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Evidence for a spike in mantle carbon outgassing during the Ediacaran period

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Supplementary Information

North Victoria Land

A total of 1147 U-Pb age analyses of zircons from sixteen late Neoproterozoic-early Ordovician samples (PRR16173, PRR19009, PRR16108, P82665, PRR16098, PRR16220, PRR16074, P82870, P82981, R14784, P82980, PRR16261, ANT4, TW11, TW9, PRR4679) met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 3566 Ma (Paleoarchean) to 450 Ma (Ordovician, Upper) with the exception of two analyses that yielded anomalously young ages (84 and 61 Ma) that presumably reflect Pb loss. A total of 83 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 629–546 Ma (Neoproterozoic, Ediacaran), contains 45 ages, and has 8 peaks in age probability at 625 Ma (n=3), 605 Ma (n=9), 591 Ma (n=10), 584 Ma (n=11), 576 Ma (n=12), 566 Ma (n=5), 558 (n=8), and 552 (n=9). A second age cluster yielded by the cumulative analysis ranges from 1195–1033 Ma (Mesoproterozoic), contains 13 ages, and has 4 peaks in age probability at 1168 Ma (n=4), 1122 Ma (n=6), 1081 Ma (n=6), and 1056 Ma (n=6).

Marie Byrd Land

A total of 676 U-Pb age analyses of zircons from four late Neoproterozoic-early Ordovician samples (PRR1715, PRR34028, PRR34239, and PRR34241) met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 3549 Ma (Paleoarchean) to 421 Ma (Silurian, Pridoli). A total of 76 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 636–491 Ma (Cryogenian-Cambrian, Furongian), contains 50 ages, and has 4 peaks in age probability at 588 Ma (n=19), 577 Ma (n=25), 537 Ma (n=12), and 509 Ma (n=6). A second age cluster yielded by the cumulative analysis ranges from 662–638 Ma (Neoproterozoic, Cryogenian), contains 5 ages, and has 1 peak in age probability at 653 Ma (n=5). One additional probability peak occurs at 962 Ma (n=3).

South Victoria Land

A total of 473 U-Pb age analyses of zircons from five late Neoproterozoic-Cambrian samples (PRR36830, PRR36831, KCQ, JMH, JIK) and one Devonian sandstone (PRR32746) met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 3255 Ma (Paleoarchean) to 514 Ma (Cambrian, Series 2) with the exception of one analysis that yielded an anomalously young age (234 Ma) that presumably reflect Pb loss. A total of 44 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 1559–1378 Ma (Mesoproterozoic), contains 11 ages, and has 1 peak in age probability at 1465 Ma (n=9). Three additional age clusters yielded by the cumulative analysis range from 1304–1086 Ma (Mesoproterozoic; n=9), 1023–971 Ma (Mesoproterozoic-Neoproterozoic; n=3), and 602–562 Ma (Neoproterozoic-Ediacaran; n=4) and contain 5 peaks in age probability at 1300 Ma (n=3), 1225 Ma (n=9), 995 Ma (n=4), 596 Ma (n=4), and 582 Ma (n=3).

Central Transantarctic Mountains

A total of 675 U-Pb age analyses of zircons from four late Neoproterozoic-early Ordovician samples (PRR13777, PRR15737, PRR15796, and PRR36589) met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 3080 Ma (Mesoarchean) to 495 Ma (Cambrian, Furongian) with the exception of two analyses that yielded anomalously young ages (84 and 61 Ma) that presumably reflect Pb loss. A total of 64 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 666–512 Ma (Tonian-Ordovician), contains 42 ages, and has 2 peaks in age probability at 649 Ma (n=4) and 565 Ma (n=23). Two additional age clusters yielded by the cumulative analysis range from 942–901 Ma (Tonian-Ordovician; n=4) and 815–769 Ma (Tonian-Ordovician; n=3) and contain 2 peaks in age probability at 922 Ma (n=4) and 792 Ma (n=3).

Queen Maud Mountains

A total of 1920 U-Pb age analyses of zircons from thirteen late Neoproterozoic-early Ordovician samples (PRR5309, PRR12970, PRR23485, PRR23610, PRR27475, 12-13-95, LUB2B, HEN2, RAM2, ANJ, APO, EDJ, and EGA) and one Triassic sandstone (PRR38521) from the Beacon Supergroup met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 3084 Ma (Mesoarchean) to 228 Ma (Triassic, Upper). A total of 188 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 714–523 Ma (Tonian-Ordovician), contains 149 ages, and has 5 peaks in age probability at 690 Ma (n=4), 666 Ma (n=9), 644 Ma (n=21), 621 Ma (n=28), and 563 Ma (n=53). Two other age clusters yielded by the cumulative analysis range from 1174–852 Ma (Tonian-Ordovician; n=24) and 805–750 Ma (Tonian-Ordovician; n=4) and contain 6 peaks in age probability at 1047 Ma (n=13), 985 Ma (n=10), 929 Ma (n=5), 875 Ma (n=4), 798 Ma (n=4), and 750 Ma (n=3). One additional probability peak occurs at 817 Ma (n=3).

