
Earth and Life

International Year of Planet Earth

Series Editors:

Eduardo F.J. de Mulder
Executive Director International Secretariat
International Year of Planet Earth

Edward Derbyshire
Goodwill Ambassador
International Year of Planet Earth

The book series is dedicated to the United Nations International Year of Planet Earth. The aim of the Year is to raise worldwide public and political awareness of the vast (but often under-used) potential of Earth sciences for improving the quality of life and safeguarding the planet. Geoscientific knowledge can save lives and protect property if threatened by natural disasters. Such knowledge is also needed to sustainably satisfy the growing need for Earth's resources by more people. Earth scientists are ready to contribute to a safer, healthier and more prosperous society. IYPE aims to develop a new generation of such experts to find new resources and to develop land more sustainably.

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John A. Talent
Editor

Earth and Life

Global Biodiversity, Extinction
Intervals and Biogeographic
Perturbations Through Time



Editor

Em. Prof. John A. Talent
Earth and Planetary Sciences
Macquarie University 2109
Australia
jatalent32@gmail.com

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Foreword

The International Year of Planet Earth (IYPE) was established as a means of raising worldwide public and political awareness of the vast, though frequently under-used, potential the earth sciences possess for improving the quality of life of the peoples of the world and safeguarding Earth's rich and diverse environments.

The International Year project was jointly initiated in 2000 by the International Union of Geological Sciences (IUGS) and the Earth Science Division of the United Nations Educational, Scientific and Cultural Organisation (UNESCO). IUGS, which is a non-governmental organization, and UNESCO, an inter-governmental organization, already shared a long record of productive cooperation in the natural sciences and their application to societal problems, including the International Geoscience Programme (IGCP) now in its fourth decade.

With its main goals of raising public awareness of and enhancing research in the Earth sciences on a global scale in both the developed and less-developed countries of the world, two operational programmes were demanded. In 2002 and 2003, the series editors together with Dr. Ted Nield and Dr. Henk Schalke (all four being core members of the Management Team at that time) drew up outlines of a science and an outreach programme. In 2005, following the UN proclamation of 2008 as the United Nations International Year of Planet Earth, the "year" grew into a triennium (2007–2009).

The outreach programme, targeting all levels of human society from decision makers to the general public, achieved considerable success in the hands of member states representing over 80% of the global population. The science programme concentrated on bringing together like-minded scientists from around the world to advance collaborative science in a number of areas of global concern. A strong emphasis on enhancing the role of the Earth sciences in building a healthier, safer and wealthier society was adopted – as declared in the Year's logo strap-line "Earth Sciences *for* Society".

The organizational approach adopted by the science programme involved recognition of 10 global themes that embrace a broad range of problems of widespread national and international concern, as follows:

- Human health: this theme involves improving understanding of the processes by which geological materials affect human health as a means identifying and reducing a range of pathological effects.
- Climate: particularly emphasizes improved detail and understanding of the non-human factor in climate change.
- Groundwater: considers the occurrence, quantity and quality of this vital resource for all living things against a background that includes potential political tension between competing neighbour nations.

- Ocean: aims to improve understanding of the processes and environment of the ocean floors with relevance to the history of planet Earth and the potential for improved understanding of life and resources.
- Soils: this thin “skin” on Earth’s surface is the vital source of nutrients that sustain life on the world’s landmasses, but this living skin is vulnerable to degradation if not used wisely. This theme emphasizes greater use of soil science information in the selection, use and ensuring sustainability of agricultural soils so as to enhance production and diminish soil loss.
- Deep Earth: in view of the fundamental importance of deep the Earth in supplying basic needs, including mitigating the impact of certain natural hazards and controlling environmental degradation, this theme concentrates on developing scientific models that assist in the reconstruction of past processes and the forecasting of future processes that take place in the solid Earth.
- Megacities: this theme is concerned with means of building safer structures and expanding urban areas, including utilization of subsurface space.
- Geohazards: aims to reduce the risks posed to human communities by both natural and human-induced hazards using current knowledge and new information derived from research.
- Resources: involves advancing our knowledge of Earth’s natural resources and their sustainable extraction.
- Earth and Life: it is over 2½ billion years since the first effects of life began to affect Earth’s atmosphere, oceans and landmasses. Earth’s biological “cloak”, known as the biosphere, makes our planet unique but it needs to be better known and protected. This theme aims to advance understanding of the dynamic processes of the biosphere and to use that understanding to help keep this global life-support system in good health for the benefit of all living things.

