

REVIEWS

Earth's Oldest Rocks. MARTIN J. VAN KRANENDONK, R. HUGH SMITHIES, and VICKIE C. BENNETT, Editors. Pp. 1307. 2007. *Developments in Precambrian Geology*. 15. Elsevier. Amsterdam. ISBN-13: 978-0-444-52810-0, ISBN-10: 0-444-52810-5. Price: USD150.

I fondly remember a graduate class in the early 1980s on Archean geology at Queen's University in Kingston, Canada, run by Herb Helmsteadt, Dugald Carmichael, Ed Ferrar, and John Haynes, with most other members of staff chipping in with talks and discussions. It was a very holistic, integrated way of teaching students about greenstone belts and shear zone-hosted gold deposits, komatiites, stromatolites, and so forth. This cross-disciplinary teaching was a "trademark" of the earth sciences at Queen's, then way ahead of its time. The class had interesting and enthusiastic students, many eager to map and analyze Archean rocks of the Canadian Shield and, in particular, the Slave craton and the Superior province. Some are now leaders in Archean studies (and authors of chapters in this book; the principal editor of this book, too, completed his Ph.D. in this department).

The most interesting aspect of the geology graduates from Queen's University (and from others throughout Canada) is the sustained collegiate manner in which they set about their tasks to study the ancient real estate of Canada, including the Acasta gneisses, now recognized as the oldest preserved rocks on our planet (described in chapter 3.1). Their systematic collaboration has yielded the most comprehensive "open source" inventory of ancient lithosphere available anywhere in the world. Field-mapping has remained a prime objective, well supported today by a number of excellent geochronology laboratories that have sprung up all over the place, rooted in the superb high-precision work at the Ontario Museum and the mentorship of Tom Krogh. In the mid-1980s, the geologists also joined forces with an emerging geophysics consortium, culminating in the Lithoprobe program that systematically paved geotransects across Canada, producing seismic images of its crust (www.lithoprobe.ca). Other geophysical methods such as teleseismic and magnetotelluric probing joined in to look deeper into the lithosphere and beyond. Thereafter, Archean mantle lithosphere studies started to flourish, following diamond discoveries in the Northwest Territories.

Great surprises and ideas continue to emerge from this nation's geobuilding. Throughout this long-term multidisciplinary investment, Canadian-based ancient rock studies have set new standards and still do, as is evident from this book. I found this particularly striking when reading chapter 8.4, by John Percival, on the Superior province, which is the world's largest and best-studied Archean landmass. John was one of those early-1980s graduate students at Queen's University, and he is now the world's spokesperson for the Superior province geoscience community. He knows this province like the back of his hand and has walked much of it on foot. Whereas for the 1982 graduate class at Queen's, the term "greenstone belt" dominated our discussions, the term has

almost entirely disappeared from Percival's latest summary of the Superior province. The Abitibi greenstone belt, for decades central to any discussions on the Superior province and firmly ingrained in the literature (an internet search using Google yields 20,500 references to this belt in 0.02 seconds), is not mentioned once in Percival's chapter. What can we make of that? Does it represent new-age Archean thinking? In his scientific analyses of the Archean Earth, Percival has no more room for this term, and I think he's right. He has written many excellent Superior province reviews over the years, and this chapter, one of the best in the book, surely is the latest leap forward in what has been part of the evolving Canadian Earth story. Greenstone belts have always been defined with one foot clearly in the modern world and the other shrouded and justified with "well, the early Earth was different then."

Percival's chapter is a call to abandon this gray-area term. Instead, his chapter clearly defines terms such as terrane, superterrane, subprovince, domain, and block for use in Archean geoscience. This is not surprising, given that the terrane terminology was mainly established using examples from Canada, and because the term greenstone belt has never had a satisfactory, clear-cut definition; all Archean geologists intuitively know what is meant by it, but they have never been able to convey this in simple concrete terms among themselves or to others. Perhaps Percival's chapter will help to overcome the angst of the Archean created through the indefinable, mystic greenstone belts.

Almost every tectonic terrane imaginable on the present Earth has an ancient counterpart somewhere in the Superior province, which is thus a tectonic vestige of a modern Earth. It is a continent formed of cratonic fragments and oceanic lithosphere amalgamated along orogenic belts for ca. 30 m.y., between 2.72 and 2.69 Ga, which is a construction process with rates comparable to those observed on the modern Earth, despite the fact that Earth's heat production then was at least twice that of today.

