratheden 4 well, 209.87 m (688.55 ft) (Geoscience Australia sample number 2231585). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) are shown. Zircon grains dated using CA-TIMS are labeled as z numbers.

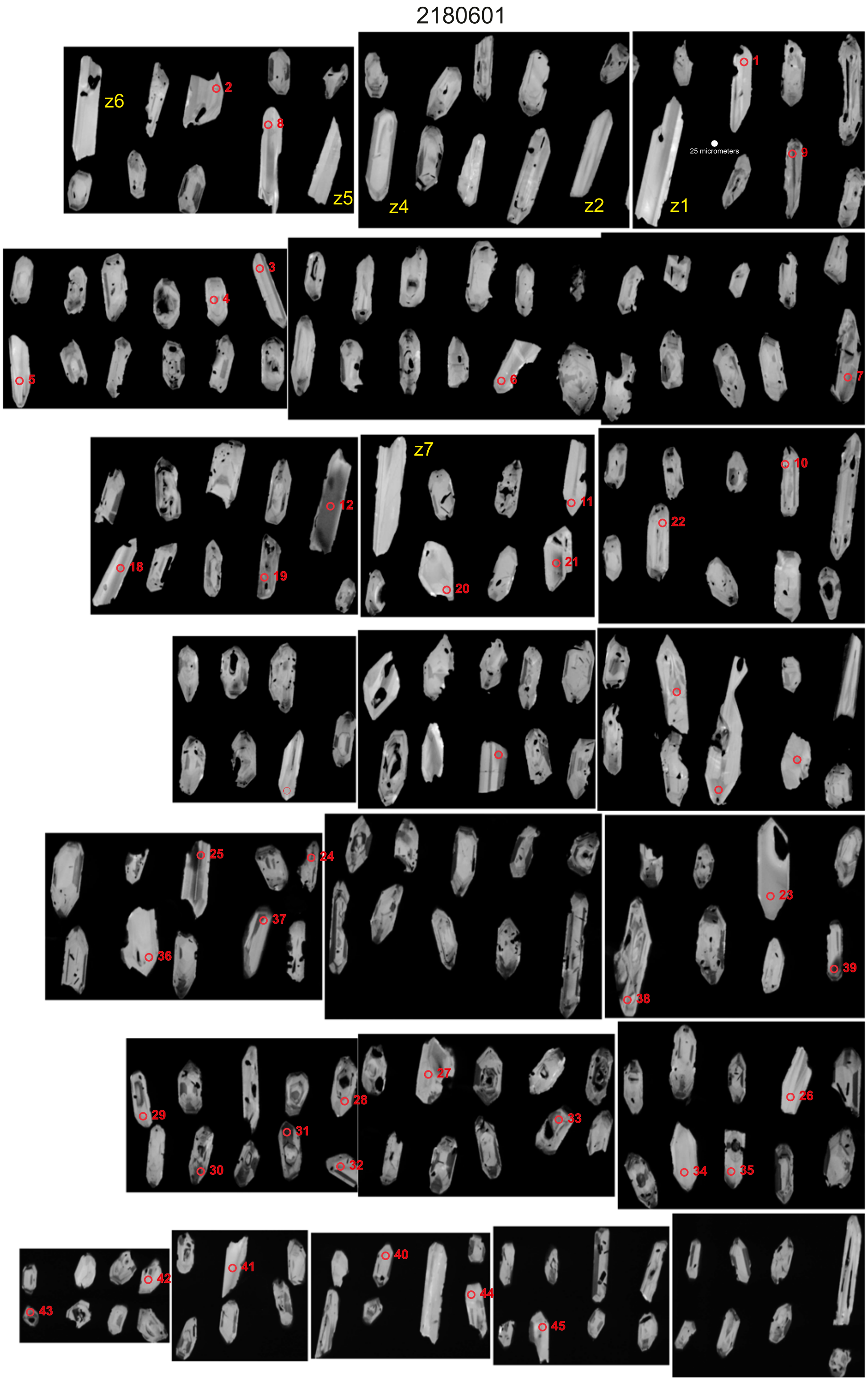


Figure S5. Cathodoluminescence images of selected zircons extracted from the Stratheden 4 well, 183.04 m (600.52 ft) (Geoscience Australia sample number 2180601) from the study by Wainman et al. (2015). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

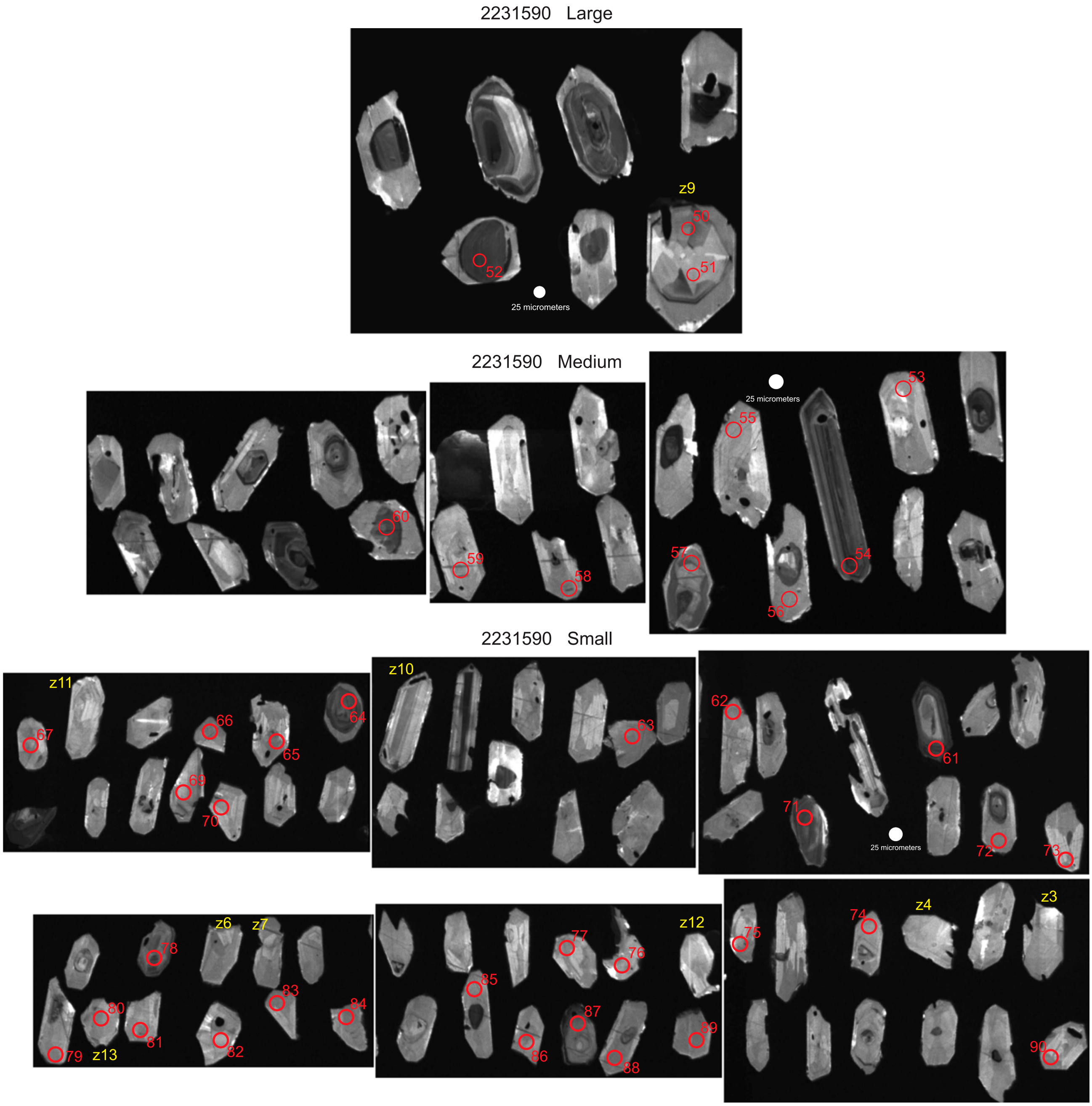


Figure S6. Cathodoluminescence images of selected zircons extracted from the Stratheden 60 well, 477.70 m (1567.26 ft) (Geoscience Australia sample number 2231590). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

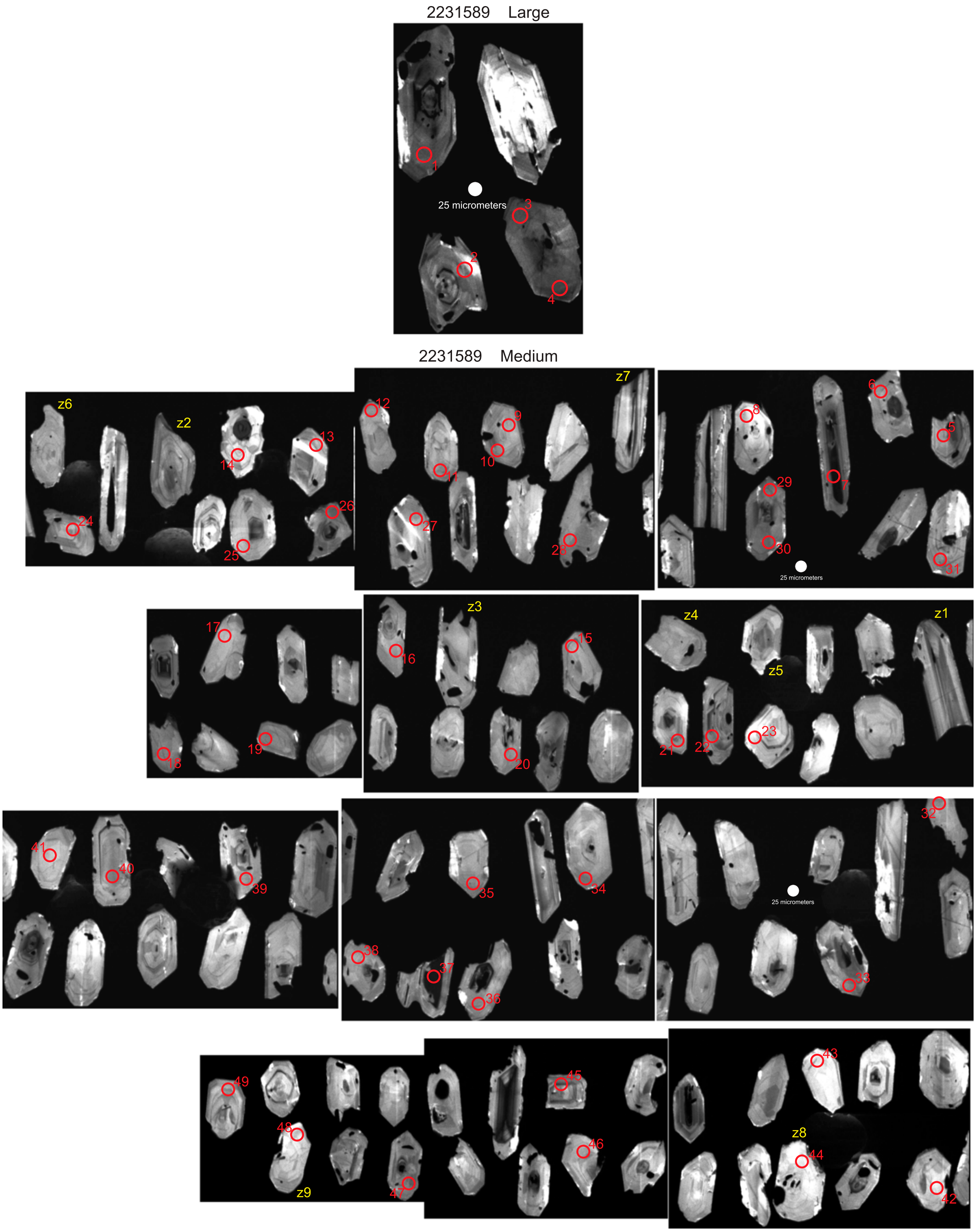


Figure S7. Cathodoluminescence images of selected zircons extracted from the Stratheden 60 well, 342.24 m (1122.84 ft) (Geoscience Australia sample number 2231589). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

