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Introduction

Snowball Earth to Cambrian explosion

Throughout the whole history of Earth and evolution of life, the Neoproterozoic has a unique position since the life forms in the foregoing four billion years were basically small bacteria. Although the Earth is designated as a habitable planet, it must have been a very boring planet for a long time. The end Proterozoic was a turning point for the evolution of life because it was at this time that large multi-cellular forms appeared and all the body plans of animals, including those for our ancestors of vertebrates, were created. Immediately prior to this period, the Earth was in a frozen state termed the "Snowball Earth". There is considerable debate over the existence of the Snowball Earth and the mechanisms leading to the switch-on and switch-off of the Snowball state converting a dead Earth to a Spring Earth. There is also considerable interest surrounding the origin and diversification of modern life. In this special issue of *Gondwana Research*, we focus on the relationship between Snowball Earth and Cambrian explosion and assemble a set of topically important papers that address the dynamic changes which occurred during late Neoproterozoic, coinciding with the assembly of the Gondwana supercontinent.

This special issue begins with a Focus paper by Meert and Lieberman (2008) on the "Neoproterozoic assembly of Gondwana and its relationship to the Ediacaran–Cambrian radiation". The authors trace the history of the final assembly of the Gondwana supercontinent in the late Proterozoic which provides a tectonic backdrop for the myriad biological, climatological, tectonic and geochemical changes leading to the Cambrian radiation. An analysis of key evolutionary events during this time period indicates that these were likely driven by internal (biological) changes, but radiation was enhanced and ecosystems became more complex because of the geochemical, ecological and tectonic changes occurring during Ediacaran–Cambrian periods.

The section on research papers starts with an overview on the "Models of Snowball Earth and Cambrian explosion" by Maruyama and Santosh (2008). The authors summarise the existing popular models on the cause and cessation of Snowball Earth. They also introduce a new concept based on Earth's magnetic intensity and propose that the 'switch-on' and 'switch-off' of the Earth's strong dynamo can lead to the onset and disappearance of the Snowball Earth. The authors postulate that cosmic radiation exerted a significant control on the mutation and therefore the Neoproterozoic Earth history illustrates the possible link from Galaxy to the genome level.

The next paper by Stern (2008) deals with "Neoproterozoic crustal growth: the solid Earth system during a critical episode of Earth history". Crustal growth and reworking occurred during the Neoproterozoic within the context of a supercontinent cycle, from the break-up of Rodinia beginning at ca. 830 Ma to the formation of a new supercontinent Greater Gondwana or Pannotia, at ca. 600 Ma. Neoproterozoic crust formation and deformation was heterogeneous in space and time. In contrast, the solid Earth system was relatively quiescent during the Tonian period (1000–850 Ma). The vigour of Cryogenian and Ediacaran tectonic and magmatic processes and the similar timing of these events and development of Neoproterozoic glaciations and metazoa suggest that climate change and perhaps increasing biological complexity was strongly affected by the solid Earth system.

Rino et al. (2008) present extensive geochronological data on zircons from major river mouths of the world in their paper on the "Grenvillian and Pan-African orogens: World's largest orogenies through geologic time", and their implications on the origin of superplume. Their results show that the Neoproterozoic was the most active period of crust formation in the Earth, implying that extensive subduction, and hence active plate tectonics, might have operated through these periods. The authors also evaluate the role of supercontinents in the mechanism of generation of superplumes. Slab-graveyard formed by the Pan-African subduction can be imaged through P-wave tomography. The tectonic history of solid Earth in the Phanerozoic seems to be controlled by the slab-graveyards formed by the Grenvillian orogeny ca. 1.0 Ga.

Van Loon (2008a) addresses the question whether the Snowball Earth could have left thick glaciomarine deposits. The most convincing evidence for the Neoproterozoic glaciation consists of diamicts with some glacial striae and of other glacial signatures. Nevertheless, diamicts of exceptional thickness were formed in a marine environment. This cannot be explained satisfactorily, as icebergs cannot have floated in an entirely frozen ocean. The author suggests that at least a considerable part of the extremely thick Neoproterozoic 'glaciomarine' deposits represent syntectonic mass-flow deposits rather than glacial deposits.