Earth's Oldest Rocks is a weighty, hard-covered book (3 kg and >6-cm-thick) that is divided into eight parts: the first is an Introduction, the next five describe in detail rocks from different Archean-type areas, and the last two parts focus on life and tectonics on the early Earth, respectively. There are 42 chapters in all, written by 81 authors, including some of the world's leading early Earth geologists (and geochemists), whose more than 2,600 combined references are collated into a single useful set of 174 pages toward the end of the book, followed by a final short but adequate subject index. The work describes many advances in reconstructions of the early Earth, highlighting some of the major discoveries about the first 1,300 m.y. of our planet. The book contains more than what its title suggests; although the bulk of the book describes the world's oldest rocks yet discovered, about one-third of the book is devoted to how the Earth may have operated before the end of the Archean. The book is not an easy travel companion; I could just squeeze it into my laptop bag without the

computer. But for those at home preparing a new or revised graduate course in early Earth studies, it is a great compilation of work up to 2006, and I highly recommend it, for it is sure to stimulate discourse.

Like Percival's chapter, a few others also reveal "new age" approaches to the Archean. Most, however, are less *avant garde*—all worth reading, nonetheless. Only a few deserve some stern comments. For example, the chapter by Piranjo (8.3: Ancient to modern Earth: The role of mantle plumes in the making of continental crust) is an attempt to summarize the weight of evidence of what is assumed to be known about mantle dynamics, particularly about the role of plumes, on the modern and the young Earth. This chapter is a summary of other summaries, some of which do a better job of it (e.g., see www.mantleplumes.org). Andersonian plumes are introduced, something Don Anderson would not be pleased about because he has never used that term. It was "scribed" into the literature in a derogatory sense by Courtillot et al. (2003) and is simply repeated here (see also Piranjo, 2007). But it is not an accurate reflection of Don Anderson's views (e.g., Anderson, 2005). He merely states that there is no robust (statistical) score to support the idea of deep mantle thermal plumes, but that there is abundant evidence for (shallow) mantle heterogeneity. This is a crucial point to linger on, in view of the theme throughout this book, in which the editors wage their bets on plumes to explain all features of Earth's oldest rocks. The fact is that there is no universal agreement about plumes, as to what they are and where they come from on the modern Earth, let alone in Archean times. Anderson would argue that the evidence called on in this book to support secular change in mantle dynamics during and after the Archean is based on circular arguments, and that plumes may also have been wanted then. The locations and properties of surface features called "hot spots" are argued by Anderson to be compatible with plate tectonics and a normal mantle that is hot (relative to the *solidi*), and variable in temperature and composition due to recycling, subduction cooling, and insulation. In his view, most features that have been attributed to plumes in the mantle do not have attributes that distinguish them from tectonically controlled features, or passive features in the mantle, such as high fertility (wet) patches; there is no compelling evidence, yet, to suggest this was or was not the case in the Early Archean, too.

Throughout the book, the editors have tried to standardize to their preferred Archean time scale. There is no consensus yet on how to subdivide the first 2 b.y. of Earth history, conventionally referred to as the Hadean (>4.0 Ga) and Archean (4.0–2.5 Ga, with the Neo-, Meso-, and Paleoproterozoic's lower boundaries at 3.0, 3.5, and 4.0 Ga, respectively). The authors of this book have adopted most of the subdivisions of the latest International Commission on Stratigraphy Geological Time Scale (GTS2004; Gradstein et al., 2005): the Archean-Neoproterozoic era (2.8–2.5 Ga), Mesoarchean era (3.2–2.8 Ga), and the Paleoproterozoic era (3.6–3.2 Ga), but then restrict the Eoarchean era to 4.0 to 3.6 Ga, because GTS2004 does not define a lower limit for the Eoarchean. In the last chapter of the book (8.6: Tectonics of the early Earth), an additional "era" is introduced, from 4.0 to 3.85 Ga, and referred to as the LHMB (the Late Heavy Meteorite Bombardment era, based on lunar stratigraphy). This shortens their Eoarchean by 150

m.y., providing a range of 3.85 to 3.6 Ga. The editors suggest that the LHMB should be the formally accepted era between the Archean and Hadean on the basis that no supracrustal sequences older than 3.85 Ga have survived this episode of inferred terrestrial bombardment. (The penultimate chapter 8.5 of this book, by Andrew Glikson, reviews the evidence for the terrestrial impact history, including but not describing the putative impact fall-out layers found in rocks of ca. 3.4–3.2 Ga in South Africa and Australia).

Tinkering with Archean stratigraphic nomenclature like this has its perils. First, the inferred terrestrial LHMB era is an opaque zone devoid of boundaries that can be defined. Second, ongoing mapping and dating is proving that older terranes are still out there waiting to be found. In the well-studied Superior province, a supracrustal sequence (the Nuvvuagittuq sequence) has recently been found to be as old and possibly older than those in Isua (Greenland) that has long reigned as the "Guinness Book of Records" sequence (the Canadian suite is well reviewed by O'Neil et al., in chapter 3.4, and the Isua region by Nutman and collaborators in chapter 3.3). Thus, future fieldwork will almost certainly require Archean boundaries to be redefined, again.