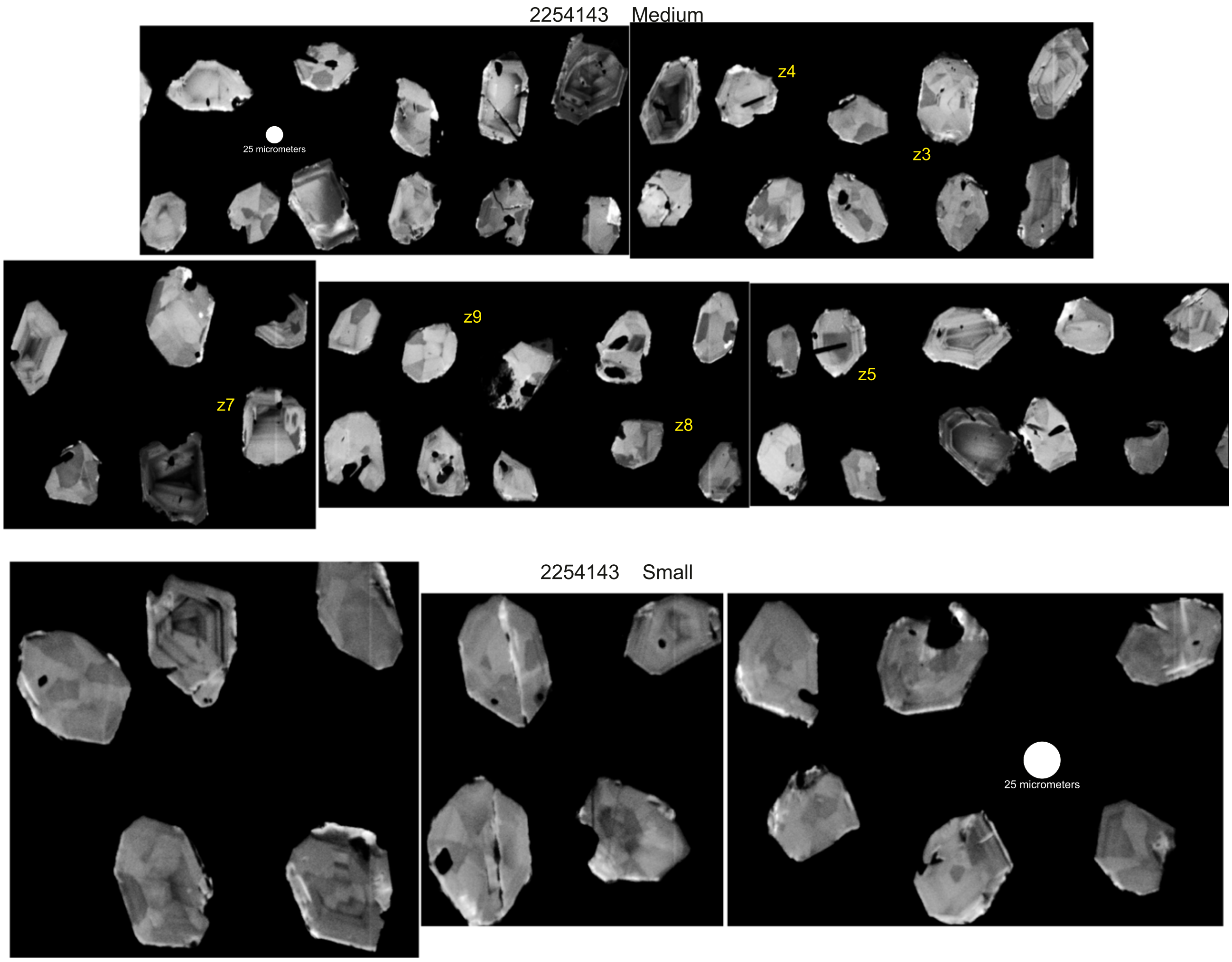


Figure S8. Cathodoluminescence images of selected zircons extracted from the Stratheden 60 well, 212.50 m (697.18 ft) (Geoscience Australia sample number 2254143). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

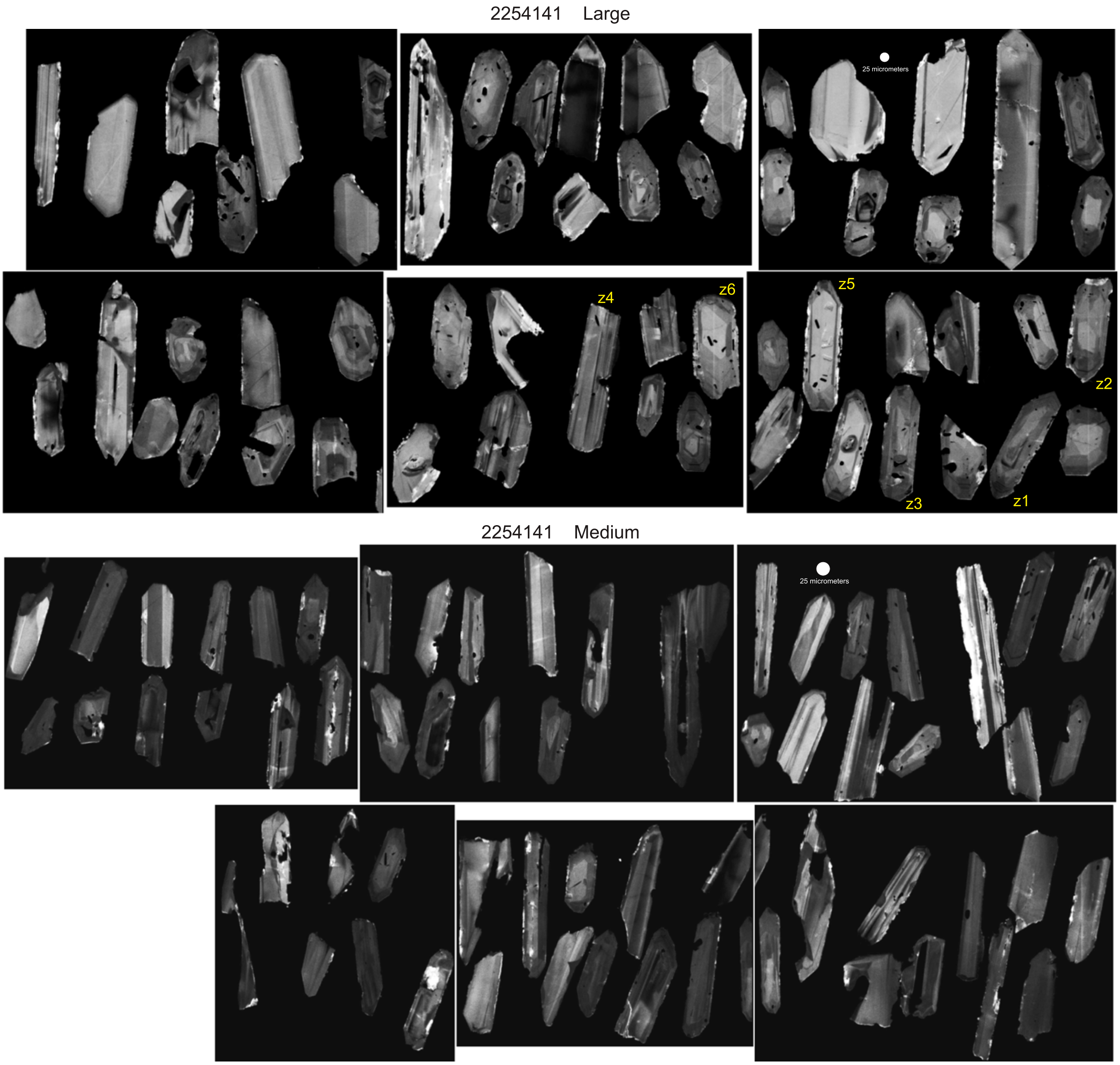


Figure S9. Cathodoluminescence images of selected zircons extracted from the Stratheden 60 well, 136.86 m (449.01 ft) (Geoscience Australia sample number 2254141). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

