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Inside:

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SCIENCE ARTICLE

Cover: The sharply outcropping cap carbonate at the base of the Nafun Group above the Marinoan glacial epoch (ca. 635 Ma) in the Jabal Akhdar, Oman. The area is characterized by several tectonic events that turned the shown stratigraphy upside down. Photo courtesy Daniel Figi. See "The case for a Neoproterozoic Oxygenation Event: Geochemical evidence and biological consequences," p. 4–11.

The case for a Neoproterozoic Oxygenation Event: Geochemical evidence and biological consequences

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ABSTRACT

The Neoproterozoic era marked a turning point in the development of the modern earth system. The irreversible environmental changes of that time were rooted in tectonic upheavals that drove chain reactions between the oceans, atmosphere, climate, and life. Key biological innovations took place amid carbon cycle instability that pushed climate to unprecedented extremes and resulted in the ventilation of the deep ocean. Despite a dearth of supporting evidence, it is commonly presumed that a rise in oxygen triggered the evolution of animals. Although geochemical evidence for oxygenation is now convincing, our understanding of the Neoproterozoic earth system and of early animal evolution has changed apace, revealing an altogether more complicated picture in which the spread of anoxia played an important role. The challenge to future researchers lies in unraveling the complex entanglement of earth system changes during this pivotal episode in Earth's history.

INTRODUCTION

Today, atmospheric oxygen plays a crucial role in shaping the surface of our planet. However, during most of Earth's history, molecular oxygen was only sparsely available and probably accumulated in two broad steps: during the Great Oxygenation (or Oxidation) Event (GOE) at 2.4 Ga (e.g., Holland, 2002) and then during the Neoproterozoic Oxygenation Event (or NOE) almost two billion years later. Both events were accompanied by tectonic upheaval, climatic extremes, and biological innovations, implying a close interaction between the biotic and abiotic realms of system Earth.

The most commonly proposed environmental trigger for early animal evolution is oxygen (Nursall, 1959; Canfield and Teske, 1996). Most animals require molecular oxygen in order to produce their energy, and this has led to the widespread presumption that a rise in atmospheric oxygen was the essential precursor to the evolution of animals (Runnegar, 1991; Catling et al., 2005). Geochemical evidence for an oxygenation event during the late Precambrian has accumulated over the past quarter century, but it is still hard to distinguish atmospheric from ocean and global from local (or even porewater) redox changes. Evidence has emerged recently that the Neoproterozoic oceans were characterized by the spread of sulphidic and ferruginous anoxic environments, which is apparently at odds with the emergence of modern animal groups for which free sulphide is lethal and anoxia unfavorable.

Here we focus attention on the NOE, exploring geochemical evidence for its existence and examining the case for a causal relationship between oxygen and early animal evolution. Considering recent evidence for widespread ocean anoxia during the NOE, we speculate that metabolic versatility during the nascent stages of animal evolution may have been a key factor in the emergence and diversification of metazoan life on our planet, while later oxygenation allowed metazoans to increase their size and mobility.

Figure 1. (A) Proposed reconstruction of atmospheric O_2 content through time expressed as percentage of present atmospheric level (PAL) of oxygen (after Canfield, 2005, with Phanerozoic estimates from Berner et al., 2003). Note that the uncertainty is quite high. Background displays redox conditions in the water column whereby the deep ocean was probably anoxic until the Great Oxygenation Event (GOE) in the early Paleoproterozoic, sulfidic during most of the Proterozoic, and primarily oxic after the Neoproterozoic Oxygenation Event (NOE). (B) The NOE possibly unleashed major biological innovations, including the appearance of new biological and ecological strategies: the first metazoans (Hoffman et al., 1990; Love et al., 2009); the appearance of first large and architecturally complex organisms during the Ediacaran (Narbonne, 2005); and the Cambrian Explosion (Marshall, 2006). A pronounced increase of maximum body size by several orders of magnitude occurred between 600 and 450 Ma. Red dots—prokaryotes; orange diamonds—protists; brown square—vendobiont (probable multicellular eukaryote, e.g., *Dickinsonia*); blue squares—animals; green line—vascular plants (Payne et al., 2009). (C) $\delta^{13}C$ record throughout Earth's history (compiled by Campbell and Allen, 2008). (D) Normalized seawater $^{87}Sr/^{86}Sr$ curve (from Shields, 2007). (E) Compilation of sulfur isotope data measured in sulphide- and sulphate-bearing minerals. $\Delta^{34}S$ values in the Archean do not exceed 20‰ and maximal Paleo- and Mesoproterozoic $\Delta^{34}S$ values are around 45‰. It is only from the Neoproterozoic on that sulphur fractionation attains values between 40 and 70‰. Upper red curve illustrates maximal $\delta^{34}S_{sulfate}$ values and is offset by −55‰ (lower line) (most values were compiled by Canfield and Farquhar, 2009). (F) Compilation of molybdenum concentrations in black shales from different sections around the world (mainly from Scott et al., 2008, and references therein). (G) Compilation of vanadium concentrations in black shales. Precambrian data are rather sparse but still indicate a significant step toward much higher enrichment of V in black shales during the Precambrian-Cambrian transition (Precambrian data mainly from C. Scott, 2010, pers. comm.). (H) Key aspects of the Precambrian history of hexavalent chromium in sea water. Increasing Cr isotope fractionation ($\delta^{53}Cr$) recorded in banded iron formations (BIFs) between 2.8 and 2.45 Ga indicate rise in oxidative weathering with a possible return to reduced atmospheric oxygen levels between 2.45 and 1.9 Ga. BIFs deposited during the late Neoproterozoic between ca. 750 Ma and the Precambrian-Cambrian boundary record strongly positive $\delta^{53}Cr$ values ranging from 0.9‰ to 4.9‰, which may provide further evidence for the NOE (from Frei et al., 2009).

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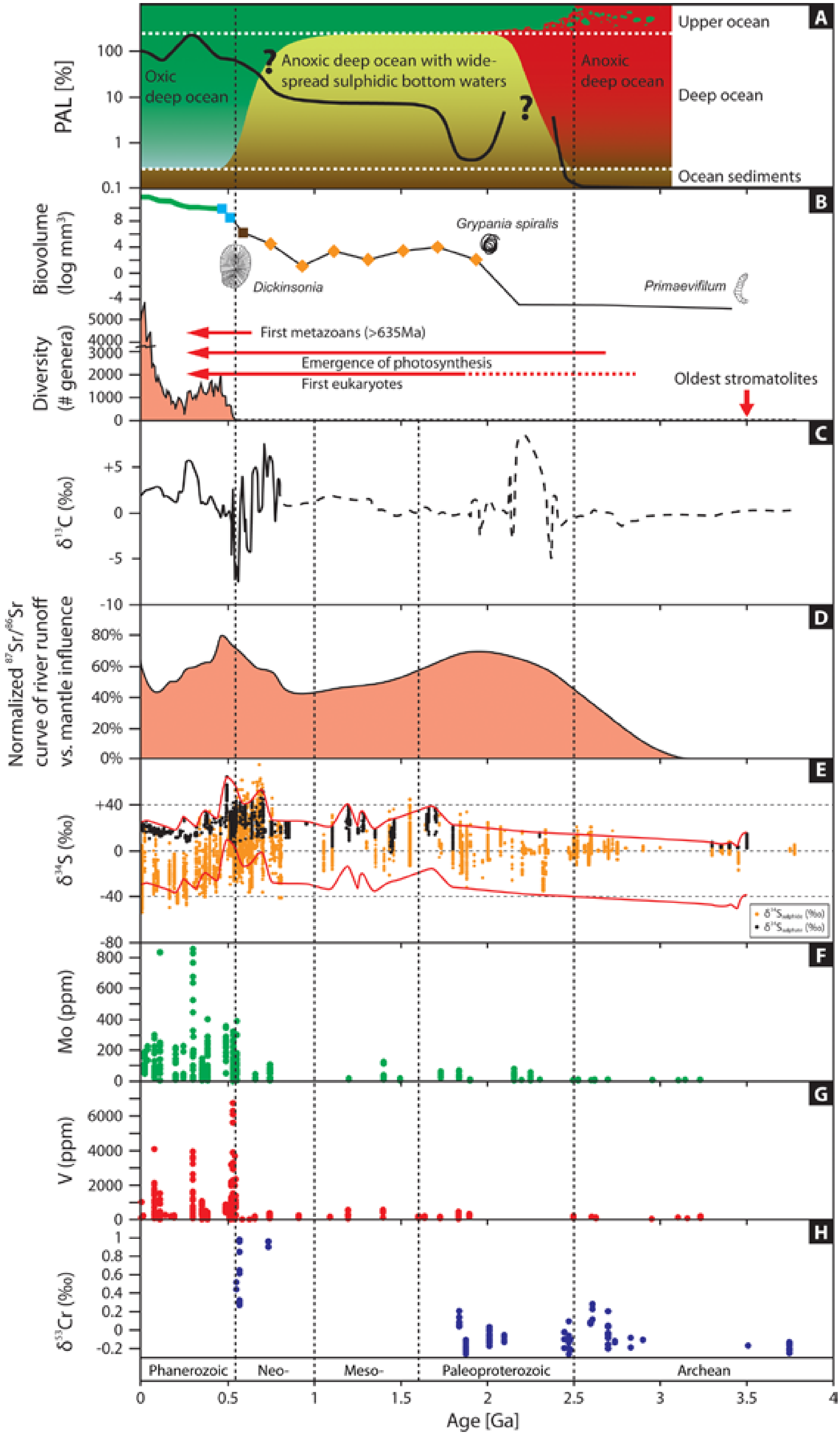

A
Upper ocean
Deep ocean
Ocean sediments
PAL [%]
Oxic deep ocean
Anoxic deep ocean with wide-spread sulphidic bottom waters
Anoxic deep ocean
B
Biovolume (log mm³)
Grypania spiralis
Dickinsonia
Primaevifilum
Diversity (# genera)
First metazoans (>635Ma)
Emergence of photosynthesis
First eukaryotes
Oldest stromatolites
C
δ¹³C (‰)
D
Normalized ⁸⁷Sr/⁸⁶Sr curve of river runoff vs. mantle influence
E
δ³⁴S (‰)
F
Mo (ppm)
G
V (ppm)
H
δ⁵³Cr (‰)
Phanerozoic
Neo-
Meso-
Paleoproterozoic
Archean
Age [Ga]

GEOLOGICAL SETTING OF EARLY ANIMAL EVOLUTION

By the beginning of the Neoproterozoic era, most of the continental crust had amalgamated into one vast supercontinent, Rodinia, which began to split apart after ca. 800 Ma (Evans, 2009). By ca. 700 Ma, our planet was dotted with microcontinents, predominantly at lower latitudes (Hoffman and Li, 2009). These crustal fragments accreted a series of volcanic arcs after ca. 650 Ma and underwent serial collision, culminating in the formation of a new supercontinent, Gondwana, by ca. 520 Ma (Campbell and Squire, 2010). The rifting of Rodinia formed the tectonic backdrop to decreasing levels of atmospheric pCO_2 (Riding, 2006), which plunged the planet toward glaciation that reached low latitudes by 716 Ma (Macdonald et al., 2010). How long this global cooling endured is still unknown, but isotopic evidence points to two or more intervals of extreme cold: from ca. 716 Ma to ca. 670 Ma (referred to but not proven to be equivalent to the "Sturtian" glaciations in Australia) and from ca. 650 Ma to 635 Ma (ascribed to the Elatina or "Marinoan" glaciation in Australia). Earlier Neoproterozoic glaciations ca. 750 Ma, and later ones (e.g., the ca. 580 Ma Gaskiers glaciation), have enjoyed less attention and are unlikely to have been of global reach (Fairchild and Kennedy, 2007). The extraordinary circumstance of low altitude, equatorial ice cover (Hoffman and Li, 2009) at least twice during the Neoproterozoic led in part to the controversial "Snowball Earth Hypothesis" (Kirschvink, 1992; Hoffman et al., 1998), which has dominated debate on the Neoproterozoic earth system over the past decade.

Rodinia was possibly Earth's first green supercontinent because the oceans that surrounded it witnessed a remarkable diversification of eukaryotic life forms (Figs. 1 and 2). The first green algae (and possibly lichen) emerged around this time (Porter, 2004; Knoll et al., 2006) and would have revolutionized weathering and the global carbon cycle once they made it to land (Heckman et al., 2001; Lenton and Watson, 2004). Acritarch diversity (and presumably the diversity of eukaryotic plankton in general) crashed after Rodinia began to break up during the run-in to the Cryogenian glaciations (Nagy et al., 2009), but some new heterotrophic forms appeared as well. For example, the first appearance of biomineralizing eukaryotes in the form of fossil testate amoebae heralded the onset of glaciation around the world (Nagy et al., 2009).