The first task of the leading Earth scientists appointed as theme leaders was the production of a set of theme brochures. Some 3500 of these were published, initially in English only but later translated into Portuguese, Chinese, Hungarian, Vietnamese, Italian, Spanish, Turkish, Lithuanian, Polish, Arabic, Japanese and Greek. Most of these were published in hard copy and all are listed on the IYPE web site.

It is fitting that, as the International Year’s triennium terminates at the end of 2009, the more than 100 scientists who participated in the 10 science themes should bring together the results of their wide ranging international deliberations in a series of state-of-the-art volumes that will stand as a legacy of the International Year of Planet Earth. The book series was a direct result of interaction between the International Year and the Springer Verlag Company, a partnership which was formalized in 2008 during the acme of the triennium.

This IYPE-Springer book series contains the latest thinking on the chosen themes by a large number of earth science professionals from around the world. The books are written at the advanced level demanded by a potential readership consisting of Earth science professionals and students. Thus, the series is a legacy of the science programme, but it is also a counterweight to the earth science information in several media formats already delivered by the numerous national committees of the International Year in their pursuit of worldwide popularization under the outreach programme.

The discerning reader will recognize that the books in this series provide not only a comprehensive account of the individual themes but also share much common ground that makes the series greater than the sum of the individual volumes. It is to be hoped

that the scientific perspective thus provided will enhance the reader's appreciation of the nature and scale of earth science as well as the guidance it can offer to governments, decision makers and others seeking solutions to national and global problems, thereby improving everyday life for present and future residents of planet Earth.



Eduardo F.J. de Mulder
Executive Director International Secretariat
International Year of Planet Earth



Edward Derbyshire
Goodwill Ambassador
International Year of Planet Earth

Series Preface

This book series is one of the many important results of the International Year of Planet Earth (IYPE), a joint initiative of UNESCO and the International Union of Geological Sciences (IUGS), launched with the aim of ensuring greater and more effective use by society of the knowledge and skills provided by the earth sciences.

It was originally intended that the IYPE would run from the beginning of 2007 until the end of 2009, with the core year of the triennium (2008) being proclaimed as a UN Year by the United Nations General Assembly. During all 3 years, a series of activities included in the IYPE's science and outreach programmes had a strong mobilizing effect around the globe, not only among earth scientists but also within the general public and, especially, among children and young people.

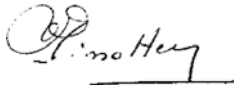
The outreach programme has served to enhance cooperation among earth scientists, administrators, politicians and civil society and to generate public awareness of the wide ranging importance of the geosciences for human life and prosperity. It has also helped to develop a better understanding of Planet Earth and the importance of this knowledge in building of a safer, healthier, and wealthier society.

The scientific programme, focused upon 10 themes of relevance to society, has successfully raised geoscientists' awareness of the need to develop further the international coordination of their activities. The programme has also led to some important updating of the main challenges the geosciences are, and will be confronting within an agenda closely focused on societal benefit.

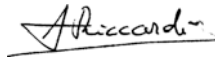
An important outcome of the work of the IYPE's scientific themes includes this thematic book as one of the volumes making up the IYPE-Springer Series, which was designed to provide an important element of the legacy of the International Year of Planet Earth. Many prestigious scientists, drawn from different disciplines and with a wide range of nationalities, are warmly thanked for their contributions to a series of books that epitomize the most advanced, up-to-date and useful information on evolution and life, water resources, soils, changing climate, deep earth, oceans, non-renewable resources, earth and health, natural hazards, and megacities.

This legacy opens a bridge to the future. It is published in the hope that the core message and the concerted actions of the International Year of Planet Earth throughout the triennium will continue and, ultimately, go some way toward helping to establish an improved equilibrium between human society and its home planet. As stated by the Director General of UNESCO, Koichiro Matsuura, "Our knowledge of

the Earth system is our insurance policy for the future of our planet". This book series is an important step in that direction.



R. Missotten
Chief, Global Earth Observation Section
UNESCO



Alberto C. Riccardi
President
IUGS

We cling to a sort of magical thinking about the impending ecological disaster. It is too easy to accept the assertions of the World's professional optimists, or the pronouncements of those who noisily deny scientific facts. If more of us cared to experience the natural world unmediated by anything at all – to simply sit, quietly, open to its sublime beauty – we might take better care of it – our heritage with its almost incomprehensibly long history!

From Sara Maitland in *A Book of Silence*, published by Granta, 2008

This volume is dedicated to my son Ross who, on the point of submitting his PhD, died in a car accident near Allora, southern Queensland, on 21 September 1991. A mathematician, biologist and statistician, his research on statistical modelling of complex ecosystems would have complemented this volume perfectly. He would have relished many of the contributions here.