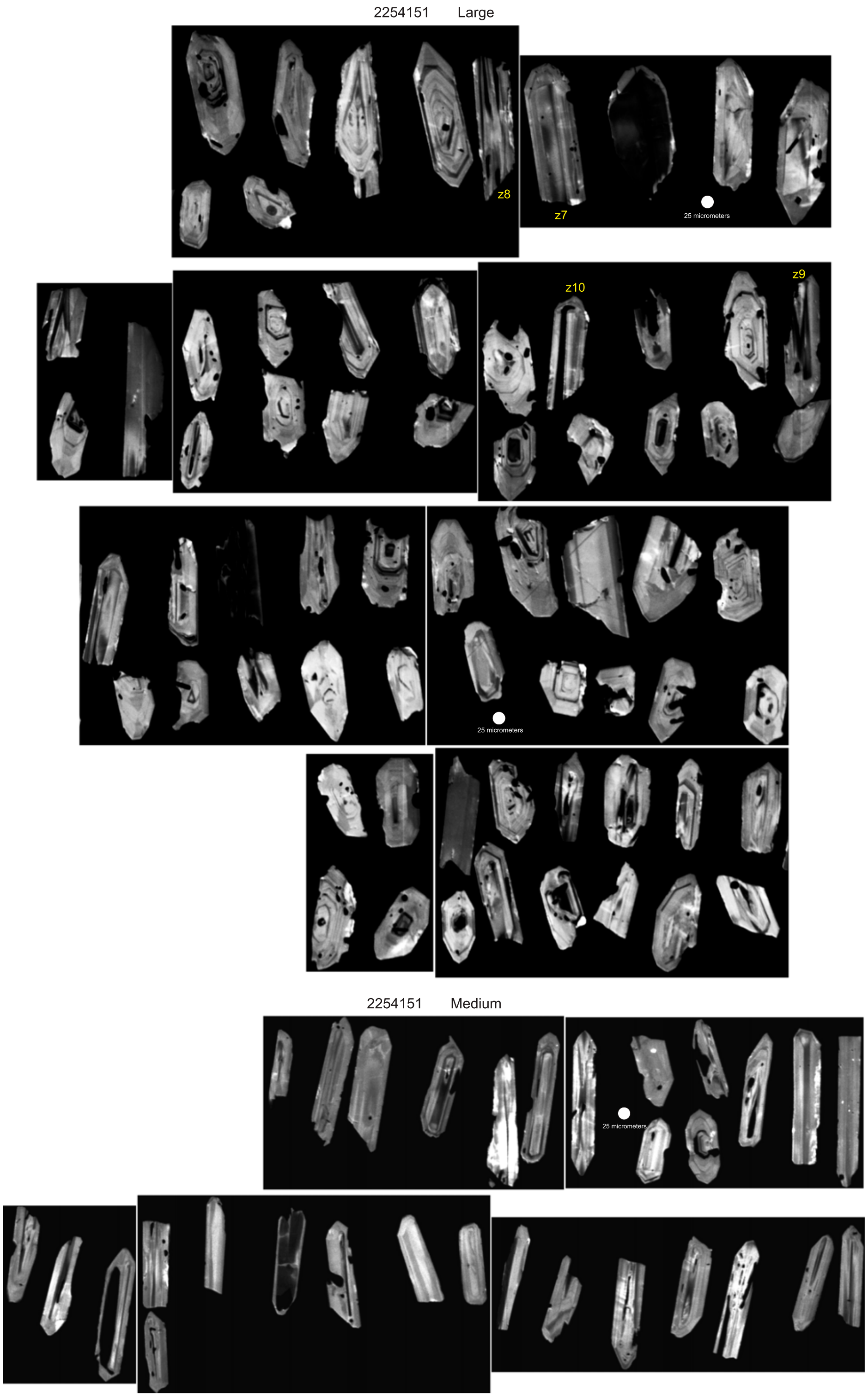


Figure S10. Cathodoluminescence images of selected zircons extracted from the Wyalla 3 well, 345.60 m (1133.86 ft) (Geoscience Australia sample number 2254151). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

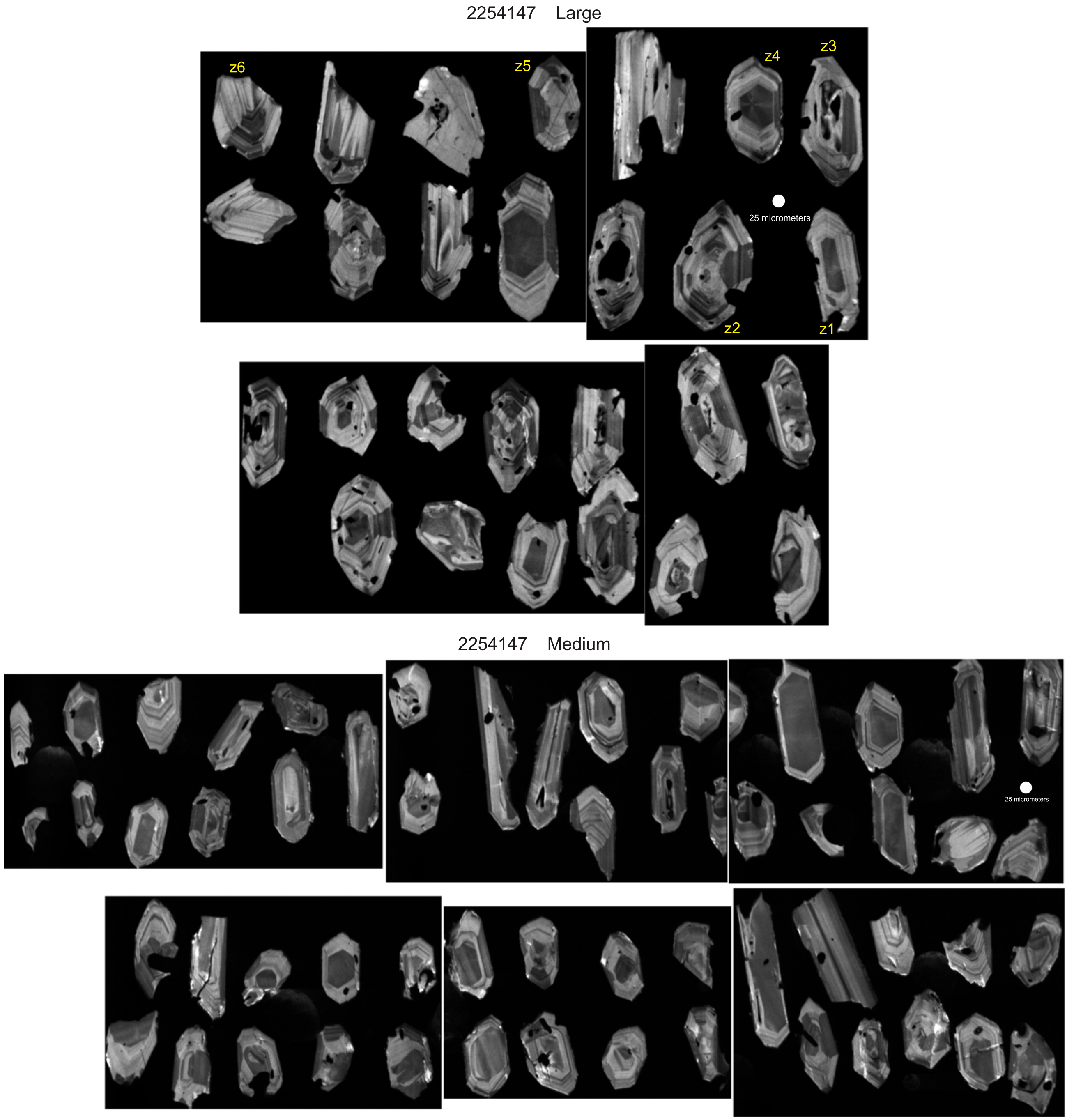


Figure S11. Cathodoluminescence images of selected zircons extracted from the Wyalla 3 well, 127.40 m (417.98 ft) (Geoscience Australia sample number 2254147). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

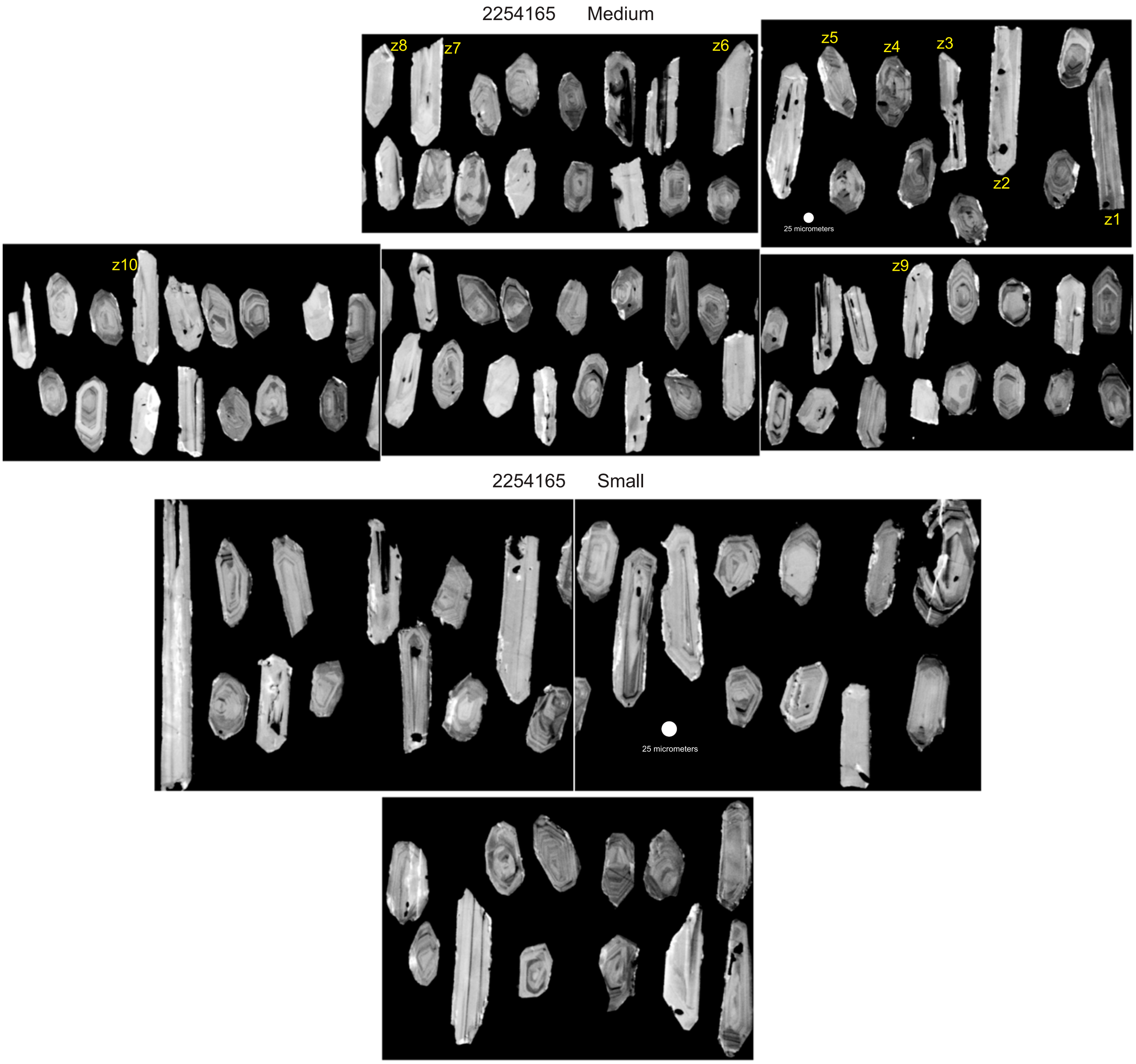


Figure S12. Cathodoluminescence images of selected zircons extracted from the Alderley 1 well, 402.76 m (1380.47 ft) (Geoscience Australia sample number 2254165). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