More puzzling is that the new chrons cut across reasonable continuous chronostratigraphy of the only well-preserved Archean sequences that exist (and which, therefore, should serve as *global* stratotypes). For example, the stratigraphy of the Witwatersrand Supergroup, exceptionally well documented through litho-, seismic- and chronostratigraphy, is now half in the Neo- and half in the Meso-Archean. Similarly, the famous stratigraphy of the Barberton greenstone belt is now part Meso- and part Paleoproterozoic. This makes a mockery of basic stratigraphic rules. The fact is that robust stratigraphy is still not applied in the Archean because golden spikes, as used in the Phanerozoic, simply have not yet been explored adequately (but do exist, for example, in the Witwatersrand Basin). Twenty-one years ago, Euan Nisbet (of *Young Earth* fame [1987], a book oddly never referred to in any of the chapters of *Earth's Oldest Rocks*) advised that Archean geologists should brush up on the rules of stratigraphy—which, after all, form the backbone of all geology (see also Bleeker [in Gradstein et al., 2005]—although he advocates using secular events to divide up Precambrian time, a flawed approach because identification of global events must be based in first instance on accurate stratigraphy). Nisbet suggested we start by identifying sensible markers, such as the Great Dyke in Zimbabwe, as interim golden spikes. Whereas one can argue about the usefulness of this particular example, reconstructing the Archean Earth and charting events that affected its evolution must be based on accurate chronostratigraphy normalized against precise chronometric dates (e.g., www.earthtime.org). If not, expect a lot more confusion through silly squabbles reminiscent of Phanerozoic stratigraphers before the advent of precise chronometrics. In the mean time, we might be better off using 100 m.y., calendar-like geon-bins (e.g., Hoffman 1991) as a practical aid.

The Preface by the editors of this book provides a very clear view of where the book is heading and what its main objectives are. The editors list 11 differences between early Earth rocks (e.g., those older than 3.2 Ga) and those thereafter (younger). "These differences tell us that the early Earth was

a vastly different planet than that of today, primarily due to a higher mantle temperature.” That is the overriding message of the editors of this book, that Earth was different then. Before 3.2 Ga, there were no plate tectonics. We must focus on understanding secular changes to understand transition to the modern Earth. But how does this vision dovetail with the facts?

In the opening chapter of Part 1 is an overview of the history of investigation of early Earth rocks by Windley, one of the doyens of Precambrian geology who has seen an awful lot of these rocks, as well as modern specimens. He states, “Probably the most surprising discovery has been that, although the secular decrease with time of radioactive heat production has been confirmed and further constrained, the geological record of rock associations, their chemical signatures, and structural relationships has been found to be more similar to, rather than very different from, that of modern plate tectonic equivalents.” In Windley’s experience, therefore, plate tectonics is ruled permissive throughout the Archean. Most other authors throughout this book flirt with both views.

The second chapter of Part 1, by Condie, another young Earth pioneer, provides a useful account of where all the rocks discussed in this book are to be found. There are some mistakes in the text (despite Condie’s assertion, no komatiites have yet been described from Isua) and on the accompanying global map (Archean cratons and reworked Archean rocks are shown incorrectly in many places, particularly in Africa and Madagascar, and Archean reworked rocks of South America, of which there are many, are not shown at all). This is a serious offence because these types of maps are often indiscriminately reproduced in the literature. More useful would have been to point out areas with uncertainties about Archean provenance. There is unequal knowledge about Archean terranes both in terms of quantity and quality and models based on maps, as in this chapter, have undefined limitations.

If it is all down to secular change, then how steady has this been? Much of Part 2 is devoted to aspects of this question, but these are rarely explained in detail. Mostly the secular change is approached from ingrained intuition. For example, komatiites reflect higher mantle temperatures because the mantle is assumed to have been dry and, therefore, the temperature of the mantle has decreased over time. In contrast, the idea that the Archean mantle may have been (partly) wet at that time, and less viscous, provides an alternative platform for the origin for komatiites (e.g., Grove and Parman, 2004) but is not debated in this book and is dismissed without argument in the last summary chapter. Recent findings that indicate water may have been present in the early mantle of the moon (e.g., Saale et al., 2008) illustrate the folly of simply assuming a dry, early Earth mantle. Unbundling this is important because a dry mantle source forms the backbone of most models that describe the structure and thickness of Archean oceanic crust and lithosphere, and in turn the prevailing geodynamic circuitry. For lack of sufficient rock preservation, geologists cannot restore a reliable section through Archean lithosphere. Whereas theoretical and numerical models show old oceanic lithosphere may have been different from that of today, it is not at all clear if the Archean lithosphere would have been thinner or thicker and, therefore, subductable or not.