Preface to this Volume

This volume is one of a series of volumes, Springer's Legacy Series, produced as a tangible by-product of the activities of UNESCO's International Year of Planet Earth. The volume was directed towards considering the broad pattern of increasing biodiversity through time, and recurrent events of minor and major ecosphere reorganization, some regional, such as the swiftly developing collapse of reef systems: or local, exemplified by the 79 AD disaster about Pompei. Intense scrutiny was sought on the pattern of physical (including isotopic), sedimentary and biotic circumstances through the time intervals during which life crises occurred. These events affected terrestrial, lacustrine and estuarine ecosystems, locally and globally, but also affected continental shelf (including intertidal) ecosystems and even deep ocean ecosystems. The pattern of such events is an important part of the backdrop against which modelling the pattern of future environmental change needs to be evaluated.

A broad spectrum of authors was sought but, inevitably, recently published exhaustive surveys resulted in lacunae in this particular volume. Authors who felt they could usefully contribute were encouraged to take liberties with subject, organization and point of view. As a consequence, some of the contributions are highly personal and digressive (such as the concluding chapter of this volume); some are essays, others are reflective overviews of broad topics, and yet others present the detailed results of specialized scholarship undertaken over many years. It is anticipated that all have adroitly balanced scientific data and inference. Writing is often a slippery commodity. An author's voice and the readability of his/her contribution can be easily lost by over-editing. Care has been taken to maintain the personal voice and viewpoints of the authors.

Every fossil, large or small, can be viewed as a time-capsule or as a data bank – as my late friend, Paul Tasch, insisted nearly 40 years ago in his *Paleobiology of the Invertebrates: Data Retrieval from the Fossil Record*. Paul's thesis was that all fossils may be viewed as parts of an infinitely larger data bank of transcendental scale and that the information each fossil can deliver (alone or in conjunction with other fossils) can answer many questions concerning the fossils themselves and the environments in which they lived. There have been countless trillions of such tiny time-capsules. Their stories – as individuals or as members of former communities, supplemented by information about the sediments on or in which they lived and were buried – provide us with grand panoramas of deep time, and provide much information about the context of the recent past, and help explain the present-day ecosphere of our planet. In this volume, 74 authors contributed 36 manuscripts that present 'snapshots' of that grand saga – the vast array of patterns, and a mind-numbing panorama of tiny events leading up to the present day – and have thereby contributed a special standpoint from which to consider our planet's immediate future.

Many scientists have interpreted parts of this saga. Some are painstakingly probing how life could have originated from the simple chemicals present on the early Earth – a long, almost intractable endeavour, developing understanding of how protocells could have formed and then imported RNA building blocks into their structure. Others – the majority – have concentrated on aspects of the ‘tree of life’ such as the relationships of now-extinct organisms. Though most of the trunk and branches of this ‘tree’ disappeared long ago, all living species are ultimately twigs of a single tree. Others have focused on reconstructing ancient environments. Such reconstructions, especially their cyclicities, gain significance as we approach the present day and consider the contribution of humankind to atmospheric chemistry, ecosystem degradation and global warming – and how the impact of these might be mollified.

The history of our biosphere, now under serious threat, is a stunningly complex story. Many ancient environments, seemingly little changed through hundreds of millions of years, are still with us. These include the environments of oceanic trenches (hadal regions) and abyssal plains, where oozes slowly form from the tests of microscopic organisms (radiolarians and foraminifers). Other environments, if not being destroyed, are changing rapidly.

If used quantitatively, exhaustive palaeontologic databases can be used not only for deciphering grand-scale patterns in the history of the biosphere, but can also be brought to bear on gross global tectonic problems – especially by quantitative analysis of biogeographic data for inferring the relative disposition and motions of crustal blocks, major and minor, during the past 550 million years or so. This has considerable potential value: being able to use data from the foldbelts of the globe where palaeomagnetic data has lost value from overprinting by subsequent tectonic episodes (intervals of intense earth movements).

Five of the nine chapters at the beginning of this volume present a fresh look at the data and methods of palaeontology (Martin Aberhan and Wolfgang Kiessling), ‘coordinated stasis’ (Carlton E. Brett), the possible impact of periodic astronomical phenomena on the history of life (Bruce S. Lieberman and Adrian L. Melott), a background chapter on climate change through time (John Dodson) and a major synthesis of much data on the development of intertidal biotas through the last 550 million years (Markes E. Johnson and B. Gudveig Baarli). Two chapters focus on marine encrusting and endolithic communities (sclerobiofacies) (Carlton E. Brett et al., and Bruno Mistiaen et al.) – the first with experimental data from shells positioned at various depths in the deep sea, the second a statistical study of Devonian epibionts. This sequence of nine chapters ends with a contribution on the significance of taphonomy and fish microfossils (‘fish-bits’) in unravelling the history of Devonian vertebrates (Carole J. Burrow and Susan Turner), and another on one of palaeontology’s most spectacular ‘windows’ on deep time, the Eocene-age Messel Pit near Darmstadt in Germany (Stephan Schaal).

