Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 250 (2006) 116–133
EPSL
www.elsevier.com/locate/epsl

# Did the Transgondwanan Supermountain trigger the explosive radiation of animals on Earth?

Richard J. Squire [a,*], Ian H. Campbell [b], Charlotte M. Allen [b], Christopher J.L. Wilson [a]

[a] *School of Earth Sciences, The University of Melbourne, Victoria, 3010, Australia*
[b] *Research School of Earth Sciences, The Australian National University, Canberra, ACT, 0200, Australia*

Received 22 September 2005; received in revised form 12 May 2006; accepted 17 July 2006
Available online 7 September 2006
Editor: V. Courtillot

**Abstract**

The explosive radiation of animals on Earth during the late Early Cambrian period (~530–510 Ma) coincides with the deposition of enormous volumes of continentally derived sedimentary rocks throughout Gondwana. We show here, that these quartz-rich sedimentary units, collected from five continents, display remarkably similar detrital-zircon U–Pb age-patterns and propose that they were sourced from either side of a >8000-km-long and generally >1000-km-wide mountain chain (the Transgondwanan Supermountain), which formed following oblique collision between East and West Gondwana, commencing at ~650 Ma. The depositional system supplied by this mountain chain was >100 km$^3$, which is equivalent to covering all 50 states of the USA with ~10 km of sediment, and it lasted for at least 260 Myr. The enormous size of the vegetation-free mountain chain, its position close to the equator and the dramatic changes in global plate-motion in response to the cessation in continent–continent collision, together with the possible appearance of biota in the soils that promoted rapid chemical weathering, resulted in extreme erosion and sedimentation rates that are arguably the highest in the geological record. This led to an unprecedented flux of P, Fe, Sr, Ca and bicarbonate ions into the oceans. The addition of Sr was responsible for seawater $^{87}Sr/^{86}Sr$ building up to the highest levels in Earth's history, whereas the addition of P and Fe provided the essential nutrients that supported a bloom of primitive life that in turn provided abundant food to support the Cambrian explosion of life. The addition of Ca and bicarbonate ions increased $CaCO_3$ supersaturation in the oceans, which allowed species in numerous phyla to simultaneously develop skeletons.

*Keywords:* Gondwana; Detrital zircons; Tectonics; Cambrian Explosion

## 1. Introduction

The sudden appearance and explosive radiation of animals on Earth during the Late Ediacaran to Early Cambrian periods (~575 to 510 Ma) [1–4] represent one of the most remarkable biological episodes in our planet's history. These catastrophic biological changes occurred coincident with dynamic plate-tectonic activity associated with amalgamation of the supercontinent Gondwana [5–8] and a variety of dramatic changes in global environmental conditions including a rapid rise in Sr isotopic values of seawater to the highest-known levels in Earth's history [9–13], the escalation in atmospheric oxygen levels [14–17], over a dozen large fluctuations

---

[*] Corresponding author. Present address: School of Geosciences, Monash University, Clayton, Victoria, 3800, Australia.
*E-mail address:* Rick.Squire@sci.monash.edu.au (R.J. Squire).

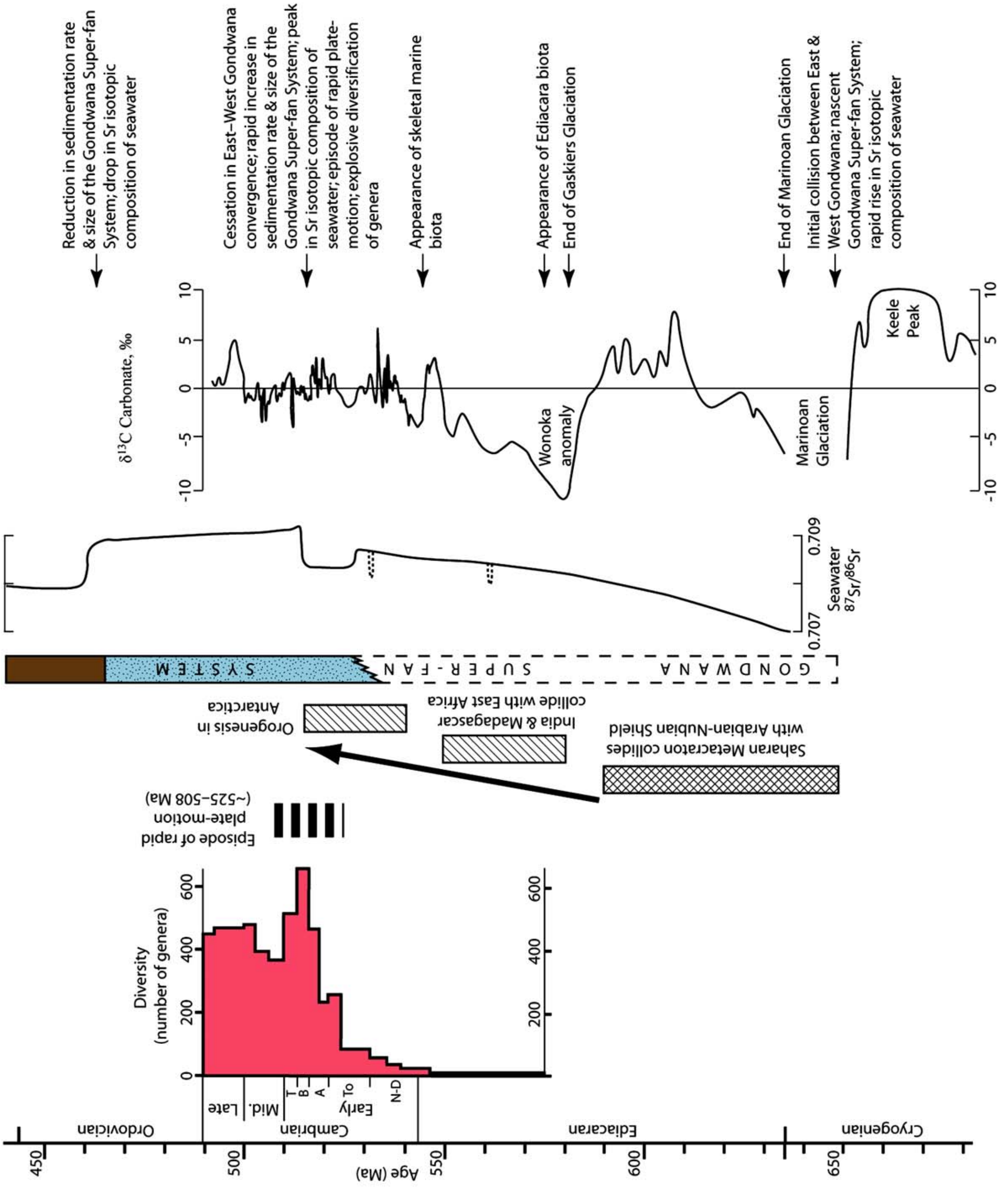
0012-821X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2006.07.032

in inorganic $\delta^{13}$C values [2,13,18] and major glaciations that included the youngest 'snowball Earth' event [4,19,20]. However, the timing of these biological, tectonic and environmental events display only broad overlap (Fig. 1), and have resulted in considerable uncertainty and varied interpretations about the trigger of the explosion of animal evolution on Earth: the aftermath to rapid climatic fluctuations between global glaciations and the extreme greenhouse conditions following 'snowball Earth' [19], the Acraman meteorite impact [21,22]; a substantial (~30°) and rapid decrease in orbital obliquity [23]; short-lived (~15 Ma) episodes of anomalously fast plate motions (i.e., inertial interchange true polar wander (IITPW) [3]); repeated methane-release thermal cycling events induced by IITPW [2]; a dramatic shift in terrestrial weathering processes that was accelerated by the expansion of an early land-based biosphere [24]; and changes in accumulation rates of continentally derived sediment during supercontinent amalgamation [9].

The two most important biological events related to the explosion of animal evolution are the appearance of Ediacaran biota at ~575 Ma [1,4] and the sudden peak in diversification of genera in the Botoman stage (~515 Ma) [2,3]. The 60-million-year gap between these events suggests that the cause of this radical biological episode was long-lived and rapidly evolving. While the Acraman meteorite impact occurred broadly coincident with the appearance of the Ediacaran biota [21], it remains unclear whether this event triggered a drastic change in evolution when recoveries from other large impacts during Earth's history have had a relatively minor effect (i.e., addition of no new phyla). The 'snowball Earth' hypothesis, which predicts a 'bottleneck and flush' style of evolution, also struggles to explain how it influenced this major biological episode because of the large time break between the youngest-known 'snowball Earth' event (Marinoan Glaciation at ~635 Ma [20]) and the first-known appearance of animals about 60 Ma later [1,4]). Moreover, similar microfossil assemblages have been observed both pre- and syn-glaciation in the USA [25] and pre- and post-glaciation in Australia [21], indicating relatively high levels of survivorship of many species during and after these glaciations. Numerical simulations of changes in orbital obliquity over the last 800 Ma indicate that they were all less than 4° [26], thus substantial (~30°) variations in the Ediacaran–Cambrian period (e.g., [27,28]) are unlikely and probably had little impact on Earth's biological evolution. Of the remaining hypotheses for the trigger of the explosive radiation of animals, most involve an interaction between the dramatic tectonic and environmental events during this interval. However, establishing the temporal links between these events has been complicated by uncertainty about the timing of amalgamation events in Gondwana and the geometry of the fragments involved [5,6,8,29–31].

One way to trace the history of Gondwanan amalgamation, and the mountains that formed during collisional orogenesis, is to trace the history of the sedimentary rocks derived from the uplifted terrane using detrital-zircon ages. Early Palaeozoic (~543–390 Ma) continentally derived quartz-rich turbidites occur extensively throughout Gondwana [7,32–38] (Figs. 2 and 3). The huge volume (~15 Mkm$^3$) of the continentally derived Cambro–Ordovician sedimentary rocks in Arabia and northern Africa, led Burke and Kraus [34] to suggest that the detritus was derived from mountainous highlands that formed during the assembly of Gondwana. In marked contrast, the large volumes of Cambro–Ordovician quartz-rich turbidites deposited along the proto-Pacific margin of Gondwana (i.e., Australia, Antarctic, and New Zealand) are generally considered to represent the product of convergent-margin orogenesis [37–40]. Here, we present correlations among these widely dispersed quartz-rich sediment piles of similar ages from the early Palaeozoic using the U–Pb age spectra of detrital zircons from the quartz-rich sedimentary rocks: similar detrital-zircon age patterns indicate similar sources, whereas different age patterns imply different sources. Previous studies on detrital-zircon age data for Early Palaeozoic quartz-rich turbidites from the proto-Pacific margin of Gondwana [37,40–42] have identified two main age populations: ~650–500 Ma and ~1200–900 Ma. Williams [43] and Williams et al. [44] pointed out that these ages match closely the 650–500 Ma and 1200–900 Ma rocks from eastern Africa, and that the broadly similar age spectra for the sedimentary units indicated provenance from the same cratonic region. However, several points remain unclear about the Gondwanan quartz-rich sedimentary rocks. What triggered the influx of detritus from Africa? What determined the extent and longevity of the overall depositional system? Were there environmental implications associated with the rapid deposition of a massive volume of quartz-rich detritus? And, what is the significance of this sediment pile with respect to the broadly coincident biological and tectonic changes?