Davies explores this in chapter 2.3 of Part 2, but his message was not heard by authors of Part 5. Such issues are central to learning more about lithosphere recycling of the young Earth and how it produced its second-hand continental rocks, the tonalite-trondhjemite-granite (TTG) suite that makes up the bulk of the early continents. The status of deciphering the origin of TTG is reviewed in Part 4 (chapters 4.2 and 4.3, by Smithies et al., using examples from the Pilbara craton, and by Gary Stevens and his coworkers, with examples from the Kaapvaal craton), whereas their field characteristics and global occurrences are recorded in many excellent chapters of Parts 3 and 4. It is remarkable that in the case of the Pilbara and the Kaapvaal, these otherwise similar rocks of the same age are argued to have resulted from entirely different tectonic processes by the respective authors. Clearly, we are still in the dark about the tectonic significance(s) of TTG, more recent claims to the contrary notwithstanding (e.g., Condie, 2008).

There are very good summary chapters on Earth’s earliest minerals in Part 2, which is another highlight of this book. Cavosie et al. review in detail the oldest terrestrial detrital minerals from the Jack Hills in Western Australia, along the northwestern periphery of the Yilgarn craton. Since the first find by Bill Compton and Bob Pidgeon, of *one* very old zircon (>4.2 Ga) in these siliciclastic rocks 22 years ago, more than 70,000 zircons have been analyzed. This work has pushed their age further back by ca. 125 m.y., to just beyond 4.4 Ga (4404 ± 8 Ma). The peak of these Hadean detrital zircons falls into the 4.2 to 4.0 Ga range, but 17 zircons have been recorded to be older than 4.3 Ga, implying that >4.3 Ga felsic rocks of some type survived on the planet until eroded and transported to form the Jack Hills metasedimentary rocks at ~3.0 Ga. This is a well-written chapter, with lots of hard data. If this chapter is read in conjunction with the next chapter (chapter 2.6 by Wyche), which describes old zircons from siliciclastics in a more central region of the Yilgarn craton, a case could be made for a more extensive area of old continental crust. Only a single zircon in the central Yilgarn was found to be older than 4.3 Ga (out of 256 analyzed), not a sound basis for forecasts, but it does suggest that we may be in for surprises as more and more sophisticated dating laboratories are established around the world. And, indeed, we have been surprised already.

Since the publication of this book, it has been discovered that at least 45 of 4,096 to 4,252 Ma zircons encapsulate microdiamond-graphite inclusions (Menneken et al., 2007), and that 18 of these have carbon isotope compositions more similar to biogenic carbon than that of mantle origin (Nemchin et al., 2008). These inclusion-bearing zircons, therefore, may tell an even more exciting tale of possible deep burial and recycling of biogenic materials to depths in excess of 120 km at relatively cool temperatures and thus a low geothermal gradient. Just such a geotherm has now been recorded from relatively high P-low T mineral assemblages in a Paleoproterozoic suture zone in South Africa, described in chapter 5.7 by Stevens and Moyen. Their calculated geotherm of ~12°C/km down to 50 km flies in the face of most Archean crustal models, but it is consistent with the formation and preservation of old diamonds, which also occur as detrital minerals in the Witwatersrand Basin. These findings should change some perceptions about tectonic processes on the young Earth.

Finding old zircons and determining their geochemical make-up and mineral inclusions have been a revelation that has set alight heated debates about what these tiny old crystals are telling about the really early Earth and, in particular, its near-surface conditions. This information has led to models that Earth's surface was cool enough to sustain water by 4.3 Ga (not such a Hadean place after all), that oceans covered the Earth before 4.2 Ga, and that continental crust formed by 4.4 Ga was subsequently recycled into the mantle. There is little focus in this book on how to resolve these speculations in earnest: how to test whether these tiny crystals are really robust proxies for oceans or puddles; whether they represent derivation from hydrothermally altered basalts, plagiogranites, or from granites derived from these; and if, indeed, they represent significant regions of Hadean continental lithosphere or mere continental islands. We simply do not know yet and controversies will rage for some time to come. Someday, we perhaps may even find a terrestrial rock as old as these minerals that will tell us more. Until then, we have to be content with proxy models that foretell ancient vanished crust, about which other chapters in Part 2 provide intriguing, complementary evidence.

Two chapters deal with the period prior to the time that the Earth and its moon separated during massive collision (4500 ± 50 Ma). Because this event provided enough energy to melt Earth completely, all previous direct evidence of earlier accretion events was effectively destroyed. There is only the exogenous material left (meteorites) by which to figure it out.

Bevan (chapter 2.2) provides a clear, if dense, overview of the meteorite archives. The oldest known igneous rock of our solar system comes from Africa (Sahara 99555). This is an angrite, dated at 4566.2 ± 0.6 Ma, sobering evidence of at least one small planet that had accreted, melted, and differentiated very early in the history of our solar system. This chapter illustrates how much detail has been roughly figured out of the history of the approximately first 70 m.y. before the formation of the Earth-moon system. Most of this exquisite work is due to the analytical advances in mass spectrometry, and a generation of dedicated isotope geochemists and petrologists that has pursued evidence for extinct radionuclides with short half-lives (<100 m.y.) with which to place the history of accretion events in chronologic order. To be sure, there are still many gaps, and whereas the exact nature of the materials from which the Earth accreted remains elusive, the details provided here are breathtaking. This chapter should be read by all young, curiosity-driven students, because there are clearly new surprises waiting to be unpacked from geology that is still preserved despite predating the cataclysmic impacts, one of which probably led to the formation of our moon. This is all reiterated in chapter 2.1 (by Taylor) within a framework of chemical evolution during the greater solar system fireworks.