The glacial interval between ca. 720 Ma and 635 Ma is thought to be the time during which the first animal lineages diverged from their single-celled ancestors (Peterson et al., 2008), presumably in intimate proximity with the icy, anoxic, and ferruginous environments of the glacial ocean (Canfield et al., 2008). Despite such challenging conditions, all modern eukaryote lineages survived Snowball Earth; i.e., the opisthokonts (e.g., fungi), the Amoebozoa (lobose amoebae), the plants (green and red algae), the chromalveolates (ciliates and dinoflagellates), and the Rhizaria (filose testae amoebae) (Porter, 2004). Although nothing resembling the common ancestor to all animals has been found in the rock record, fossil evidence for metazoan existence begins directly after the deglaciation that marks the beginning of the Ediacaran period at 635 Ma (Yin et al., 2007; Cohen et al., 2009). Putative metazoans, in the form of benthic "fronds," first attained macroscopic size following the mid-Ediacaran "Gaskiers" glaciation of ca. 580 Ma (Narbonne, 2005). The apparent association between climate change and fossil appearances, size change, and lifestyle has led naturally to the speculation that environmental factors directed biological evolution during the Neoproterozoic (e.g., Payne et al., 2009) (Figs. 1 and 2).

THE EMERGENCE OF THE METAZOANS

The abrupt appearance in the rock record of macroscopic life forms has perplexed geologists. By the middle of the nineteenth century, natural historians would speculate either that the fossil record was woefully incomplete (Darwin, 1859) or, following Abraham Gottlob Werner, that conditions had been hostile to complex life before the Cambrian (e.g., Daly, 1907). "Permissive evolution" through environmental change has continued to dominate notions of the Cambrian explosion, with the most commonly proposed trigger being oxygenation (Berkner and Marshall, 1965). Large organisms cannot exist beneath a minimum threshold of free oxygen (Catling et al., 2005). They need it to sustain their energy requirements and for structural support. Although primitive extant animals, such as the sponges (as well as their protist sister group, the choanoflagellates), are usually obligate aerobes, many animals can thrive in oxygen-poor environments, leading some to question the presumption that the very earliest animals were as dependent on oxygen as their modern counterparts (Budd, 2008). The existence of large, mobile animals since the beginning of the Phanerozoic certainly means that oxygen levels have not fallen beneath a minimum threshold since that time, but this fact cannot tell us when atmospheric oxygen first rose to such heights.

The biological case for a rise in oxygen during the Precambrian was first made in the 1920s with Oparin and Haldane independently realizing that life must have evolved under reducing conditions (Haldane, 1929; Oparin, 1938). Nursall (1959) postulated that Earth emerged from its anoxic state toward the end of the Precambrian and that this oxygenation event was the key environmental trigger for the Cambrian explosion. Geological evidence for the GOE almost two billion years earlier (Melezhik et al., 2005) led to the two-stage oxygenation paradigm and implied that the NOE, if it existed, could only represent the further oxygenation of the surface environment (Holland, 2009) and/or the oxygenation of the deep ocean (Canfield, 1998). A crucial prediction of the Nursall hypothesis was that the first metazoan fossils should be found above geochemical evidence for a rise in atmospheric oxygen, but it has taken a long time to approach consensus as to the timing of either.

The oldest undisputed traces of modern animal groups—trace fossils, sponge remains, and calcified tubes (of stem-group cnidarians; see Xiao et al., 2000)—are at ca. 555 Ma, 20 million years older than the oldest animal fossils (trilobites) known to Darwin. The earliest multicellular macrofossils may be those from Newfoundland and England (e.g., Ivesheadia) and are at least as old as 575 Ma. Although their biological affinity is open to dispute, this problem need not be a cause of concern if macroscopic size itself can be shown to necessitate the presence of oxygen (Catling et al., 2005). Similarly, locomotion requires the energy provided by oxygen, and the first evidence for true mobility derives from the

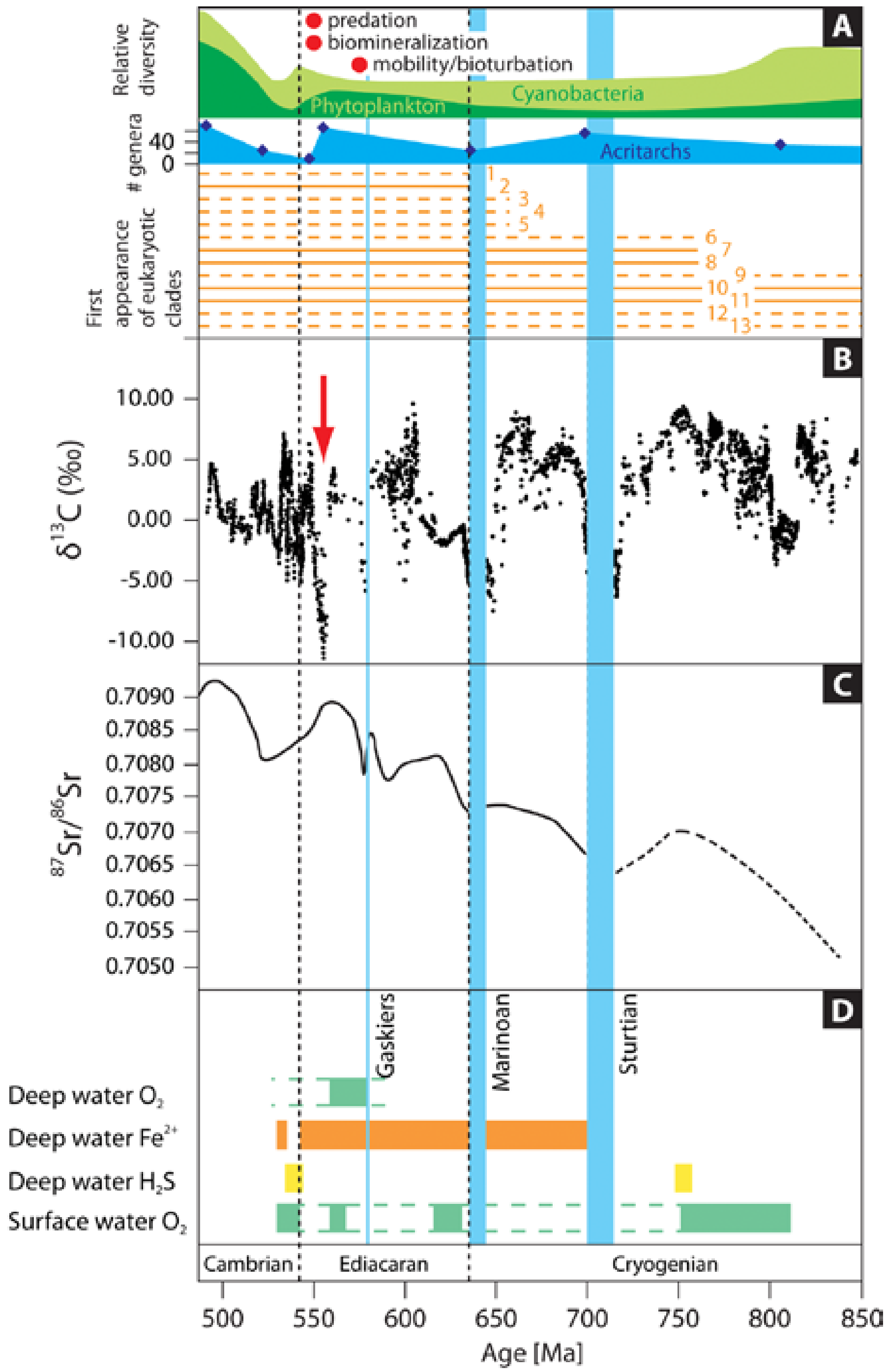

Figure 2. (A) Compilation showing the emergence of predation (Bengtson and Zhao, 1992), biomineralization (Grotzinger et al., 2000), and mobility (Liu et al., 2010); the relative diversity of cyanobacteria and phytoplankton through time (modified after Moczydlowska, 2008); acritarch diversity; and first appearance of eukaryotic clades. 1—brown algae; 2—animals; 3—haptophytes; 4—diatoms; 5—chrysophyte algae; 6—green algae; 7—lobose amoebae; 8—euglyphid amoebae; 9—fungi; 10—vaucheriacean algae; 11—red algae; 12—dinoflagellates; 13—ciliates (modified after Porter, 2004). (B) Secular variation in the carbon isotopic composition ($\delta^{13}C$) of marine carbonates from 850 to 490 Ma (modified after Halverson et al., 2005; Halverson, 2006). The negative $\delta^{13}C$ anomalies characterizing the Sturtian and Marinoan glacial intervals suggest they were globally synchronous. Shuram/Wonoka excursion indicated by red arrow. (C) Seawater $^{87}Sr/^{86}Sr$ curve for the same interval (data for the Ediacaran period from Sawaki et al., 2010). (D) Summary of marine conditions through the last half of the Neoproterozoic and into the early Cambrian (from Canfield et al., 2008).

very same strata (Liu et al., 2010). If these latest findings are confirmed, Nursall's threshold must have been reached by ca. 570 Ma.

Microscopic metazoans may have existed even further back in time. Spiny acritarchs, similar to those that bear purported animal embryos, have been found in rocks as old as 635 Ma (Yin et al., 2007; Cohen et al., 2009), while the earliest sponge biomarkers are of similar antiquity (Love et al., 2009). Although these findings imply that some "primitive," non-bilaterian animals existed during the Snowball Earth glaciations, in the absence of taxonomic identification, they fail to constrain ambient oxygen levels at that time.

The fossil record thus confirms that animals were relative latecomers, arriving more than a billion years after the evolution of the eukaryotic cell (Knoll et al., 2006). Molecular estimates for the origin of animals (Peterson et al., 2008) agree with the fossil record and converge on the Cryogenian period (850–635 Ma) and, in particular, its later, glacial parts (Snowball Earth) as the cradle of animal evolution. The same study constrains the emergence of bilaterian animals (and of locomotive and digestive musculature) to lie within the later Ediacaran period (after the ca. 580 Ma Gaskiers glaciation and the most extreme negative $\delta^{13}C$ excursion of the entire rock record). While geological changes are regarded by some as "scenery rather than as major players" in early animal evolution (Budd, 2008), it is hard to ignore the extraordinary climatic and tectonic context. It has been suggested that evolutionary progress requires not only genetic possibility but also ecological opportunity (Knoll et al., 2006). Oxygenation, related to the remarkable tectonic and environmental revolutions of the later Neoproterozoic, may have provided such opportunity, but until recently we have known little about its nature and timing.

MARSHALLING THE GEOCHEMICAL EVIDENCE FOR NEOPROTEROZOIC OXYGENATION

Carbon Isotopes

The carbon isotope record provides insight into the Neoproterozoic global carbon cycle. Since the pioneering study of Knoll et al. (1986), it has been known that Neoproterozoic seawater was characterized by unusually high $\delta^{13}C$, averaging +5‰ before the onset of glaciation (Figs. 1 and 2). Such high values indicate that the proportion of carbon buried as organic matter was elevated from ca. 850 Ma until ca. 720 Ma, and this has been linked to a general diversification of eukaryotic plankton, which altered the dynamics of organic matter production and decomposition (Knoll, 2003). Enhanced organic burial on subsiding, passive margins of the rupturing supercontinent, possibly carried down with the first widespread marine carbonate snow (Riding, 2006), may also have been responsible. Because organic burial allows oxygen released from photosynthesis to collect in the atmosphere, sustained high $\delta^{13}C$ implies a drawdown in atmospheric CO_2 and a concomitant rise in net oxygen production, albeit well before the earliest known metazoan fossils.

This story still holds but has since gained a twist. The Neoproterozoic carbon isotope record is also characterized by negative $\delta^{13}C$ excursions of uncertain duration that began after 811 Ma (Macdonald et al., 2010) and ended near the Precambrian-Cambrian boundary. The low $\delta^{13}C$ values are commonly associated with episodes of cooling, while in some cases values are so low that they defeat explanation by conventional isotope mass balance. The largest of these, the Shuram-Wonoka excursion, took place during the middle of the Ediacaran period and was first identified by Pell et al. (1993) and Burns and Matter (1993) from strata in Australia and Oman, respectively. The excursion, constrained to beneath the first appearance of *Cloudina* and the disappearance of the large spiny, "acanthomorphic" acritarchs (typical of the early Ediacaran), is a global $\delta^{13}C$ signal and can be explained by the oxidation of a vast deep-ocean pool of dissolved organic carbon (Rothman et al., 2003). This hypothesis is supported by the apparent decoupling of $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records (Swanson-Hysell et al., 2010), which, if confirmed, represents the massive consumption and injection of oxidants into the deep marine environment (Hayes and Waldbauer, 2006).

Strontium Isotopes

Estimating changes in net oxygen rise from the $\delta^{13}C$ record requires the assumption that the rates of chemical weathering (and presumably also of carbon dioxide outgassing) remained constant or increased during the interval of high $\delta^{13}C$. The $^{87}Sr/^{86}Sr$ ratio of seawater is predicted to rise if the relative contribution of continental weathering to the oceans increases and so can be used to test the nutrient (P) surge hypothesis. A marked rise during the Neoproterozoic was noted by Derry et al. (1992), and it reached an all-time maximum by the end of the Cambrian period (Shields, 2007). Superimposed on this rise are short-lived positive shifts caused by enhanced weathering after deglaciation, driven largely by warmer temperatures and unusually high atmospheric pCO_2 (Kasemann et al., 2005; Bao et al., 2008). Pulses of globally integrated weathering rates raised net oxygen production, but increases in outgassing would be needed to sustain irreversible shifts in oxygen production (Shields, 2007). For example, the appearance of modern soil biota (e.g., Yuan et al., 2005) has been linked to irreversible changes in chemical weathering during the Neoproterozoic (Heckman et al., 2001; Lenton and Watson, 2004; Kennedy et al., 2006). However, any irreversible change in weathering rates will lead to global cooling unless compensated for by higher outgassing and an accelerated global carbon cycle, which may explain why Gondwanan orogenesis, characterized presumably by exceedingly high erosion rates, enhanced marine productivity and carbon dioxide drawdown (Campbell and Squire, 2010) and was accompanied by low $\delta^{13}C$ values, high atmospheric pCO_2, and some of the highest mean temperatures of the Phanerozoic (Trotter et al., 2008).