John Dodson maintains that the components and processes of Earth’s climate system are subject to the same physical laws as the rest of the Universe. Climate change occurs in response to changes in Earth’s orbit about the Sun. The behaviour of the climate system can therefore be understood and predicted through careful, systematic study. On a grand scale, rearrangements of continents through plate-tectonic motions have surely wrought massive changes in global climate during deep time.

The first four of the next nine chapters present a survey of latest Precambrian embryos and the Early Cambrian Chengxiang faunas from China and explain their evolutionary significance (Jun-yuan Chen); grand-scale evolution during the

Ordovician is chronicled by Arnold I. Miller; Jiří Frýda details the revolution in gastropod classification that has come from ontogenies revealed by SEM photography; and Philippe Steemans et al. discuss innovations in the micro- and megafossil plant record, from earliest plant spores to earliest seeds. Three chapters provide a panorama on the appearance and disappearance of a unique group, the tentaculitids (Eberhard Schindler), results of intensive investigation of shell morphology of Palaeozoic ammonoids (Dieter Korn and Christian Klug) and the outcomes of statistical studies of Late Palaeozoic trilobites (Rudy Lerosey-Aubril and Raimund Feist). The sequence ends with an overview of the evolution of cladid crinoids (Gary D. Webster) and an elegantly illustrated synthesis of the aerodynamics and origin of flight during the dinosaur–bird transition (Sankar Chatterjee and R. Jack Templin).

There were several important thresholds in the saga of life. The first of these was the origin of single-cell organisms on the surface of Earth, occurring as much as 3.7 billion years ago. The next great event, about 2.7 billion years ago, was development of photosynthesizing bacteria and production of their waste product, oxygen. Increasing levels of oxygen facilitated development of lowly multicellular organisms and, eventually (around 575 million years ago), the swift rise to prominence of bizarre soft-bodied creatures known as the Ediacara fauna. The name of another old friend, the late Martin Glaessner, is closely associated with elegant, early work on the strange Ediacaran animals. Martin drew analogies to present-day groups including jellyfish, sea pens and flat worms, but these assumptions were eventually, in large measure, discarded when it became clear that most were not related to Cambrian and younger groups. Dolf Seilacher was the great motivator in bringing about this rethinking.

Recent discoveries of phosphatised embryos of more than 100 taxa in the Duoshantou phosphate deposit (580 million years ago) at Weng'an, Guizhou, China, some so beautifully preserved that 'fact maps', the sequence of cell division, can be inferred. They include lineages closely related to living sponges, cnidarians and bilaterians (Jun-Yuan Chen, herein). Their discovery is consistent with the suggestion that several lineages of metazoan life (including the above major lineages), previously thought to be of Cambrian age or younger, flourished before the Cambrian explosion – despite not being known yet from fossilised mature individuals.

Close affinities between many of the appreciably younger Maotianshan Shale biota (c. 530 mya) found in the Chengjiang, Haikou and Anning areas near Kunming in Yunnan, China and the appreciably younger Burgess Shale biota (c. 505 mya) of British Columbia, Canada, accord with these lineages having rapidly become geographically (perhaps globally) widespread and, as suggested by Chen Junyuan, having possibly become less rapidly evolving following the Early Cambrian 'explosion'.

By the beginning of the Cambrian period (542 mya), the acme of the Ediacara fauna had passed, following the first readily recognisable mass extinction (perhaps a suite of associated sub-events) or grand-scale but gradual faunal turnover in Earth's history, referred to by some as the Kotlin Crisis. Though rare elements of the Ediacara fauna survived into the Cambrian, they declined dramatically in size, diversity and abundance of them through the Kotlin Crisis.

It was succeeded by the earliest Cambrian assemblages containing trace fossils and, finally, by the 'Big Bang' in animal evolution: the appearance of almost all groups of bilaterian animals – the groups that constitute nearly all of our present-day faunas. There had been rapid diversification of grazing animals with shells

composed of phosphate or calcium carbonate – this is considered to be a response to the appearance of the first ‘predators’.