In this study, we correlated the early Palaeozoic quartz-rich sedimentary rocks throughout Gondwana to assess the tectonic implications of the sediment-dispersion system. Special emphasis is placed on new data from quartz-rich turbidites from southeastern Australia, because they provide exposures of late Early Cambrian to Early Devonian sedimentary units in Gondwana (Figs. 2b and 3). We use this section to delineate different source terranes


Reduction in sedimentation rate & size of the Gondwana Super-fan System; drop in Sr isotopic composition of seawater
Cessation in East–West Gondwana convergence; rapid increase in sedimentation rate & size of the Gondwana Super-fan System; peak in Sr isotopic composition of seawater; episode of rapid plate-motion; explosive diversification of genera
Appearance of skeletal marine biota
Appearance of Ediacara biota
End of Gaskiers Glaciation
End of Marinoan Glaciation
Initial collision between East & West Gondwana; nascent Gondwana Super-fan System; rapid rise in Sr isotopic composition of seawater
δ13C Carbonate, ‰
-10
-5
0
5
10
Wonoka anomaly
Marinoan Glaciation
Keele Peak
Seawater 87Sr/86Sr
0.707
0.709
GONDWANA SUPER-FAN SYSTEM
Orogenesis in Antarctica
India & Madagascar collide with East Africa
Saharan Metacraton collides with Arabian-Nubian Shield
Episode of rapid plate-motion (~525–508 Ma)
Diversity (number of genera)
0
200
400
600
Late
Mid.
T
B
A
To
N-D
Early
Ordovician
Cambrian
Ediacaran
Cryogenian
Age (Ma)
450
500
550
600
650

and to assess the areal and temporal shifts in provenance. A new interpretation for the amalgamation of Gondwana is derived from this approach.

## 2. Methods

Eleven samples were selected for detrital-zircon age dating from early Palaeozoic quartz-rich sandstone in western Victoria (Figs. 2 and 3), each being composed of abundant quartz with lesser detrital muscovite, biotite, feldspar and low-grade metamorphic rock fragments. Three samples were obtained from locations with tightly constrained biostratigraphic ages: ST36 (Eastonian 3–4; ~452–449 Ma); ST39 (Wenlock; ~428–423 Ma); and ST47 (Emsian; ~400–390 Ma). The Grampians Group (ST77) and Glen Creek Sandstone (ST48) samples have inferred Late Ordovician to Late Silurian and Middle Silurian to Early Devonian ages, respectively [45]. The other samples are late Early to Middle Cambrian or Late Cambrian in age based on structural and stratigraphic relationships [7,45].

Zircon ages were determined using laser ablation inductively coupled plasma–mass spectrometry. Some 971 analyses (one analysis per grain) were performed, and all samples contained broken and rounded zircon grains suggesting that abrasion occurred during sedimentary transportation. Standard heavy liquid and electromagnetic techniques were used to separate the zircons from whole rocks at The University of Melbourne. Several unknown populations were mounted with standard zircons (TEMORA 2 and R33), and NIST 610 glass, cast in epoxy, and polished to expose zircon interiors at the Research School of Earth Sciences, The Australian National University, using the technique reported in Bryan et al. [46].

We employed a $^{208}$Pb-based common-Pb correction to all ages reported here [47]. Systemic Hg prevents direct measurement of common-Pb content ($^{204}$Pb) so it is modelled assuming concordance of the Th–U–Pb system, and that common Pb is the only reason for discordance. The reported dates are $^{207}$Pb/$^{206}$Pb ages for grains older than 800 Ma, and $^{206}$Pb/$^{238}$U ages for younger grains. An analysis is classified as robust and used to construct age spectra if two criteria are met: homogeneity and concordance. If the uncertainty in the isotope relied on for age exceeded three times that expected based on counting statistics, the analysis was rejected. Zircons that were not concordant at the 10% level were also rejected. Of the grains analysed, 554 (57%) were robust, based on the criteria described above. U–Pb and Pb–Pb ratios and ages for the robust analyses are provided in Supplementary Table 1 and plots of these data, generated using AGEDISPLAY [48], are shown in Fig. 4. Precision and accuracy of the analyses are represented by results of zircon standard R33, presented at the base of Supplementary Table 1.

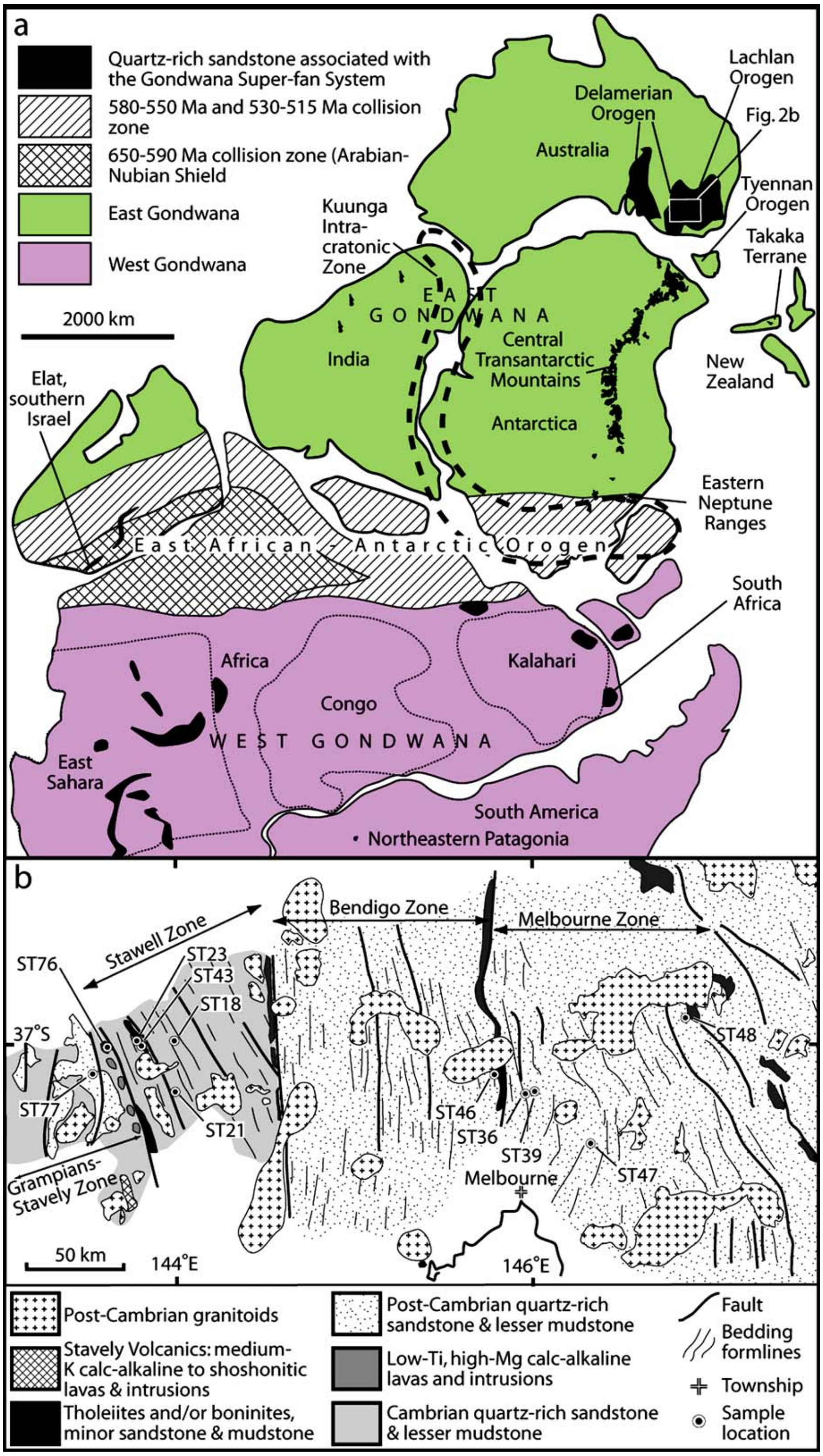
## 3. Results

Early and Middle Ordovician zircons dominate the Middle Silurian to Early Devonian Glen Creek Sandstone (ST48), whereas the Late Cambrian Monageeta Shale (ST46) contains abundant ~550–500 Ma zircons. In strong contrast, almost all the other samples display a dominant composite peak at ~650–550 Ma, a secondary composite peak at ~1200–900 Ma and generally minor Palaeoproterozoic and Archean peaks. However, subtle variations in the minor age peaks enable several of these samples with broadly similar age spectra to be distinguished (see below).

### *3.1. Correlation of Gondwanan detrital-zircon age spectra*

The Early and Middle Cambrian quartz-rich sedimentary units from the Kanmantoo Group in South Australia [40], Junction Formation in New Zealand [42], lower parts of the Goldie Formation in Antarctica [37,41,49] and Table Mountain Group in South Africa [50] all display a dominant composite peak at ~650–550 Ma, a secondary composite peak at ~1200–900 Ma and minor Palaeoproterozoic and Archean peaks, thus matching closely the Early and Middle Cambrian Leviathan and Albion formations (ST23 and ST43) in southeastern Australia (Fig. 4). The Early Cambrian quartz-rich units of the Tal Group from northern India [51] and the El Jagüelito

Fig. 1. Major geological, biological and environmental events related to development of the Transgondwanan Supermountain and Gondwana Super-fan System during the late Neoproterozoic to Ordovician interval. Cross-hatched boxes represent the timing and duration of collisional orogenesis associated with diachronous East–West Gondwana convergence [5,60] (highlighted by the large arrow). The intervals recording the greatest flux of quartz-rich sediment associated with the Gondwana Super-fan System are stippled in blue, whereas those with lower depositional rates are shown in grey; dashed lines during the Ediacaran period indicate that the depositional rates are inferred (i.e., sedimentary units not preserved). Remaining data are from the following sources: major episodes of Neoproterozoic glaciation [4,20,90]; Sr-isotope values for seawater [9,12]; carbon isotope values for carbonate [2,18], diversity of genera [2]; and episode of rapid plate motion [79]; N–D, Nemakit–Daldynian; To, Tommotian; A, Atdabanian; B, Botoman; T, Toyonian; Mid, Middle.


a
Quartz-rich sandstone associated with the Gondwana Super-fan System
580-550 Ma and 530-515 Ma collision zone
650-590 Ma collision zone (Arabian-Nubian Shield
East Gondwana
West Gondwana
2000 km
Lachlan Orogen
Delamerian Orogen
Fig. 2b
Australia
Tyennan Orogen
Takaka Terrane
Kuunga Intra-cratonic Zone
EAST GONDWANA
India
Central Transantarctic Mountains
New Zealand
Antarctica
Elat, southern Israel
Eastern Neptune Ranges
East African - Antarctic Orogen
South Africa
Africa
Kalahari
Congo
WEST GONDWANA
East Sahara
South America
• Northeastern Patagonia
b
Bendigo Zone
Melbourne Zone
Stawell Zone
ST76
ST23
ST43
ST18
37°S
ST48
ST77
ST21
ST46
ST36
ST39
ST47
Grampians-Stavely Zone
Melbourne
50 km
144°E
146°E
Post-Cambrian granitoids
Post-Cambrian quartz-rich sandstone & lesser mudstone
Fault
Bedding formlines
Stavely Volcanics: medium-K calc-alkaline to shoshonitic lavas & intrusions
Low-Ti, high-Mg calc-alkaline lavas and intrusions
Township
Tholeiites and/or boninites, minor sandstone & mudstone
Cambrian quartz-rich sandstone & lesser mudstone
Sample location