In the next chapter (2.3), Davies returns to his numerical experiments of the early Earth, constrained by first-order thermal and broad-brush geochemical data. His prior results ruled out plate tectonics before the Proterozoic, essentially because a dry, hotter mantle would produce a basaltic crust so thick as to inhibit or preclude subduction. These results have held consensus over the last three decades, but absence of plate tectonics in Hadean Earth models remains based more

on intuition than hard, falsifiable hypotheses. Hadean (and Archean) heat-loss functions, for example, remain poorly understood and, in particular, the response of surface heat loss relative to the greater internal radioactive heat production. Thus, how the Earth coped with all that extra internal heat production is a burning issue that has not been doused yet. Davies' more recent modeling, expanded on in this chapter, comes to a very different conclusion, mainly because it is now recognized that the upper mantle could have been depleted to such degrees (as a result of Hadean lithosphere formation) that partial melting thereof could have yielded only a thin oceanic crust. The latter may well have been subducted as part of a plate circuit.

The next chapter (2.4, by Kamber) reviews in simple terms the chemical constraints on such Hadean crust that may have existed, and how and why it was different from Archean crust. This very informative chapter highlights again the new springboards that have been constructed by the isotope geochemists from which to explore new cryptic territories. Part of this is based on the relatively recent findings of the very old zircons mentioned above. Kamber places less faith in the isotope models than do the individual scientists referred to in his review, and he stresses the large number of uncertainties in the models. But in the end, Kamber concludes that the Hadean surface probably comprised basaltic to ultramafic crust that differentiated internally to yield a small volume of granitoids (from which the oldest zircons may have been derived). Yet he warns against calling this continental crust. His arguments rest on findings of exceptionally enriched and depleted Lu/Hf isotope ratios in complementary reservoirs that do not show up in younger, Archean rocks. It is argued that this crust was somehow destroyed toward the end of the Hadean. Only afterward could a different geodynamic system produce the type of crusts of the modern world, including (micro-)continents. More recent Nd isotope analyses are consistent with this conclusion (e.g., Bennett et al., 2007).

There is a gap of almost 400 m.y. between Earth's oldest minerals and its first preserved indigenous rocks, the Acasta gneisses in northwestern Canada (4.03–3.69 Ga), discovered by Sam Bowring in the 1980s. Since then, an avalanche of new U/Pb dating has shown much more Archean rock. However, studies and syntheses of the oldest rock terranes throughout the world have yet to reach the same integrated levels of understanding as those of the Superior province and Slave craton. This book allows glimpses across the globe at local bits and pieces that provide important clues toward deciphering how the Earth might have worked during its first 2.5 b.y.

Part 3 offers six chapters on Eoarchean gneiss complexes, including the first chapter, on the Acasta gneisses, which are the only rocks to date with robust isotopic evidence that Hadean crust was reworked in the formation of early Archean granitoids. The next chapter (by Harley and Kelly) deals with high-grade rocks of the Napier Complex of Enderby Land in the East Antarctic Shield (with the exquisite color maps, by far the best summary of these rocks I have yet seen) that straddles the Archean-Hadean boundary (4.0–3.85 Ga). These rocks rival those of the Acasta gneisses in age, composition, and complexity, although they attained much greater grades of metamorphism in Antarctica (the highest grades of

ultrahigh temperature metamorphism anywhere in the world's crust: 1,000–1,120°C, at 20–35 km depth, at ca. 2.6 Ga). This chapter highlights the wealth of data that can be extracted from these Archean terranes. The Napier complex records a history of processes spanning more than 1,400 m.y. (4.0–2.6 Ga). “Reading” this history requires dedicated field studies and lots of subsequent perseverance in laboratories. This chapter does as good a job as any in conveying that message. The closest Archean rocks to these oldest rocks of Antarctica occur in southern India. In their Gondwana setting, they were contiguous. In the future, these Indian rocks may also reveal new information, and the absence of a description of Paleoproterozoic Indian rocks in the present volume is a distinct anomaly.

There is no compelling evidence in Antarctica that correlations exist between different Archean terranes of the Napier Complex, something it has in common with the Itsaq Complex (Greenland) that is described in the next chapter, by Nutman et al. These observations suggest that in both regions, distinct terranes comprise individual continental blocks that formed between 4.0 and 3.6 Ga and amalgamated along suture zones at about 3.6 Ga. Nutman and his collaborators have long advocated some form of horizontal tectonics, indeed, plate tectonics, to explain their field observations and laboratory analyses of these gneisses and the Isua supracrustal rocks (3.8–3.7 Ga). Their findings have since been strengthened by the discovery of a sheeted dike complex in the Isua sequence (Furness et al., 2007).