There is evidence from latest Precambrian (Ediacaran) trace fossils (burrows and trails) of organisms ingesting soft sediments and thereby obtaining nourishment from tiny organisms that lived in or very close to the surface of shallow-marine sands and silts. By Middle Cambrian time, tiny animals had begun to utilize the oozes of deep oceanic seafloors – specifically the ultra-fine soft, siliceous sediments on the abyssal plains – as a new food source. The first 60 million years of this saga (not elaborated herein) is presently being elaborated by Yoshitaka Kakuwa of the University of Tokyo.

Though the saga of life displays a broad pattern of increasing biodiversity through time, there have been recurrent events of minor and major ecosphere reorganisation. Scales range from minor and local events, scarcely discriminable from the normal ‘background’ pattern of extinctions, to the mother of all extinction events at the end of the Permian era when as much as 95% of all taxa became extinct, globally. Most, perhaps all, of these events including the end-Permian life crisis were not instantaneous but involved significant intervals of time with definable sub-events.

Though the Kotlin Crisis appears to have been spread over a substantial period of time, it could be regarded as the first of at least eight (rather than five) major events – if one includes the Hangenberg Extinction (360 mya) in the latest Devonian and the now swiftly developing Anthropogenic Event as well. They have been referred to as First-Order extinction events, but how one draws a line between these and the most devastating among the 85–90 other extinction events (many regional rather than global; compilation made by the late Otto Walliser) lacks consensus. Among these are the complex Ireviken Event (Silurian: Llandovery–Wenlock boundary, about 428 mya), the Lau Event (mid-Late Silurian; Lennart Jeppsson et al., herein), the Klonk Event (spanning the Silurian–Devonian boundary), the Taghanic Event (mid-Devonian: late Givetian, about 385 mya; James J. Zambito IV et al., herein) and possibly the Cenomanian–Turonian Event (about 93.5 mya).

These ‘Second Order’ extinction events as well as the largest of all extinction events about the Permian–Triassic boundary (mentioned above; around 251 mya) were not instantaneous as one might expect had they been generated by an asteroid or comet impact. Rather, they were, ‘packages of sub-events’. For example, Lennart Jeppsson, from an enormous database of painstakingly and systematically accumulated conodonts (about a half million of them), from the island of Gotland, has discriminated eight discrete extinction episodes (sub-events) that together constitute the Ireviken Event at the base of the Middle Silurian. At least five of these sub-events can be identified elsewhere around the globe (cf. Peter D. Molloy and Andrew J. Simpson). Lennart and fellow workers have shown that a subsequent (mid-Late Silurian) global extinction event, the Lau Event, not only had a significant impact globally, but also can be shown from intensive sampling to have included sub-events defined by identifiable ‘data points’.

Popular science, as noted above, refers to five major extinction events punctuating the broad increase in biodiversity that occurred through Phanerozoic time (the last 550 million years of Earth history) and ignores the rest. Characteristics of the database on which this assertion is based smooth out all but the most dramatic events. But even then, the massive Late Devonian ‘extinction event’ is a composite of data from three significant events: the Lower Kellwasser (late Frasnian, early in the *linguiformis* Conodont Zone), Upper Kellwasser (at the base of the Famennian) and Hangenberg (latest Famennian) global extinction events.

James J. Zambito IV et al. believe that lesser studied and more frequent events that resulted in faunal restructuring and replacement at regional to global scales may have had a greater aggregate effect on the evolution of life than the 'Big Eight'. This they exemplify by the late Middle Devonian (Givetian) Taghanic Biocrisis in the type area, northern Appalachian North America, where three main bioevents – a series of pulsed biotic transitions and extinctions – ultimately resulting in an end to previous faunal provinciality and appearance of a global cosmopolitan fauna.

Enzo Farabegoli and Cristina Perri, by meticulous observation, have demonstrated the 'mother of all extinction events' at the Permian–Triassic boundary consisted of at least three sub-events.

Gerta Keller insists that the massive Cretaceous–Cenozoic (K/T) Boundary Event (about 65.5 mya) could not have been connected with the Chicxulub bolide on the Yucatan Peninsula, the widely accepted 'culprit'. She argues that it impacted about 300,000 years before the K/T global extinction event and points to the voluminous extrusion of the Deccan Traps volcanics as a more likely driving force behind the devastating K/T extinction event. Jeffrey D. Stilwell and Eckart Håkansson probe extinction/survivorship patterns of some of the biota through the K/T boundary interval, and Vivi Vajda neatly analyses the important role of fungi as a driving force in normalisation of the terrestrial carbon cycle following that massive extinction event.