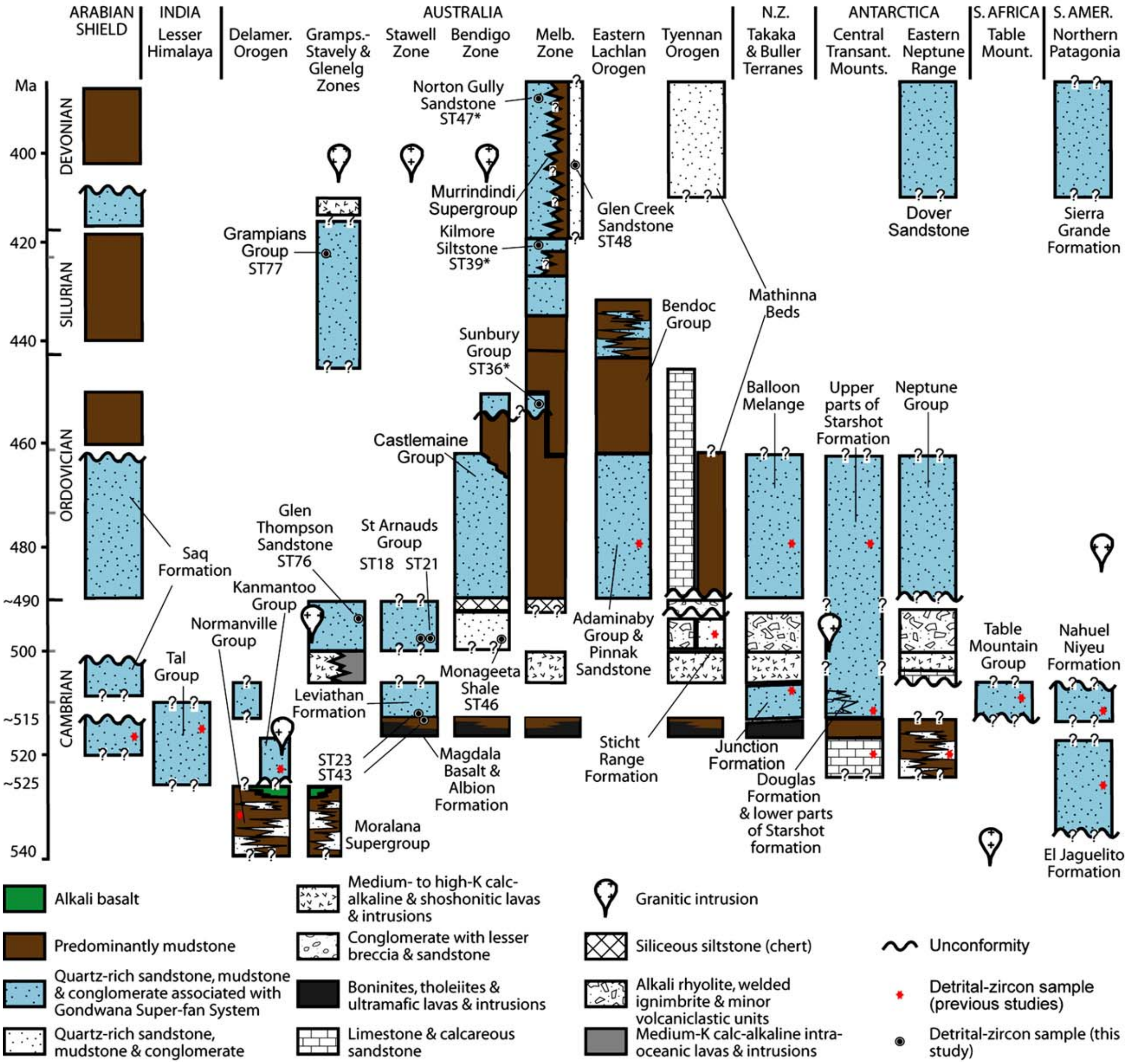


Fig. 3. Time-versus-space chart showing the distribution and stratigraphic relationships of the Cambrian to Early Devonian quartz-rich successions in East Gondwana (i.e., India [51], Australia [7,45], New Zealand [42], Antarctica [7,37,41,49], South Africa [50] and northern Patagonia [52]. The stratigraphic position of detrital-zircon samples discussed is shown. Modified after Squire and Wilson [7]. Tas., Tasmania; N.Z., New Zealand; S., South; Amer., America; Delamer., Delamerian; Gramps., Grampian; Melb., Melbourne; Transant., Transantarctic; Mount., Mountain.

Formation from northeastern Patagonia [52] also display prominent composite peaks at ~650–550 Ma and ~1200–900 Ma, although the units from India also have a composite peak at ~800–650 Ma whereas a major ~535 Ma peak is present in the sedimentary units from northern Patagonia. Composite plots of detrital-zircon age data from Cambrian and Ordovician quartz-rich sedimentary units in southern Israel display broad peaks at ~650–

---

Fig. 2. Simplified location maps. (a) Pre-Jurassic configuration of East and West Gondwana, showing the main tectonic elements and known distribution of early Palaeozoic quartz-rich sedimentary units [6,7,33,37,51,52]. (b) Simplified geological map of the western Lachlan and eastern Delamerian orogens in southeastern Australia [7] showing the distribution of the main early Palaeozoic units and the location of detrital-zircon samples analysed for this study.

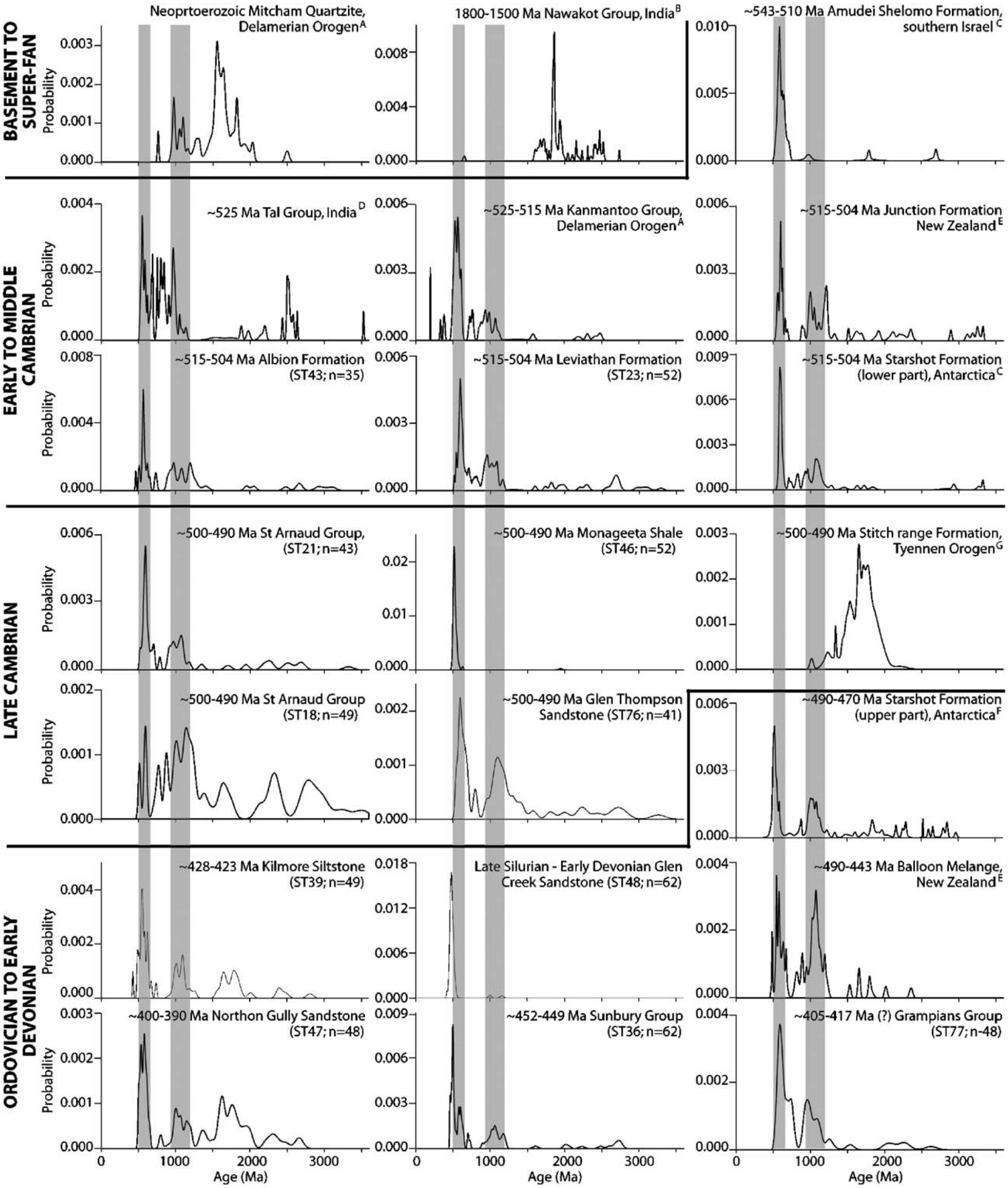


Fig. 4. Summary of the detrital-zircon components from East Gondwana. Detrital-zircon U/Pb age spectra for quartz-rich sandstones from this and previous studies (A [32], B [51], C [41], D [53], E [42], F [49] and G [54]). n, number of analyses.