Sulfur Isotopes

Sulfur isotope discrimination (marine sulfate $\delta^{34}S$ – pyrite sulfide $\delta^{34}S$) increased to modern values during the Neoproterozoic-Cambrian transition (Canfield and Teske, 1996). Canfield and Teske argued that this change reflected a rise in atmospheric oxygen above the 0.05 present atmospheric level (PAL) necessary for sulfide-oxidizing bacteria (*Beggiatoa*). Recent studies indicate that this rise probably occurred during the middle Ediacaran (Fike et al., 2006; Halverson and Hurtgen, 2007), but sulfide oxidizers are now thought to have evolved much earlier (Johnston et al., 2005). It is difficult to know whether this increase in $\Delta^{34}S$ is related directly to higher oxygen levels or instead to the increased complexity of the sedimentary sulfur cycle caused by bioturbating animals (Canfield and Farquhar, 2009). In any case, this represents a change in the sedimentary sulfur cycle, possibly corresponding to an increase in the global ocean sulphate reservoir.

Iron Speciation

Canfield et al. (2007) presented evidence from a deep marine succession in Newfoundland that the proportion of highly reactive Fe versus total iron decreased to modern, oxic values after the ca. 580 Ma Gaskiers glaciation. Comparison with modern marine Fe speciation indicates that bottom waters changed locally from anoxic to oxic just before frondose life forms colonized the deep ocean seafloor in Newfoundland. Ediacaran macrofauna tolerated, and possibly required, free oxygen, consistent with their large size. Compilations of Fe speciation data (Canfield et al., 2008) indicate that the deep marine environment was anoxic during most of the Neoproterozoic, becoming ferruginous between about 720 Ma and 580 Ma, but was occasionally sulfidic both before and after (Fig. 2). A major handicap arises from problems in correlating the Gaskiers and other mid-Ediacaran glacigenic deposits to published carbon and sulfur isotope records, and, more fundamentally, determining to which extent, if any, deep-water redox conditions influenced life and death in the productive upper layers of the water column (Butterfield, 2009).

Redox-Sensitive Trace Metals

Molybdenum concentrations (and Mo/total organic carbon [TOC] in euxinic shales) increase to Phanerozoic values in black shales sometime between 665 Ma and 530 Ma (Scott et al., 2008), a pattern also recognized in vanadium concentrations, which are generally enriched under similar conditions (Fig. 1). Because molybdenum is scavenged from seawater under sulfidic conditions, this shift could indicate that the global ocean molybdate reservoir rose during this time due to increased Mo delivery to the ocean through oxidative weathering and a retreat of sulfidic sinks. This supports the case that much of the Neoproterozoic deep ocean was anoxic until the late

Precambrian (Canfield, 1998). Once the deep ocean had undergone its irreversible oxygenation (except for episodic oceanic anoxic events), the build-up of sulfate levels ensured that the effects of future carbon cycle perturbations on atmospheric oxygen could be buffered by an ocean sulfate capacitor.

Chromium Isotopes

This new method may be the only one capable of tracing increases in atmospheric oxygen, because chromium isotopes are fractionated during subaerial weathering. Sparse data imply that atmospheric oxygen levels were higher during the late Ediacaran than after the Great Oxygenation Event (Frei et al., 2009), but more data are needed.

In summary, the carbon and strontium isotope records provide evidence for increased carbon burial, which led to cooling and then to anoxic ferruginous conditions after ca. 750 Ma. The sulfur isotope record provides ambiguous evidence for atmospheric oxygenation during the later Neoproterozoic, but taken together, $\delta^{34}S$, Fe speciation, and Mo records indicate that a larger ocean sulphate reservoir led first to anoxic sulfidic conditions and later to the near-permanent ventilation of the deep marine environment. The extreme nature of the Neoproterozoic $\delta^{13}C$ record still puzzles but also intriguingly suggests that the diversification of large, mobile, and skeletal metazoans around the Ediacaran-Cambrian boundary may have been contemporaneous with the further oxygenation of the surface environment.

OXYGENATION AND THE FOSSIL RECORD

It has been questioned whether deep ocean changes reflect a concomitant rise in atmospheric oxygen or merely indicate deep ocean ventilation due to the introduction of filter feeding and planktic metazoans (Butterfield, 2009); however, a general oxygenation event seems likely considering mounting evidence for elevated weathering rates, nutrient availability, and oxygen production during the Ediacaran. In this regard, we find the interpretation of large spiny acritarchs of the early Ediacaran as the diapause egg cysts of primitive metazoans (Yin et al., 2007) to be compelling. This interpretation permits the possibility that the metazoans evolved in response to environmental oxygen stress, while at the same time explaining why such characteristic acritarchs are never found in rocks younger than the postulated NOE (Cohen et al., 2009).

Although the Ediacaran $\delta^{13}C$ record cannot be read simply in terms of organic carbon burial, the possibility of a vast pool of dissolved organic carbon is intriguing. If the Shuram-Wonoka $\delta^{13}C$ anomaly represents the exhaustion of this pool, its culmination, at ca. 551 Ma (Condon et al., 2005), could correspond to a rise in atmospheric oxygen just before the late Ediacaran–Cambrian emergence of modern animal phyla. Although the Cambrian explosion was undoubtedly accelerated through a cascade of knock-on effects arising from the arms race of frenetically evolving hard parts and eyes, etc., it seems likely that oxygenation, perhaps through the extra possibilities gained from their larger size and energy-sapping musculature, was a key factor. Furthermore, rising oxygen levels in the atmosphere and oceans could also have had an indirect effect on biological innovation by increasing the availability of bioessential trace elements (Anbar and Knoll, 2002).

But what about the earliest stages of metazoan evolution, which molecular clocks and the fossil record constrain to the earlier, but more enigmatic, interval of prolonged global cold? Did oxygen play a role in those, too? Evidence for an increase in fractional organic carbon burial, and therefore pre-glacial oxygenation, is strong. However, oxygen is more soluble in cold waters, and so the return of Archean-like ferruginous conditions by 750 Ma seems counterintuitive and suggests that any rise in oxygen levels was reversible. In this regard, pre-Ediacaran pulses in oxygen production may have been curbed by the drawdown of CO_2 and global cooling, which subdued rates of weathering and may have driven new innovations in photosynthesis (Riding, 2006). Whatever the reasons, animal diversification during this most eventful of geological intervals means that a new paradigm is emerging whereby the spread of anoxia rather than an abundance of oxygen could become the hallmark of early animal evolution.

Can we surmise from this unexpected association that our earliest metazoan ancestors were not oxygenophiles at all? To support this case, we note that many extant animals are facultative anaerobes and so are not wholly dependent on oxygen to make a living (Budd, 2008). As well as parasite worms, many free-living invertebrates and even the common mussel can live without oxygen. Astoundingly, some Loriciferans can even withstand free sulfide (Danovaro et al., 2010), which is toxic to all other known metazoans. This extraordinary ability is not secondarily derived but stems from their unusual mitochondria, which resemble hydrogenosomes. Until now, such organelles had only been found in single-celled life forms such as ciliates (Mentel and Martin, 2010) and so supports the argument that the ability to withstand anoxia and even sulphide may have existed near the base of the metazoan family tree (Theissen et al., 2003). The enzymes used in the facultatively anaerobic mitochondria of metazoans are nearly identical across all animal lineages (Martin and Müller, 2007), which indicates a common origin from a metazoan ancestor that lived in the variously oxic, ferruginous, and sulfidic Neoproterozoic oceans.

Being able to withstand anoxia, while at the same time benefitting from the energy yield of an aerobic metabolism, might also have been important during the earlier diversification of eukaryotes because all six eukaryote supergroups (Hampl et al., 2009) contain members with anaerobic mitochondria, including the green algae (Mus et al., 2007). The ability to inhabit oxygenated as well as anoxic environments is, therefore, hardwired into all major eukaryote lineages (Fritz-Laylin et al., 2010). Extending this to metazoans complements, if not challenges, the widespread presumption that oxygenation led directly to animal evolution and implies a three-stage process whereby metabolically versatile, multicellular heterotrophs initially evolved during a prolonged interval of climatic and environmental extremes as part of an overall diversification of eukaryotes on Earth. Mobility and macroscopic size were attained in a second stage during ocean ventilation in the Ediacaran period. Irreversible atmospheric oxygenation by the close of the Precambrian paved the way to the Cambrian explosion, leading to the emergence of all modern animal phyla.

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REFERENCES CITED

Anbar, A.D., and Knoll, A.H., 2002, Proterozoic ocean chemistry and evolution: A bioinorganic bridge?: Science, v. 297, no. 5584, p. 1137–1142.

Bao, H., Lyons, J.R., and Zhou, C., 2008, Triple oxygen isotope evidence for elevated CO_2 levels after a Neoproterozoic glaciation: Nature, v. 453, no. 7194, p. 504–506.

Bengtson, S., and Zhao, Y., 1992, Predatorial borings in late Precambrian mineralized exoskeletons: Science, v. 257, no. 5068, p. 367–369.

Berkner, L.V., and Marshall, L.C., 1965, On the origin and rise of oxygen concentration in the Earth's atmosphere: Journal of the Atmospheric Sciences, v. 22, no. 3, p. 225–261.

Berner, R.A., Beerling, D.J., Dudley, R., Robinson, J.M., and Wildman, R.A., 2003, Phanerozoic atmospheric oxygen: Annual Review of Earth and Planetary Sciences, v. 31, no. 1, p. 105–134.

Budd, G.E., 2008, The earliest fossil record of the animals and its significance: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 363, p. 1425–1434.

Burns, S.J., and Matter, A., 1993, Carbon isotopic record of the latest Proterozoic from Oman: Eclogae Geologicae Helvetiae, v. 86, no. 2, p. 595–607.

Butterfield, N.J., 2009, Oxygen, animals and oceanic ventilation: An alternative view: Geobiology, v. 7, no. 1, p. 1–7.

Campbell, I.H., and Allen, C.M., 2008, Formation of supercontinents linked to increases in atmospheric oxygen: Nature Geoscience, v. 1, no. 8, p. 554–558.

Campbell, I.H., and Squire, R.J., 2010, The mountains that triggered the Late Neoproterozoic increase in oxygen: The Second Great Oxidation Event: Geochimica et Cosmochimica Acta, v. 74, no. 15, p. 4187–4206.

Canfield, D.E., 1998, A new model for Proterozoic ocean chemistry: Nature, v. 396, no. 6710, p. 450–453.

Canfield, D.E., 2005, The early history of atmospheric oxygen: Homage to Robert M. Garrels: Annual Review of Earth and Planetary Sciences, v. 33, no. 1, p. 1–36.

Canfield, D.E., and Farquhar, J., 2009, Animal evolution, bioturbation, and the sulfate concentration of the oceans: Proceedings of the National Academy of Sciences, v. 106, no. 20, p. 8123–8127.

Canfield, D.E., and Teske, A., 1996, Late Proterozoic rise in atmospheric oxygen concentration inferred from phylogenetic and sulphur-isotope studies: Nature, v. 382, no. 6587, p. 127–132.

Canfield, D.E., Poulton, S.W., and Narbonne, G.M., 2007, Late-Neoproterozoic deep-ocean oxygenation and the rise of animal life: Science, v. 315, no. 5808, p. 92–95.

Canfield, D.E., Poulton, S.W., Knoll, A.H., Narbonne, G.M., Ross, G., Goldberg, T., and Strauss, H., 2008, Ferruginous conditions dominated later Neoproterozoic deep-water chemistry: Science, v. 321, no. 5891, p. 949–952.

Catling, D.C., Glein, C.R., Zahnle, K.J., and McKay, C.P., 2005, Why O_2 is required by complex life on habitable planets and the concept of planetary "oxygenation time": Astrobiology, v. 5, no. 3, p. 415–438.

Cohen, P.A., Knoll, A.H., and Kodner, R.B., 2009, Large spinose microfossils in Ediacaran rocks as resting stages of early animal: Proceedings of the National Academy of Science, v. 106, p. 6519–6524.

Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A., and Jin, Y., 2005, U-Pb Ages from the Neoproterozoic Doushantuo Formation, China: Science, v. 308, no. 5718, p. 95–98.

Daly, R.A., 1907, The limeless ocean of pre-Cambrian time: American Journal of Science, v. s4–23, no. 134, p. 93–115.

Danovaro, R., Dell'Anno, A., Pusceddu, A., Gambi, C., Heiner, I., and Kristensen, R.M., 2010, The first metazoa living in permanently anoxic conditions: BMC Biology, v. 8, no. 1, p. 30.

Darwin, C.R., 1859, On the Origin of the Species: London, Murray, 502 p.

Derry, L.A., Kaufman, A.J., and Jacobsen, S.B., 1992, Sedimentary cycling and environmental-change in the late Proterozoic—Evidence from stable and radiogenic isotopes: Geochimica et Cosmochimica Acta, v. 56, no. 3, p. 1317–1329.