The next chapters deal with lesser known areas in China, and new discoveries in the northeastern part of the Superior province. Inclusion of the latter (the ~3.8 Ga Nuvvuagittug greenstone belt) seems odd in a section on early gneiss terranes. Finally, there is a description of the Narryer terrane that forms the northwest extremity of the Yilgarn craton. Whereas the latter is predominantly Neoproterozoic in age, the basement of the Narryer block is included here because it contains small enclaves of older gneisses with bits of the oldest Australian rock (a 3731 ± 4 Ga tonalite) and, more glamorous still, because it hosts the Jack Hills conglomerates from which the Earth's oldest indigenous minerals have been analyzed (see above). I found this chapter interesting because it is the only account of the regional geologic setting of the old detrital zircons. A small set of similar Hadean zircons (six grains, with one concordant date of 4.35 Ga) has now been described from quartzites in the more central parts of the Yilgarn craton (the Youanmi terrane). This discovery is described in chapter 2.6, a little misplaced perhaps in the sequence set out in the book, but nevertheless exciting in that it certainly makes it plausible that more Hadean rocks will eventually be discovered.

The next two parts (comprising 12 chapters) deal with the two best-preserved Paleo- to Mesoarchean cratons in the world, the Pilbara (Part 4) and the Kaapvaal (Part 5) cratons (3.6–3.0 Ga). There are adequate overviews of both cratons, their supracrustal rocks (greenstone belts), and surrounding plutonic rocks (granitoids of various kinds), with respective interpretations about their origins. Both parts include one chapter on economic mineral deposits (the only reference in this book to early Archean mineralization, except for the BIF of Isua). The oldest ores summarized from the Kaapvaal

craton are Mesoarchean (3.1–3.0 Ga) shear zone-hosted gold deposits from Barberton (chapter 5.8, by Dziggie et al.). Deposits described from the Pilbara craton are the oldest known mineral deposits anywhere (other than the BIF in Isua). These include 3.49 Ga barite deposits, good descriptions of ~3.5 to 3.2 Ga VHMS base-metal deposits, and Earth's oldest porphyry Mo-Cu deposits (3.3 Ga). Shear zone-hosted gold deposits are claimed to be the oldest in the world (no absolute dates are available) and have produced about 65 tonnes Au. Whereas all these Early Archean mineral deposits found to date are relatively small fry, they are significant, nonetheless, to aid further understanding of early Earth's upper crustal hydrothermal processes. Differences and similarities to modern counterparts are discussed, and the Pilbara chapter provides an overview of the variability of early Archean mineralization as far as this can be achieved with such a small database. Attempts at establishing secular changes in Earth's metallogenic processes based on this meager data, however, are at best intuitive. The approach is in need of serious rethinking, particularly because we know next to nothing about such types of mineralization in modern oceanic plateaus, let alone their Archean equivalents in which the ores are inferred to have originated (see below).

The other three chapters in Part 4 deal with the early history of the Pilbara craton (3.6–3.2 Ga). This is essentially an extensive summary of the impressive amount of fieldwork carried out there during the last 15 years, mostly spearheaded by the two lead authors of this book, both at the Geological Survey of Western Australia. Much geochemical data is incorporated, particularly of the basaltic-felsic (greenstone belt) sequences and the surrounding gregarious granitoid batholiths. The pre-3.2 Ga history of the craton is interpreted entirely in terms of vertical processes related to convective overturn (in the mantle and crust), a theme that has dominated thinking in Australia since the 1960s, despite strong alternative views expressed in the 1990s by outsiders, such as by Stan White and his Dutch group of researchers, and teams of Japanese geologists guided through Shigenori Maruyama. However, the simple Australian plume model of decades ago has given way to a more complex multiple plume hypothesis to account for episodic granite magmatism associated with apparently cyclic basalt-andesite-felsic events; first through fractional crystallization in the mantle, followed by intracrustal partial melting and convective overturn. A 400-m.y.-long period, starting with formation of a large oceanic plateau of the Kerguelen type, followed by its internal differentiation, is envisaged to have yielded all the geologic elements that we see preserved today in the eastern Pilbara. Subduction surrounding the protocraton started abruptly at ca. 3.2 Ga, which the editors of this book believe represents a global event.