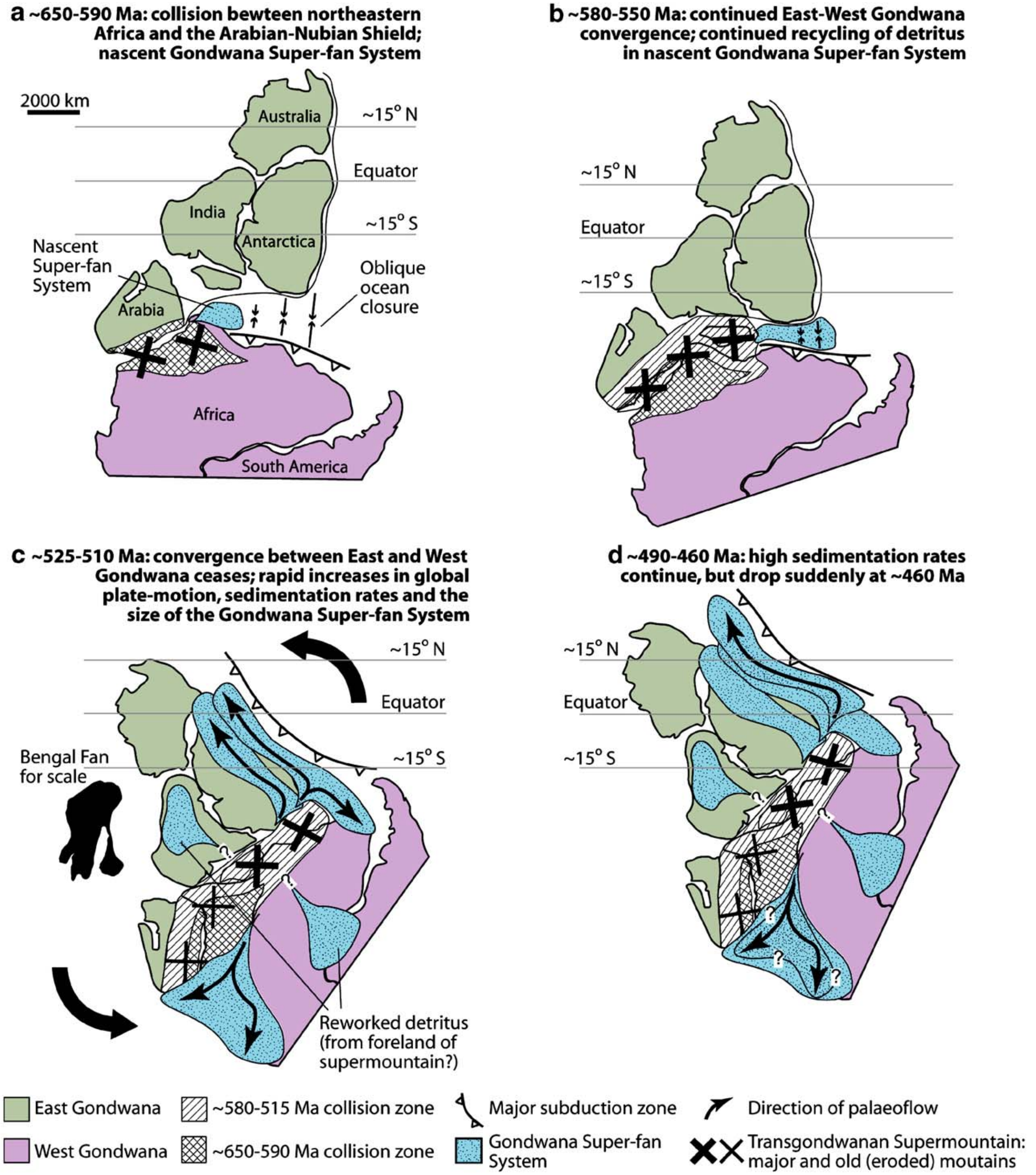


Fig. 5. A schematic reconstruction showing the major features associated with evolution of the Transgondwanan Supermountain and Gondwana Super-fan System. (a–d) Oblique convergence between East and West Gondwana from ~650 and 515 Ma resulted in the establishment of an enormous mountain chain (Transgondwanan Supermountain). The Gondwana Super-fan System developed as a result of this collisional event and tectonic events along the proto-Pacific margin of East Gondwana (see Ref. [7]). Deposition associated with the super-fan system lasted for at least 260 Myr. The present-day areal extent of the Bengal and Nicobar fans [36], are shown in black for scale. Palaeogeography of the continents are modified after Kirschvink et al. [3].

550 Ma, ~1200–900 Ma and ~800–650 Ma [33], although individual units such as the Amudei Shelomo Formation in southern Israel [32] have single composite peaks at ~650–550 Ma with very few ~1200–900 Ma zircons [32]. Despite these minor differences, the presence of a dominant composite peak at ~650–550 Ma and secondary composite peak ~1200–900 Ma for detrital zircons from these Early Cambrian quartz-rich successions strongly links these sedimentary units in East and West Gondwana during this time. The paucity of Palaeoproterozoic detrital zircons in these units precludes the presently-exposed Neoproterozoic to lowermost Cambrian basement rocks to many of these successions as an important source (e.g., passive-margin quartz-rich successions of the Mitcham Quartzite from Australia [40], the Kawakot Group from India [53] and the Cobham Formation from Antarctica [41]; Fig. 4). In contrast, Palaeoproterozoic zircons are generally common in the Late Cambrian quartz-rich sedimentary units from western Victoria (ST18, ST21, ST46, ST76), and define a dominant peak in the Sticht Range Formation from Tasmania [54]. Thus a varied source was present in these parts of East Gondwana during the Late Cambrian.

The Early to Middle Ordovician quartz-rich sandstone of the Adaminaby Group in eastern Australia [45], Balloon Melange in New Zealand [42] and upper parts of the Starshot Formation in Antarctica [49] are distinguished from the Early to Middle Cambrian quartz-rich sandstone of southeastern Australia (e.g., Leviathan Formation [7]) by significant populations of ~510–485 Ma detrital zircons (see Fig. 4). The younger zircons in these sedimentary units represent the involvement of late Cambrian to early Early Ordovician zircon-bearing source rocks [45,55]. Deposition of the Gondwanan sedimentary units in southeastern Australia and New Zealand generally ceased by the Late Ordovician or Early Silurian (Fig. 3). The only exception was in the Melbourne Zone of southeastern Australia, where deposition of quartz-rich detritus was nearly continuous from the earliest Ordovician until the Emsian (late Early Devonian) [45] periods. The upper Silurian (ST39) and lower Devonian (ST47) sedimentary units in southeastern Australia display a progression towards fewer 510–485 Ma and more 2000–1550 Ma zircons, recording the reduced involvement of the late Cambrian source rocks and increased involvement of older source material.

Not only the time of cessation of sedimentation but also the initial influx of quartz-rich sandstones dominated by ~650–550 Ma and ~1200–900 Ma zircons varied across Gondwana (Fig. 3). Deposition of Early Cambrian quartz-rich sedimentary units including the Tal Group in India [51], Kanmantoo Group in South Australia [40] and the Amudei Shelomo Formation in southern Israel have inferred commencement ages between about 535 and 525 Ma, whereas in western Victoria (ST43 and ST23), New Zealand [42], Antarctica [37,41,49,56] and possibly South Africa [50], this influx did not start until ~515 Ma [7]. In Tasmania, the influx commenced even later at ~500 Ma [54].

## 4. The Transgondwanan Supermountain and the Gondwana Super-fan System

The appearance of quartz-rich sedimentary units displaying the prominent ~650–550 Ma and ~1200–900 Ma composite peaks on what is now five different continents (e.g., India, Israel, Africa, Australia, New Zealand, South America and Antarctica) during the Early Cambrian, is the most striking feature of the Early Palaeozoic detrital-zircon age spectra from Gondwana. The timing of this enormous sediment influx from similar source-rocks coincides with the build-up in seawater $^{87}Sr/^{86}Sr$ ratios to as high as ~0.7095 [57] during the Late Cambrian to Early Ordovician periods. The dramatic rise in Sr isotopic levels for seawater from the beginning of the Ediacaran period (~635 Ma) to the highest-known level in Earth's history, also broadly coincides with the convergence of East and West Gondwana [5] (Fig. 1). Although this rise in Sr isotope values for seawater has previously been attributed to the very high erosion-rates of Pan African (~650–500 Ma) orogenic belts such as those separating the Kalahari and Congo cratons [57–59], we propose that this dramatic change in ocean chemistry was largely driven by extremely high amounts of erosion predominantly from the >8000-km-long and generally >1000-km-wide East African–Antarctic Orogen [6] (Fig. 2a; discussed further below). This very large orogen is composed of a complex association of crustal blocks, accreted micro-continental fragments and juvenile island arc rocks that developed during one of the biggest-known continent–continent collisions in Earth's history [6,8] following closure of the Mozambique Ocean between about 650 and 515 Ma [5,60]. Near the Arabian–Nubian shield, the rocks from this collision zone are generally low-to-medium metamorphic grades [8,61], whereas those from East Africa to the Eastern Neptune Ranges (Antarctica) are typically much higher grade, reaching granulite facies in places [8,62]. The striking correlation in ages between the rocks from this orogen and detrital-zircon age spectra for the quartz-rich sedimentary units, clearly shows that the detritus was derived from the mountains that developed along this long collisional zone. Furthermore, the size of the East African–Antarctic Orogen is large enough to supply the huge volume of quartz-rich detritus dispersed over such a remarkably large areal extent. Here, we refer to the surface expression of this collisional zone as the Transgondwanan Supermountain to emphasise its palaeogeographic significance.

The river systems that drained to either side of the enormous Transgondwanan Supermountain, transported huge sediment volumes and then deposited them in a series of giant sedimentary fans (Fig. 5), named here the Gondwana Super-fan System. The proximal parts of this system were probably large foreland basins, whereas the distal parts of the system were major intercontinental basins (e.g., the Mozambique Ocean [5,60]). Although the actual volume of sediment deposited by the super-fan system is difficult to estimate, Fergusson and Coney [36] suggested that the Ordovician quartz-rich turbidites in southeastern Australia (i.e., the Lachlan Orogen) were deposited in a fan that had an undeformed areal extent comparable to the present-day ~30 Mkm$^3$ Bengal Fan [63]. In addition, Burke and Kraus [34] calculated that ~15 Mkm$^3$ of Cambro–Ordovician quartz-rich sedimentary rocks were deposited in Arabia and northern Africa. These fans represent less than half the interpreted areal extent of the Gondwana Super-fan System (Fig. 5d), thus the total volume of the depositional system must be at least twice the combined size of these two systems or >90 Mkm$^3$. Alternatively, the inferred areal extent of the Gondwana Super-fan System during the Cambro–Ordovician period is at least 3.5 times larger than the modern-day Bengal Fan (Fig. 5c), which makes the volume of the Gondwana Super-fan System >100 Mkm$^3$. This volume of material is comparable to eroding an average of only 12.5 km of material from the 8000-km-long and at least 1000-km-wide East African–Antarctic Orogen. This is enough detritus to cover all 50 states of the USA with a layer of sedimentary rocks about 10 km thick.

The eventual shutdown of the super-fan system is recorded by a sudden reduction in areal extent of the quartz-rich sedimentary rocks during the Late Ordovician (Fig. 3), which broadly coincides with a rapid fall in seawater $^{87}$Sr/$^{86}$Sr ratios (Fig. 1). The Late Silurian (ST39) and late Early Devonian (ST47) quartz-rich turbidites in the Melbourne Zone, Australia, may represent the final depositional stage of the Gondwana Super-fan System. Therefore, deposition and reworking associated with the Gondwana Super-fan System occurred for *at least* 260 Myr (i.e., 650 to 390 Ma).

