Globally synchronous Marinoan deglaciation indicated by U-Pb geochronology of the Cottons Breccia, Tasmania, Australia

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ABSTRACT

U-Pb zircon data from the uppermost Cottons Breccia, representing the Marinoan glacial-postglacial transition on King Island, Tasmania, provide the first direct age constraint on the Cryogenian-Ediacaran boundary in Australia. Zircons in four samples from the topmost meter of the Cottons Breccia, dated by sensitive high-resolution ion microprobe, exhibit two modes ca. 660 Ma and ca. 635 Ma. The younger component predominates in the uppermost sample, a possibly volcanolithic dolomitic sandstone, apparently lacking glacially transported debris, in the transition to cap carbonate. Chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) U-Pb dating of euhedral zircons from that sample yields a weighted-mean age of 636.41 ± 0.45 Ma. Equivalence to published TIMS ash bed dates from Cryogenian-Ediacaran transitional strata in Namibia (635.51 ± 0.82 Ma, within glacial deposit) and China (635.23 ± 0.84 Ma, 2 m above glacial deposit) supports correlation of those strata to the Australian type sections and globally synchronous deglaciation at the end of the Cryogenian Period.

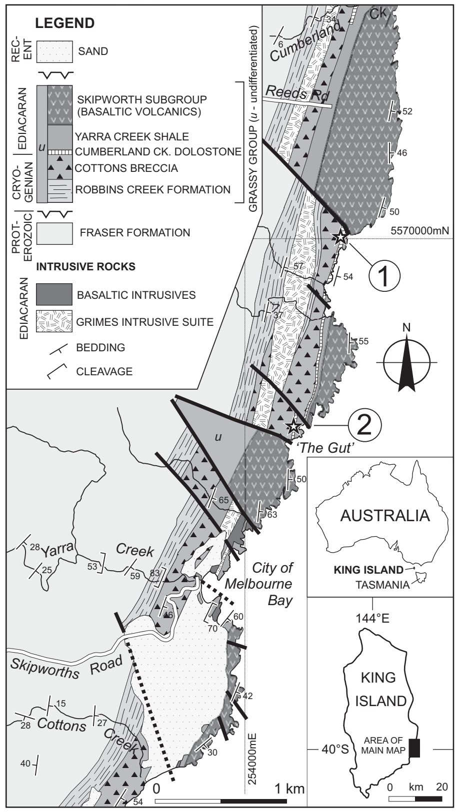

Figure 1. Geological map of part of southeastern King Island, Tasmania, showing two localities (numbered) from which dated samples were collected. Ck—Creek.

INTRODUCTION

Low paleolatitude (Embleton and Williams, 1986; Schmidt et al., 1991; Sohl et al., 1999) glaciogenic strata of the late Neoproterozoic Elatina Formation of South Australia directly inspired the snowball Earth hypothesis, in which climate feedbacks are predicted to generate abrupt and globally synchronous deglaciation (Kirschvink, 1992; Hoffman et al., 1998). Selection of the stratigraphic transition between glaciogenic Elatina Formation and overlying Nuccaleena Formation cap carbonate for the basal Ediacaran global stratotype section and point (GSSP) was intellectually founded on this concept (Knoll et al., 2006), although no precise geochronology has been available for the Elatina-Nuccaleena succession or its regional equivalents. The numerical age of this crucial horizon is generally inferred from lithostratigraphic and chemostratigraphic correlation with distinctively similar glaciogenic and cap carbonate units in south China and Namibia, both dated precisely by U-Pb isotope dilution–thermal ionization mass spectrometry (ID-TIMS) on zircons, to within 1 m.y. of 635 Ma (Hoffmann et al., 2004; Condon et al., 2005). Recently acquired unexpectedly young dates associated with the preceding Sturtian glaciation and its immediately overlying sediments (Fanning and Link, 2008; Kendall et al., 2006, 2009), together with alternative Neoproterozoic correlations within Australia (Calver et al., 2004; Grey and Calver, 2007), fostered lingering doubts about the age of the basal Ediacaran GSSP (e.g., Kendall et al., 2009; Grey et al., 2011). Until now, an Re-Os black shale age of 643.0 ± 2.4 Ma from the Tindelpina Shale Member, overlying Sturtian glacial deposits (Kendall et al., 2006), has provided a maximum age constraint on the GSSP horizon.