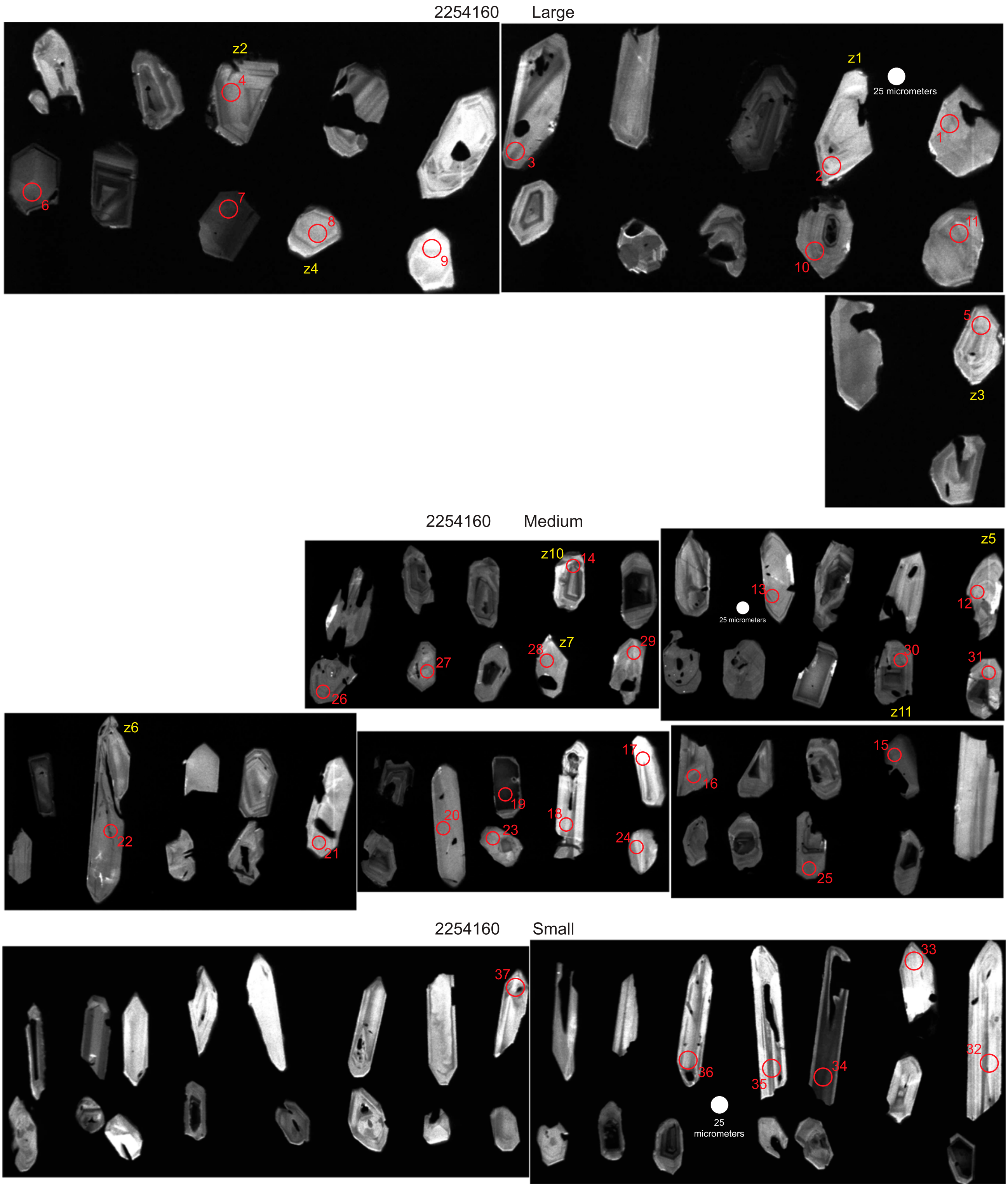


Figure S13. Cathodoluminescence images of selected zircons extracted from the Alderley 1 well, 156.17 m (512.37 ft) (Geoscience Australia sample number 2254160). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

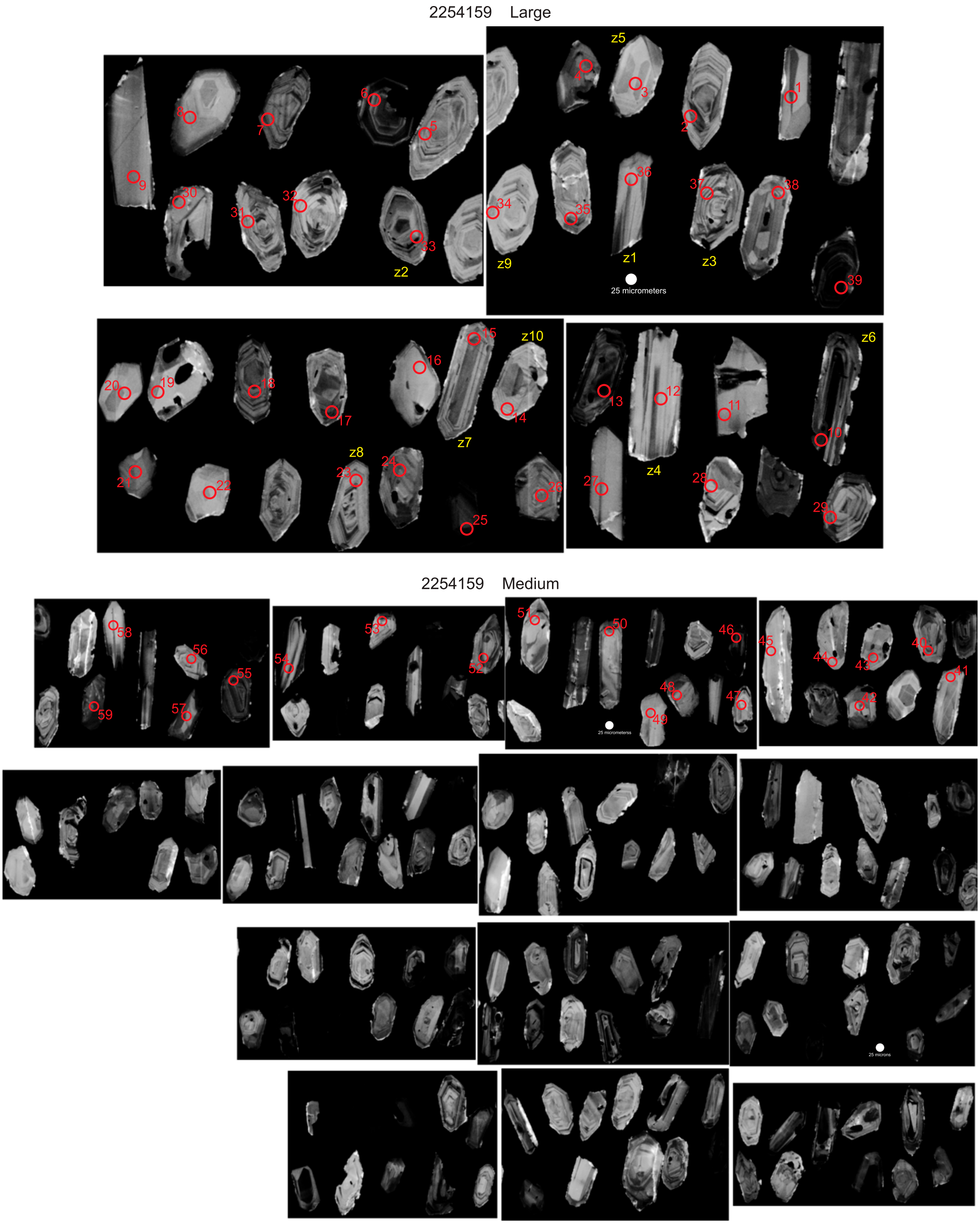


Figure S14. Cathodoluminescence images of selected zircons extracted from the Alderley 1 well, 135.29 m (443.86 ft) (Geoscience Australia sample number 2254159). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

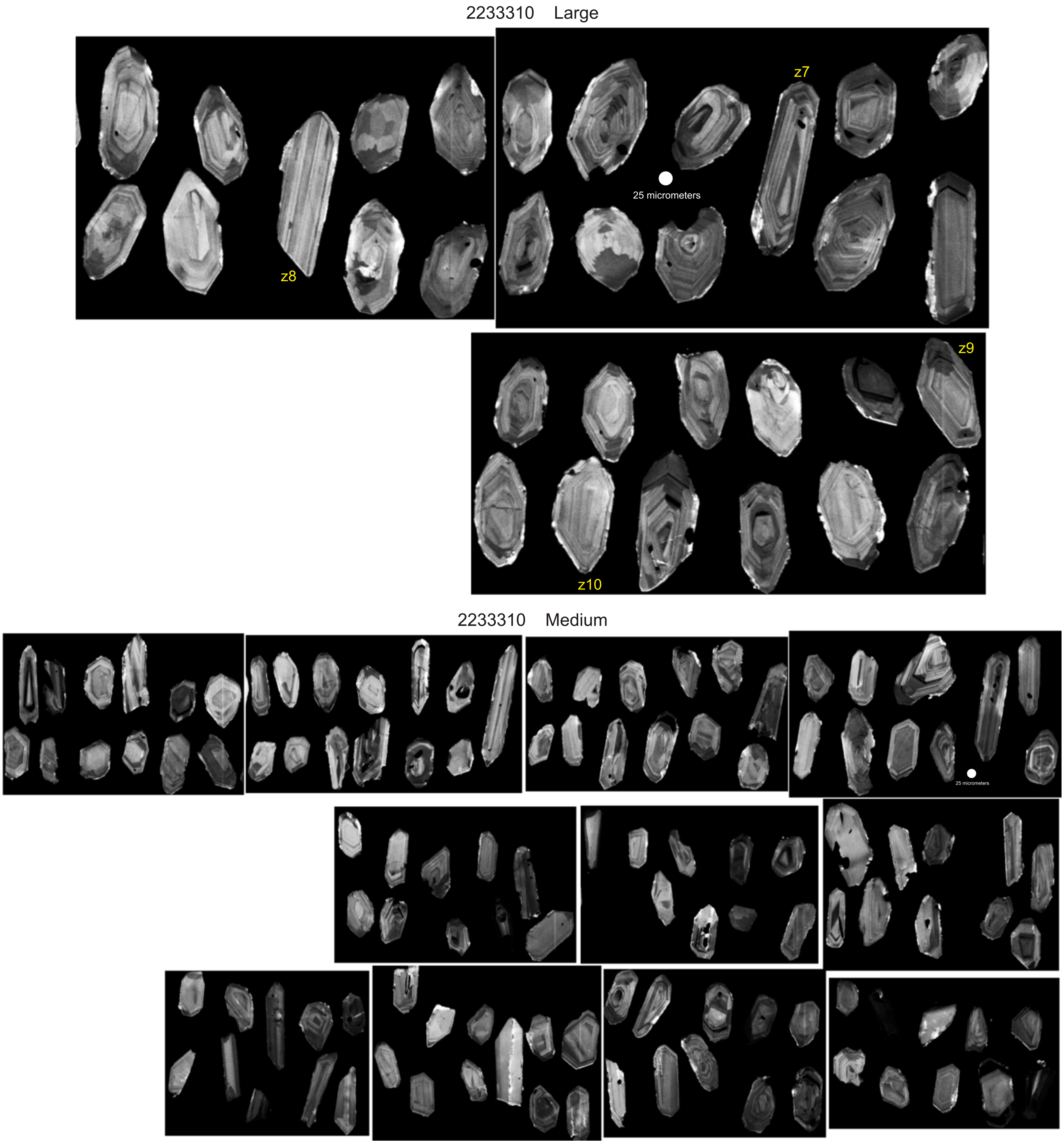


Figure S15. Cathodoluminescence images of selected zircons extracted from the Guluguba 2 well, 509.43 m (1671.40) (Geoscience Australia sample number 2233310). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