## 5. New interpretation of Gondwana amalgamation

Recognition of the Transgondwanan Supermountain, with its extensive and long-lived depositional system (the Gondwana Super-fan System), has important implications for interpreting the tectonic evolution of Gondwana. Orogenesis associated with the collision between northeastern Africa and the Arabian–Nubian Shield at ~650–590 Ma [60] probably records the first stage in the development of the Transgondwanan Supermountain, but the most extensive development of the mountain chain did not commence until ~580 Ma, when the continuation of oblique convergence between East and West Gondwana resulted in East Africa colliding with India and Madagascar [5]. The timing of this event coincided with widespread drowning of cratonic margins in northern Africa and Arabia [9]. Boger and Miller [5] suggested that the duration of convergence along the East African margin was relatively short-lived (~580–550 Ma), and that the main collisional zone between East and West Gondwana was the ~530–515 Ma Kuunga Suture [29] that mated Antarctica and Australia with India, Africa and South America (Fig. 2a). However, the enormous volume of quartz-rich sedimentary rocks deposited either side of the Kuunga Suture after ~530 Ma display detrital-zircon age-spectra that match closely the ages of rocks from the East African–Antarctic Orogen. Furthermore, if the Kuunga Suture was a major suture, then amalgamation of Gondwana involved three large continent–continent collisional events (i.e., the northeastern margin of Africa, the East African margin and the Kuunga Suture) in rapid succession; of these, the youngest two collisional events were anomalously short-lived (~15 to 30 Ma each) given their great length (>4000 km) and highly irregular (curved) margins. These features, together with the absence of evidence for significant arc-related magmatism associated with closure of the oceanic basin separating India and Antarctica, suggest that the Kuunga suture was not the major continent–continent collision-zone between East and West Gondwana and should herein be referred to as the Kuunga intracratonic zone. Most importantly, in the current context, the high-strain zones that define the Kuunga intracratonic zone are locally less than 100 km wide [64–66] compared with generally >1000 km for the East African–Antarctic Orogen [6]. Thus any contribution of quartz-rich detritus of the Gondwana Super-fan System from mountains produced during the formation of the Kuunga intracratonic zone will be trivial compared to those produced from the East African–Antarctic Orogen.

Despite the remarkably similar detrital-zircon age spectra for the Gondwana Super-fan System during the Early and Middle Cambrian, the timing for commencement of the influx of quartz-rich detritus gets younger from the northeastern margin of Africa towards the proto-Pacific Ocean. This change of time of the onset of sedimentation was probably the result of oblique East–West

Gondwana collision (Fig. 5). We suggest that the irregular (non-linear) shapes of the >8000-km-long colliding margins and/or oblique convergence between the two palaeocontinental blocks, combined with episodic reorganisation of global plate-motion, produced several pulses of uplift and basin development that resulted in the major fluxes of quartz-rich sediment (Figs. 3 and 5). Although no >535 Ma quartz-rich sandstones of the Gondwana Super-fan System are known, sediment deposition probably commenced at ~650 Ma from mountains produced by the collision of northeastern Africa and the Arabian–Nubian Shield, but these sedimentary successions were continually recycled during progressive convergence between East and West Gondwana and thus are not preserved (cf., development of the SongPan Ghazê following diachronous collision of North and South China [67]), as discussed further in the next section.

The Cambrian and Early Ordovician to Early Devonian quartz-rich sedimentary units of the Gondwana Super-fan System from the proto-Pacific margin of Gondwana may be distinguished by the presence of younger detritus (i.e., ~510–485 Ma zircons), although the upper Silurian (ST39) and lower Devonian (ST47) sedimentary units display a progression towards fewer 510–485 Ma and more 2000–1550 Ma zircons. In addition, comparisons of detrital-mica ages for the Early Cambrian and Ordovician sandstone units in southeastern Australia suggest that the younger packages had undergone a later thermal event that reset all the detrital micas near the end of the Cambrian [68]. The thermal pulse may have been caused by major late Early Cambrian magmatic events that occurred in response to the dramatic change(s) in global plate-motions following the cessation in convergence between East and West Gondwana at ~515 Ma [5,7]. For example, along the >4000-km-long proto-Pacific margin of Australia, New Zealand and Antarctica, large volumes of forearc oceanic crust and back-arc-basin basalt were generated at ~515 Ma [7,69,70]. This event not only established an extensive new depo-centre in to which the quartz-rich detritus of the Gondwana Super-fan System was deposited, but it may have also provided the heat engine for local (i.e., much of the proto-Pacific margin of Gondwana) crustal melting and thus a modified source of quartz-rich sedimentary rocks. The progression towards fewer 510–485 Ma and more 2000–1550 Ma zircons recorded by the upper Silurian (ST39) and lower Devonian (ST47) sedimentary units (Fig. 4) may represent the eventual exhaustion of source rocks containing the 510–485 Ma zircons and erosion of at least part of the older (pre-Ordovician) quartz-rich basement. It is important to note that the markedly different detrital-zircon age-spectra for Late Cambrian to earliest Devonian quartz-rich sedimentary rocks in Tasmania and the Melbourne Zone (e.g., samples ST46 and ST48 and the Sticht Range Formation; Fig. 4) suggest an entirely local source was present in these areas, thus increased levels of mixing probably occurred during the final stages of deposition associated with the Gondwana Super-fan System. The source of this locally derived detritus in Tasmania and the Melbourne Zone may have been a micro-continent that collided with the proto-Pacific margin of Gondwana in the late Cambrian [7].

## 6. Potential effect of erosion of the Transgondwanan Supermountain on environmental change

Erosion rates and sediment production are controlled by a combination of climate, vegetation-cover, biological activity in the soil and relief. All are important, but the role of relief is critical. Rocks may weather rapidly in a warm tropical climate but, in the absence of relief, the weathering products will blanket the decaying rocks with a thick layer of soil that will protect them from further weathering and erosion. Relief allows the mechanical erosion of the protective soils, which is essential for continuous chemical erosion, and it will be most effective when the soils are devoid of vegetation.

The role of primitive soil biota in accelerating erosion may have become important after 700 Ma. During Phanerozoic weathering, soil biota promoted chemical weather and the formation of pedogenic clay minerals by retaining cations and water in soils, by increasing fluid residence times [71], and most importantly, by producing organic acids that attack silicate minerals [72]. Erosion rates in the presence of appropriate soil biota can be one to two orders of magnitude faster than abiotic erosion [72–75]. Kennedy et al. [24] noted that appropriate biota became available in terrestrial soils by 700 Ma and possible as early as 1000 Ma. They attribute a systematic change through time from feldspar- and quartz-dominated mudstone and siltstone in the Precambrian to smectite- and kaolinite-dominated claystone, and an increase in kaolinite and expandable clays at the expense chlorite and illite in marine mudstone, from ~650 Ma to the present, to increased soil-biota activity. They suggested that this is due to a fundamental change in the dominant weathering mechanism from mechanical weathering in the Precambrian to more efficient biota-assisted chemical weathering after ~650 Ma. If their argument is correct, the period between 650 and at least 390 Ma may have been unique in Earth's history for its extreme levels of continental erosion and sedimentation. Not only was the Transgondwanan Supermountain the largest, or one of the largest, mountain ranges in the history of the planet (the mountains produced by the Grenville orogeny are the other contender), but also they were close to the equator (see Fig. 5) and presumably in a region of high rainfall. Moreover, the continents were devoid of protective plants that might have slowed mechanical weathering, and soil biota had evolved to the point that they could accelerate chemical weathering. Erosion consumes greenhouse $CO_2$, which most likely led to global cooling between 650 and 390 Ma and to higher oxygen solubility in the oceans. Although high O in the Cambrian ocean may have contributed to the Cambrian Explosion it would not have been the trigger for the start of the radiation. If global cooling and increased O levels in the oceans were the key, the great explosion in species would have occurred earlier, during one of the major global glaciations of the Neoproterozoic.

The period between about 900 and 650 Ma involved break-up of the supercontinent Rodinia, with relatively minor continent–continent collisions [76,77]. The main assembly of Gondwana did not commence until closure of the Mozambique Ocean began at 650 Ma, resulting in the initial development of the Transgondwanan Supermountain. Erosion of the supermountain started as soon it began to form, but most of these early sedimentary units were deposited in the closing Mozambique Ocean (Fig. 5a–b). As the ocean closed the sedimentary detritus was caught in the pincer movement of the closing basin, uplifted into the evolving mountains and continually recycled back into the ocean basin until closure was complete. There is no record of the early quartz-rich sedimentary rocks in the Gondwana Super-fan System because they were eroded (recycled) soon after they were deposited. Extensive recycling is important in the present context because it had a homogenising influence on the quartz-rich detritus of the Gondawana Super-fan System and explains why the two dominant peaks (~650–550 and ~1200–900 Ma), which characterise the sedimentary rocks of the super-fan system, can be recognised in quartz-rich successions from as far apart as Africa, India, Antarctica, South America, Australia and New Zealand. The presence of only the 650–550 Ma peak in parts of the Arabian Shield indicate a different source in which the ~1200–900 Ma zircons were possibly less abundant (see Fig. 5c). Sediment preservation during this late Neoproterozoic period was limited to occurrences of locally derived detritus that lack the double peaks and were deposited on stable platforms (e.g., southeastern Australia [40] and Antarctica [49]). However, Sr isotopes provide an unambiguous and continuous record of enhanced erosion during this period. Fig. 1 shows a rapid increase in seawater $^{87}Sr/^{86}Sr$ ratios during the Ediacaran, which is interpreted to be due to the addition of soluble Sr, derived from continental weathering, to the oceans [58,59]. Note that the main increase starts at about 635 Ma, shortly after the Transgondwanan Supermountain began to form.

The build-up of preserved quartz-rich successions of the Gondwana Super-fan System was delayed until ~535–525 Ma and it continued to 390 Ma. The start of sediment preservation in the super-fan system coincides with the final stages of closure of the Mozambique Ocean. From this time, the pincer movement of the closing Mozambique Ocean began to first slow and finally stop, thus removing the mechanism that so effectively recycled the super-fan detritus in the closing Mozambique Ocean. As a consequence, preserved sedimentary units now began to accumulate in the super-fan systems that developed near both ends of the closed ocean (Fig. 5c). By 515 Ma the collision of East and West Gondwana was complete [5] and the Transgondwanan Supermountain was at its maximum extent. We suggest that this was a period of intense erosion, produced by a combination of steep relief over a large area, a complete absence of vegetation, active soil biota on the continents and high level of precipitation associated with the position of the Transgondwanan Supermountain close to the equator (see Fig. 5c). This interval coincided with a sudden rise in the seawater Sr isotope curve that peaked ~515 Ma at the highest value recorded in the geological record, confirming that this was a period of unusually high erosion (Fig. 1). As an aside, we suggest that the Grenville-aged orogenies did not produce a comparable $^{86}Sr/^{87}Sr$ anomaly because erosion rates during this interval were slower, possibly because terrestrial soil biota had not evolved to the point that they could breakdown tektosilicates fast enough to have a significant influence on the $^{86}Sr/^{87}Sr$ of the oceans. High $^{86}Sr/^{87}Sr$ continued throughout the Cambrian and into the Ordovician as the Transgondwanan Supermountain continued to shed detritus into the Gondwana Super-fan System (Fig. 5d).

Variations in carbon isotopes in marine carbonates are used to monitor variations in buried organic carbon, which is thought to control the oxygen content of the atmosphere. Organic C is strongly depleted in $^{13}\delta C$ relative to marine carbonate with a fractionation factor of $28.5 \pm 2.0$ [16]. As a consequence, $^{13}\delta C$ in marine carbonates increases as the amount of buried organic carbon in sedimentary rocks increases. $^{13}\delta C$ marine carbonates increased steadily through the Neoproterozoic, from +1 at 1000 Ma, to a maximum of about +11, but more typically >5, from 800 to 650 Ma [18], followed by a period of steady decline in $^{13}\delta$ between about 650 Ma and 543 Ma. This simple overall trend in $^{13}\delta C$ was punctuated by several short excursions to negative $^{13}\delta C$, typically from −5 to −10‰, which correlate with the Sturtian, Marinoan and Gaskiers glaciations [18]. Each for these anomalies consists of a rapid decline in $^{13}\delta$ followed by a gradual return to positive values. The Neoproterozoic period was followed by an episode of widely oscillating $^{13}\delta$C, especially during the late Early Cambrian period, where at least ten oscillations of up to 6‰ are recorded [2] (Fig. 1).