STRATIGRAPHIC SETTING

The late Cryogenian–Ediacaran Grassy Group crops out along the southeast coast of King Island, 100 km northwest of Tasmania (Fig. 1). The succession is of lower greenschist metamorphic facies (Meffre et al., 2004) and is weakly deformed. Near the base of the Grassy Group, the 50–150-m-thick Cottons Breccia is dominantly diamictite and lonestone-bearing sandstone and siltstone. This unit is generally considered to be a Marinoan glacial deposit, i.e., equivalent to the Elatina Formation of South Australia (Calver and Walter, 2000; Calver et al., 2004; Hoffman et al., 2009; Calver, 2011). Direen and Jago (2008) disputed the glacial origin of the Cottons Breccia, but later accepted correlation with the Elatina Formation (Jago and Direen, 2009). Within the Cottons Breccia, a lower diamictite member, a middle tuffaceous sandstone member, and an upper diamictite-sandstone member are recognized. The middle tuffaceous member has a basaltic composition (Calver, 2012) and consists of altered volcanic shards (Fig. 2A; Direen and Jago, 2008). Conformably overlying the Cottons Breccia, the 6–10-m-thick Cumberland Creek Dolostone (Meffre et al., 2004) shares remarkable lithological and stable isotopic similarities with the Nuccaleena Formation and correlative Marinoan cap carbonates across Australia and other regions (Calver and Walter, 2000; Hoffman et al., 2009), including the dated successions in Namibia and south China. Like the Nuccaleena Formation, it is a pale gray (weathering to pale yellow) laminated peloidal dolomicrite, grading up into interbedded limestone and shale. Low-angle swaley cross-lamination and giant wave ripples (Allen and Hoffman, 2005) are locally present; the crests of the ripples display (as in the Nuccaleena Formation) a preferred north-south orientation (Hoffman and Li, 2009). In both units, $\delta^{13}C_{carbonate}$ is 0‰ to –4‰, decreasing upsection (Calver and Walter, 2000; Hoffman et al., 2009). The Grassy Group continues upward in section through the Yarra Creek Shale, with noted similarities to the post-Nuccaleena Brachina Formation in South Australia (Calver and

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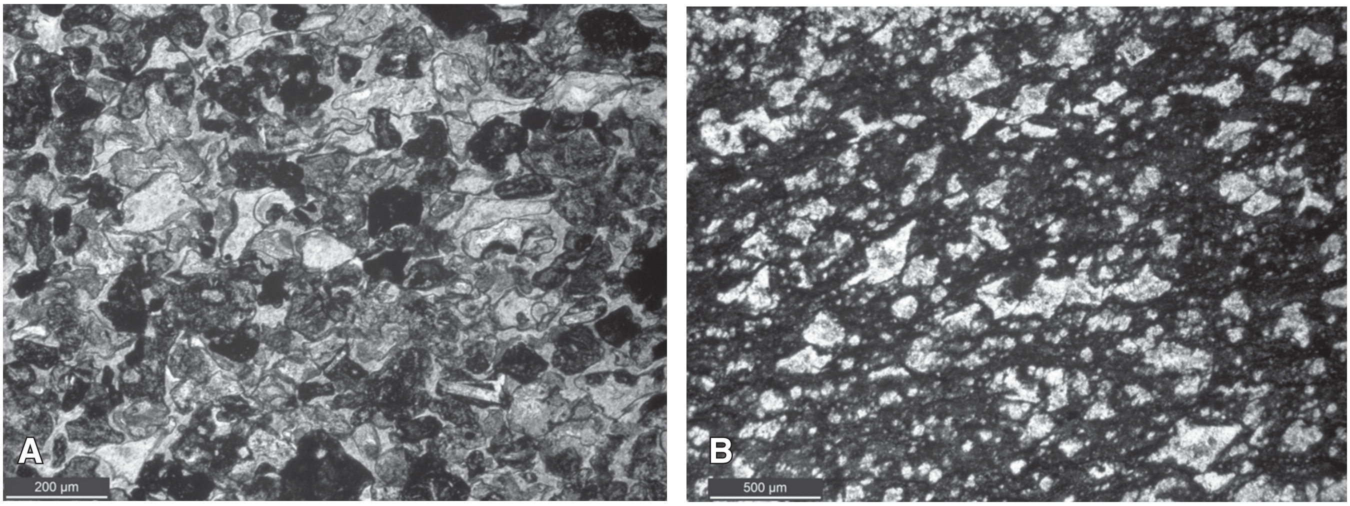