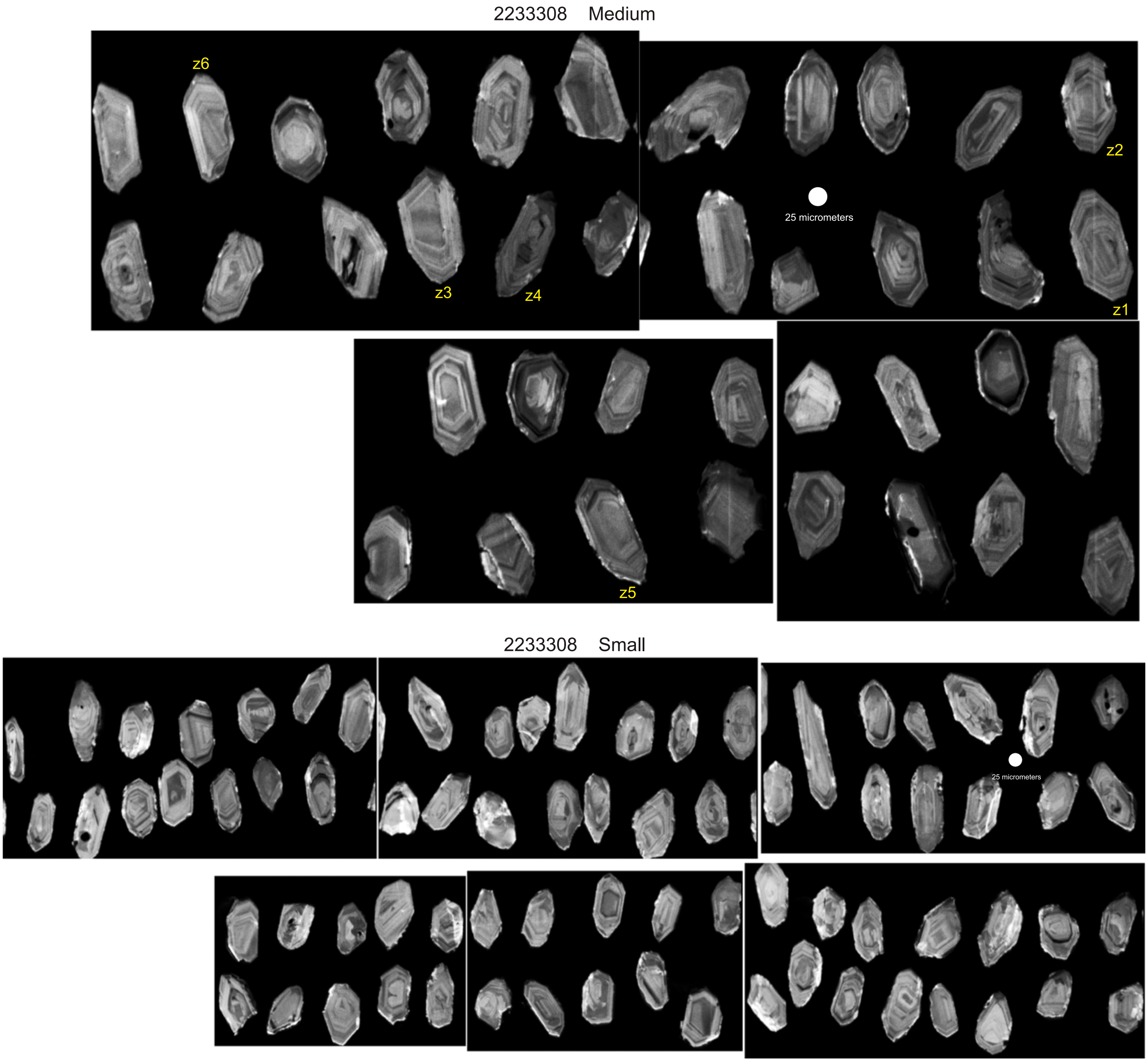


Figure S16. Cathodoluminescence images of selected zircons extracted from the Guluguba 2 well, 428.57 m (1406.07 ft) (Geoscience Australia sample number 2233308). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) are shown. Zircon grains dated using CA-TIMS are labeled as z numbers.

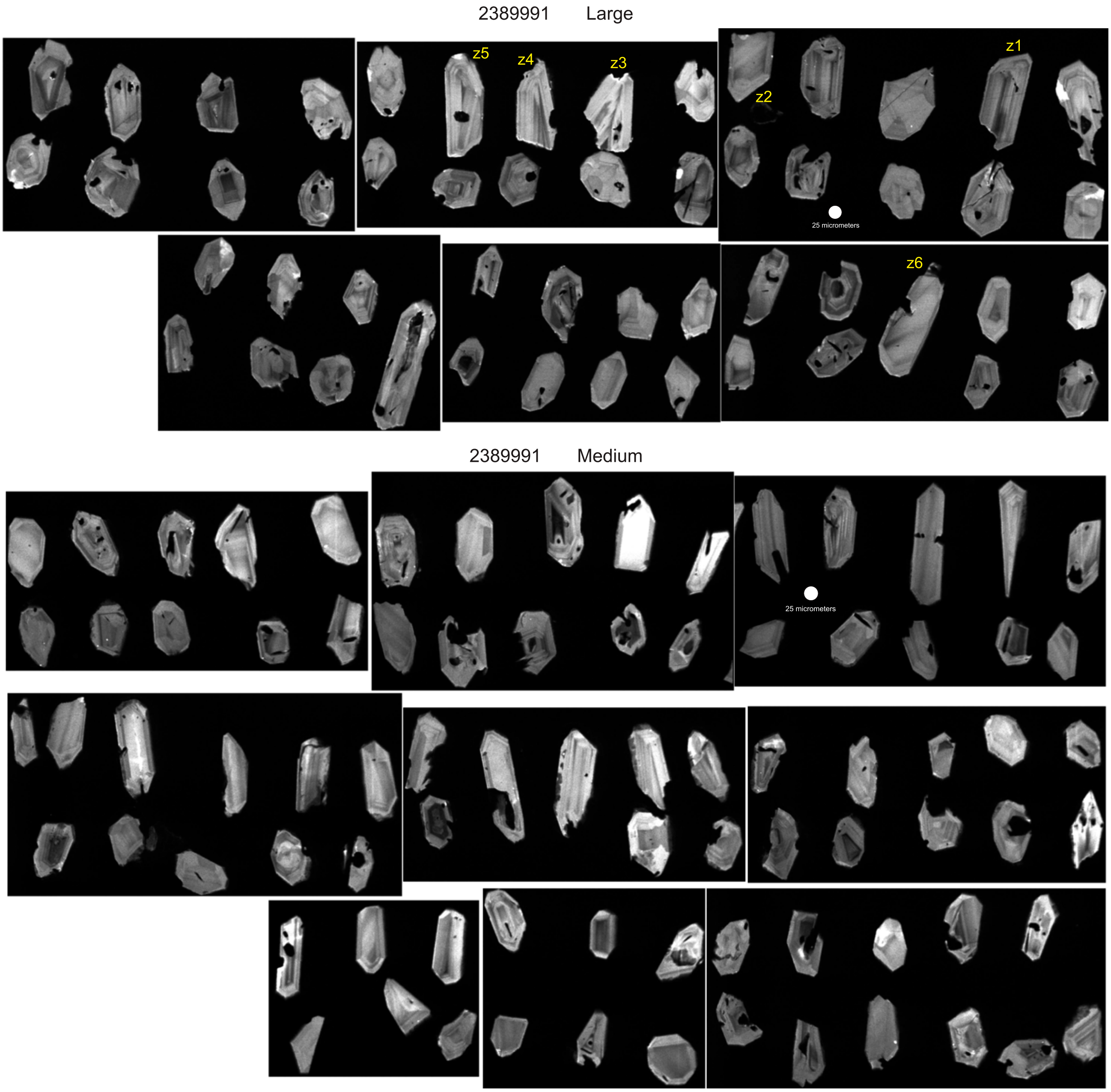


Figure S17. Cathodoluminescence images of selected zircons extracted from the Cameron 1 well, 221.40 m (726.38 ft) (Geoscience Australia sample number 2389991). Grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