Evans, D.A.D., 2009, The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction: Geological Society [London] Special Publication 327, p. 371–404.

Fairchild, I.J., and Kennedy, M.J., 2007, Neoproterozoic glaciation in the Earth System: Journal of the Geological Society, v. 164, no. 5, p. 895–921.

Fike, D.A., Grotzinger, J.P., Pratt, L.M., and Summons, R.E., 2006, Oxidation of the Ediacaran ocean: Nature, v. 444, no. 7120, p. 4.

Frei, R., Gaucher, C., Poulton, S.W., and Canfield, D.E., 2009, Fluctuations in Precambrian atmospheric oxygenation recorded by chromium isotopes: Nature, v. 461, no. 7261, p. 250–253.

Fritz-Laylin, L.K., Assaf, Z.J., Chen, S., and Cande, W.Z., 2010, *Naegleria gruberi De Novo* basal body assembly occurs via stepwise incorporation of conserved proteins: Eukaryotic Cell, v. 9, no. 6, p. 860–865, doi: 10.1128/EC.00381-09.

Grotzinger, J.P., Watters, W.A., and Knoll, A.H., 2000, Calcified metazoans in thrombolite-stromatolite reefs of the terminal Proterozoic Nama Group, Namibia: Paleobiology, v. 26, no. 3, p. 334–359.

Haldane, J.B.S., 1929, The origin of life: Rationalist Annual, v. 148, p. 3–10.

Halverson, G.P, 2006, A Neoproterozoic chronology: Neoproterozoic Geobiology and Paleobiology, p. 231–271.

Halverson, G.P., and Hurtgen, M.T., 2007, Ediacaran growth of the marine sulfate reservoir: Earth and Planetary Science Letters, v. 263, no. 1–2, p. 32–44.

Halverson, G.P., Hoffman, P.F., Schrag, D.P., Maloof, A.C., and Rice, A.H.N., 2005, Toward a Neoproterozoic composite carbon-isotope record: Geological Society of America Bulletin, v. 117, no. 9, p. 1181–1207.

Hampl, V., Hug, L., Leigh, J.W., Dacks, J.B., Lang, B.F., Simpson, A.G.B., and Roger, A.J., 2009, Phylogenomic analyses support the monophyly of Excavata and resolve relationships among eukaryotic supergroups: Proceedings of the National Academy of Science, v. 106, p. 3859–3864.

Hayes, J.M., and Waldbauer, J.R., 2006, The carbon cycle and associated redox processes through time: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 361, 1470, p. 931–950.

Heckman, D.S., Geiser, D.M., Eidell, B.R., Stauffer, R.L., Kardos, N.L., and Hedges, S.B., 2001, Molecular evidence for the early colonization of land by fungi and plants: Science, v. 293, no. 5532, p. 1129–1133.

Hofmann, H.J., Narbonne, G.M., and Aitken, J.D., 1990, Ediacaran remains from intertillite beds in northwestern Canada: Geology, v. 18, no. 12, p. 1199–1202.

Hoffman, P.F., and Li, Z.-X., 2009, A palaeogeographic context for Neoproterozoic glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 277, no. 3–4, p. 158–172.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P., 1998, A Neoproterozoic Snowball Earth: Science, v. 281, no. 5381, p. 1342–1346.

Holland, H.D., 2002, Volcanic gases, black smokers, and the great oxidation event: Geochimica et Cosmochimica Acta, v. 66, no. 21, p. 3811–3826.

Holland, H.D., 2009, Why the atmosphere became oxygenated: A proposal: Geochimica et Cosmochimica Acta, v. 73, no. 18, p. 5241–5255.

Johnston, D.T., Wing, B.A., Farquhar, J., Kaufman, A.J., Strauss, H., Lyons, T.W., Kah, L.C., and Canfield, D.E., 2005, Active microbial sulfur disproportionation in the Mesoproterozoic: Science, v. 310, no. 5753, p. 1477–1479.

Kasemann, S.A., Hawkesworth, C.J., Prave, A.R., Fallick, A.E., and Pearson, P.N., 2005, Boron and calcium isotope composition in Neoproterozoic carbonate rocks from Namibia: Evidence for extreme

environmental change: Earth and Planetary Science Letters, v. 231, no. 1–2, p. 73–86.
Kennedy, M., Droser, M., Mayer, L.M., Pevear, D., and Mrofka, D., 2006, Late Precambrian oxygenation; Inception of the clay mineral factory: Science, v. 311, no. 5766, p. 1446–1449.
Kirschvink, J., 1992, Late Proterozoic low-latitude global glaciation: The Snowball Earth, *in* Schopf, J.W., and Klein, C., eds., The Proterozoic Biosphere: Cambridge University Press, p. 51–52.
Knoll, A.H., 2003, Life on a Young Planet: The First Three Billion Years of Evolution on Earth: Princeton, New Jersey, Princeton University Press, 304 p.
Knoll, A.H., Hayes, J.M., Kaufman, A.J., Swett, K., and Lambert, I.B., 1986, Secular variation in carbon isotope ratios from Upper Proterozoic successions of Svalbard and East Greenland: Nature, v. 321, no. 6073, p. 832–838.
Knoll, A.H., Javaux, E.J., Hewitt, D., and Cohen, P., 2006, Eukaryotic organisms in Proterozoic oceans: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 361, no. 1470, p. 1023–1038.
Lenton, T.M., and Watson, A.J., 2004, Biotic enhancement of weathering, atmospheric oxygen and carbon dioxide in the Neoproterozoic: Geophysical Research Letters, v. 31.
Liu, A.G., McIlroy, D., and Brasier, M.D., 2010, First evidence for locomotion in the Ediacara biota from the 565 Ma Mistaken Point Formation, Newfoundland: Geology, v. 38, no. 2, p. 123–126.
Love, G.D., Grosjean, E., Stalvies, C., Fike, D.A., Grotzinger, J.P., Bradley, A.S., Kelly, A.E., Bhatia, M., Meredith, W., Snape, C.E., Bowring, S.A., Condon, D.J., and Summons, R.E., 2009, Fossil steroids record the appearance of Demospongiae during the Cryogenian period: Nature, v. 457, no. 7230, p. 718–721.
Macdonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss, J.V., Cohen, P.A., Johnston, D.T., and Schrag, D.P., 2010, Calibrating the Cryogenian: Science, v. 327, no. 5970, p. 1241–1243.
Marshall, C.R., 2006, Explaining the Cambrian "Explosion" of animals: Annual Review of Earth and Planetary Sciences, v. 34, no. 1, p. 355–384.
Martin, W.F., and Müller, M., 2007, Origin of mitochondria and hydrogenosomes: Heidelberg, Germany, Springer, 306 p.
Melezhik, V.A., Fallick, A.E., Hanski, E.J., Kump, L.R., Lepland, A., Prave, A.R., and Strauss, H., 2005, Emergence of an aerobic biosphere during the Archean-Proterozoic transition: Challenges of future research: GSA Today, v. 15, no. 11, p. 4–11.
Mentel, M., and Martin, W., 2010, Anaerobic animals from an ancient, anoxic ecological niche: BMC Biology, v. 8, no. 1, p. 32.
Moczydlowska, M., 2008, The Ediacaran microbiota and the survival of Snowball Earth conditions: Precambrian Research, v. 167, no. 1–2, p. 1–15.
Mus, F., Dubini, A., Seibert, M., Posewitz, M.C., and Grossman, A.R., 2007, Anaerobic acclimation in *Chlamydomonas reinhardtii*: Journal of Biological Chemistry, v. 282, no. 35, p. 25,475–25,486.
Nagy, R.M., Porter, S.M., Dehler, C.M., and Shen, Y., 2009, Biotic turnover driven by eutrophication before the Sturtian low-latitude glaciation: Nature Geoscience, v. 2, no. 6, p. 415–418.
Narbonne, G.M., 2005, The Ediacara Biota: Neoproterozoic origin of animals and their ecosystems: Annual Review of Earth and Planetary Sciences, v. 33, no. 1, p. 421–442.
Nursall, J.R., 1959, Oxygen as a prerequisite to the origin of the Metazoa: Nature, v. 183, no. 4669, p. 1170–1172.
Oparin, A., 1938, The Origin of Life: New York, Macmillan, 270 p.
Payne, J., Boyer, A., Brown, J., Finnegan, S., Kowalewski, M., Krause, R., Lyons, S., McClain, C., McShea, D., and Novack-Gottshall, P., 2009, Two-phase increase in the maximum size of life over 3.5 billion years reflects biological innovation and environmental opportunity: Proceedings of the National Academy of Sciences, v. 106, no. 1, p. 24.
Pell, S.D., McKirdy, D.M., Jansyn, J., and Jenkins, R.J.F., 1993, Ediacaran carbon isotope stratigraphy of South Australia—An initial study: Transactions of the Royal Society of South Australia, v. 117, no. 4, p. 153–161.
Peterson, K.J., Cotton, J.A., Gehling, J.G., and Pisani, D., 2008, The Ediacaran emergence of bilaterians: Congruence between the genetic and the geological fossil records: Philosophical Transactions of the Royal Society B: Biological Sciences, v. 363, no. 1496, p. 1435.
Porter, S.M., 2004, The fossil record of early eukaryotic diversification: Paleontological Society Papers, v. 10, p. 35–50.
Riding, R., 2006, Cyanobacterial calcification, carbon dioxide concentrating mechanisms, and Proterozoic-Cambrian changes in atmospheric composition: Geobiology, v. 4, p. 299–316.
Rothman, D.H., Hayes, J.M., and Summons, R.E., 2003, Dynamics of the Neoproterozoic carbon cycle: Proceedings of the National Academy of Sciences, v. 100, no. 14, p. 8124–8129.
Runnegar, B., 1991, Precambrian oxygen levels estimated from the biochemistry and physiology of early eukaryotes: Global and Planetary Change, v. 5, no. 1–2, p. 97–111.
Sawaki, Y., Ohno, T., Tahata, M., Komiya, T., Hirata, T., and Maruyama, S., Windley, B.F., Han, J., Shu, D., and Li, Y., 2010, The Ediacaran radiogenic Sr isotope excursion in the Doushantuo Formation in the Three Gorges area, South China: Precambrian Research, v. 176, p. 46–64.
Scott, C., Lyons, T.W., Bekker, A., Shen, Y., Poulton, S.W., Chu, X., and Anbar, A.D., 2008, Tracing the stepwise oxygenation of the Proterozoic ocean: Nature, v. 452, no. 7186, p. 5.
Shields, G.A., 2007, A normalised seawater strontium isotope curve: Possible implications for Neoproterozoic-Cambrian weathering rates and the further oxygenation of the Earth: Earth, v. 2, no. 2, p. 35–42.
Swanson-Hysell, N.L., Rose, C.V., Calmet, C.C., Halverson, G.P., Hurtgen, M.T., and Maloof, A.C., 2010, Cryogenian glaciation and the onset of carbon-isotope decoupling: Science, v. 328, no. 5978, p. 608–611.
Theissen, U., Hofmeister, M., Grieshaber, M., and Martin, W., 2003, Single eubacterial origin of eukaryotic sulfide: Quinine oxidoreductase, a mitochondrial enzyme conserved from the early evolution of eukaryotes during anoxic and sulfidic times: Molecular Biology and Evolution, v. 20, p. 1564–1574.
Trotter, J.A., Williams, I.S., Barnes, C.R., Lecuyer, C., and Nicoll, R.S., 2008, Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry: Science, v. 321, no. 5888, p. 550–554.
Xiao, S., Yuan, X., and Knoll, A.H., 2000, Eumetazoan fossils in terminal Proterozoic phosphorites?: Proceedings of the National Academy of Sciences, v. 97, no. 25, p. 13,684–13,689.
Yin, L., Zhu, M., Knoll, A.H., Yuan, X., Zhang, J., and Hu, J., 2007, Doushantuo embryos preserved inside diapause egg cysts: Nature, v. 446, no. 7136, p. 661–663.
Yuan, X., Xiao, S., and Taylor, T.N., 2005, Lichen-like symbiosis 600 million years ago: Science, v. 308, no. 5724, p. 1017–1020.

Manuscript received 5 May 2010; accepted 16 June 2010.

CALL FOR AWARD NOMINATIONS

2011 JOHN C. FRYE ENVIRONMENTAL GEOLOGY AWARD

Nominations due 31 March

In cooperation with the Association of American State Geologists (AASG), GSA makes an annual award for the best paper on environmental geology published either by GSA or by a state geological survey.

Anyone may submit a nomination, following these criteria:

1. The paper must be from a GSA or state geological survey publication;
2. The paper must have been published during the preceding three full calendar years; and
3. The nomination must include a paragraph stating the pertinence of the paper (see basis for selection).

Basis for Selection

Each paper will be judged on its uniqueness or significance as a model of its type of work along with its overall worthiness. It is preferred that the paper be directly applicable to informed laypersons (e.g., planners, engineers). In addition, nominated papers must

1. Establish an environmental problem or need;
2. Provide substantive information on the basic geology or geologic process pertinent to the problem;
3. Relate the geology to the problem or need;
4. Suggest solutions or provide appropriate land-use recommendations based on the geology;
5. Present the information in a manner that is understandable and directly usable by geologists; and
6. Address the environmental need or resolve the problem.