In summarizing their 30 years of research in the Barberton greenstone belt, Lowe and Byerly (Part 5, chapter 5.3) essentially come to similar conclusions, although they envisage the change from plume to tectonic accretion processes to have occurred closer to 3.1 Ga. There is no crisp explanation given for this sudden change in the Earth's mantle dynamics by either of these two groups. Assigning an Archean plume origin on the basis of geochemistry of present-day hot spots is not straightforward (e.g., Luguet et al., 2008). To base such

models on Archean mantle geochemistry that is argued to have undergone an unknown degree of secular change between 3.6 and 3.2 Ga, in addition to the low-temperature metasomatism that has affected most igneous rocks throughout Archean terranes, is even more prone to criticism. Detailed field descriptions of 3.5 to 3.4 Ga mafic-ultramafic volcanic sequences in Barberton (chapter 5.4, by Dann and Grove) yield different conclusions that invoke subduction processes for their generation. The same sequences in Barberton thus continue to be interpreted in radically different ways. The reasons for this are not clear, but a lack of detailed chemical stratigraphy of the volcanic sequences is surely one of them. Another is that the metasomatism, most dramatically in the form of ubiquitous silicification, changes the field and geochemical characteristics of rocks. The latter is summarized in chapter 5.5 by Hofmann and Wilson (based on observations in the 3.4 Ga Nondweni greenstone belt).

Whether there are real differences in the way that these two southern hemisphere cratons evolved in the Paleoproterozoic remains to be established. This is a task that can only be completed when both cratons reach the same maturity of integrated studies as is seen across the cratons of Canada. For example, at present there are almost no detailed deep geophysical data across the Pilbara. The absence of abundant old diamonds and kimberlites may indicate that there are important lithospheric mantle differences between the two cratons, inherited from the Archean and/or superimposed at later times. There is need for new observations in both regions to test this. Mineral geochemistry as a proxy for mantle lithosphere stratigraphy, such as that described in chapter 8.2, by Griffin and O'Reilly, hints in these directions, but these types of studies have inherent uncertainties that are too large for reliable chronostratigraphy, and are thus no substitute for hard-slog isotope work.

Part 6 deals with a disparate set of Paleoproterozoic gneiss terranes described in four chapters, with three based on North American regions (in Minnesota, Manitoba, and Wyoming) and one in Russia (the Siberian craton). The reason for omitting many other existing areas of this age on other continents is not provided. It does reflect one of the few real shortcomings of the book.

Part 7, *Life on early Earth*, comprises six chapters. The first, by Whitehouse and Fedo, is probably the most interesting because it provides a welcome, "not afraid to speak up" overview of the claims to the oldest evidence for life; for example, from Isua and, more importantly, from the possibly older (>3825 Ma²) granulite gneisses on Akilia Island, 25 km south of Nuuk (dominantly pyroxene-amphibole-quartz gneisses, but nowhere in this book is even a simple P/T determination of the Akilia mineral assemblages given, fundamental data that are also notably missing from information about the majority of other terranes described in this book). Both the absolute age of the Akilia gneisses and their relative ages, based on outcrop, some of it shrouded beneath glacial deposits, are disputed. All published evidence of life based on carbon, sulfur, and silica isotope analyses of these rocks is now widely discredited. Moreover, the carbon in apatite (the basis for claiming chemical evidence for earliest life on Earth in Mojzsis et al., 1996; no P/T data there, either) has never been rediscovered and its very existence, therefore, is in doubt.

Having recently visited Akilia Island and these now infamous outcrops, I am not surprised about these disputes; if anyone can squeeze evidence of life out of these, described as BIF (which they are certainly not), which must have been heated to more than 600°C, then that person deserves a medal. The chapter has a useful table summarizing the evidence for life in the Early Archean sequences; the oldest and genuine contender for this remains the carbon isotope data on graphite globules in the well-preserved upper "pelagic" horizons of metatubidites of the Isua complex described by Mike Rossing in 1999, close to his base camp, where you can now find a handwritten warning not to use a hammer in the vicinity, which will, it is hoped, be respected (Fig. 1). A twist in the story at the end of this chapter is that all BIF in Isua (and by inference elsewhere) can be regarded as the oldest evidence for life, a variant on using the oldest granites as global biomarkers (e.g., Rosing et al., 2006).

The other chapters in this part are very useful reviews of what is generally putative or accepted (possible, probable, respectively) evidence for early life in Early Archean rock sequences of the Pilbara, based on field observations (van Kranendonk, chapter 7.2), light stable isotope signatures (carbon and sulfur, Ueno, 7.3), and organic geochemistry (Marshall, 7.4). The final two chapters deal with the sulfur isotopes (>3.5 Ga: Mojzsis, 7.5) and with the secular evolution of Sr, C, and O isotopes, recorded in marine sedimentary rocks (Shields, 7.6), both from a more global perspective. These bear on the changing chemical and physical conditions of the exosphere, particularly those of the atmosphere and hydrosphere, and how these may have affected the paleo-ecodynamics of our young Earth. These are tough stories for field geologists, and they get more complex all the time (e.g., Philippot et al., 2008), yet they form the basis of a new understanding of why and/or how life in the Archean evidently thrived (that much is clear from these chapters in Part 7) and when and/or how it might have started (which is a story for another time). Field geologists need to take stock of these complexities if they are to recognize which are the important "Rosetta stones" to collect for their geochemical colleagues.