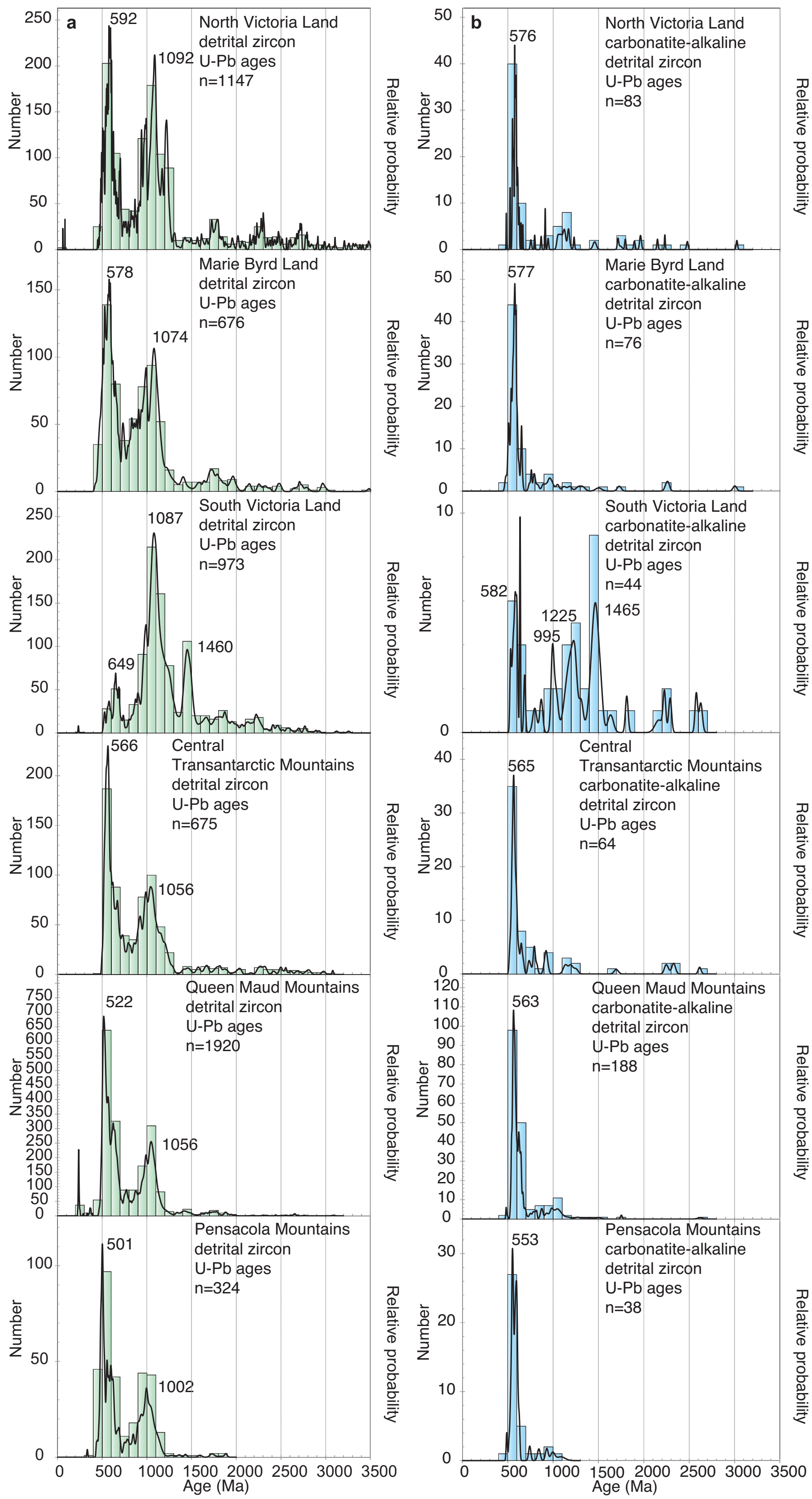
Pensacola Mountains

A total of 324 U-Pb age analyses of zircons from two late Neoproterozoic-early Ordovician samples (PRR16935 and PRR33274) met acceptable concordance thresholds. The cumulative zircon age suite from all of the samples (Supplementary Figure 2A) ranges from 1884 Ma (Paleoproterozoic) to 436 Ma (Silurian, Llanovery) with the exception of one analysis that yielded an anomalously young age (334 Ma) that presumably reflects Pb loss. A total of 38 carbonatite-alkaline U-Pb age analyses met acceptable concordance thresholds (Supplementary Figure 2B). The dominant age cluster yielded by the cumulative analysis ranges from 628–525 Ma (Ediacaran-Cambrian, Terreneuvian), contains 31 ages, and has 2 peaks in age probability at 596 Ma (n=12) and 553 Ma (n=12).