Quaternary Geology and Geomorphology Division

2011 FAROUK EL-BAZ AWARD FOR DESERT RESEARCH

Nominations due 2 April

Submit nominations, including (1) a statement of the significance of the nominee's research, (2) a curriculum vitae, (3) letters of support, and (4) copies of no more than five of the nominee's most significant publications related to desert research to Sara Rathburn, Dept. of Geosciences, Colorado State University, Fort Collins, CO, 80523-1482, USA; rathburn@cnr.colostate.edu. Please submit electronically unless hard-copy previously approved.

The Farouk El-Baz Award for Desert Research rewards excellence in desert geomorphology research worldwide. It is intended to stimulate research in desert environments by recognizing an individual whose research has significantly advanced the understanding of the Quaternary geology and geomorphology of deserts. Although the award primarily recognizes achievement in desert research, the funds that accompany it may be used for further research. The award is normally given to one person but may be shared by two people if the recognized research was the result of a coequal partnership. Any scientist from any country may be nominated. Because the award recognizes research excellence, self-nomination is not permitted. Neither nominators nor nominees need be GSA Members. Monies for the award are derived from the annual interest income of the Farouk El-Baz Fund, administered by the GSA Foundation.

2011 HISTORY AND PHILOSOPHY OF GEOLOGY STUDENT AWARD

Applications due 3 May

This award, established by GSA's History and Philosophy of Geology Division in 2004, is made possible by a bequest from the estate of Mary C. Rabbitt. The award applies to GSA Annual Meeting paper proposals based on the following topics: (1) the history of geology; (2) a literature review of ideas for a technical work or thesis/dissertation; and/or (3) some imaginative aspect of the history of geology not previously thought of. Consideration will be given to both undergraduate and graduate students who are in good standing at the time of application; the presentation may take place after the student has graduated. Students must be lead authors on the paper (faculty advisors may be listed as second authors), and while both oral and poster presentations are acceptable, oral presentations are preferred. Applicants need not be GSA members or members of the History and Philosophy of Geology Division.

Further guidelines and the application form are online at http://gsahist.org/HoGaward/awards.htm. *Questions?* Contact the Division secretary-treasurer, Jane P. Davidson, at jdhexen@unr.edu.

Please send nominations to Grants, Awards, and Recognition,
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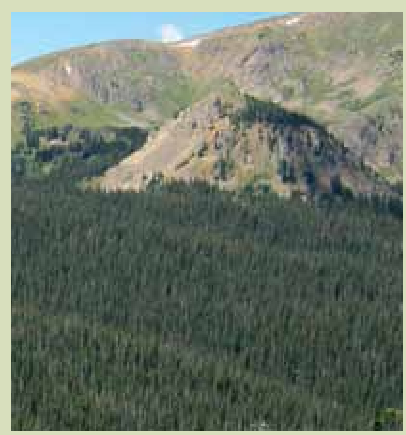

Patrick Burns, U.S. Forest Service Frasier Experimental Forest, Summer 2010.

Fall/Winter 2011–2012

The next GeoCorps America fall/winter season runs from Sept. 2011 through May 2012. Land managers and other partners who want to host fall/winter GeoCorps interns must submit their position descriptions through the GeoCorps website, www.geosociety.org/geocorps/, by **1 April.**

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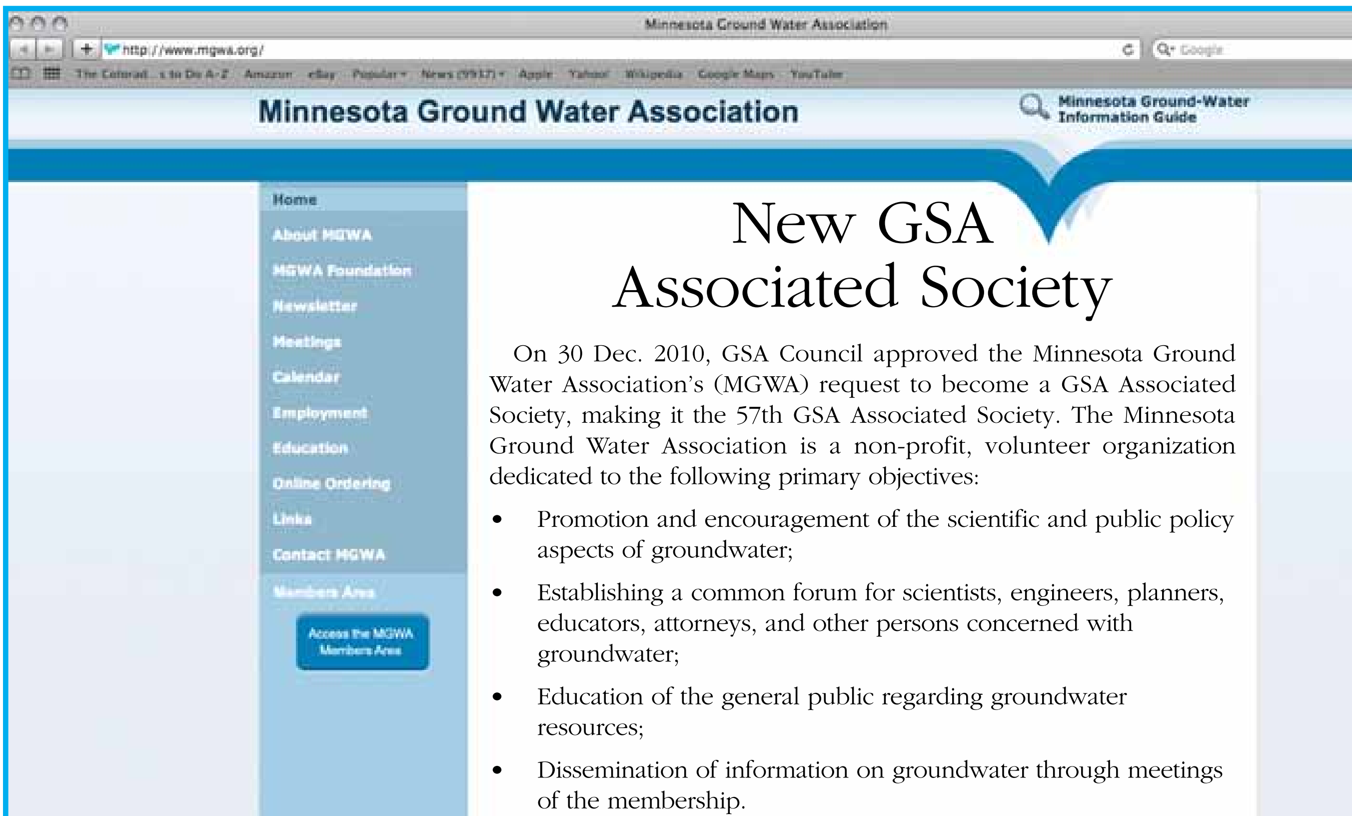

New GSA Associated Society

On 30 Dec. 2010, GSA Council approved the Minnesota Ground Water Association's (MGWA) request to become a GSA Associated Society, making it the 57th GSA Associated Society. The Minnesota Ground Water Association is a non-profit, volunteer organization dedicated to the following primary objectives:

- Promotion and encouragement of the scientific and public policy aspects of groundwater;
- Establishing a common forum for scientists, engineers, planners, educators, attorneys, and other persons concerned with groundwater;
- Education of the general public regarding groundwater resources;
- Dissemination of information on groundwater through meetings of the membership.

For more information on MGWA, go to www.mgwa.org. For a full list of GSA Associated Societies and for information about how your organization can become a GSA Associated Society, go to **www.geosociety.org/divisions/.**

Dates & Deadlines

April: First announcement of topical and discipline sessions published in the April/May *GSA Today.*

April: Electronic abstract form posted at **www.geosociety.org.**

June: Second announcement and registration information published in the June *GSA Today.*

7 June: Space request deadline.

26 July: Abstracts due by 11:59 p.m. PDT.

13 August: Technical program finalized.

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Minneapolis, Minnesota, skyline at night. Photo by Greg Benz, http://carbonsilver.com/blog.

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Students: GSA-ExxonMobil Field Camp Scholar Awards of $US2000 will be given to GSA student members to attend a field camp of their choice. Awards will be based on diversity, financial need, and merit.

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Questions? Please contact Jennifer Nocerino, jnocerino@geosociety.org, +1-303-357-1036.

Note: See p. 29 of this issue for more information about a related program, the GSA-ExxonMobil Big Basin Field Award.

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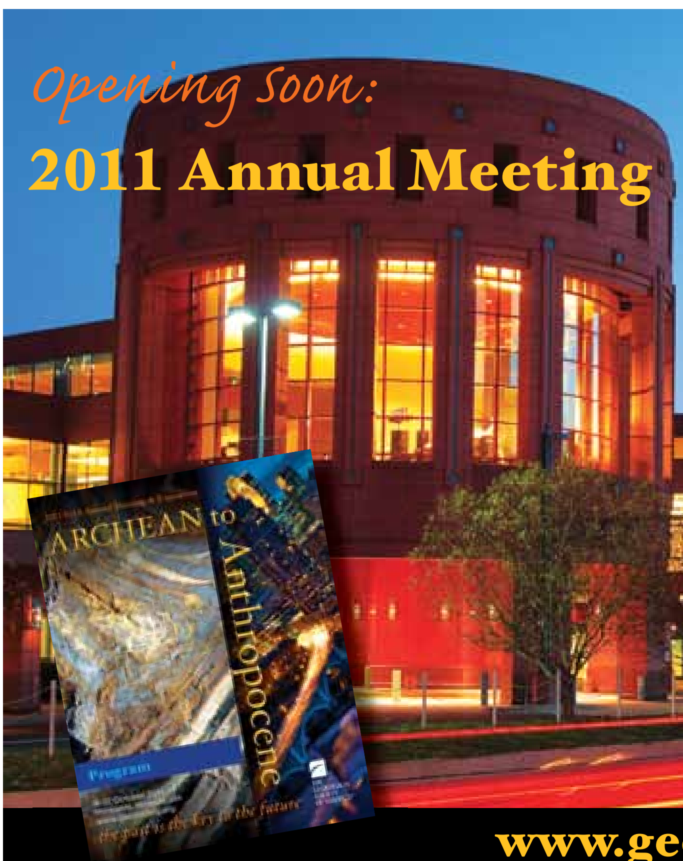

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Deadline: 7 June 2011

From longtime experience, we can tell you that planning early for your business meeting, alumni party, reception, banquet, or social gathering at GSA meetings makes your event that much easier and gets the word out to more people.

To be included in the program book for the GSA's 2011 Annual Meeting & Exposition in Minneapolis, Minnesota, USA, and to reserve space for your event at the headquarters hotel or at the convention center, please complete the space request form online as soon as you can. The space request page at **www.geosociety.org/meetings/2011/** will go live the middle of this month. Also online will be our Event Planning Guide to help you determine if indeed your event should be submitted through the space request system and to answer other questions you may have.

www.geosociety.org/meetings/2011/

Photo used with permission from Meet Minneapolis Official Convention & Visitors Association. Minneapolis, Minnesota, skyline at night. Photo by Greg Benz, http://carbonsilver.com/blog.

"May you live in interesting times…"

Larry Meinert

Many have heard of this reputed Chinese proverb. The current political climate, both in Washington D.C. and the nation at large, is nothing if not interesting. It might be argued that I began my service as the 25th GSA-USGS Congressional Science Fellow in uniquely interesting times, with sweeping electoral changes, spiraling national debt, and growing worries about the country's future.

For those not familiar with the Congressional Science Fellowship program, this year there are 29 Congressional Science Fellows, each sponsored by a major scientific organization, such as the American Chemical Society, the American Physical Society, and, in my case, a partnership of the Geological Society of America and the U.S. Geological Survey. All are under the larger umbrella of the American Association for the Advancement of Science (AAAS) Congressional Science and Engineering Fellows Program. More information about the GSA-USGS Fellowship is available at **www.geosociety.org/csf/scifello.htm.** I can say from first-hand experience that it is a fantastic opportunity, and I would encourage all geologists, at any stage of your career, to consider applying. It will be the best year of your life.

The fellowship year starts 1 September with a two-week orientation program run by AAAS. Fellows are mentored about the intricacies of the legislative, executive, and judicial branches of government and provided with practical advice from former fellows about their experience and how to survive and make an impact on federal policy. The network of current and former fellows is extremely valuable. Current and former fellows serve in key staff positions in Congress and federal agencies; they can be consulted for information and counsel.

After the orientation program, fellows are turned loose on Capitol Hill to find where they will work for the rest of the fellowship year. Following the advice of many former fellows, I interviewed broadly, including the personal offices of Representatives and Senators, committee offices in the House and Senate, and with both Democratic and Republican staffs. Another consideration was that many of the personal and committee offices I interviewed with were going to be affected by the then-upcoming November elections. Thus, one could be in the position of selecting an office or committee that might not exist in another month!

In the end, I joined the staff of Congresswoman Gabrielle Giffords* (D-AZ). I found much to attract me to this office representing the southeastern corner of the Grand Canyon state, including having two former fellows on the permanent staff and fantastic geology throughout the district and the surrounding area (I did field research for my Ph.D. thesis just south of the border in the Cananea district of Sonora, Mexico). In addition, the Congresswoman serves on the House Science and Technology Committee with subcommittees on Technology and Innovation, Energy and Environment, and Research and Science Education. All of these are areas where my background as a geologist, research scientist, and science educator can be utilized.

