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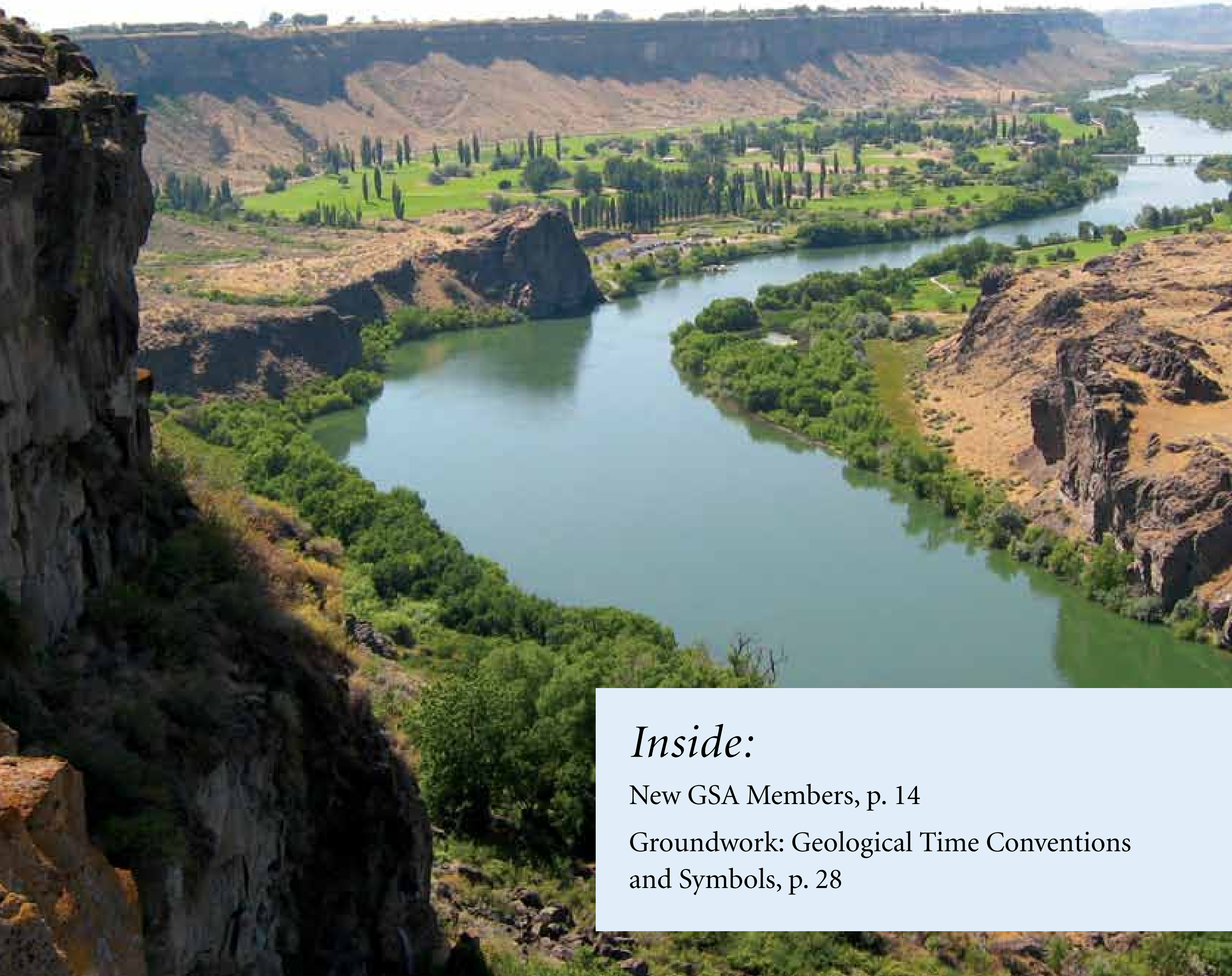
A human-induced hothouse climate?