Santosh and Omori (2008) in their paper "CO_2 windows from mantle to atmosphere: models on ultrahigh-temperature metamorphism and speculations on the link with melting of snowball Earth" attempt a correlation of the melting phase of major snowball Earth events in the planet with the processes associated with extreme crustal metamorphism and formation of ultrahigh-temperature (UHT) granulite facies rocks. They recognize a direct involvement of CO_2-rich fluids in generating

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UHT assemblages and speculate a link among CO_2 liberation from the carbonated tectosphere, UHT metamorphism and major earth processes. The abundant CO_2 liberated by subsolidus decarbonation along consuming plate boundaries was probably one of the factors that contributed to the greenhouse effect thereby triggering the deglaciation of Snowball Earth. They propose that UHT rocks might represent windows for the transfer of CO_2 from the mantle into the mid crust and ultimately to the atmosphere.

In a sister contribution, Omori and Santosh (2008) present theoretical models and thermodynamic computations on "Metamorphic decarbonation in the Neoproterozoic and its environmental implication". Their computations show that the extra flux of CO_2 added to the atmosphere through a Himalayan scale UHT metamorphism would raise the steady state temperature by 4 °C from 15 °C. Their estimate of the maximum degassing rate during UHT metamorphism suggests that the duration of the Marinoan Snowball Earth was probably shorter, and the recovery from an ice-covered Earth to ocean-covered Earth was faster than previous estimates.

Kawai et al. (2008) report the occurrence of ice-drafted dropstones in their paper on "Neoproterozoic glaciation in the mid-oceanic realm: an example from hemi-pelagic mudstones on Llanddwyn Island, Anglesey, UK". Dropstones of sandstone, chert, and basalt occur as matrix-supported exotic clasts in a 1 m-thick, hemi-pelagic mafic mudstone. These dropstones, reported for the first time in this study, occur specifically in hemi-pelagic mafic mudstone that is located at the structural top of ocean plate stratigraphy that records a ridge-trench transition; they are supplementary to dropstones associated with extensive tillites reported in shallow marine sequences of continental shelf facies and in back-arc basins.

Utsunomiya and co-authors (2008) re-investigate the mid-Cretaceous pulse in the circum-Pacific orogen in their paper, "Preserved paleo-oceanic plateaus in accretionary complexes: Implications for the contributions of the Pacific superplume to global environmental change". The synchronous occurrence of paleo-oceanic plateaus in accretionary complexes indicates that Pacific superplume pulse activities roughly coincided at the Permo-Triassic boundary and the Vendian–Cambrian boundary interval. The authors believe that the CO_2 expelled by the Pacific superplume probably contributed to environmental catastrophes. The scale of the Pacific superplume activity roughly corresponds to the scale of drastic environmental change in the Vendian–Cambrian boundary.

Ohno et al. (2008) in their paper, "Determination of $^{88}Sr/^{86}Sr$ mass-dependent isotopic fractionation and radiogenic isotope variation of $^{87}Sr/^{86}Sr$ in the Neoproterozoic Doushantuo Formation" present isotopic data that suggest an extreme greenhouse condition after the Marinoan glaciation. High atmospheric CO_2 content caused sudden precipitation of cap carbonate from the surface seawater with high $^{87}Sr/^{86}Sr$ and lighter $\delta^{88}Sr$ ratios. Subsequently, the mixing of the underlying seawater, with unradiogenic Sr isotope compositions and normal $\delta^{88}Sr$ ratios, probably caused gradual decrease of the $^{87}Sr/^{86}Sr$ ratios of the seawater and deposition of carbonate with normal $\delta^{88}Sr$ ratios. Through a combination of $^{87}Sr/^{86}Sr$ and $\delta^{88}Sr$ isotope systematics, the study provides new insights on the surface evolution after the Snowball Earth.