The maximum $^{13}\delta$C values for Neoproterozoic marine carbonates at ~670 Ma (the Keele Peak [18,78]) is well above the modern value of 0 and above all Tertiary values, which do not exceed +3‰, implying a much higher fraction of buried organic C between 800 and 650 Ma than today or at any time during the Tertiary. Derry et al. [16] suggested that three factors control the amount of buried C: (i) sedimentation rate; (ii) high organic productivity stimulated by high nutrient supply in the form of dissolved P and Fe; and (iii) an anoxic water column to retard the oxidation of buried organic C. The period 900 to 650 Ma is of low seawater $^{86}$Sr/$^{87}$Sr [13] and no major continent–continent collision events [76,77], so the high buried C during this interval could not have been due to a high rate of sedimentation. Derry et al. [16] concluded that the high $^{13}\delta$C values must therefore be due to an anoxic water column between 900 and 650 Ma and that the reduction in $^{13}\delta$C between 650 and 543 Ma was due to an overturn of the formally stagnant water column by the Late Proterozoic glacial events. However, the broad shifts in $^{13}\delta$C though the Neoproterozoic correlate inversely with $^{86}$Sr/$^{87}$Sr, implying that high sedimentation rates can lead to low $^{13}\delta$C. We suggest that $^{13}\delta$C is controlled, not by sedimentation rates, but by sediment isolation rates. As noted above, 900 to 650 Ma was a major period of rifting and break-up on Earth, in which no major continent–continent collisions have been identified. We suggest that between 900 and 650 Ma, while the continental fragments of Rodinia drifted apart, continentally derived detritus accumulated mainly at the rifted margins along which the continents separated. Sediment accumulation may have been slow but the sedimentary units that were deposited were preserved so that they accumulated large amounts of isotopically light organic carbon, which drove upper-ocean C to positive values (see also [2]). From ~650 Ma the large continental fragments of East and West Gondwana began to collide forming the Transgondwanan Supermountain. This was a period of rapid sedimentation, but it was also a period of rapid continental erosion. The sedimentary units on the former stable shelves of the continental fragments, which lay within the collision zone, were uplifted and eroded, and their organic C oxidized. This would have released isotopically negative organic C into the atmosphere and upper-ocean and lowered the $^{13}\delta$C of marine carbonates. As previously noted, the principal source of sedimentation between 650 and 540 Ma was recycling of the quartz-rich sedimentary units of the Gondwana Super-fan System within the closing Mozambique Ocean. Although the marked increase in seawater $^{87}$Sr/$^{86}$Sr during this period shows that it involved rapid sedimentation, and by inference rapid organic-carbon burial, this material was uplifted and eroded as fast as it was deposited so that the recycling process resulted in no net change in the buried organic-carbon budget. The only contribution to the net buried organic-carbon budget came from the previously undisturbed continental shelf sedimentary rocks that were pushed into the orogenic zone. We suggest that the end of the systematic decline in $^{13}\delta$C at 543 Ma marks the point at which the closing Mozambique Ocean ceased to receive a significant contribution of new continental shelf sedimentary units that had not previously been recycled.

The short $^{13}\delta$C excursions associated with glaciations are probably due to marine transgression–regression events [9]. Global glaciation events produce extensive continental ice sheets, which result in a marine regression. At the end of the glaciation, the ice sheets melt and sea levels return to pre-glaciation levels. During regressions, formally shallow sedimentary units on the continental shelf are exposed to erosion and oxidation, and isotopically light carbon is rapidly released to the atmosphere. During transgressions the sedimentary successions in the inner continental shelf are gradually restored and slowly accumulate isotopically light organic carbon. As a consequence, glacial events lead to a rapid decline in $^{13}\delta$C followed by a gradual return to ‘normal’ values. These glacially associated negative excursions in $^{13}\delta$C are superimposed on the steady decline in $^{13}\delta$C between 650 and 543 Ma.

The origin of the second-order oscillations in $^{13}\delta$C during the Cambrian is problematical. Brasier and Lindsay [9] suggest that positive excursions are due to marine transgressions and negative excursions to regressions. However the number of documented regressions–transgressions in this period is small compared with the number of excursions, making this explanation unlikely. Kirschvink and Raub [2] suggest an alternate hypothesis in which the $^{13}\delta$C excursions are attributed to the periodic release of large volumes of methane gas that had previously been trapped in the sedimentary rocks. Their hypothesis proposes that isotopically-light organic carbon accumulated in sedimentary units on the margins of low-latitude fragments of Rodinia during the Late Neoproterozoic. These organic-rich successions were then moved to high latitudes where conditions favoured trapping biogenic methane in layers of gas hydrate. Sedimentation continued until the geothermal gradient pushed these units out of the clathrate stability field and built up reservoirs of high-pressure methane. Finally continental drift returned the sedimentary rocks to low latitudes where they were gradually warmed and subjected to transient stochastic releases of global-warming, isotopically light, greenhouse methane into the atmosphere. Kirschvink and Raub [2] attribute these releases to small seismic events, sediment failure, sediment erosion or eddy change, perhaps induced by an episode of rapid plate-motion during the late Early Cambrian [79]. Our Supermountain hypothesis provides a simple explanation for the Kirschvink and Raub [2] stochastic methane burps. We suggest that they resulted from the periodic release of pockets of hydrocarbons trapped in sedimentary rocks as a consequence of rapid erosion of the Transgondwanan Supermountain. Recent estimates suggest that only 5 to 25% of the global C budget is stored in gas hydrates compared with 50% in fossil fuels such as coal, oil and natural gas [80]. We therefore suggest that the light C released during erosion of the supermountains comes from the oxidation of fossil fuels; a modern analogue is 7 trillion cubic feet of natural gas, currently trapped in the Globe area of the New Guinea Highlands [81], which will eventually be released by erosion if they are not exploited for commercial purposes.

The burial of organic C has important implications for the partial pressure of $O_2$ in the atmosphere. Oxygenic photosynthesis splits the water molecule through reactions of the form

$$CO_2 + H_2O = CH_2O + O_2$$

If the organic C produced by reactions of this type is buried in the sedimentary successions, and therefore effectively removed from the system so that it cannot back-react with $O_2$, the $O_2$ concentration in the atmosphere will increase [82]. The increase in $^{13}\delta C$ between 1000 and 670 Ma, followed by an overall decrease between 670 and 543 Ma is attributed to increased burial of organic C between 1000 and 760 Ma, followed by a decrease to 543 Ma. If buried C is the principle factor controlling the $O_2$ content of the atmosphere, atmospheric $O_2$ increased during the Neoproterozoic and reached a maximum at 670 [18,82,83], after which it declined to 543 Ma. Although the $O_2$ content of the atmosphere may have declined between 670 and 543 Ma it was obviously still sufficient to sustain metazoans. $^{13}\delta C$ for marine carbonates near the Ediacaran–Cambrian boundary was close to zero, which is similar to the modern value [2] and it oscillated around zero throughout the Cambrian. The decline in $^{13}\delta C$ between 670 and 543 Ma, therefore, does not require the $O_2$ level of the atmosphere to fall below that required for metazoans.

There is other evidence for an increase in atmospheric $O_2$ during the Neoproterozoic. Canfield and Teske [15] report radiation of non-photosynthetic marine sulphide-oxidizing bacteria and a marked increase in sulphur-isotope fractionation between 1000 and 640 Ma, which they argue require atmospheric $O_2$ to be at least 5–18% of the present level.

## 7. Implication for the explosion of animal-life on Earth

As noted earlier, the Ediacaran period records the most dynamic biological episode in Earth's history: the sudden appearance of soft-bodied filter-feeding Ediacaran biota from ~575 Ma [1,4]. Complex life requires two critical ingredients: oxygen and nutrients. Brasier and Lindsay [9] suggested that the environmental conditions that triggered this dramatic biological event were strongly influenced by the extremely high and rapidly increasing rates of sediment accumulation and subsidence associated with amalgamation of the supercontinent Gondwana (e.g., [58]). However, we propose here that the source of the enormous flux of continentally derived sediment, which triggered this catastrophic biological event, was not the extensive hinterland margins of Gondwana but the Transgondwanan Supermountain. As we have already stressed, this extensive mountain range was formed during a unique window in Earth's history. Not only were they one of, if not the most extensive mountain chain in the history of the Earth, but they formed in the high-rainfall region close to the equator during a time when the continents where devoid of protective plants and when soil biota may have evolved to the point that they could accelerate chemical weathering. The erosion of earlier mountain belts, such as those associated with the Grenville-age orogenesis, may have been hindered by the absence of suitable soil biota and later mountains were protected from mechanical erosion by vegetation. We suggest that rapid erosion of the Transgondwanan Supermountain resulted in the entry of an unprecedented large flux of dissolved weathering products, including Fe, P, Sr, Ca and bicarbonate ions, into the oceans. The flux of these elements exceeded that recorded during any previous period of Earth's history. This view is supported by the generally rapid increase in $^{87}Sr/^{86}Sr$ during the Ediacaran and Early Cambrian interval, which is not seen during any earlier period, including the ~1200 to 900 Ma Grenville-aged orogenesis [13,84]. We further suggest that this massive build-up of P and Fe in the oceans, starting at ~650 Ma, provided the critical nutrients that led to an unprecedented bloom of primitive life, especially green algal, which in turn, provide abundant food from which more complex live forms were able to evolve. That is, the period between ∼650 and 543 Ma was unique in Earth's history because this was the first time the P and Fe contents of the oceans rose to the level where they could sustain abundant primitive life. More-advanced life forms exploited this opportunity, multiplied rapidly and evolved. This argument is supported by the widespread occurrence of phosphatic sedimentary units [9], together with early skeletal fossils that first appeared at ∼545 Ma [85].

An important element of this argument is that mass flux of P and Fe from erosion of the Transgondwanan Supermountain was sufficient to produce a significant increase in the concentration of these elements in the ocean. The role of P is critical because it is essential for life. The residence time for P in the oceans is short, only $10^5$ years [16]. A build-up of P in the oceans therefore requires a high flux of P into the oceans so that it is supplied at a higher rate than it is removed. In this respect, erosion of the Transgondwanan Supermountain appears to differ from erosion of the mountains produced by the Grenville-aged orogenesis. As noted above, there is no recorded increase in seawater $^{87}Sr/^{86}Sr$ associated with the 1200–900 Ma event, implying that the rate of erosion of mountains associated with this orogenesis was not high enough for the mass flux of Sr into the oceans to exceed the rate of removal. The residence time for Sr in the oceans is $2.5 \times 10^6$ years [86], which is an order of magnitude higher than the residence time for P. If erosion rates where too low to influence oceanic Sr, they would have had even less influence on the concentration of P with its lower residence time. Therefore, we suggest that erosion of mountains associated with the 1200–900 Ma orogenesis did not produce the first radiation of large animals because the erosion rate was too slow to produce a significant build-up of P in the oceans at that time.