Six contributions focus on past biogeography: a quantitative analysis of brachiopod biogeography in northern Asia through several time-slices of the Early and Middle Devonian (John A. Talent et al.); the biogeography of Pennsylvanian crinoids and blastoids (Johnny Waters and Gary D. Webster); the biogeography of Late Mesozoic ostracods of western Australia (Michelle Guzel); two contributions that, to a degree, complement one another: one on Mesozoic dinosaurs of the southern hemisphere (Federico Fanti), the other on Mesozoic mammals (Thomas H. Rich and Patricia Vickers-Rich); and extinction patterns in North American Miocene gastropods (Edward J. Petuch). The time is ripe for using large databases! Databases thus generated, coupled with increased knowledge of past climate, are important for modelling the biosphere and its history, specifically past patterns of biogeography and, from these patterns, information on the disposition of crustal blocks (major and minor) during at least the past 550 million years – and of the pattern of extinction events, exemplified earlier, that have affected life regionally and even globally since the appearance of the first metazoan life-forms.

Two contributions round out the volume: environmental shifts during the Cenozoic (Brian McGowran) and a comprehensive survey of the biostratigraphy, phylogenetic palaeoecology and palaeobiogeography of Australian marsupials (Karen H. Black et al.). The latter, serendipitously, draws attention to the impact of climate change on Australia's marsupials over the past 55 million years. Their chapter ends with the words: '...it seems probable that the next time the history of these unique marsupials is reviewed there will be considerably less scepticism about the capacity of climate change to drive extinctions'.

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Sydney, NSW, Australia

John A. Talent

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Contributors

Martin Aberhan Museum für Naturkunde, Leibniz Institute for Research on Evolution and Biodiversity, Humboldt University Berlin, D-10115 Berlin, Germany, martin.aberhan@mfn-berlin.de

Anita Andrew CSIRO Petroleum Exploration, North Ryde, NSW 1670, Australia, a.andrew@dem.csiro.au

Michael Archer University of New South Wales, Sydney, NSW, Australia, m.archer@unsw.edu.au

B. Gudveig Baarli Department of Geosciences, Williams College, Williamstown, MA 01267, USA, gbaarli@williams.edu

Gordon C. Baird Department of Geosciences, SUNY College at Fredonia, Fredonia, NY 14063, USA, Gordon.Baird@fredonia.edu

Karen H. Black Evolution of Earth and Life Sciences Research Group, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia, k.black@unsw.edu.au

Carlton E. Brett Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013, USA, carlton.brett@uc.edu

Pierre Breuer Geological Technical Services Division, Dhahran 31311, Saudi Aramco, Saudi Arabia, pierre.breuer@aramco.com

Denise Brice Laboratoire de Paleontologie stratigraphique FLST and ISA, UMR 8014 CNRS, 59046 Lille cedex, France, d.brice@isa-lille.fr

Carole J. Burrow Geosciences, Queensland Museum, Hendra, Qld 4011, Australia, carole.burrow@gmail.com

Monica J. Campi Department of Primary Industries, GeoScience Victoria, Melbourne, Vic 3001, Australia; School of Life and Environmental Sciences, Deakin University, Burwood, Vic 3125, Australia, monica.campi@dpi.vic.gov.au

Sankar Chatterjee Museum of Texas Tech University, Lubbock, TX 79409, USA, SANKAR.CHATTERJEE@ttu.edu

Jun-Yuan Chen LPS Institute of Geology and Palaeontology of Academia Sinica, Nanjing 210008, People's Republic of China; Institute of Evolution and Developmental Biology, Nanjing University, Nanjing 210093, People's Republic of China, chenjunyuan@163.net; chenjy@nju.edu.cn

Carlo Corradini Dipartimento di Scienze della Terra, Università di Cagliari, I-09127 Cagliari, Italy, corradin@unica.it; ccorr@unimo.it

John Dodson Institute for Environmental Research, Australian Nuclear Science and Technology Organisation, Sydney, NSW, Australia, john.dodson@ansto.gov.au

Federico Fanti Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Studiorum Università di Bologna, 40126 Bologna, Italy, federico.fanti@unibo.it

Enzo Farabegoli Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Studiorum – Università di Bologna, 40126 Bologna, Italy, enzo.farabegoli@unibo.it

Raimund Feist Laboratoire de Paléontologie, Institut des Sciences de l'Evolution, Université Montpellier II, 34095 Montpellier, France, raimund.feist@univ-montp2.fr

Jiří Frýda Faculty of Environmental Sciences, Czech University of Life Sciences Prague, 165 21 Suchbátka, Czech Republic; Czech Geological Survey, 118 21 Prague 1, Czech Republic, bellerophon@seznam.cz