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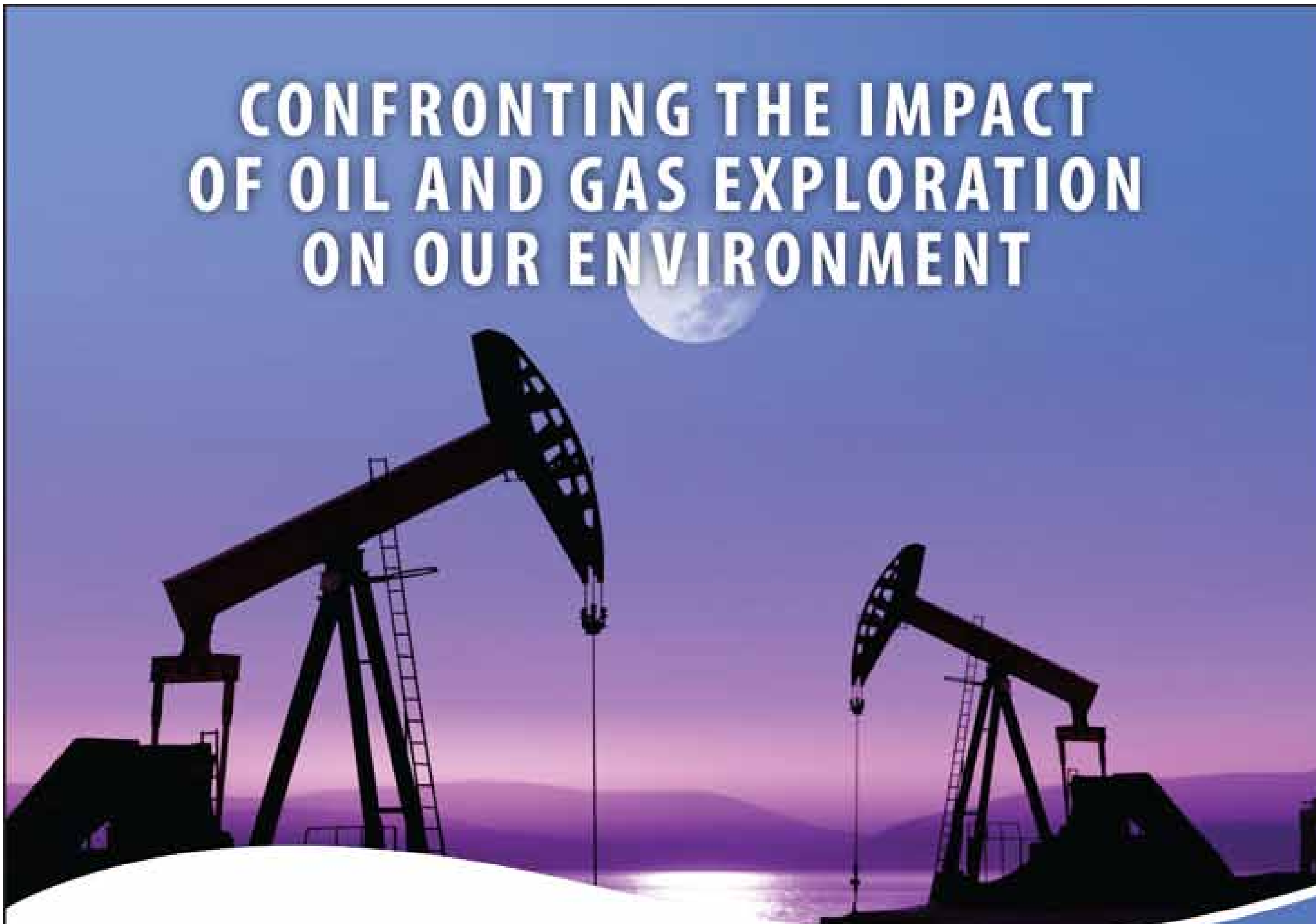

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SCIENCE ARTICLE

Cover: Thick basalts like this exposure in the Snake River Canyon of Idaho are genetically connected with the older Columbia River Basalts. The peak eruptive pulse of the Columbia River Basalts was probably responsible for ~1.5 °C of global warming as the result of releasing, in just over 400,000 years—as much carbon dioxide as human fossil-fuel burning emits in a century at current rates. Older and larger large igneous provinces (LIPs) have been linked to onset of hothouse climate and mass extinction at multiple intervals in Earth's history. The Kidder and Worsley article in this issue explores the interplay between LIPs, warming feedbacks, and cooling feedbacks in considering whether carbon dioxide release via human fossil-fuel burning can force a hothouse climate. (Photo courtesy of K.E.A. Giles.) See related article, p. 4–11.