I started working in Congresswoman Giffords' office at the end of September and experienced the last few days of the legislative session before Congress adjourned. The really "interesting times" began as the campaign season heated up for the November elections, which brought about dramatic changes in the American political landscape. In the Senate, six seats switched parties, and in the House there was a net gain of 63 Republican seats, which is more than the 54 seat swing of the "Republican Revolution" in 1994. To put the 2010 election in perspective, this was the largest such gain for a single party since 1948, and the highest of any midterm election since 1938—interesting times indeed!

Although the results of the 2010 midterm elections will be analyzed and debated for years to come, there are some immediate effects that will impact both the legislative process and my fellowship experience, particularly in the House of Representatives, where the majority party controls almost everything, ranging from the rules of procedure to the size (and in some cases, existence) of individual committees. For example, one of the committees that I had interviewed with, the House Select Committee on Energy Independence and Global Warming, has been abolished.

Beyond the politics of which party controls the Congressional agenda, the elections also illustrated an undercurrent—that the role of science is declining in American political discourse. This should be of concern to all scientists. Admittedly, part of this is a longstanding American tradition of skepticism of "experts," as commented upon since at least the time of Mark Twain, who wrote, "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact." But coupled with legitimate concerns about how to accurately measure and interpret complex data, such as in the field of climate change study, even normal anti-expert feelings can transform into a general distrust of science and scientists. One of the more disturbing statements that I have heard more than a few times in the past several months is that "scientists (and by implication, science) are just another interest group"; i.e., everybody is entitled to an

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USGS science for a changing world

opinion and science is just another opinion. As scientists, we have to do a better job of telling our story, and as a Congressional Science Fellow, I will do my best to help educate about the scientific process.

This anti-science phenomenon also has appeared in the budget-cutting arena and has moved beyond the episodic historical trend of trimming the budgets of federal agencies such as the National Science Foundation (NSF) to include non–peer review evaluation of the worth of specific scientific investigations. For example, the official House of Representatives website of the Majority Leader for the 112th Congress (http://republicanwhip.house.gov/YouCut/Review.htm) includes a link to the NSF database and invites citizens to submit specific grant numbers that they believe are wasteful. Of course, disputes about how to properly fund science are not new (in this case, dating back to the founding of the NSF in 1950), nor are attacks on wasteful scientific funding restricted to any particular political party, as illustrated by the famous "Golden Fleece awards" started by the late Sen. William Proxmire (D-Wis.) in 1975. But there is an important distinction to be made between appropriate citizen concern about spending and the integrity of the peer review process, which is the basis of most modern science and publication. With the convening of the 112th Congress in January, the interesting times continue, and I look forward to reporting on developments in a future column.

This manuscript is submitted for publication by Larry Meinert, 2010–2011 GSA-USGS Congressional Science Fellow, with the understanding that the U.S. government is authorized to reproduce and distribute reprints for governmental use. The one-year fellowship is supported by GSA and by the U.S. Geological Survey, Department of the Interior, under Assistance Award no. G10AP00128. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. government. Meinert is working in the office of Representative Gabrielle Giffords (D-AZ) and can be reached at larry.meinert@mail.house.gov.

***Editor's note:** This report was written before the tragic shooting of Congresswoman Gabrielle Giffords and others on 8 January 2011. Larry Meinert was not in Tucson at the time; he continues his work in Giffords' Washington D.C. office, where members of her staff continue to carry out the functions of the office.

Shortly after the shooting, GSA posted the following statement at the top of its Web page, including a personal note from GSA President Joaquin Ruiz:

> GSA is shocked and saddened by the recent violence against U.S. Congresswoman Gabrielle Giffords (D-AZ) and her staff and constituents. Giffords' office is host to the 2010–2011 GSA-USGS Congressional Science Fellow, Larry Meinert. "Representative Giffords has been an enlightened supporter of higher education and science," said GSA President Joaquin Ruiz. "I have known her for many years and have always been impressed by her commitment to our country and her humanity." GSA, along with all of Giffords' friends and colleagues in the geoscience community, wish her and everyone affected by this event a fast and complete recovery. Our condolences extend to the families of the victims of this senseless act.

2011 GSA Section Meeting Mentor Programs

STUDENTS—Meet Your Career Mentors!

Roy J. Shlemon Mentor Program in Applied Geoscience. *Sponsored by the GSA Foundation.* This is a chance for students to discuss career opportunities and challenges with professional geoscientists from multiple disciplines. Students will receive FREE lunch tickets in their registration packets to attend this program.

The John Mann Mentors in Applied Hydrogeology Program. *Sponsored by the GSA Foundation.* This event presents opportunities for students interested in applied hydrogeology or hydrology as a career to interact and network with practicing hydrogeologic professionals. This program is a focused, small-scale event that features a FREE lunch. Students will receive tickets to attend in their registration packets.

Space for these events is limited, so plan to arrive early: first come, first served.
Questions? Contact jnocerino@geosociety.org.

NORTHEASTERN/NORTH-CENTRAL JOINT SECTION MEETING
Pittsburgh, Pennsylvania, USA
Shlemon Mentor Luncheons
Sun., 20 March, and Mon., 21 March, noon–1:30 p.m.
Mann Mentors in Applied Hydrogeology Luncheon
Tues., 22 March, noon–1:30 p.m.

SOUTHEASTERN SECTION MEETING
Wilmington, North Carolina, USA
Shlemon Mentor Luncheon
Thurs., 24 March, noon–1:30 p.m.
Mann Mentors in Applied Hydrogeology Luncheon
Fri., 25 March, noon–1:30 p.m.

SOUTH-CENTRAL SECTION MEETING
New Orleans, Louisiana, USA
Shlemon Mentor Luncheon
Mon., 28 March
Mann Mentors in Applied Hydrogeology Luncheon
Tues., 29 March

ROCKY MOUNTAIN/CORDILLERAN JOINT SECTION MEETING
Logan, Utah, USA
Shlemon Mentor Luncheon
Wed., 18 May, 11:45 a.m.–1:15 p.m.
Mann Mentors in Applied Hydrogeology Luncheon
Thurs., 19 May, 11:45 a.m.–1:15 p.m.

GSA Foundation Update

Donna L. Russell, *Director of Operations*

GSA Mentor Programs

Roy J. Shlemon Mentors in Applied Geology
John Mann Mentors in Applied Hydrogeology
Geology in Government
Geology in Industry
Women in Geology

Total students impacted PER YEAR: more than 1,500

Held at GSA's Section and Annual Meetings, mentor programs are designed to facilitate mentoring relationships between professionals in the field of applied geology and university students. Mentor volunteers—from private and public businesses and government agencies—represent a broad range of backgrounds, education, and experience.

Who Benefits?

Mentor programs aim to help students connect with a mentor to discuss their current scholarly pursuits and/or their future employment. The relaxed atmosphere at these events gives students a chance to ask the tough questions normally not asked in a classroom or an interview. The student-to-mentor ratio is kept low to allow the students to drive the interaction based on their questions. Building a professional network is a lifelong process and these venues allow students to build their network which is essential in finding a satisfying position.

These venues also assist our mentors. There is a natural human tendency to enjoy passing along knowledge to someone who is eager to listen, so mentors have been willing to volunteer their time and energy. This enables the mentors to become better teachers and managers and can also provide the ability to "recruit" students. Both mentors and students leave these events expressing feelings of personal and professional growth.

For more information, go to **www.geosociety.org/mentors/** or contact Donna Russell at the GSA Foundation, +1-303-357-1054, drussell@geosociety.com

Most memorable early geologic experience:

An early geology memory I have is collecting Devonian fossils with my brother when I was 13 years old. We were written up in the local newspaper and our collection was displayed in the Wyckoff, New Jersey, library. WOW!!!

—Arthur P. Schultz

In Memoriam

The Society notes with regret the deaths of the following members (notifications received between 1 Aug. and 20 Dec. 2010).

William E. Benson
7 Sept. 2010
Springfield, Virginia, USA

Allen S. Braumiller
29 Jan. 2010
Ocean Springs, Mississippi, USA

Gretchen Luepke Bynum
3 July 2010
Fremont, California, USA

Ernest H. Carlson
Notified 3 Dec. 2010
Kent, Ohio, USA

Claire B. Davidson
21 Oct. 2010
Mitchellville, Maryland, USA

David B. Doan
27 Mar. 2010
State College, Pennsylvania, USA

William E. Edmunds
Notified 10 Dec. 2010
Camp Hill, Pennsylvania, USA

Einar B. Ekren
Notified 28 Oct. 2010
White Sulphur Springs, Montana, USA

Paul C. Franks
26 Aug. 2010
Tulsa, Oklahoma, USA

Arthur J. Goldberg
21 Mar. 2010
Gaithersburg, Maryland, USA

Richard F. Hadley
19 Jan. 2010
Englewood, Colorado, USA

Ronald M. Hedberg
24 Sept. 2008
Woodbridge, Connecticut, USA

Este F. Hollyday
9 Apr. 2009
Nashville, Tennessee, USA

Elizabeth R. King
10 Aug. 2010
Reston, Virginia, USA

Owen Kingman
22 Aug. 2010
Grand Junction, Colorado, USA

Phillip S. Kistler
Notified 16 Nov. 2010
La Jolla, California, USA

James W. Knox
Notified 28 Oct. 2010
Murphysboro, Illinois, USA

George E. Kronman
1 Sept. 2010
Houston, Texas, USA

Noel C. Krothe
8 Oct. 2010
Bloomington, Indiana, USA

Carol M. La Delfe
Notified 3 Dec. 2010
Los Alamos, New Mexico, USA

Edwin R. Landis
23 Aug. 2010
Golden, Colorado, USA

William M. Lukens
Notified 16 Aug. 2010
Sandpoint, Idaho, USA

Gerald E. Marrall
27 July 2010
San Marino, California, USA

William McBee Jr.
1 Apr. 2010
Midland, Texas, USA

Judson Mead
10 Oct. 2010
Bloomington, Indiana, USA

Seymour Merrin
12 May 2010
Santa Fe, New Mexico, USA

Beate Mocek
1 July 2010
Lawrence, Kansas, USA

John Montagne
Notified 2 Sept. 2010
Bozeman, Montana, USA

Jared R. Morrow
7 Oct. 2010
San Diego, California, USA

Eric W. Mountjoy
18 June 2010
Montreal, Quebec, Canada

Richard W. Murphy
8 Sept. 2010
Weybridge, Surrey, UK

Willis H. Nelson
26 Aug. 2010
Los Altos, California, USA

Meredith Eggers Ostrom
11 Nov. 2010
Madison, Wisconsin, USA

Priscilla C. Patton
Notified 15 Sept. 2010
Lakewood, Colorado, USA

David A. Phoenix
Notified 27 Sept. 2010
Laguna Niguel, California, USA

E.C. Pirkle
12 Jan. 2010
Aiken, South Carolina, USA

Johannes H. Schellekens
6 Oct. 2010
Mayaguez, Puerto Rico

Marshall K. Shurnas
1 Jan. 2007 (notified 29 Nov. 2010)
Lafayette, Colorado, USA

Paul G. Silver
Notified 6 Aug. 2010
Washington, D.C.

Charles E. Stearns
27 June 2010
Las Vegas, Nevada, USA

Donald B. Tait
13 Sept. 2010
Thornton, Colorado, USA

Tjeerd H. van Andel
17 Sept. 2010
Cambridge, Cambridgeshire, UK

Robert H. Weber
19 May 2010
Albuquerque, New Mexico, USA

Harold Williams
28 Sept. 2010
St. John's, Newfoundland, Canada

Thomas C. Winter
8 Oct. 2010
Lakewood, Colorado, USA

John S. Wonfor
4 Nov. 2010
Calgary, Alberta, Canada

To honor one of these colleagues with a memorial, please go to **www.geosociety.org/pubs/memorials/.** This page also lists the memorials already completed (PDFs).

If you would like to contribute to the GSA Memorial Fund, please contact the GSA Foundation, +1-303-357-1054, drussell@geosociety.org, www.gsafweb.org.

Call for GSA Committee Service

Impact the Future of Geoscience—
Serve on a GSA Committee!

2012–2013 COMMITTEE VACANCIES

Deadline to apply or submit nominations: 15 July 2011

GSA invites you to volunteer or nominate one of your fellow GSA Members to serve on Society committees or as a GSA representative to other organizations. Learn more about each committee and access the nomination form at **www.geosociety.org/aboutus/committees/.** You can also download the form and send a hard-copy nomination to Pamela Fistell, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA; fax: +1-303-357-1074; phone +1-303-357-1044 or +1-800-472-1988, ext. 1044; pfistell@geosociety.org. **Terms begin 1 July 2012** (unless otherwise indicated).

COMMITTEE, SECTION, AND DIVISION VOLUNTEERS:

Council Thanks You!