The last chapters of the book (Part 8) attempt to paint a global picture of the young Earth before 3.2 Ga. A different Earth emerges through the unwavering opinion of the editors of this book. Plate tectonics of any form were absent on the early Earth, in their opinions. Tectonics and lithosphere formation for the first 1,300 m.y. were driven by vigorous mantle overturn during which the earliest cratons remained stationary above long-lived (>300 m.y.) upwelling mantle cells and related plume heads. In chapters 8.3 to 8.6, plumes ruled an early world that was pelted by asteroids. Hansen (chapter 8.1) agrees it was different early on, not necessarily because of mantle plumes, but rather because of a regionally extensive, thin, ductile (weak) layered crust that insulated the underlying mantle during those early days. She bases this idea on interesting and intriguing remote sensing views of the surface features on Venus (with seven excellent radar images reproduced from the Magellan Mission, available, with others, at <<http://pdsmaps.wr.usgs.gov/maps.html>>) and shows convincingly that ovoid and arcuate regions (Atalanta-Vinmara and Lavinia) resemble some terrestrial granite-greenstone terranes, such as those of the Pilbara. Might this planet's

A



B

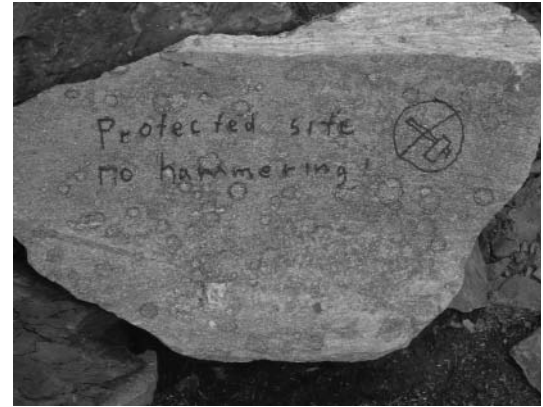


FIG. 1. Metaturbidites, dipping steeply to the left, showing coarse sandy base (pale) and dark shale tops. The latter bear graphite nodules with carbon isotope signatures indicative of photosynthesis. These have been interpreted as the oldest chemical signs of life on Earth (Rosing, 1999; see also chapter 7.1). Isua Supracrustals, Greenland. The small stone in the foreground of the outcrop (A) is shown enlarged in B.

surface provide a good analogue for that of the young Earth, particularly before 4.0 Ga? I find this a little hard to swallow, in part because the surface conditions on Venus are very hot and dry, and we have learned from the early zircon work described in this book that this was not so on Earth from 4.4 Ga onward. This suggests different cooling mechanisms on each of these two planets, then and now. Moreover, whereas Hansen argues that Venus may have a thin ductile “skin,” all indications are that at least by the Paleoarchean, Earth’s surface was bimodal and the preserved continental lithosphere from those times invariably retains a thick skin of depleted competent lithosphere (see the following chapter 8.2, by Griffin and O’Reilly), with an effective elastic thickness that was able to sustain thick and widespread sedimentary deposits by 3.4 Ga. This type of comparative planetary science reminds me of flippant remarks by the famous geologist A.M. Macgregor, who first described the Archean gregarious batholiths surrounded by the arcuate greenstone belts of the Zimbabwe craton. In 1951, he stated: “It is perhaps presumptuous to suggest that the craters of the Moon may be of the same nature [as these granite-greenstone terrains].” This could be argued about seriously, then, but sampling has spoiled the discourse. It will unfortunately take much longer, if ever, to land on Venus to test this fantasy.

The book then comes to a firm (Warren) Hamiltonian conclusion: “Assuming that the hot young Earth was just like the modern one retards understanding” (Hamilton, 2007, written commun.). Trying to weigh the evidence carefully when judgment is not always based on foolproof blindfold tests, and when the amount of material preserved to work with is so tiny, we are almost all prone to become biased through working in our own backyards. Be that as it may, Martin van

Kranendonk and his co-editors should be congratulated on collating this volume. Inevitably, a book of this nature contains many repeats. But the many authors provide views from different angles; this helps to make a rich mixture of facts and ideas that clarify a number of fundamental issues about our young Earth and its coevolving life, many of which remain to be answered.

While I was reading, my mind wandered back frequently to those lively discussions at Queen’s, marvelling at the progress that has been made in the intervening 30 years. This book is worth getting if you want to find out how facts can change ideas and if you wish to wonder about Earth’s deepest past.

MAARTEN DE WIT

AEON-AFRICA EARTH OBSERVATORY NETWORK
UNIVERSITY OF CAPE TOWN
RONDEBOSCH 7701, SOUTH AFRICA
August 21, 2008

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