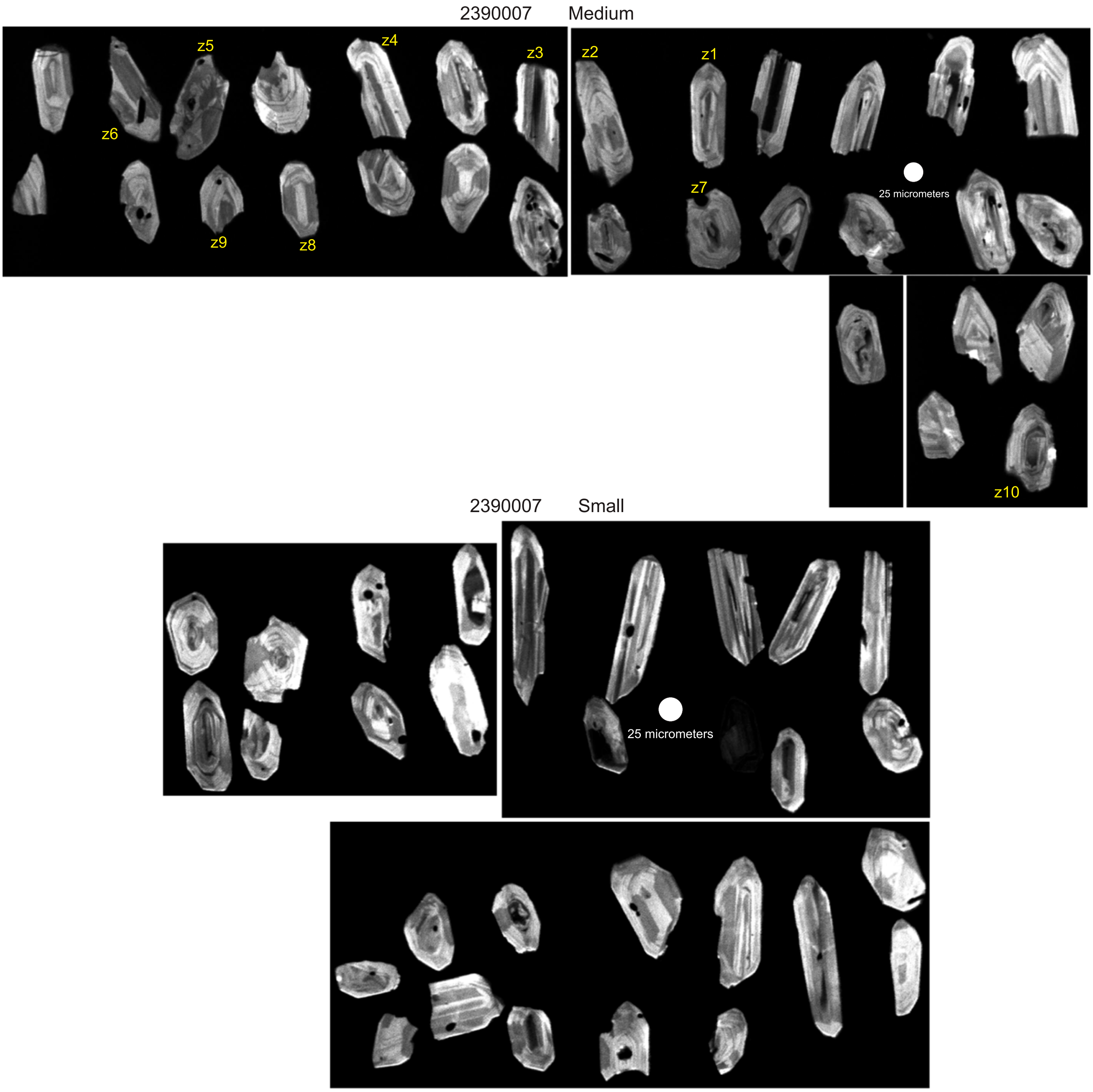
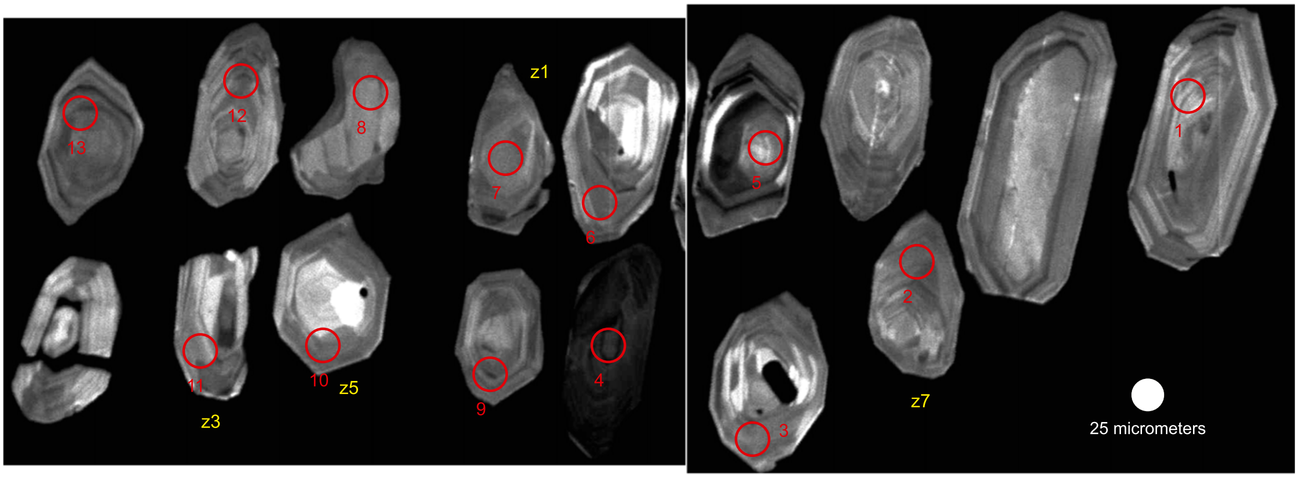


Figure S18. Cathodoluminescence images of selected zircons extracted from the Pleasant Hills 25 well, 335.08 m (1099.34 ft) (Geoscience Australia sample number 2390007). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

2390011 Medium



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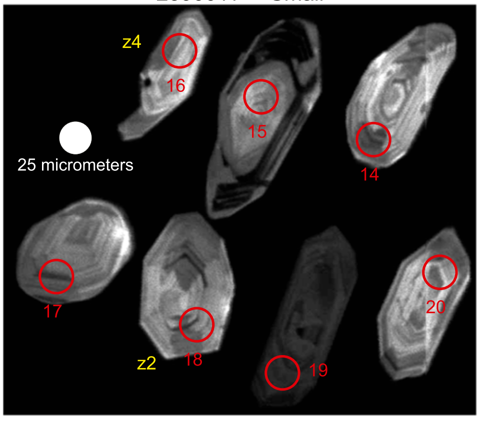

Figure S19. Cathodoluminescence images of selected zircons extracted from the Pleasant Hills 25 well, 511.51 m (1678.18 ft) (Geoscience Australia sample number 2390011). Zircon grains dated using LA-ICPMS methods are marked by circles, with analysis labels. Zircon grains dated using CA-TIMS are labeled as z numbers.

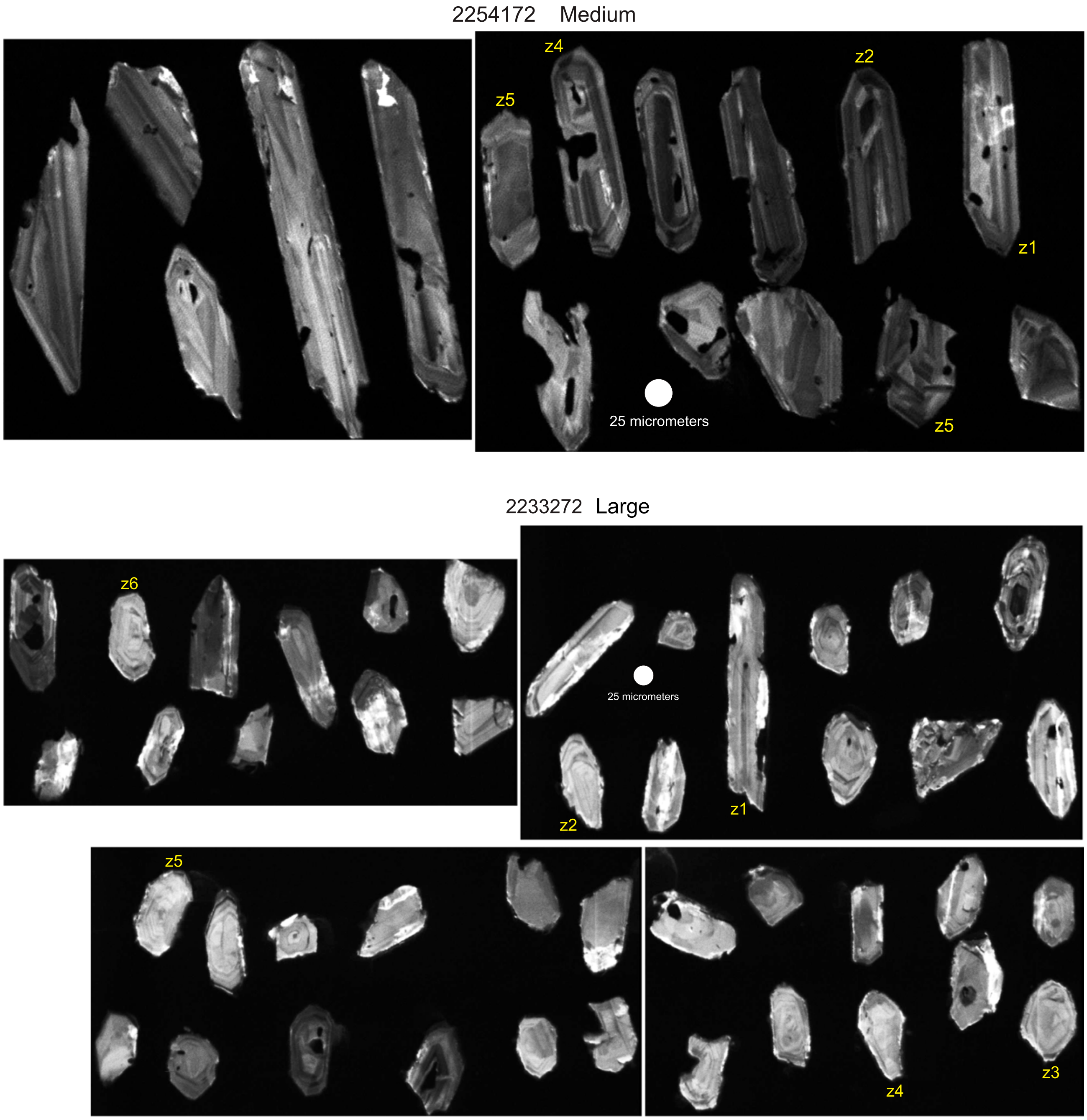

Figure S20. Cathodoluminescence images of selected zircons extracted from the Indy 4 well, 202.00 m (662.73 ft) (Geoscience Australia sample number 2233272). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

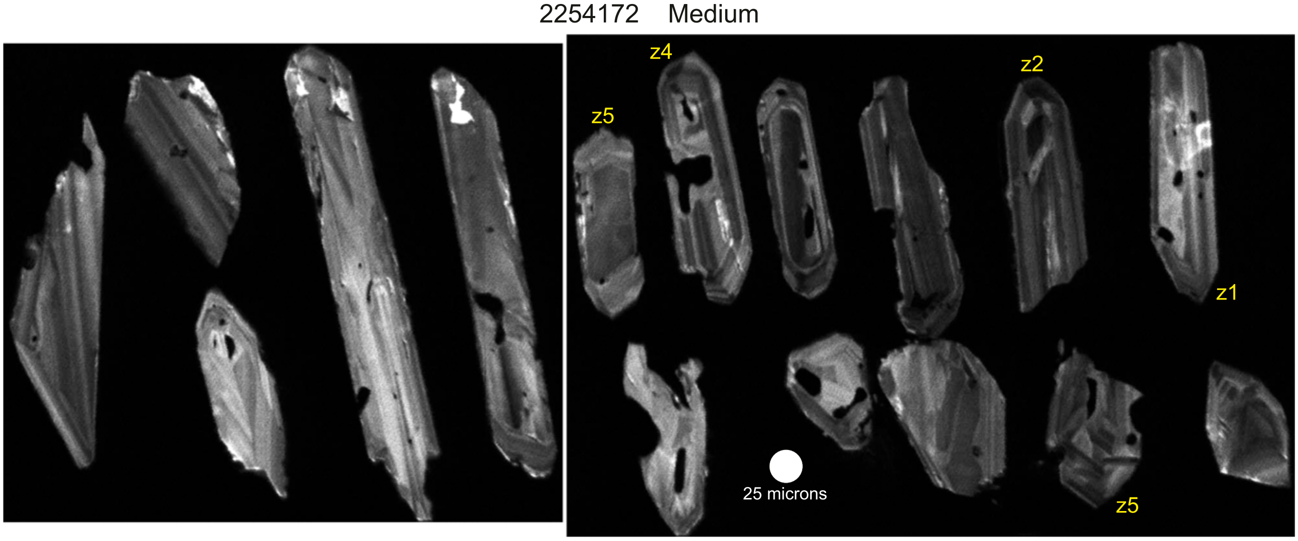

Figure S21. Cathodoluminescence images of selected zircons extracted from the Indy 3 well, 159.76 m (524.15 ft) (Geoscience Australia sample number 2254172). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