COMMITTEE	No. of Vacancies	Length of Term
Arthur L. Day Medal Award (T/E)	two	3 years
Diversity in the Geosciences (AM, T/E)	three	3 years
Education (AM, B/E, T/E)	one	2 years
Geology and Public Policy (AM, B/E, T/E)	two	3 years
	one	2 years
Joint Technical Program (T/E)	two	2 years, starts 1 Dec. 2011
Membership (B/E)	one	3 years
Nominations (B/E, T/E)	two	3 years
Penrose Conferences and Field Forums (T/E)	two	3 years
Penrose Medal Award (T/E)	two	3 years
Professional Development (T/E)	one	3 years
Research Grants (B/E, C)	six	3 years
Young Scientist Award (Donath Medal) (T/E)	two	3 years

GSA REPRESENTATIVES TO OTHER ORGANIZATIONS	No. of Vacancies	Length of Term
GSA Representative to the AGI Environmental Geoscience Advisory Committee	one	3 years, starts 1 Jan. 2012
North American Commission on Stratigraphic Nomenclature (NACSN) (AM, possibly B/E)	one	3 years, starts 1 Nov. 2012
U.S. National Committee for Soil Science (USNC/SS)	one	3 years, starts 1 July 2012

GSA Council acknowledges the many member-volunteers who, over the years, have contributed to the Society and to our science through involvement in the affairs of the GSA. Your time, talent, and expertise help build a solid and lasting Society.

AM—Meets at the Annual Meeting • B/E—Meets in Boulder or elsewhere
C—Extensive time commitment required during application review period (15 Feb.–15 Apr. 2012)
T/E—Communicates by phone or electronically

NOTICE

of Spring 2011 GSA Council Meeting

Meetings of the GSA Council are open to Fellows, Members, and Associates of the Society, who may attend as observers, except during executive sessions. Only councilors and officers may speak to agenda items, except by invitation of the chair.

Council will meet next on Friday, 29 April, 1–4:30 p.m.; Saturday, 30 April, 8 a.m.–noon; and Monday, 2 May, 8 a.m.–noon. The GSA corporate meeting will be Friday, 29 April, 4:30–5 p.m. Meeting location: TBA.

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GSA ELECTIONS

GSA's success depends on you—its members—and the work of the officers serving on GSA's Executive Committee and Council.

In early March, you will receive a postcard with instructions for accessing your electronic ballot via our secure website; biographical information on the nominees will be online for you to review at that time. Paper versions of both the ballot and candidate information will also be available.

Please help shape GSA's future by voting on the nominees listed here.

2011 Officer and Council Nominees

PRESIDENT
(July 2011–June 2012)
John W. Geissman
University of Texas at Dallas
Richardson, Texas, USA

VICE PRESIDENT
(July 2011–June 2012)
George H. Davis
University of Arizona
Tucson, Arizona, USA

TREASURER
(July 2011–June 2012)
Jonathan G. Price
Nevada Bureau of Mines & Geology
Reno, Nevada, USA

COUNCILOR POSITION 1
(July 2011–June 2015)
Harvey Thorleifson
University of Minnesota
Minneapolis, Minnesota, USA
Janet S. Herman
University of Virginia
Charlottesville, Virginia, USA

COUNCILOR POSITION 2
(July 2011–June 2015)
Laura F. Serpa
University of Texas at El Paso
El Paso, Texas, USA
Robert J. Tracy
Virginia Polytechnic Institute and State University
Blacksburg, Virginia, USA

COUNCILOR POSITION 3
(July 2011–June 2015)
Russell S. Harmon
U.S. Army Research Office–Environmental Science Division
Research Triangle Park, North Carolina, USA
John M. Holbrook
University of Texas at Arlington
Arlington, Texas, USA

Ballots accepted beginning 10 March 2011
Ballots due electronically or postmarked by 9 April 2011

2011 GSA Section Meetings

Be a part of the geoscience action with ***GSA's spring meetings!***

Pittsburgh, Pennsylvania, USA. Photo courtesy Greater Pittsburgh Chamber of Commerce.

NORTHEASTERN/NORTH-CENTRAL
Joint Meeting

20–22 March 2011 • Pittsburgh, Pennsylvania, USA

Pittsburgh is built around the confluence of the Monongahela and Allegheny Rivers, which join in the city to form the Ohio River. This area offers a variety of geologically interesting venues, including excellent examples of the Allegheny Front separating the Valley and Ridge and Appalachian Plateau Provinces.

Grandfather Mountain; image courtesy North Carolina Tourism.

SOUTHEASTERN

23–25 March 2011 • Wilmington, North Carolina, USA

This meeting will follow the theme "Exploration to Exploitation: Geosciences' Role in Natural Resource Stewardship" and will be held at the new Wilmington Convention Center on the banks of the scenic Cape Fear River, just minutes from the scenic North Carolina coast.

SOUTH-CENTRAL

27–29 March 2011 • New Orleans, Louisiana, USA

Headquarters for this meeting will be at the historic Chateau Bourbon hotel in New Orleans' French Quarter, within easy walking distance of the winding Natchez River. Field trips will assess the impacts of Hurricane Katrina, investigate the effects of sea-level rise on the Louisiana coastal plain, and explore the Cane Bayou by canoe.

New Orleans cityscape, 2007; photo courtesy New Orleans Convention and Visitors Bureau.

ROCKY MOUNTAIN/CORDILLERAN
Joint Meeting

18–20 May 2011 • Logan, Utah, USA

Logan is located at a nexus of western geology, with the Rocky Mountains to the east, the Basin and Range to the west, and the Snake River Plain to the north. Geologic formations near Logan range in age from paleo-Proterozoic to Quaternary and in character from crystalline to karst.

Early registration deadline: 18 April

Old Main on the Utah State University Campus, with the stunning Wellsville Mountains in the background. Photo by Donna Barry.

Find more meeting information at **www.geosociety.org/meetings/** and look for your meeting brochures in the mail.

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Classified Rates—2011

Ads (or cancellations) must reach the GSA advertising office no later than the first of the month, one month prior to the issue in which they are to be published. Contact advertising@geosociety.org, +1.800.472.1988 ext. 1053, or +1.303.357.1053. All correspondence must include complete contact information, including e-mail and mailing addresses. To estimate cost, count 54 characters per line, including punctuation and spaces. Actual cost may differ if you use capitals, boldface type, or special characters. Rates are in U.S. dollars.

Classification	Per Line for 1st month	Per line each addt'l month (same ad)
Positions Open	$8.90	$8.65
Fellowship Opportunities	$8.90	$8.65
Opportunities for Students		
First 25 lines	$0.00	$4.50
Additional lines	$4.50	$4.50

Positions Open

**NSERC – INDUSTRIAL RESEARCH CHAIR
SALT AND CONTINENTAL MARGIN TECTONICS
DEPARTMENT OF EARTH SCIENCES
DALHOUSIE UNIVERSITY**

The Dept. of Earth Sciences at Dalhousie University invites applications for an NSERC Industrial Research Chair (IRC) in Salt and Continental Margin Tectonics from individuals who have demonstrated exceptional promise in their field. Research on salt tectonics and tectono-sedimentary processes on continental margins, related to petroleum exploration and development, is expected to be a focus of the Chair. The anticipated appointment is tenure-track and will be made at a level commensurate with the applicant's experience.

For more information please visit **http://earthsciences.dal.ca/index2.html.**

**FACULTY POSITION IN HYDROGEOLOGY
AUSTIN PEAY STATE UNIVERSITY**

The Dept. of Geosciences at Austin Peay State University, Tennessee, invites applications for a tenure-track position in hydrogeology at the assistant professor level beginning Fall 2011. Details about the position and how to apply can be found at **www.apsu.edu/human-resources/faculty/currentjobopenings.** Information about the department can be found at www.apsu.edu/geosciences.

**THE SUSAN CUNNINGHAM RESEARCH CHAIR
IN GEOLOGY, SCHOOL OF GEOGRAPHY AND
EARTH SCIENCES, MCMASTER UNIVERSITY**

The School of Geography and Earth Sciences (SGES) at McMaster University in Hamilton, Ontario, Canada, invites applications for a full-time tenure track position in sedimentary geology at the assistant or associate professor level beginning 1 July 2011.

McMaster University is among leading Canadian universities with 24,000 full time undergraduate and 3,000 graduate students. SGES has 29 full time faculty members, and has a long tradition of excellence in research and teaching in sedimentary geology. For further information about SGES please visit **www.science.mcmaster.ca/geo/.**

At the time of appointment the successful candidate must have a Ph.D. in earth or environmental sciences, geology, or geophysics and a record of publishing in academic journals. We are particularly interested in an individual with a strong background and research experience in sedimentary basin analysis, physical sedimentology, petroleum geology, seismic/sequence stratigraphy. The applicant should have experience in the application of remote sensing, 3-D subsurface modeling, and quantitative sedimentology and their use in field-based research. The candidate is expected to develop a well-funded, externally recognized, research program; to take a leadership role in the future growth of sedimentary geology within the School; and to enhance linkages and collaboration with industrial partners. The applicant should have a strong commitment to undergraduate/graduate teaching and supervision.

All qualified candidates are encouraged to apply; however Canadians and permanent residents will be considered first for this position. McMaster University is strongly committed to employment equity within its community, and to recruiting a diverse faculty and staff. The University encourages applications from all qualified candidates, including women, members of visible minorities, Aboriginal persons, members of sexual minorities, and persons with disabilities.

Applicants should send a cover letter outlining their research interests, a copy of their curriculum vitae, a brief teaching dossier including a statement of teaching philosophy (max. 2 pages). These materials may be sent as hard copy or electronic copy as a pdf file. Electronic (PDF) copies of no more than three published reprints or works in progress may also be sent to the Chair of the Search Committee by the closing date 30 April 2011. Candidates are required to ensure that three references send letters of recommendation to the Search Committee Chair by the closing date. Evaluation of files will begin on their receipt.

Dr. Bruce Newbold, Chair, Search Committee, School of Geography and Earth Sciences, General Science Building, Room 206, McMaster University, 1280 Main Street West , Hamilton, Ontario, Canada L8S 4K1, +1-905-525-9140, ext. 27948, Fax: +1-905-546-0463, e-mail: newbold@mcmaster.ca.

SUBSURFACE HYDROGEOLOGY/GEOPHYSICS
(OPEN RANK, TENURE-ELIGIBLE)
WICHITA STATE UNIVERSITY

The Dept. of Geology at Wichita State University invites applications for a faculty position in hydrogeology/geophysics beginning August 2011. We are seeking to hire a tenure-eligible assistant professor, but exceptional candidates may be considered at associate or full professor rank. This position is eligible for the A.L. Abercrombie Professorship in Geophysics. In particular, we seek a candidate with research expertise in the application of geophysical methods to environmental and ground water issues, and an interest in sustainability. In addition to developing an externally funded research program, successful candidates will be expected to teach introductory, major, and graduate level classes, including hydrogeology and shallow-earth geophysics. The candidate must have a Ph.D. in the Geosciences, an established record of publication commensurate with the applicant's career stage, and is expected to complement our existing departmental strengths in low-temperature geochemistry, paleontology, petroleum geology, sedimentology, stratigraphy, and structural geology and interact with broader segments of the WSU community.

Candidates must go on line at http://jobs.wichita.edu to apply for the position. Interested applicants should submit cover letter, curriculum vitae, statements of research and teaching interests, and contact information for at least three references. Applicants should also send copies of relevant publications to the Search Committee Chair, Department of Geology, 1845 Fairmount Ave., Wichita State University, Wichita, KS 67260-0027. We will begin review of applications on 15 March 2011; however, applications will be accepted until the position is filled. Wichita State University is an Affirmative Action/Equal Opportunity university. Applicants with an interest in broadening participation in higher education and members of underrepresented groups are encouraged to apply. Offers of employment are contingent upon completion of a satisfactory criminal background check as required by Board of Regents policy. Additional details of the Dept. of Geology and Wichita State University may be viewed at our Web pages: **www.wichita.edu/geology** and **www.wichita.edu**.

DIRECTOR, MUSEUM OF GEOLOGY
AND ASSOCIATE OR PROFESSOR OF
GEOLOGY/GEOLOGICAL ENGINEERING (ME9804)
SOUTH DAKOTA SCHOOL OF
MINES AND TECHNOLOGY

The South Dakota School of Mines and Technology is seeking a Director for the Museum of Geology at the associate or professor level. The Museum of Geology is a research center dedicated to geology and paleontology, which will be pursuing accreditation through the American Association of Museums. The director's responsibilities will include managing the activities of the museum, strengthening museum research and outreach programs, broadly disseminating laboratory activities and research results, writing proposals to obtain competitively awarded grants to fund the Museum, supervising activities of students, faculty, and staff, as well as initiating and sustaining collaborative interactions with faculty, governmental, tribal, and industrial partners. The director will focus on ensuring the continued growth and success of the Museum of Geology as a research center, building upon a foundation provided by a new 33,000-square-foot research facility that houses over 500,000 specimens. Although the majority of the director's time will be committed to administration, opportunities for teaching in paleontology and geology, as well as directing student research, will be available.

An earned doctorate in Paleontology or Geology is required. Prior experience as a Museum Director and/or Curator, as well as experience in developing partnerships between higher education, industry, and government agencies is strongly preferred. Familiarity with federal and tribal regulations, as well as with the responsibilities of supervising and funding a museum is required. A record of established research in vertebrate paleontology with a background in geology and national recognition in the above area(s) as demonstrated by publications and conference participation is required. Ideally, the candidate's research area should complement existing institutional research activities. Evidence of ability to secure external funding and the ability to manage substantial budgets with multiple partners is also required. Candidates must exhibit effective written and verbal communications skills.

The position is a twelve (12) month tenure track faculty appointment. Salary is commensurate with experience and qualifications.