Cumulative Carbonatite-Alkaline U-Pb Age Dataset

The dominant age cluster yielded by the cumulative analysis of 493 carbonatite-alkaline zircon U-Pb ages ranges from 1561–474 Ma (Mesoproterozoic-Ordovician, Lower), contains 464 ages, and has 20 peaks in age probability at 1461 Ma (n=15), 1230 Ma (n=17), 1169 Ma (n=21), 1123 Ma (n=22), 1051 Ma (n=22), 989 Ma (n=18), 942 Ma (n=13), 928 Ma (n=12), 912 Ma (n=13), 869 Ma (n=8), 815 Ma (n=10), 795 Ma (n=11), 756 Ma (n=9), 665 Ma (n=15), 646 Ma (n=30), 623 Ma (n=46), 576 Ma (n=124), 565 Ma (n=123), 526 Ma (n=22), and 483 Ma (n=6). Two older age clusters range from 2321-2205 (Paleoproterozoic; n=7) and 1772-1697 (Paleoproterozoic; n=4) and contain 3 peaks in age probability at 2230 Ma (n=6), 1749 Ma (n=3), and 1715 Ma (n=4). One age probability peak also occurs at 2619 Ma (n=3).

Figure S1 | Physiographic map of the Antarctic continent. Circles show sample localities of Neoproterozoic-Triassic stratigraphic successions within the six principal study regions located on the flank and outboard of the East Antarctic craton.


a
North Victoria Land detrital zircon U-Pb ages n=1147
592
1092
Marie Byrd Land detrital zircon U-Pb ages n=676
578
1074
South Victoria Land detrital zircon U-Pb ages n=973
1087
649
1460
566
Central Transantarctic Mountains detrital zircon U-Pb ages n=675
1056
Queen Maud Mountains detrital zircon U-Pb ages n=1920
522
1056
Pensacola Mountains detrital zircon U-Pb ages n=324
501
1002
Number
Relative probability
Age (Ma)
b
North Victoria Land carbonatite-alkaline detrital zircon U-Pb ages n=83
576
Marie Byrd Land carbonatite-alkaline detrital zircon U-Pb ages n=76
577
South Victoria Land carbonatite-alkaline detrital zircon U-Pb ages n=44
582
995
1225
1465
Central Transantarctic Mountains carbonatite-alkaline detrital zircon U-Pb ages n=64
565
Queen Maud Mountains carbonatite-alkaline detrital zircon U-Pb ages n=188
563
Pensacola Mountains carbonatite-alkaline detrital zircon U-Pb ages n=38
553

5

Figure S2 | Cumulative probability density plots (PDP) and histograms. a, Cumulative U-Pb age data (n=5715) for detrital zircons found in Neoproterozoic-Triassic sandstones (n=46) from each of the six study areas. **b,** Cumulative detrital zircon U-Pb age data (n=493) for carbonatite-alkaline detrital zircons from the same samples.

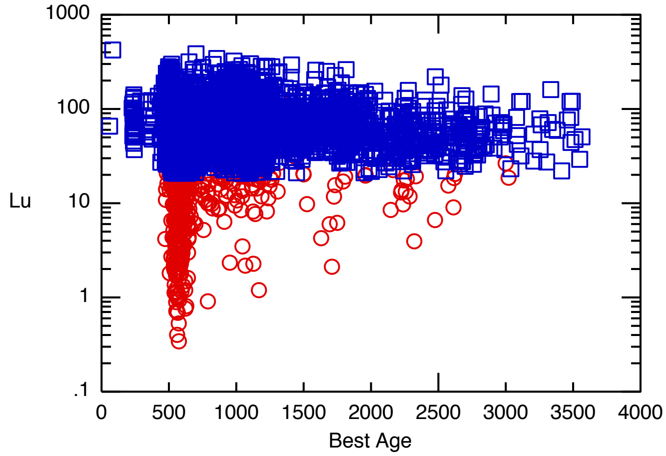


Figure S3 | Cross-plot of Lu concentration versus age for detrital zircons. Detrital zircons show a marked 600-500 Ma spike for detrital zircons possessing low (<20.7 ppm) Lu concentrations (red), a trace element marker for zircons derived from carbonatite and alkaline parent rocks.