The explosive radiation of marine fauna during the Early Cambrian occurred coincident with rapid growth of the Gondwana Super-fan System as the Transgondwanan Supermountain rotated and drifted close to the equator (Fig. 5a–c). The marked increase in seawater $^{87}Sr/^{86}Sr$ at that time and the high levels attained (Fig. 1), show that this was a period of extremely rapid erosion of the supermountain. As argued earlier, erosion of the Transgondwanan Supermountain may have periodically released large amounts of hydrocarbons, including the greenhouse gas methane, into the atmosphere, which would have raised surface temperatures. The Late Paleocene thermal maximum, during which surface waters rose by 4 to 8 °C, and which is associated with a dramatic radiation of mammalian fauna, is interpreted to be due the release of methane stored as, or trapped under, gas clathrate ([2] and references therein). Kirschvink and Raub [2] point out that increases in surface temperature correlate strongly with biodiversity and have argued that releases of methane gas during the Cambrian could have produced a similar increase in the temperature of surface water and be responsible for the Early Cambrian radiation. We agree that this could be a contributing factor.

Rapid erosion of the Transgondawanan Supermountain during the Early Cambrian may also be responsible for the sudden appearance of skeletal marine fauna. High erosion rates must have resulted in a marked increase in the Ca and bicarbonate flux down the rivers that drained the enormous mountain chain and to a concomitant increase in seawater $CaCO_3$ supersaturation. This suggestion is supported by a study by Brennan et al. [87] of halite fluid inclusions, collected from each side of the Ediacaran–Cambrian boundary, which is interpreted to show that seawater Ca increases by a factor of three between 543 and 515 Ma. Furthermore, Riding [88] found that cyanophytes changed from silicified throughout most of the Proterozoic to first weakly calcified in the upper Proterozoic and then to strongly calcified in the Early Cambrian. Because the morphological forms of the calcified and silicified cyanophytes are similar, Riding [88] argued that this change is more likely to be due to a change in seawater chemistry than to evolution of the species. The case becomes stronger when all phyla are considered. The sudden appearance of skeletal marine phyla from ∼545 Ma [85] could be due to evolution of a number of species advancing to a point where they could suddenly precipitate $CaCO_3$ (e.g., [89]), but it is more likely to be due to increasing $CaCO_3$ supersaturation in seawater making it possible for all phyla to precipitate $CaCO_3$ for the first time. A simple evolutionary explanation for the sudden appearance of hard bodies in numerous phyla requires species from all phyla to simultaneously evolve to the point were they could produce skeletons; an unlikely coincidence. On the other hand, the correlation of the appearance of skeletal phyla with the most rapid period of erosion in Earth's history and the occurrence of thin-walled skeletons in uppermost Ediacaran, immediately prior to the start of the Cambrian, provides strong support for the increasing $CaCO_3$ supersaturation hypothesis.

## Acknowledgements

This work was funded by Leviathan Resources and by an Australian Research Council Linkage grant. Gordon Holm and Asaf Raza from The University of Melbourne are thanked for their thin-section preparation and assistance with zircon separation. We thank J. Brocks, J. Chappell, M. Harrowfield, P. Vickers-Rich and I. Williams for their insightful comments and J. Kirschvink and F. Fluteau for their very constructive reviews.

## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2006.07.032.

## References

[1] S.A. Bowring, P. Myrow, E. Landing, J. Ramenzani, J. Grotzinger, Geochronological constraints on terminal Neoproterozoic events and the rise of metazoans, Geophys. Res. Abstr. (EGS, Nice) 5 (2003) 13,219.

[2] J.L. Kirschvink, T.D. Raub, A methane fuse for the Cambrian explosion: true polar wander, C. R. Geosci. 335 (2003) 71–83.

[3] J.L. Kirschvink, R.L. Ripperdan, D.A. Evans, Evidence for a large-scale reorganization of Early Cambrian continental masses by inertial interchange true polar wander, Science 277 (1997) 541–545.

[4] G.M. Narbonne, J.G. Gehling, Life after snowball; the oldest complex Ediacaran fossils, Geology 31 (2003) 27–30.

[5] S.D. Boger, J.M. Miller, Terminal suturing of Gondwana and the onset of the Ross–Delamerian Orogeny: the cause and effect of an Early Cambrian reconfiguration of plate motions, Earth Planet. Sci. Lett. 219 (2004) 35–48.

[6] J. Jacobs, R.J. Thomas, Himalayan-type indenter-escape tectonics model for the southern part of the late Neoproterozoic–early Paleozoic East African–Antarctic orogen, Geology 32 (2004) 721–724.

[7] R.J. Squire, C.J.L. Wilson, Interaction between collisional orogenesis and convergent-margin processes: evolution of the Cambrian proto-Pacific margin of East Gondwana, J. Geol. Soc. Lond. 162 (2005) 749–761.

[8] R.J. Stern, Arc-assembly and continental collision in the Neoproterozoic East African Orogen; implications for the consolidation of Gondwanaland, Annu. Rev. Earth Planet. Sci. 22 (1994) 319–351.

[9] M.D. Brasier, J.F. Lindsay, Did supercontinental amalgamation trigger the "Cambrian explosion"? in: A.Y. Zhuravlev, R. Riding (Eds.), The ecology of Cambrian radiation, Columbia University Press, New York, 2001, pp. 69–89.

[10] V.A. Melezhik, I.M. Gorokhov, A.B. Kuznetsov, A.E. Fallick, Chemostratigraphy of Neoproterozoic carbonates: implications for 'blind dating', Terra Nova 13 (2001) 1–11.

[11] G.A. Shields, J. Veizer, Precambrian marine carbonate isotope database: version 1.1, Geochem. Geophys. Geosyst. 3 (2002) 1031.

[12] J. Veizer, Strontium isotopes in seawater through time, Annu. Rev. Earth Planet. Sci. 17 (1989) 141–167.

[13] M.R. Walter, J.J. Veevers, C.R. Calver, P. Gorjan, A.C. Hill, Dating the 840–544 Ma Neoproterozoic interval by isotopes of strontium, carbon and sulfur in seawater, and some interpretative models, Precambrian Res. 100 (2000) 371–433.

[14] D.E. Canfield, K.S. Habicht, T. Bo, The Archean sulfur cycle and the early history of atmospheric oxygen, Science 288 (2000) 658–661.

[15] D.E. Canfield, A. Teske, Late Proterozoic rise in atmospheric oxygen from phylogenetic and stable isotopic studies, Nature 382 (1996) 127–132.

[16] L.A. Derry, A.J. Kaufman, S.B. Jacobsen, Sedimentary cycling and environmental change in the Late Proterozoic: evidence from stable and radiogenic isotopes, Geochim. Cosmochim. Acta 56 (1992) 1317–1329.

[17] M.A. Hurtgen, M.A. Arthur, G.P. Halverson, Neoproterozoic sulfur isotopes, the evolution of microbial sulfur species, and the burial efficiency of sulfide as sedimentary pyrite, Geology 33 (2005) 41–44.

[18] G.P. Halverson, P.F. Hoffman, D.P. Schrag, A.C. Maloof, A.H.N. Rice, Toward a Neoproterozoic composite carbon-isotope record, Geol. Soc. Amer. Bull. 117 (2005) 1181–1207.

[19] P.F. Hoffman, A.J. Kaufman, G.P. Halverson, D.P. Schrag, A Neoproterozoic snowball earth, Science 281 (1998) 1342–1346.

[20] K.H. Hoffmann, D.J. Condon, S.A. Bowring, J.L. Crowley, U–Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia; constraints on Marinoan glaciation, Geology 32 (2004) 817–820.

[21] K. Grey, M.R. Walter, C.R. Calver, Neoproterozoic biotic diversification; snowball Earth or aftermath of the Acraman impact? Geology 31 (2003) 459–462.

[22] G.E. Williams, M.W. Wallace, The Acraman asteroid impact, South Australia: magnitude and implications for the late Vendian environment, J. Geol. Soc. Lond. 160 (2003) 545–554.

[23] G.E. Williams, History of the Earth's obliquity, Earth-Sci. Rev. 34 (1983) 1–49.

[24] M.J. Kennedy, M. Droser, L.M. Mayer, D. Pevear, D. Mrofka, Late Precambrian oxygenation; inception of the clay mineral factory, Science 311 (2006).

[25] F.A. Corsetti, A.N. Olcott, C. Bakermans, The biotic response to Neoproterozoic snowball Earth, Palaeogeogr. Palaeoclimatol. Palaeoecol. 232 (2006) 114–130.

[26] B. Levrard, J. Laskar, Climate friction and the Earth's obliquity, Geophys. J. Int. 154 (2003) 970–990.

[27] D.M. Williams, J.F. Kasting, L.A. Frakes, Low-latitude glaciations and rapid changes in the Earth's obliquity explained by obliquity–oblateness feedback, Nature 396 (1998) 453–455.

[28] G.E. Williams, History of the Earth's obliquity, Earth-Sci. Rev. 34 (1993) 1–49.

[29] J.G. Meert, A synopsis of events related to the assembly of eastern Gondwana, Tectonophysics 362 (2003) 1–40.

[30] J.J. Veevers, Pan–African is Pan–Gondwanaland: oblique convergence drives rotation during 650–500 Ma assembly, Geology 31 (2003) 501–504.

[31] J.J. Veevers, Gondwanaland from 650–500 Ma assembly through 320 Ma merger in Pangea to 185–110 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating, Earth-Sci. Rev. 68 (2004) 1–132.

[32] D. Avigad, K. Kolodner, M. McWilliams, H.M. Persing, T. Weissbrod, Origin of northern Gondwana Cambrian sandstone revealed by detrital zircon SHRIMP dating, Geology 31 (2003) 227–230.

[33] D. Avigad, A. Sandler, K. Kolodner, R.J. Stern, M. McWilliams, N. Miller, M. Beyth, Mass-production of Cambro–Ordovician quartz-rich sandstone as a consequence of chemical weathering of Pan–African terranes: environmental implications, Earth Planet. Sci. Lett. 240 (2005) 818–826.

[34] K. Burke, J.U. Kraus, Deposition of immense Cambro–Ordovician sandstone bodies, now exposed mainly in N. Africa and Arabia, during the aftermath of the final assembly of

Gondwana, Summit 2000 32, Geological Society of America, Reno, Nevada, 2000, p. 249.

[35] P. Courjault-Rade, F. Debrenne, A. Gandin, Palaeogeographic and geodynamic evolution of the Gondwana continental margins during the Cambrian, Terra Nova 4 (1992) 657–667.

[36] C.L. Fergusson, P.J. Coney, Implications of a Bengal Fan-type deposit in the Paleozoic Lachlan Fold Belt of southeastern Australia, Geology 20 (1992) 1047–1049.

[37] J.W. Goodge, P. Myrow, D. Phillips, C.M. Fanning, I.S. Williams, Siliciclastic record of rapid denudation in response to convergent-margin orogenesis, Ross Orogen, Antarctica, Spec. Pap. — Geol. Soc. Am. 378 (2004) 105–126.

[38] P.W. Haines, T. Flöttmann, Delamerian Orogeny and potential foreland sedimentation; a review of age and stratigraphic constraints, Aust. J. Earth Sci. 45 (1998) 559–570.

[39] P.J. Coney, A. Edwards, R. Hine, F. Morrison, D. Windrim, The regional tectonics of the Tasman Orogenic System, eastern Australia, J. Struct. Geol. 12 (1990) 519–543.