In the following contribution on "Sr isotope excursion across the Precambrian-Cambrian boundary in the Three Gorges area, South China", Sawaki et al. (2008a) present chemostratigraphy of $^{87}Sr/^{86}Sr$ ratios from drilled core samples which display a smooth curve and a large positive anomaly just below the PC/C boundary between the upper part of Baimatuo Member of the Dengying Formation and the lower part of the Yanjiahe Formation. The combination of $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ data indicates that the $^{87}Sr/^{86}Sr$ excursions preceded the $\delta^{13}C$ negative excursion, and suggests that global regression or formation of the Gondwana supercontinent, possibly together with a high atmospheric pCO_2, caused biological depression.

Sawaki et al. (2008b) in their next paper on "Internal structures and U–Pb ages of zircons from a tuff layer in the Meishucunian Formation, Yunnan Province, South China" present results from cathodoluminescence (CL) imaging and in-situ U–Pb dating with LA-ICP-MS and nano-SIMS. U–Pb dating shows a distinct unimodal age population dependent on the structure:531 ± 17 Ma for the oscillatory rims and 515 Ma for the dull structures. The U–Pb nano-SIMS age of 536.5 ± 2.5 Ma is considered to record the depositional age of the tuff. The results are used to precisely identify the PC/C boundary.

Komiya et al. (2008a) in their contribution on "Evolution of the composition of seawater through geologic time, and its influence on the evolution of life" report results on in-situ analyses of major, trace, and rare earth elements of carbonate minerals to estimate the redox condition of seawater through time. The results show low oxygen content of seawater after the Snowball Earth until the late Ediacaran, an increase in the late Ediacaran, and a significant decrease around the Precambrian–Cambrian and Nemakit/Daldynian–Tommotian boundaries. The authors attribute these variations to global regression and dissolution of methane hydrates.

In his paper "The nature of *Mawsonites* (Ediacara fauna)" Van Loon (2008b), addresses the debate on the origin of some representatives of the Ediacara fauna. He concludes that the sedimentary genesis of *Mawsonites* is not tenable, as several physical processes should have been involved. He concludes that *Mawsonites* must be considered as a fossil, either an imprint or a true fossil.

The "Occurrence of phosphatic microfossils in an Ediacaran–Cambrian mid-oceanic paleo-atoll limestone of southern Siberia" is reported by Uchio et al. (2008) where they present results from SEM and EMPA analyses and confirm a primary phosphatic composition of the shells. Because phosphatic microfossils are generally scarce in the Ediacaran but abundant from the Lower Cambrian, in particular within pre-trilobitic SSF assemblages, the phosphatic fossil-bearing limestone in the Kurai area is considered to belong to the Lower Cambrian. The present find proves that mid-oceanic paleo-seamounts as well as continental shelf domains had already been inhabited by diverse metazoans in the Ediacaran–Cambrian transitional interval.

Ishikawa et al. (2008) in their paper, "Carbon isotope chemostratigraphy of a Precambrian/Cambrian boundary section in the Three Gorge area, South China: Prominent global-scale isotope excursions just before the Cambrian Explosion" report high-resolution δ^{13}C chemostratigraphy of a drill core sample and identify two positive and two negative isotope excursions. The patterns of the δ^{13}C shift are irrespective of lithotype, suggesting a primary origin of the record. The authors conclude that the general feature of the δ^{13}C profile best represents the global change in seawater chemistry and correlate their results with the cause of the global-scale sea-level fall at the base of the Tommotian stage. They identify a synchronism between the environmental changes and rapid diversification of skeletal metazoa.

Komiya et al. (2008b) in their contribution on "Ca isotopic compositions of dolomite, phosphorite and the oldest animal embryo fossils from the Neoproterozoic in Weng'an, South China" report Ca isotopic ratios (^{44}Ca/^{42}Ca and ^{43}Ca/^{42}Ca) for phosphorite, dolostone and phosphatic animal embryo fossils using a multiple collector, inductively coupled plasma-mass spectrometer (MC-ICP-MS). The results demonstrate that the fractionation between phosphorite/dolostone and seawater was very small and suggest that at the emergence of the Weng'an biota, seawater was deficient in Ca probably due to mass deposition of phosphorite/dolostone and to the beginning of Ca-biomineralization.