Figure 2. Thin-section microphotographs (plane polarized light). A: Sample 5 of tuffaceous, basaltic sandstone of middle member of Cottons Breccia. Mineralogy is predominantly fine-grained chlorite with minor sericite and carbonate. B: Sample 4 of uppermost bed of Cottons Breccia at locality 2; lithic wacke of angular sand-sized grains of chlorite + muscovite + dolomite, in matrix of hematitic dolomitic mudstone.

Walter, 2000), and further upward into a thick volcanic succession, the Skipworth Subgroup, dated by Sm-Nd at 579 ± 16 Ma (mean square of weighted deviates, MSWD = 1.6; Meffre et al., 2004). The Grimes Intrusive Suite (Meffre et al., 2004), intruding the Yarra Creek Shale and older units, has been dated as 575 ± 3 Ma (U-Pb sensitive high-resolution ion microprobe, SHRIMP, on zircon; Calver et al., 2004).

SHRIMP U-Pb GEOCHRONOLOGY

Measurements were conducted using the SHRIMP II ion microprobes at the John de Laeter Centre for Isotope Research at Curtin University (Perth, Australia). Data acquisition and processing are fully outlined in the GSA Data Repository[1]. In order to best constrain the ages of sedimentation, euhedral zircons were preferred targets for SHRIMP analyses. The data therefore may not accurately reflect total detrital age distributions. From locality 1 (Fig. 1), two samples contain euhedral to variably rounded zircons. Sample 1 is from a granule-bearing red sandstone lens within massive diamictite, 1 m below the top of the Cottons Breccia, while sample 2 is partly dolomitized, sparsely pebbly sandy diamictite 0.5 m below the top. Samples 3 and 4, from locality 2, contain zircons that are euhedral to rounded, and predominantly euhedral, respectively. Sample 3 is a red, poorly sorted pebbly sandstone, ~1 m below the base of the cap carbonate. Sample 4 is from a 0.7-m-thick bed of flat laminated, purplish-gray, dolomitic, fine-grained sandstone that grades up into the cap carbonate. Sample 5, from the middle (tuffaceous sandstone) member at locality 2, yielded only five zircons that returned basement ages, and is not discussed further.

A total of 167 dated grains yielded ^{207}Pb-corrected ^{238}U/^{206}Pb ages between 687 Ma and 613 Ma (Table DR1 in the Data Repository). Ages in each sample are dispersed, or slightly dispersed, beyond analytical precision, and two age components can be differentiated using the algorithm of Sambridge and Compston (1994). An older component, ca. 660 Ma, is predominant in samples 1–3. A younger component, ca. 636 Ma, is strongly predominant in sample 4 (Table 1).

CHEMICAL ABRASION–THERMAL IONIZATION MASS SPECTROMETRY U-Pb GEOCHRONOLOGY

The predominance of relatively young and similar-aged zircons shown by the SHRIMP dating in sample 4 prompted submission of an additional aliquot of this sample to the Isotope Geology Laboratory at Boise State University (Idaho, USA) for chemical abrasion (CA) TIMS U-Pb dating. U-Pb dates were obtained from nine zircon crystals imaged via cathodoluminescence (Table DR2 and Fig. DR6). Eight zircons yielded statistically equivalent ^{206}Pb/^{238}U dates with a weighted mean of 636.41 ± 0.34 Ma (±0.45 m.y. including systematic tracer calibration error; MSWD = 1.5) (Fig. 3); a single crystal yielded an older date of 666.8 ± 2.6 Ma. Allowing for the lower precision inherent in the SHRIMP dating, there is excellent agreement between the two U-Pb techniques as regards both the presence of a bimodal age distribution and the age of the predominant youngest zircon component in sample 4 (Fig. 4).