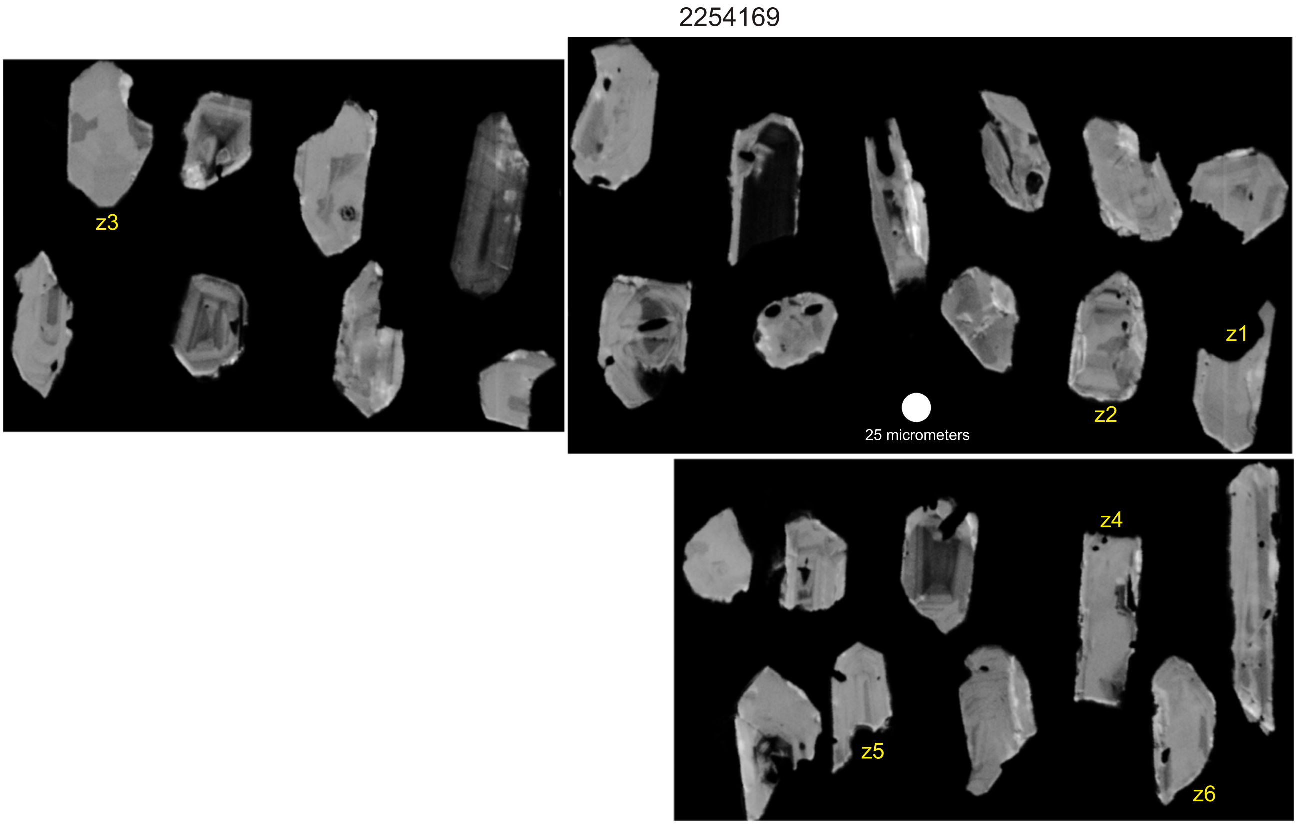

Figure S22. Cathodoluminescence images of selected zircons extracted from the Indy 3 well, 104.62 m (343.24 ft) (Geoscience Australia sample number 2254169). Zircon grains dated by chemical abrasion–thermal ionization mass spectrometry are shown, labeled as z numbers.

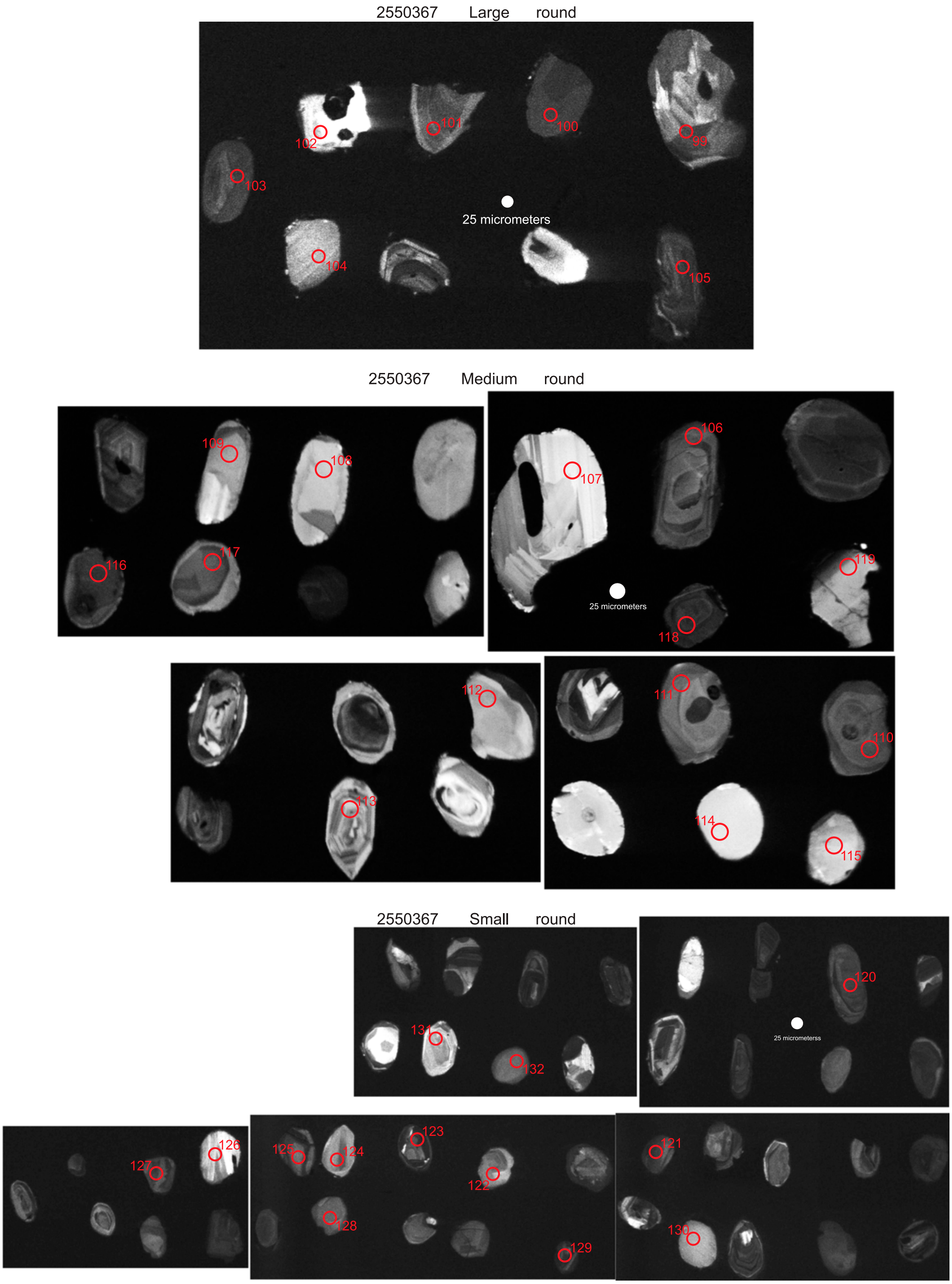

Figure S23. (A) Cathodoluminescence (CL) images of selected angular zircons extracted from the Zeus 7 well, 1677.51 m (5470.83 ft) (Geoscience Australia sample number [GA] 2550367). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. (B) The CL images of selected rounded zircons extracted from the Zeus 7 well, 1677.51 m (5470.83 ft) (GA 2550367). Zircon grains dated by CA-TIMS and spot analyzed by LA-ICPMS are shown. Zircon grains dated using LA-ICPMS methods are marked with circles with analysis labels; zircon grains dated using CA-TIMS are labeled as z numbers.