In the next paper, Shu (2008) provides a synthesis on "Cambrian explosion: Birth of tree of animals". The Cambrian Explosion consists of three major episodes and this unique Big Bang of life has been recognized as having given birth to the entire morphological Tree Of Animals (TOA, or metazoans). Fossil evidence suggests that the three major episodes of the Cambrian Explosion are responsible for the earliest radiations of the three subkingdoms of animals respectively. Among the four most significant milestones of morphological origins and radiations in animal history, the first one (i.e. appearance of metazoans) took place in the Ediacaran Period or earlier times, and the other three can be seen in the windows available from the Chengjiang and the Meishucunian fossil assemblages. The author summarises the various new discoveries and advances in understanding the early evolution of life.

Z. Zhang et al. (2008) in their paper, "Early Cambrian radiation of brachiopods: A perspective from South China" summarises the history of benthic suspension-feeding marine invertebrates which first appeared in the Lower Cambrian. The authors synthesise data from the Yangtze Platform (South China) where well-exposed Lower Cambrian stratigraphic succession represents shallow to deeper water environments. The fossil assemblage from this region bears witness to the first major phase of evolutionary radiation of brachiopods during the 'Cambrian explosion' interval of metazoans. The authors address the possibility that a large part of this radiation occurred within, or only just before early Cambrian time.

X. Zhang et al. (2008) in their contribution, "Cambrian Burgess Shale-type Lagerstätten in South China: Distribution and significance" demonstrate that the Burgess Shale-type Lagerstätten in South China are not evenly spaced through the Cambrian and appear to be concentrated in the Lower Cambrian, particularly in the Canglangpuian and Qiongzhusian stages, much reduced in number from the uppermost Lower Cambrian. Their study shows that both siliciclastic platform facies and slope basin facies (shale basin) could preserve soft-bodied fossils. The Cambrian Burgess Shale-type Lagerstätten in South China provide examples for exceptionally preserved biota in a chronological succession an are important in understanding the Cambrian explosion events.

Li et al. (2008) report "Vase-shaped microfossils from the Ediacaran Weng'an biota, Guizhou, South China" which could probably represent primitive sea sponges. The Vase-shaped microfossils (VSMs) expand our knowledge of the Neoproterozoic protozoans in the Weng'an biota. Microscopic observations indicate that the VSMs from both the Weng'an biota and the Kuanchuanpu Formation are preserved in either single-layered or multi-layered walls, and composed of calcium phosphate in chemical composition. The discovery of the VSMs from the Doushantuo phosphorite is an important contribution to the Weng'an biota, and provide clues on the early evolution and diversification of protozoans during Precambrian–Cambrian interval.

In their paper, "A preliminary note on the dispersal of the Cambrian Burgess Shale-type faunas", Han et al. (2008) list the similar elements of faunas shared by the Early Cambrian Chengjiang fauna and the Middle Cambrian Burgess Shale fauna in arriving at a better understanding of the palaeogeographic relationship between the South China Block and Laurentia. The authors discuss the geographic and biological contributions to the cosmopolitan geographic distribution of the Burgess Shale-type faunas that the pelagic larvae, which probably acquired their first bloom in the Cambrian, might have promoted the dispersal.

The final paper in this special issue is by Liu et al. (2008) on "Origin, diversification, and relationships of Cambrian lobopods". This extinct group was regarded as closely related to modern onychophorans and tardigrades, but the similarities are based on the few species of Cambrian lobopods and often on a fairly general level. Based on the discovery of new creatures and based on new observations on fossil lobopods, the authors consider that Cambrian lobopods reveal a close relationship with arthropods.

The 23 papers presented in this special issue focus on a range of themes which collectively address one of the most critical periods in the history of Earth, broadly coinciding with the birth of the Gondwana supercontinent. We thank all the authors for their valuable contributions to this special issue. We also express our sincere thanks to all the referees who spared their valuable time and efforts to provide knowledgeable reviews. We are grateful to *Gondwana Research* for undertaking the publication of this special issue. The Guest Editors hope that the papers presented in this special issue would further enthuse scientists in solving some of the key issues associated with Solid Earth processes and their relation to surface environment as well as life evolution.

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