In thin section, sample 4 is a red-brown (hematitic) dolomitic mudstone, with ~25% clear, sand-size (0.1–0.5 mm) altered lithic grains

TABLE 1. SUMMARY OF SHRIMP U-Pb RESULTS FOR COTTONS BRECCIA SAMPLES

Sample (registered number)	N/n	Age range (Ma)	Weighted mean age (Ma)	Age components (Ma)
1 (R008184)	76/61	687–625	654.4 ± 4.3 (MSWD = 1.77) slightly dispersed	662.5 ± 5.2 (70%) 639.4 ± 7.3 (30%)
2 (R008185)	30/21	665–616	644.4 ± 6.5 (MSWD = 3.08) dispersed	653.5 ± 5.3 (66%) 629.6 ± 7.1 (34%)
3 (R008186)	28/18	668–625	647.4 ± 6.2 (MSWD = 2.81) dispersed	653.3 ± 5.0 (77%) 633.0 ± 9.2 (23%)
4 (R008187)	90/67	674–613	638.0 ± 2.5 (MSWD = 1.31) slightly dispersed	661.9 ± 13.0 (6%) 636.8 ± 2.3 (94%)

Note: N/n—total number of analyses/number of reliable analyses; the latter calculated after averaging pairs of analyses in statistical agreement, and excluding those interpreted to have lost radiogenic Pb, of Mesoproterozoic or Paleoproterozoic age, likely processing contaminants, or those with low UO^+/U^+. Weighted mean ages (MSWD—mean square of weighted deviates) and age components (proportions in parentheses) are based only on reliable data, n, and are listed with 95% uncertainties. Age components are determined using the algorithm of Sambridge and Compston (1994). Registered sample numbers are those of Mineral Resources Tasmania.

[1]GSA Data Repository item 2013312, SHRIMP and CA-TIMS U-Pb dating methods and results, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

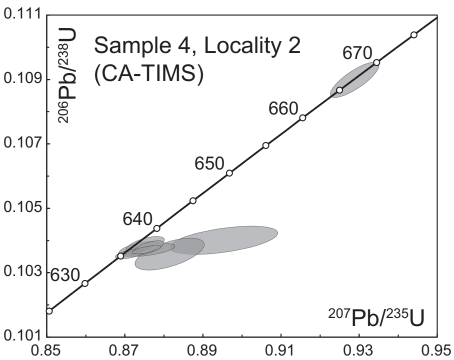

Figure 3. U-Pb concordia diagram illustrating chemical-abrasion thermal ionization mass spectrometry (CA-TIMS) results for sample 4.

composed of fine-grained chlorite, muscovite, and carbonate (Fig. 2B). Many grains are highly angular, with cuspate outlines suggestive of shards. No detrital or volcanic quartz is visible. Grain shapes and mineralogy are comparable to the shard-rich, tuffaceous sandstone of the middle member (Fig. 2A). However, while the grains may be of altered volcanic origin, conclusive evidence of a primary air-fall origin is lacking.

DISCUSSION

Although the Cottons Breccia zircons studied herein are notionally detrital in origin, a number of factors suggest that the ca. 636 Ma zircons in sample 4 are first-cycle volcanic zircons, penecontemporaneous or nearly so with sedimentation. These factors are the abundance of euhedral zircon grains in this sample (Figs. DR1 and DR6), the predominance of the ca. 636 Ma zircon age component, the age equivalence of individual zircons shown by the CA-TIMS dating, the possible volcanic origin of the sand grains, and the presence of known ash beds (albeit mafic) lower in the succession. The SHRIMP data show that in the other three samples, the same (or a very similar) age component is present, but subordinate to a ca. 662–653 Ma detrital component (Table 1). These samples all contain visible evidence, in the form of sparse pebbles and granules, of extrabasinal input, and a preponderance of rounded zircons (Fig. DR1). Only in sample 4, at the transition to the cap carbonate, does the possible first-generation volcanic zircon input predominate (~90%), consistent with these zircons being introduced from a different source, possibly an ash fall, than the glacially transported detrital material.