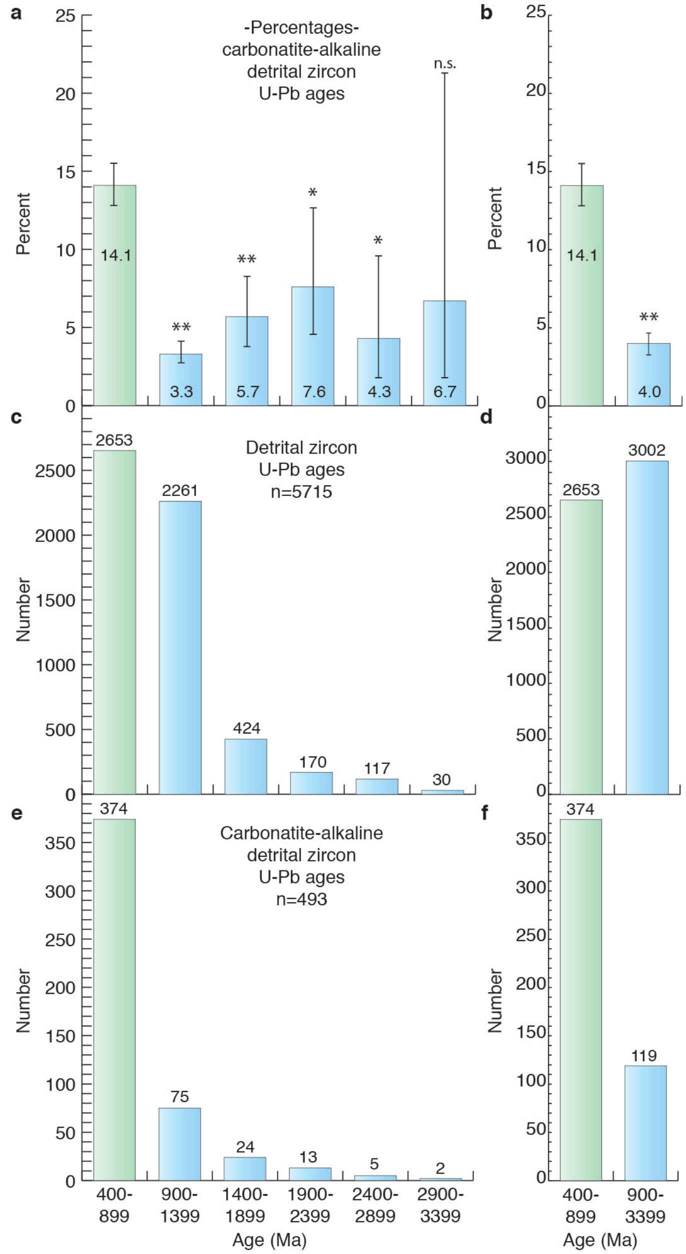


Figure S4 | Statistical significance of changes in carbonatite-alkaline abundance in zircon age population. a, Histogram showing the percentages and their range of certainty at 95% confidence (bars) of carbonatite-alkaline zircons binned by 500 million year increments. P-values yielded by Chi-squared tests comparing percentages of carbonatite-alkaline zircons for older time intervals to the youngest (400-899 Ma) interval; ***P* < .001, **P* < .025, n.s.: not statistically significant. 95% confidence intervals: 12.8-15.5% (400-899 Ma), 2.7-4.1% (900-1399 Ma), 3.8-8.3% (1400-1899 Ma), 1.8-9.6% (2400-2899 Ma), and 1.8-21.3% (2900-3399 Ma). **b,** Histogram showing the percentages and range of certainty at 95% confidence (bars) of carbonatite-alkaline detrital zircons binned by <900 Ma and >900 Ma ages. P-values-as in (a)-yielded by Chi-squared test comparing percentages of carbonatite-alkaline zircons for <900 Ma and >900 Ma age bins. 95% confidence intervals: 12.8-15.5% (<900 Ma) and 3.3-4.7% (>900 Ma). **c,** Cumulative detrital zircon U-Pb age data (n=5715) binned by 500 million year increments. **d,** Cumulative detrital zircon U-Pb age data binned by <900 Ma and >900 Ma ages. **e,** Cumulative carbonatite-alkaline detrital zircon U-Pb age data (n=493) binned by 500 million year increments. **f,** Cumulative carbonatite-alkaline detrital zircon U-Pb age data binned by <900 Ma and >900 Ma ages. Numbers within columns in (a-b) show percentages for each age bin; numbers on top of columns in (c-f) show total number of data for each bin.