Philippe Gerrienne University of Liège, Paléobotanique, Paléopalynologie et Micropaléontologie, B-4000 Liège 1, Belgium, p.gerrienne@ulg.ac.be

Henk Godthelp Vertebrate Palaeontology Laboratory, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia, h.godthelp@unsw.edu.au

Rimma T. Gratsianova[†] Trofimuk Institute of Petroleum Geology and Geophysics (IPGG), Siberian Branch, Russian Academy of Science (SB RAS), Universitetskii Prospect, 3, 630090 Novosibirsk, Russia

Michelle Guzel School of Life and Environmental Sciences, Deakin University, Burwood, Vic 3125, Australia, mguz@deakin.edu.au

Eckart Håkansson School of Earth and Geographical Sciences, University of Western Australia, Crawley, WA 6009, Australia; Geological Institute, University of Copenhagen, DK-1350 Copenhagen K, Denmark, eckart@cyllene.uwa.edu.au

Suzanne J. Hand Vertebrate Palaeontology Laboratory, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia, s.hand@unsw.edu.au

Chris Holmden Saskatchewan Isotope Laboratory, Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada, ceh933@mail.usask.ca

Karla Parsons Hubbard Department of Geology, Oberlin College, Oberlin, OH 44074, USA, karla.hubbard@oberlin.edu

Lennart Jeppsson Department of Geology, University of Lund, SE 223 62 Lund, Sweden, Lennart.Jeppsson@geol.lu.se

Markes E. Johnson Department of Geosciences, Williams College, Williamstown, MA 01267, USA, markes.e.johnson@williams.edu

Gerta Keller Department of Geosciences, Princeton University, Princeton, NJ 08544, USA, gkeller@princeton.edu

Wolfgang Kiessling Museum für Naturkunde, Leibniz Institute for Research on Evolution and Biodiversity, Humboldt University Berlin, D-10115 Berlin, Germany, wolfgang.kiessling@mfn-berlin.de

Tat'yana P. Kipriyanova Trofimuk Institute of Petroleum Geology and Geophysics (IPGG), Siberian Branch, Russian Academy of Science (SB RAS), Uinversitetskiy Prospect, 3, 630090 Novosibirsk, Russia

Christian Klug Palaeontologisches Institut, CH-8006 Zürich, Switzerland, chklug@pim.uzh.ch

Dieter Korn Museum für Naturkunde, Leibniz-Institut für Evolutions und Biodiversitätsforschung an der Humboldt-Universität zu Berlin, D-10115 Berlin, Germany, dieter.korn@museum.hu-berlin.de

Anna Kozłowska Institute of Palaeobiology, Polish Academy of Sciences, 00-818 Warszawa, Poland, akd@twarda.pan.pl

Alfred C. Lenz Department of Earth Sciences, University of Western Ontario, London, ON N6A 5B7, Canada, aclenz@uwo.ca

Rudy Lerosey-Aubril Senckenberg Forschungsinstitut und Naturmuseum Frankfurt, 60325 Frankfurt am Main, Germany, rudy.leroseyaubril@senckenberg.de

Bruce S. Lieberman Department of Geology, and Natural History Museum/Biodiversity Research Center, University of Kansas, Lawrence, KS 66045, USA, blieber@ku.edu

Christian Loones Musée d'Histoire Naturelle et d'Ethnologie, 59000 Lille, France, loones_christian@hotmail.com

Monika Masiak Institute of Geological Sciences, Polish Academy of Sciences, 00-818 Warszawa, Poland, mmasiak@twarda.pan.pl

Paula Mauller-Mendlowicz Department of De Estratigrafia e paleontologia, FGEL, UERJ, Rio de Janeiro, RJ, Brasil, mendlowicz@gmail.com

Ruth Mawson Earth and Planetary Sciences, Macquarie University 2109, Australia, rmawson37@gmail.com

Brian McGowran Earth and Environmental Sciences, The University of Adelaide, Adelaide, SA 5005, Australia, brian.mcgowran@adelaide.edu.au

Adrian L. Melott Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA, melott@ku.edu

Arnold I. Miller Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013, USA, arnold.miller@uc.edu

Bruno Mistiaen Laboratoire de Paleontologie stratigraphique FLST and ISA, UMR 8014 CNRS, 59046 Lille cedex, France, b.mistiaen@isa-lille.fr

Peter D. Molloy[†] Earth and Planetary Sciences, Macquarie University 2109, Australia

Paula J. Noble Department of Geological Sciences and Engineering, University of Nevada, Reno, NV 89557-0138, USA, noblepj@unr.edu