[40] T.R. Ireland, T. Flöttmann, C.M. Fanning, G.M. Gibson, W.V. Priess, Development of the Early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian Orogen, Geology 26 (1998) 243–246.

[41] J.W. Goodge, P. Myrow, I.S. Williams, S.A. Bowring, Age and provenance of the Beardmore Group, Antarctica; constraints on Rodinia supercontinent breakup, J. Geol. 110 (2002) 393–406.

[42] R. Jongens, J.D. Bradshaw, A.P. Fowler, The Balloon Melange, Northwest Nelson; origin, structure, and emplacement, N. Z. J. Geol. Geophys. 46 (2003) 437–448.

[43] I.S. Williams, Response of detrital zircon and monazite, and their U–Pb isotopic systems, to regional metamorphism and host-rock partial melting, Cooma Complex, southeastern Australia, Aust. J. Earth Sci. 48 (2001) 557–580.

[44] I.S. Williams, J.W. Goodge, P. Myrow, K. Burke, J. Kraus, Large scale sediment dispersal associated with the late Neoproterozoic assembly of Gondwana, Abstr. — Geol. Soc. Austr. 67 (2002) 238.

[45] A.H.M. VandenBerg, C.E. Willman, S. Maher, B.A. Simons, R.A. Cayley, D.H. Taylor, V.J. Morand, D.H. Moore, A. Radojkovic, The Tasman Fold Belt System in Victoria, Geological Survey of Victoria Special Publication, 2000, 462 pp.

[46] S.E. Bryan, C.M. Allen, R.J. Holcombe, C.R. Fielding, U–Pb zircon geochronology of Late Devonian to Early Carboniferous extension-related silicic volcanism in the northern New England Fold Belt, Aust. J. Earth Sci. 51 (2004) 645–664.

[47] W. Compston, I.S. Williams, C.E. Meyer, U–Pb geochronology of zircons from lunar breccia 73217 using a sensitive high mass-resolution ion microprobe, JGR, J. Geophys. Res., B 89 (1984) 525–534 (Suppl.).

[48] K.N. Sircombe, AGEDISPLAY: an EXCEL workbook to evaluate and display univariate geochronological data using binned frequency histograms and probability density distributions, Comput. Geosci. 30 (2004) 21–31.

[49] J.W. Goodge, I.S. Williams, P. Myrow, Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: detrital record of rift-, passive-, and active-margin sedimentation, Geol. Soc. Amer. Bull. 116 (2004) 1253–1279.

[50] R. Armstrong, M.J. de Wit, D. Reid, D. York, R. Zartman, Cape Town's Table Mountain reveals rapid Pan–African uplift of its basement rocks, J. Afr. Earth Sci. 27 (1998) 10–11.

[51] P.M. Myrow, N.C. Hughes, T.S. Paulsen, I.S. Williams, S.K. Parcha, K.R. Thompson, S.A. Bowring, S.C. Peng, A.D. Ahluwalia, Integrated tectonostratigraphic analysis of the Himalaya and implications for its tectonic reconstruction, Earth Planet. Sci. Lett. 212 (2003) 433–441.

[52] R.J. Pankhurst, C.W. Rapela, C.M. Fanning, M. Márquez, Gondwanide continental collision and the origin of Patagonia, Earth-Sci. Rev. 76 (2006) 235–257.

[53] P.G. DeCelles, G.E. Gehrels, J. Quade, B. LaReau, M. Spurlin, Tectonic implications of U–Pb zircon ages of the Himalayan orogenic belt in Nepal, Science 288 (2000) 497–499.

[54] R.F. Berry, G.A. Jenner, S. Meffre, M.N. Tubrett, A North American provenance for Neoproterozoic to Cambrian sandstones in Tasmania? Earth Planet. Sci. Lett. 192 (2001) 207–222.

[55] M.G. Laird, J.D. Bradshaw, A. Wodzicki, Stratigraphy of the upper Precambrian and lower Paleozoic Bowers Supergroup, Northern Victoria Land, Antarctica, Int. Union Geol. Sci., Ser. B 4 (1982) 535–542.

[56] A.J. Rowell, D.A. Gonzales, L.W. McKenna, K.R. Evans, E. Stump, W.R. Van Schmus, Lower Paleozoic rocks in the Queen Maud Mountains, revised ages and significance, Int. Symp. Antarct. Earth Sci. 7 (1997) 201–207.

[57] C.J. Nicholas, The Sr isotopic evolution of the oceans during the 'Cambrain Explosion', J. Geol. Soc. Lond. 153 (1996) 243–254.

[58] L.A. Derry, M.D. Brasier, R.M. Corfield, A.Y. Rozanov, A.Y. Zhuraviev, Sr and C isotopes in lower Cambrian carbonates from the Siberian craton: a plaeoenvironmental record during the 'Cambrian explosion', Earth Planet. Sci. Lett. 128 (1994) 671–681.

[59] A.J. Kaufman, S.B. Jacobsen, A.H. Knoll, The Vendian record of Sr and C isotopic variations in seawater: implications for tectonics and paleoclimate, Earth Planet. Sci. Lett. 84 (1993) 27–41.

[60] M.G. Abdelsalam, E.-S.M. Abdel-Rahman, E.-F.M. El-Faki, B. Al-Hur, F.-R.M. El-Bashier, R.J. Stern, A.K. Thurmond, Neoproterozoic deformation in the northeastern part of the Saharan Metacraton, northern Sudan, Precambrian Res. 123 (2003) 203–221.

[61] R.M. Shackleton, The final collision zone between East and West Gondwana: where is it? J. Afr. Earth Sci. 23 (1996) 271–287.

[62] S. Muhongo, J.-L. Lenoir, Pan–African granulite-facies metamorphism in the Mozambique belt of Tanzania: U–Pb zircon geochronology, J. Geol. Soc. Lond. 151 (1994) 343–347.

[63] J.R. Curray, Possible greenschist metamorphism at the base of a 22-km sedimentary section, Bay of Bengal, Geology 19 (1991) 1097–1100.

[64] S.D. Boger, C.J.L. Wilson, C.M. Fanning, Early Palaeozoic tectonism within the East Antarctic craton: the final suture between east and west Gondwana? Geology 29 (2001) 463–466.

[65] C.J. Carson, C.M. Fanning, C.J.L. Wilson, Timing of the Progress Granite, Larsemann Hills: evidence for Early Palaeozoic orogenesis within the east Antarctic Shield and implications for Gondwana assembly, Aust. J. Earth Sci. 43 (1996) 539–553.

[66] I.C.W. Fitzsimons, A review of tectonic events in the East Antarctic Shield and implications for Gondwana and earlier supercontinents, J. Afr. Earth Sci. 31 (2000) 3–23.

[67] A. Yin, S. Nie, An indentation model for the North and South China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia, Tectonics 12 (1993) 801–813.

[68] P.W. Haines, S.P. Turner, S.P. Kelley, J.-A. Wartho, S.C. Sherlock, 40Ar–39Ar dating of detrital muscovite in provenance investigations: a case study from the Adelaide Rift Complex, South Australia, Earth Planet. Sci. Lett. 227 (2004) 297–311.

[69] A.J. Crawford, R.F. Berry, Tectonic implications of Late Proterozoic–Early Palaeozoic igneous rock associations in Western Australia, Tectonophysics 214 (1992) 37–56.

[70] C. Münker, A.J. Crawford, Cambrian arc evolution along the SE Gondwana active margin; a synthesis from Tasmania–New Zealand–Australia–Antarctica correlations, Tectonics 19 (2000) 415–432.
[71] H. Chamley, Clay Sedimentology, Springer, Berlin, 1989 623 pp.
[72] S.A. Welch, W.J. Ullman, The effect of microbial glucose metabolism on bytownite feldspar dissolution rates between 5° and 35 °C, Geochim. Cosmochim. Acta 63 (1999) 3247–3259.
[73] W.W. Barker, J.F. Banfield, Biologically versus inorganically mediated weathering reactions: relationships between minerals and extracellular microbial polymers in lithobiontic communities, Chem. Geol. 132 (1996) 55–69.
[74] P.V. Brady, R.I. Dorn, A.J. Brazel, J. Clark, R.B. Moore, T. Glidewell, Direct measurement of the combined effects of lichen, rainfall, and temperature on silicate waethering, Geochim. Cosmochim. Acta 63 (1999) 3293–3300.
[75] S.A. Welch, W.J. Ullman, The effect of organic acids on plagioclase dissolution rates stoichiometry, Geochim. Cosmochim. Acta 57 (1993) 2725–2736.
[76] I.W.D. Dalziel, Pacific margin of Laurentia and east Antarctica–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent, Geology 21 (1991) 598–601.
[77] P.F. Hoffman, Did the breakout of Laurentia turn Gondwanaland inside–out? Science 252 (1991) 1409–1412.
[78] A.J. Kaufman, A.H. Knoll, G.M. Narbonne, Isotopes, ice ages, and terminal Proterozoic earth history, Proc. Natl. Acad. Sci. U. S. A. 94 (1997) 6600–6605.
[79] D.A.D. Evans, True polar wander and supercontinents, Tectonophysics 362 (2003) 303–320.
[80] A.V. Milkov, Global estimates of hydrate-bound gas in marine sediments: how much is really out there? Earth-Sci. Rev. 66 (2004) 183–197.
[81] Oil Search Limited, Annual Report, 2005, p. 96.
[82] D.J. Des Marais, H. Strauss, R.E. Summons, J.M. Haynes, Carbon isotope evidence for stepwise oxidation of the Proterozoic environment, Nature 359 (1992) 605–609.
[83] A.H. Knoll, J.M. Hayes, A.J. Kaufman, K. Swett, I.B. Lambert, Secular variations in carbon isotopes ratios from upper Proterozoic successions of Svalbard and East Greenland, Nature 321 (1986) 832–838.
[84] G. Shields, J. Veizer, Precambrian marine carbonate isotope database: version 1.1, Geochem. Geophys. Geosyst. 3 (6) (2002), doi:10.1029/2001GC000266.
[85] M.W. Martin, D.V. Grazhdankin, S.A. Bowring, D.A.D. Evans, M.A. Fedonkin, J.L. Kirschvink, Age of Neoproterozic bilaterian body and trace fossils, White Sea, Russia: implications for metazoan evolution, Science 288 (2000) 841–845.
[86] D.A. Hodell, G.A. Mead, P.A. Mueller, Variation in the strontium isotopic composition of seawater (8 Ma to present): implications for chemical weathering rates and dissolved fluxes to the oceans, Chem. Geol. 80 (1990) 291–307.
[87] S.T. Brennan, T.K. Lowenstein, J. Horita, Seawater chemistry and the advent of biocalcification, Geology 32 (2004) 473–476.
[88] R. Riding, Cyanophyte calcification and changes in ocean chemistry, Nature 299 (1982) 814–815.
[89] K.J. Peterson, M.A. McPeek, D.A.D. Evans, Tempo and mode of early animal evolution: inferences from rocks, Hox, and molecular clocks, Paleobiology 31 (2005) 36–55.
[90] S. Zhang, G. Jiang, J. Zhang, B. Song, M.J. Kennedy, N. Christie-Blick, U–Pb sensitive high-resolution ion microprobe ages from the Doushantuo Formation in south China: constraints on late Neoproterozoic glaciations, Geology 33 (2005) 473–476.