We emphasize that our 636.41 ± 0.45 Ma CA-TIMS date, from immediately below the Cryogenian-Ediacaran lithologic contact on King Island, is almost identical to the only two other comparably high-resolution TIMS U-Pb dates obtained from ash beds in Marinoan glaciogenic rocks or cap carbonates, 635.51 ± 0.82 Ma from ~30 m below the top of the glacigenic Ghaub Formation in Namibia (Hoffmann et al., 2004)

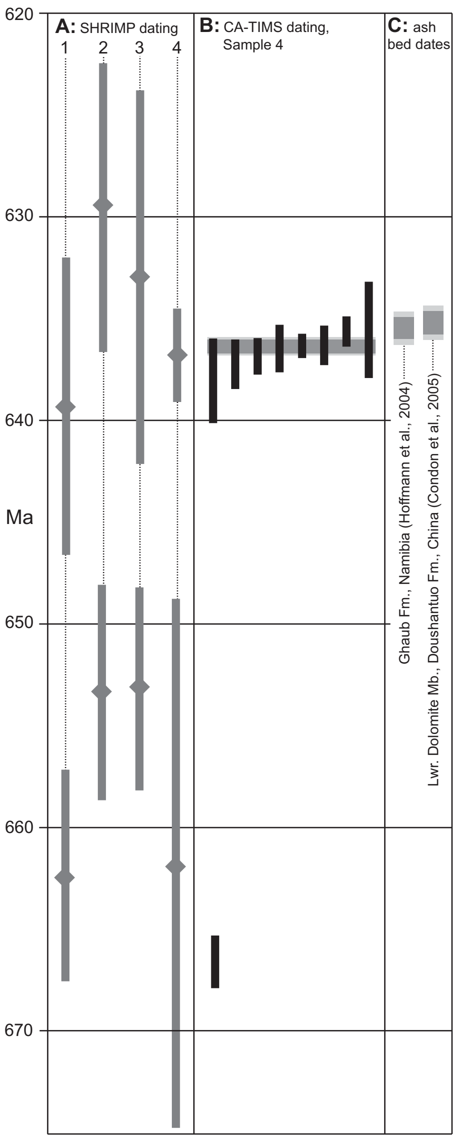

Figure 4. Results of U-Pb dating. A: Zircon age components derived from mixture modeling of sensitive high-resolution ion microprobe (SHRIMP) data from samples 1–4 of Cottons Breccia (see text and Table DR1; see footnote 1). B: Plot of individual $^{206}Pb/^{238}U$ dates from 9 single zircons from sample 4 analyzed by chemical-abrasion thermal ionization mass spectrometry (CA-TIMS); error bars (black) are at 2σ confidence interval; weighted mean date of 8 youngest zircons (636.41 ± 0.34 [0.45] Ma, MSWD = 1.5) is shown in gray; shorter error bar, reflecting analytical uncertainty only, is darker shade; longer error bar, reflecting analytical plus tracer uncertainty, is lighter gray. C: Isotope-dilution TIMS U-Pb dates (shown as range of 2σ uncertainties, as for B) of Hoffmann et al. (2004) and Condon et al. (2005) from ash beds in Ghaub Formation and cap dolostone at base of Doushantuo Formation, respectively. Mb.—Member; Fm.—Formation.

and 635.23 ± 0.84 Ma from 2.3 m above the base of the cap carbonate in south China (Condon et al., 2005; all age errors including tracer calibration uncertainties following Schmitz and Davydov, 2012). In suggesting a ca. 636 Ma age for the Cottons Breccia, our data do not support the correlation of the Cottons Breccia with the younger than 582 Ma Croles Hill Diamictite of northwest Tasmania, as proposed by Calver et al. (2004). Equivalents of the terminal Cryogenian glaciation may be missing at a cryptic unconformity in northwest Tasmania (Calver, 2011). A stratigraphic break or condensed section is also indicated within the Yarra Creek Shale (Hoffman et al., 2009). Our data strongly support age equivalence of the Ghaub Formation, Nantuo Tillite, and Cottons Breccia (and by extension the Elatina Formation), thereby adding geochronometric weight to the correlation hypothesis that underlies the definition of the base of the Ediacaran system. The profound paleoclimatic transition between low-latitude glacial deposits and their distinctive cap carbonates may be diachronous or isochronous (Hoffman et al., 2007; Rose and Maloof, 2010), but that issue is at a temporal resolution that currently evades the most precise geochronometric techniques.

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