Maria Cristina Perri Dipartimento di Scienze della Terra e Geologico-Ambientali, Alma Mater Studiorum – Università di Bologna, 40126 Bologna, Italy, mariacristina.perri@unibo.it

Edward J. Petuch Department of Geosciences, Florida Atlantic University, Boca Raton, FL 33431, USA, epetuch@fau.edu

Elodie Petus University of Liège, Paléobotanique, Paléopalynologie et Micropaléontologie, B-4000 Liège 1, Belgium, elodiepetus@hotmail.fr

Simon R. Poulson Department of Geological Sciences and Engineering, University of Nevada, Reno, NV 89557-0138, USA, poulson@mines.unr.edu

Thomas H. Rich Museum Victoria, Melbourne, Vic 3001, Australia; School of Geosciences, Monash University, Vic 3800, Australia, trich@museum.vic.gov.au

Stephan Schaal Senckenberg Forschungsinstitut und Naturmuseum Frankfurt, 60325 Frankfurt am Main, Germany, stephan.schaal@senckenberg.de

Eberhard Schindler Senckenberg Forschungsinstitut und Naturmuseum Frankfurt, 60325 Frankfurt am Main, Germany, eberhard.schindler@senckenberg.de

Hans Peter Schönlaub Kötschach 350, A-9640 Kötschach-Mauthen, Austria, hp.schoenlaub@aon.at

Andrew J. Simpson Department of Earth and Planetary Sciences, Museum Studies and Centre for Ecostratigraphy and Palaeobiology (MUCEP), Macquarie University 2109, Australia, andrew.simpson@mq.edu.au

Trisha Smrecak Paleontological Research Institution, Ithaca, NY 14850, USA, trish.smrecak@gmail.com

Philippe Steemans University of Liège, Paléobotanique, Paléopalynologie et Micropaléontologie, B-4000 Liège 1, Belgium, p.steemans@ulg.ac.be

Jeffrey D. Stilwell Applied Palaeontology and Basin Studies Group, School of Geosciences, Monash University, Clayton, Vic 3800, Australia; Centre for Evolutionary Research, Australian Museum, Sydney, NSW, Australia, Jeffrey.Stilwell@sci.monash.edu.au

John A. Talent Earth and Planetary Sciences, Macquarie University 2109, Australia, jatalent32@gmail.com

R. Jack Templin National Aeronautical Establishment (Retired), 2212 Aster Street, Ottawa, ON, Canada, K1H 6R6, jtemplin@rogers.com

Susan Turner School of Geosciences, Queensland Museum Geosciences, Hendra, Qld 4011, Australia; School of Geosciences, Monash University, Melbourne, Vic 3800, Australia, paleodeadfish@yahoo.com; sue.turner@qm.qld.gov.au

Vivi Vajda Department of Earth and Ecosystem Sciences, Lund University, 223 62 Lund, Sweden, vivi.vajda@geol.lu.se

Patricia Vickers-Rich School of Geosciences, Monash University, Melbourne, Vic 3800, Australia; Museum Victoria, Vic 3001, Australia, pat.rich@sci.monash.edu.au

Sally Walker Department of Geology, University of Georgia, Athens, GA 30602, USA, swalker@gly.uga.edu

Johnny Waters Department of Geology, Appalachian State University, Boone, NC 28608, USA, watersja@appstate.edu

Gary D. Webster School of Earth and Environmental Sciences, Washington State University, Pullman, WA 99164-2812, USA, webster@wsu.edu

Jane Wigforss-Lange Department of Geology, University of Lund, SE 223 62, Lund, Sweden, Jane.Wigforss-Lange@geol.lu.se

Yevgeniy A. Yolkina[†] Trofimuk Institute of Petroleum Geology and Geophysics (IPGG), Siberian Branch, Russian Academy of Science (SB RAS), Universitetskiy Prospect, 3, 630090 Novosibirsk, Russia

Valentina N. Yolkina[†] Trofimuk Institute of Petroleum Geology and Geophysics (IPGG), Siberian Branch, Russian Academy of Science (SB RAS), Universitetskiy Prospect, 3, 630090 Novosibirsk, Russia

James J. Zambito IV Department of Earth and Atmospheric Sciences, Central Michigan University, Mt. Pleasant, MI 48859, USA, zambi1jj@cmich.edu

Mikolaj K. Zapalski Faculty of Geology, Warsaw University, 02-089 Warszawa, Poland, m.zapalski@uw.edu.pl

Matthew K. Zimmerman Department of Geological Sciences and Engineering, University of Nevada, Reno, NV 89557-0138, USA, zimmerk2000@yahoo.com