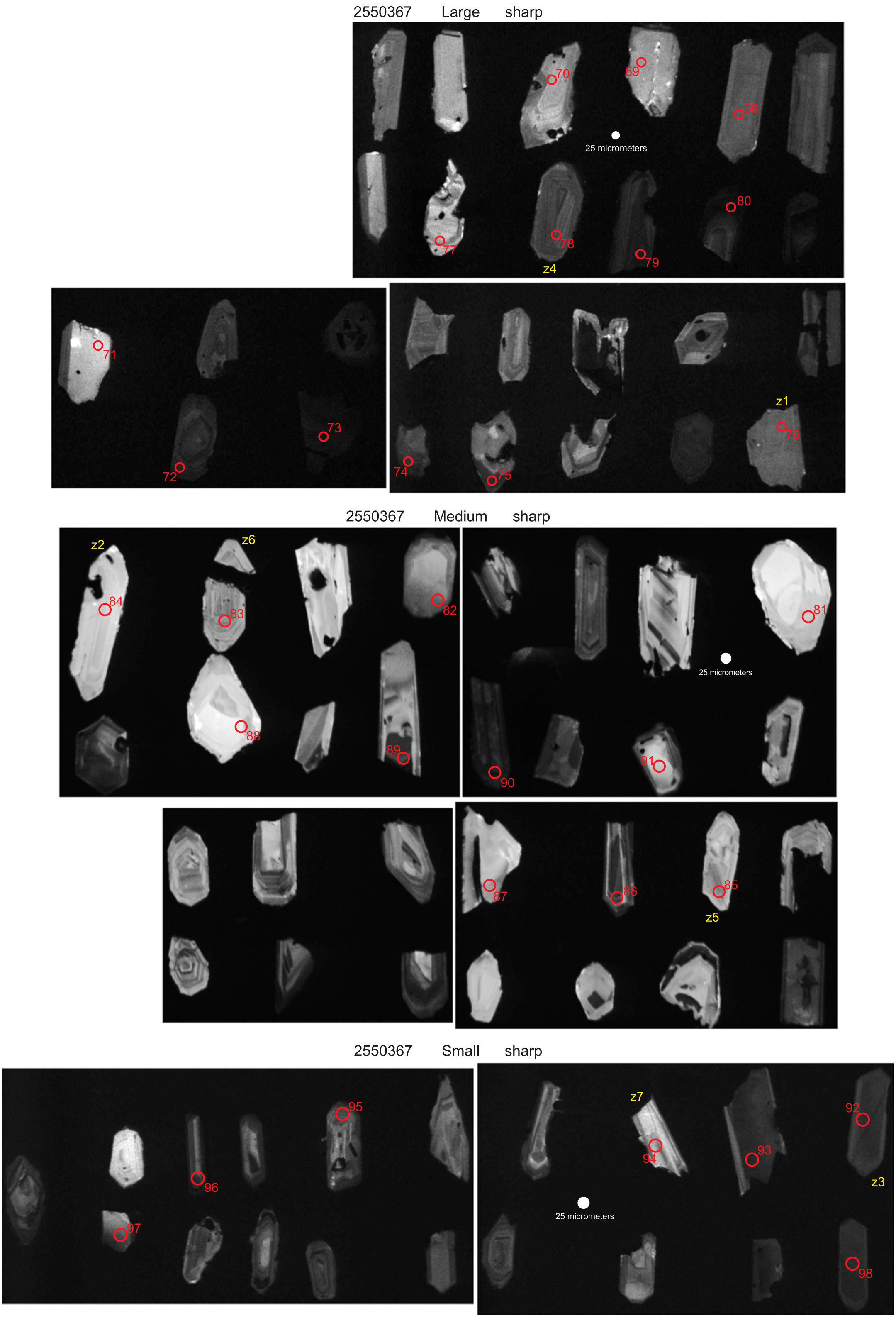

Figure S23. Continued.

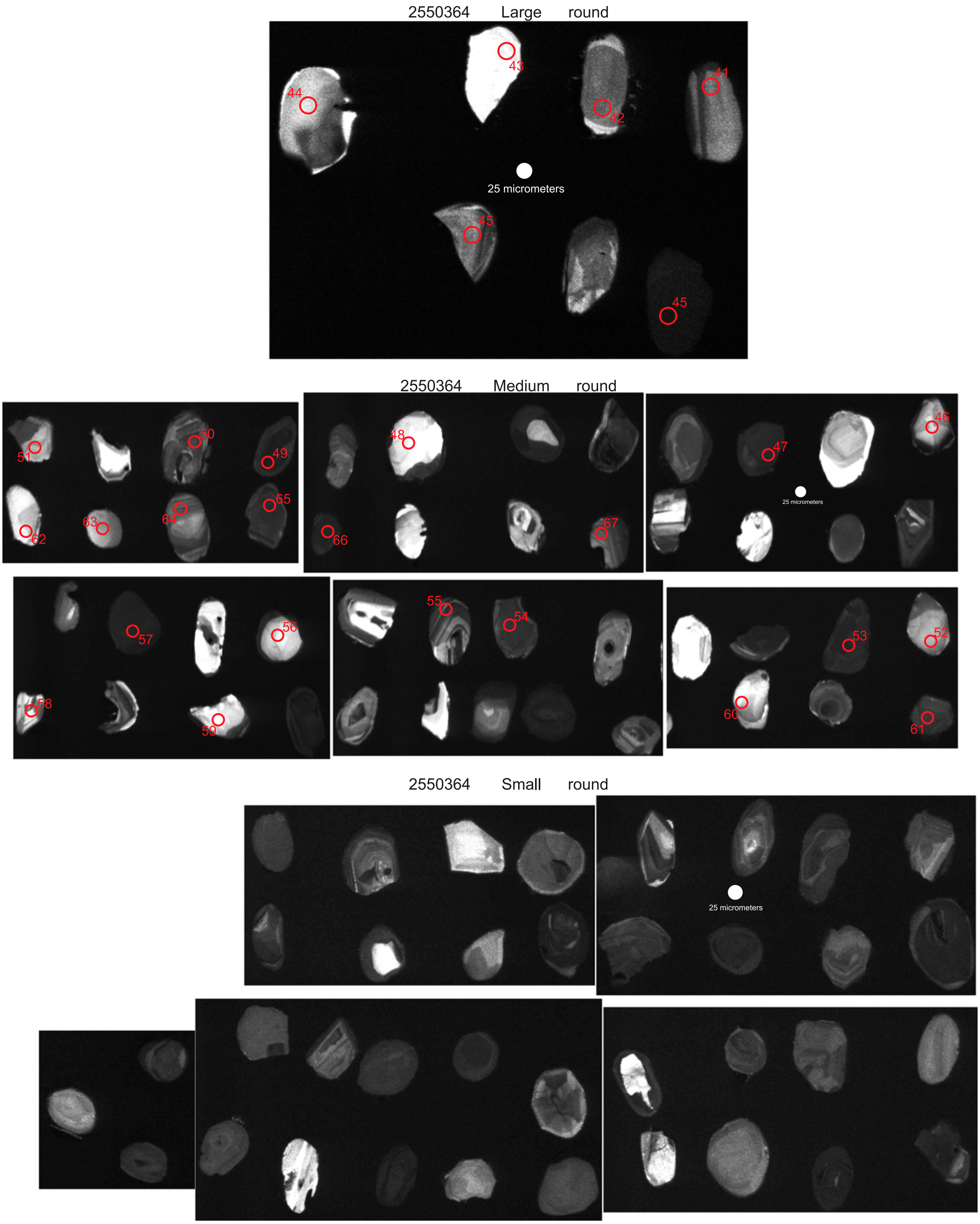

Figure S24. (A) Cathodoluminescence (CL) images of selected angular zircons extracted from the Zeus 7 well, 1659.31 m (5443.92 ft) (Geoscience Australia [GA] sample number 2550364). Grains dated by chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) and spot analyzed by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) are shown. (B) The CL images of selected rounded zircons extracted from the Zeus 7 well, 1659.31 m (5443.92 ft) (GA 2550364). Zircon grains dated by CA-TIMS and spot analyzed by LA-ICPMS are shown. Zircon grains dated using LA-ICPMS methods are marked with circles with analysis labels; zircon grains dated using CA-TIMS are labeled as z numbers.

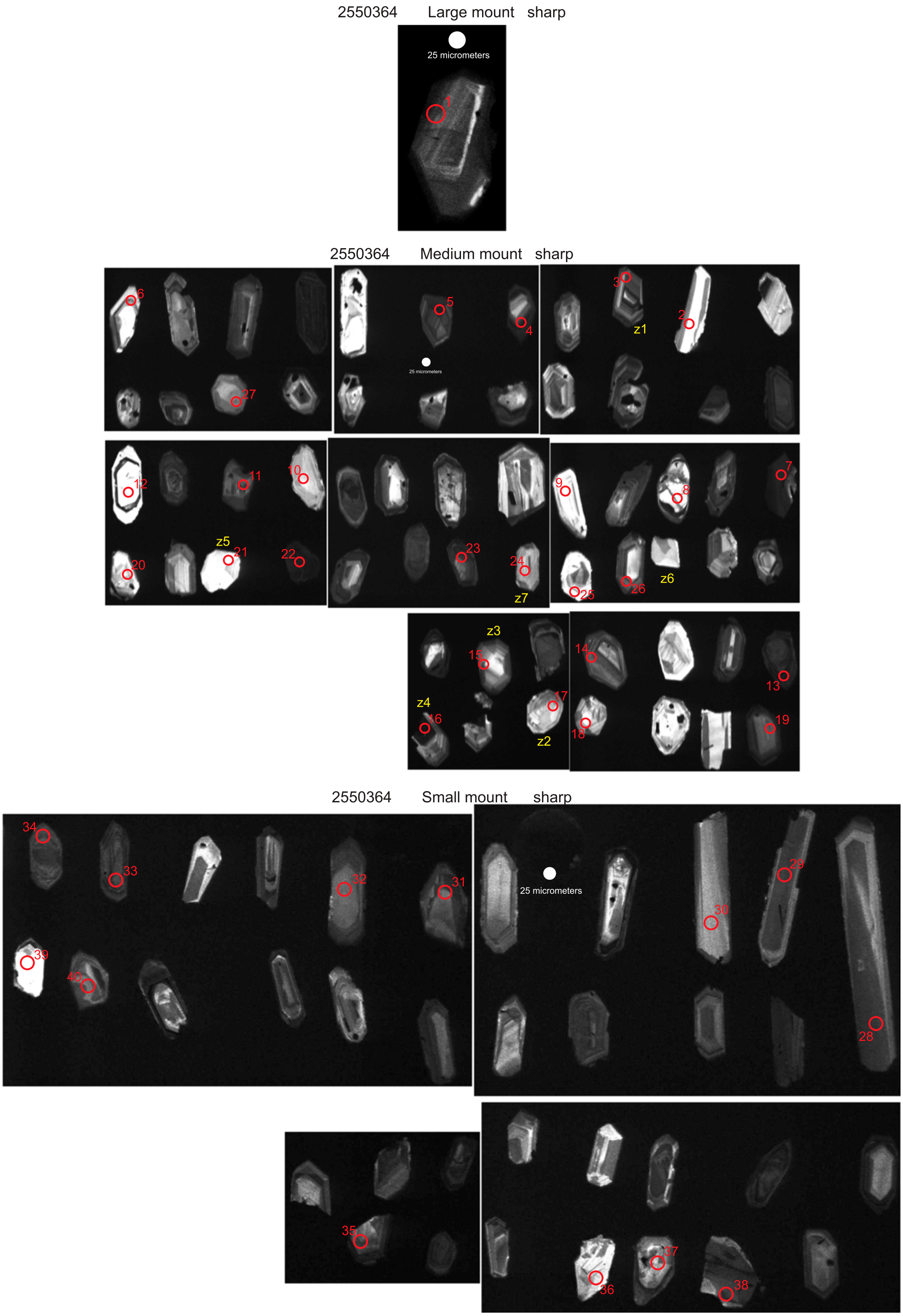

Figure S24. Continued.

Table S1. Laser Ablation–Inductively Coupled Plasma Mass Spectrometry Isotopic Uranium–Lead and Trace Element Concentration Data (Excel spreadsheet)

Table S2. Uranium–Lead Isotopic Data (Excel spreadsheet)