The School of Mines is a public state university offering baccalaureate, masters, and doctoral degrees in science and engineering with a student population of approximately 2,400 traditional and non-traditional learners representing 40 states and 27 countries. The university is located at the foot of the beautiful Black Hills in Rapid City, South Dakota's second largest city. Twenty-five miles from Mount Rushmore, Rapid City has a relatively mild climate and the Black Hills offer numerous opportunities for summer and winter outdoor experiences. For more information regarding Rapid City and the university, visit **http://visitrapidcity.com/ and www.sdsmt.edu.**

The School of Mines is committed to recruiting and retaining a diverse workforce. Individuals interested in this position must apply online at **http://sdmines.sdsmt.edu/sdsmt/employment.** Human Resources can provide accommodation to the online application process and can be reached at +1-605-394-1203. Review of applications will begin 1 April 2011, and will continue until the position is filled. Employment is contingent upon completion of a satisfactory background investigation. This position is funded from other funds and is needed to support the educational and research missions of the university.

SDSM&T is an EEO/AA/ADA employer & provider.

Opportunities for Students

Graduate Student Opportunities in Organic Geochemistry at Baylor University. Paid research and teaching assistantships are available for M.S. and Ph.D. students with interests in organic geochemistry, biogeochemistry, and biofuels. A USDA-funded research position will apply molecular spectroscopy (nuclear magnetic resonance and near infrared spectroscopy) to quantify the impacts of agricultural practices on switchgrass biochemistry and soil carbon cycling. An NSF-funded research position will use ^{13}C nuclear magnetic resonance and stable isotope ratio mass spectrometry to investigate the influence of land-use on river carbon exports. Other research areas include: the role of fire in the Earth system, proxy development and paleoclimate investigations, affects of atmospheric CO_2 concentration on soil biogeochemical processes, fate and transport of nanoparticles in aquatic systems, and soil carbon (biochar) sequestration. Contact Professor Bill Hockaday at William_Hockaday@baylor.edu. Learn more at **http://www.baylor.edu/geology**. Application deadline: 15 March 2011 for fall semester enrollment.

Wanted: Summer Field Paleontologist. The Standing Rock Sioux Tribe is seeking to hire a Summer Field Paleontologist to assist the Tribe's Paleontologist in conducting a summer field camp from June to August 2011. Work will take place in the fossil-rich badlands of South Dakota. The incumbent will be expected to supervise several field assistants and/or volunteers of varying skill and knowledge levels, know and teach various field paleontology methods and techniques, and be able to keep good field notes and documentation of fossil localities. During times of inclement weather, work will be temporarily moved to the Paleontology Lab in Fort Yates, North Dakota, where the incumbent will assist in regular lab work including, fossil preparation and molding and casting. Applicants must have a Bachelor's degree in geology or related field with paleontology field work experience or working on their Master's degree in paleontology (preferred). Ph.D. candidates are also welcome to apply. Must have knowledge of geological and paleontological concepts, methods and techniques. Must be able to lift heavy loads and work under adverse conditions typical for the badlands of South Dakota. Must possess a valid driver's license and be able to provide own transportation to and from the field camp. To apply, please send resume to ashaw@standingrock.org or call Allen Shaw at +1-701-854-3141 for more information.

Fellowship Opportunities

JACKSON POSTDOCTORAL FELLOWS PROGRAM
JACKSON SCHOOL OF GEOSCIENCES
THE UNIVERSITY OF TEXAS AT AUSTIN

The Jackson School of Geosciences (JSG) at The University of Texas at Austin announces a new school-wide postdoctoral fellows program and invites applications for 2011–2012. This highly competitive institutional award is open to recent doctorates (degree within the past three years) in geosciences. We welcome applicants with research interests across the full range of geosciences disciplines. The postdoctoral fellow is expected to pursue their own independent research interests. The appointment is for two years with a salary of US$60,000 per year plus health and dental benefits. Research support of US$10,000 per year is also provided. Successful applicants can begin their program as early as 1 Sept. 2011 but no later than 31 Dec. 2011.

To apply, submit a current CV that includes education, employment history, awards, publications, and extramural funding record, a short (2–3 page) statement of research interests and proposed research, and the names and contact information for three references. Deadline for applications is 15 March 2011. Applicants should send applications electronically as e-mail attachments to PostDocJSG@jsg.utexas.edu.

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BIGHORN BASIN FIELD AWARD

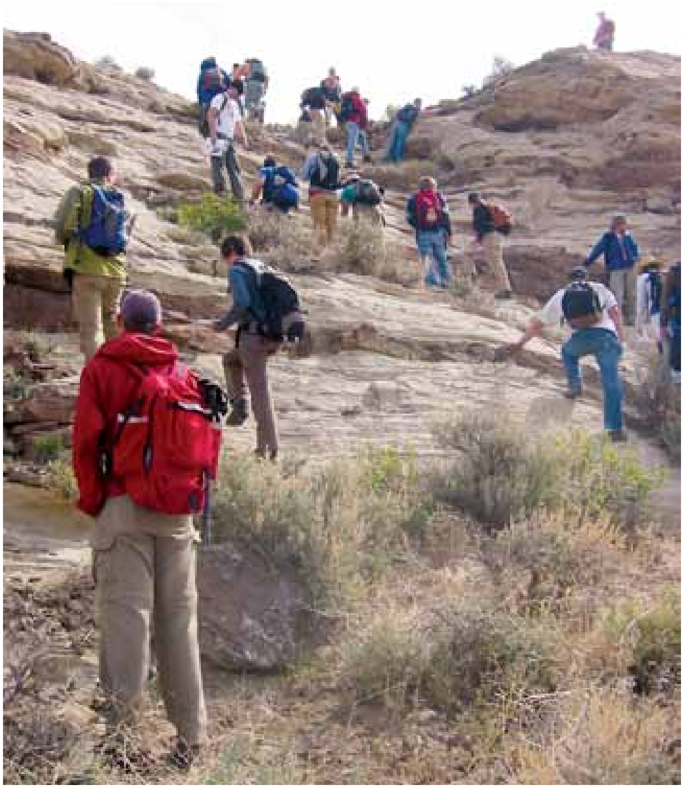
Professional Development Opportunity for Students and Faculty

Award application deadline: 1 April

Field schools have long been a mainstay for geoscience education. They offer an intensive hands-on experience using classroom and laboratory knowledge to solve geological problems in the field. GSA, in cooperation with ExxonMobil, currently offers members a one week field course during which they can learn practical, multidisciplinary, integrated basin exploration. The third annual GSA-ExxonMobil Bighorn Basin Field School Award offers up to 20 undergraduate and graduate students and five faculty members a chance to receive this high-quality educational experience in the spectacular Bighorn Basin of north-central Wyoming, USA. The course is free to accepted participants, and all transportation, meals, and living expenses are covered.

COURSE FORMAT

The Integrated Basin Exploration Field School provides an opportunity to study excellent exposures of individual hydrocarbon system play elements, such as source, seal, reservoir and structure, within a prolific hydrocarbon basin. The school is centered in Cody, Wyoming, USA, surrounded by the Beartooth Mountains, Rattlesnake Mountain, Cedar Mountain, Heart Mountain, and the McCulloch Peaks. Participants will work in teams of four students and one faculty member. The majority of the course is field-based, supplemented by lectures and exercises in the classroom.



For more than a century, the Bighorn Basin has been a focus of study by academic, industry, and government geoscientists, who focused on the exceptional outcrop exposures, as well as subsurface borehole and seismic data. Our current understanding of the basin derives from both industry and academic perspectives. This is not, however, a course on the detailed geology of the Bighorn Basin. Instead, our objectives are to introduce the concepts of integrated basin analysis, including evaluation, prediction, and assessment of play element distribution and quality, using the Bighorn Basin as a natural laboratory. Via this laboratory, we will explore the concepts, methods, and tools of petroleum geoscience used on a day-to-day basis in the energy industry. Discussions on the outcrop and in the classroom will focus on how we make decisions with limited data and how critical information is identified in order to evaluate risk versus uncertainty. We also use the excellent field setting to teach fundamental geoscience skills in structure, stratigraphy, geochemistry, and more.

The importance of integration across disciplines and scales is stressed throughout the course. We will also focus on fundamental basin formation, fill, and evolution processes and their interaction to create play elements from regional to prospect scale. These discussions will include consideration of plate motions, paleogeography, sequence stratigraphy, structural deformation, sedimentology, rock properties, subsurface imaging, burial history, and fluid migration.

By the end of the course, teams will have generated play element maps, play summary charts, cross sections, and play fairway maps. Highlights of this course include the presentation of these ideas to the group and the ensuing discussions about how these ideas and play assessments can be further developed.

INSTRUCTORS

Steve May, Chief Geoscientist, ExxonMobil Upstream Research Co.; Lori Summa, Senior Technical Consultant, ExxonMobil Upstream Research Co.; Bob Stewart, Supervisor, ExxonMobil Exploration Co.; and Gary Gray, Technical Team Leader, ExxonMobil Upstream Research Co. These geoscientists represent over 100 years of research in integrated basin analysis, with specific skills in tectonics, geochemistry, structure, sequence stratigraphy, sedimentology, paleontology, hydrocarbon systems analysis, and integrated play analysis.

APPLICATIONS

Please submit a résumé or curriculum vitae, academic transcripts, two letters of recommendation, and a cover letter by 1 April to http://rock.geosociety.org/ExxonMobilAward. Undergraduates, graduates, and professors are encouraged to apply. **Questions?** Contact Jennifer Nocerino, jnocerino@geosociety.org, +1-303-357-1036.

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Science Articles

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June: P. Hammer, R. Clowes, F. Cook, K. Vasudevan, and A. van der Velden, "The big picture: A lithospheric cross section of the North American continent"

July: P. Reiners, C. Riihimaki, and E. Heffern, "Clinker geochronology, Plio-Pleistocene glaciation, and landscape evolution in the northern Rockies"

Groundwork articles:

In the queue: S. O'Connell and M.A. Holmes, "Obstacles to the recruitment of minorities into the geosciences"

In the queue: J. Libarkin, E.G. Ward, S. Anderson, G. Kortemeyer, and S. Raeburn, "Revisiting the geoscience concept inventory: A call to the community"

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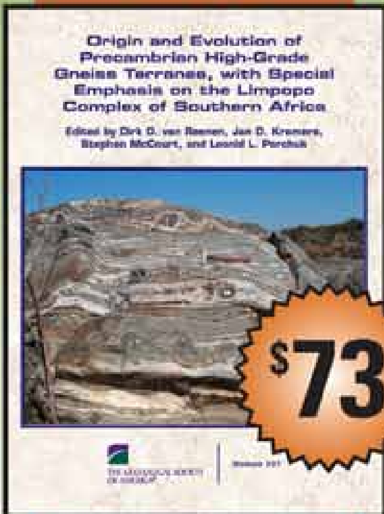
Memoir 207



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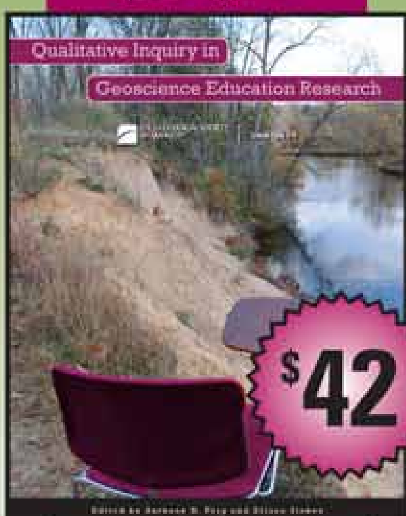
Origin and Evolution of Precambrian High-Grade Gneiss Terranes, with Special Emphasis on the Limpopo Complex of Southern Africa

Edited by Dirk D. van Reenen, Jan D. Kramers, Stephen McCourt, and Leonid L. Perchuk

Many early Precambrian high-grade metamorphic provinces differ subtly from more recent ones, with higher temperatures at shallower depth in the crust. This may in part be attributed to higher crustal heat production. The question of what else might have been different presents a challenge, as the control "everything else being equal" is removed from the experiment. Memoir 207 addresses these issues. The first section deals with mineralogic and petrologic aspects of high-grade metamorphism, including melting and the nature of fluids. Chapters 6 to 13 focus on the Limpopo Complex of southern Africa, with case studies and reviews of its geochronology and crustal evolution, and of the regional structural and burial-exhumation history. Problems of unraveling the effects of successive tectonometamorphic events in a polymetamorphic province are addressed from the geochronologic and the petrologic perspectives. The last two chapters include numerical simulations of lower crustal diapirism in high-grade metamorphism, and a review of tectonic models for the Limpopo Complex. This well-rounded book is relevant to the big question of uniformitarianism in plate tectonics and its effects.

Special Paper 474



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Qualitative Inquiry in Geoscience Education Research

Edited by Anthony D. Feig and Alison Stokes

This Special Paper is for geoscientists and science educators wishing to learn more about qualitative research methodologies and their potential application in geoscience education and geocognition research. The volume presents a diverse range of papers reporting on qualitative and mixed-methods investigations into geoscience education in formal (K–12, undergraduate, and graduate) and informal settings, as well as chapters focusing on theoretical and philosophical aspects of qualitative inquiry. Various tools and approaches are explored, including validity and reliability, phenomenography, ethnography, hermeneutics, grounded theory, mixed-methods approaches, and the construction of models. As well as showcasing recent research, this volume will provide insight into an alternative research approach for those new to, interested in, or even skeptical of qualitative inquiry.

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