A human-induced hothouse climate?

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ABSTRACT

Hothouse climate has been approached or achieved more than a dozen times in Phanerozoic history. Geologically rapid onset of hothouses in 10^4–10^5 yr occurs as HEATT (haline euxinic acidic thermal transgression) episodes, which generally persist for less than 1 million years. Greenhouse climate preconditions conducive to hothouse development allowed large igneous provinces (LIPs), combined with positive feedback amplifiers, to force the Earth to the hothouse climate state. The two most significant Cenozoic LIPs (Columbia River Basalts and much larger Early Oligocene Ethiopian Highlands) failed to trigger a hothouse climate from icehouse preconditions, suggesting that such preconditions can limit the impact of CO_2 emissions at the levels and rates of those LIPs.

Human burning of fossil fuels can release as much CO_2 in centuries as do LIPs over 10^4–10^5 yr or longer. Although burning fossil fuels to exhaustion over the next several centuries may not suffice to trigger hothouse conditions, such combustion will probably stimulate enough polar ice melting to tip Earth into a greenhouse climate. Long atmospheric CO_2 residence times will maintain that state for tens of thousands of years.

INTRODUCTION

Human fossil-fuel burning injects CO_2 into Earth's atmosphere at geologically unprecedented rates that far outstrip natural rates of change in CO_2 emissions. Evaluating related warming in coming centuries has warranted considerable scientific attention (e.g., IPCC, 2007, and references therein). The geologic record preserves accounts of ancient warmth beyond the range of human experience and allows investigation of humanity's potential to revive such warmth. For instance, Hay (2011) concluded that human activities and related systemic feedbacks could push Earth's climate into a Mesozoic-like greenhouse climate.

Simulations of ancient climate (e.g., Berner, 2004; Park and Royer, 2011) rely on CO_2 as the master climate-controlling greenhouse gas over the long term. On geological time scales, volcanic emissions provide one critical atmospheric input of this gas. Removal of CO_2 by silicate weathering reactions results in cooling only if the carbon is buried as carbonate minerals and/or organic matter. Compensation for monotonically increasing solar luminosity by CO_2-drawdown feedbacks (e.g., Kasting and Ackerman, 1986; Kiehl and Dickinson, 1987) has been important through Earth history, and has probably confined Earth's Phanerozoic temperature range to the icehouse-greenhouse-hothouse climates discussed herein.

Climate simulations using higher temporal resolution that focus on hot climate intervals known from the geological record are increasingly successful as data sets with higher temporal and spatial resolution from ancient climates become available for model validation and calibration. Although such models have tended to underestimate the degree of ancient warmth (Kiehl, 2011), more accurate simulations are emerging. For example, Kiehl and Shields (2005) used an initial condition of 3550 ppmv (~12× the 280 ppm preindustrial CO_2 level) to accurately simulate Late Permian ocean temperatures and to reproduce predicted greenhouse-style thermohaline circulation. Assumptions of ~16× preindustrial CO_2 levels by Winguth et al. (2010) and by Huber and Caballero (2011) approximate warm climates at the Paleocene-Eocene Thermal Maximum (PETM) and in the Early Eocene, respectively.

Kidder and Worsley (2010) proposed more than a dozen geologically brief (<1 Ma) excursions from greenhouse to hothouse climate in the Phanerozoic (Table 1). These include the PETM and some oceanic anoxic event (OAE) pulses (e.g., Leckie et al., 2002), many of which are interpreted as warming intervals (e.g., Jenkyns, 2003) and have also been linked to LIP activity and extinctions (e.g., Keith, 1982; Kerr, 1998; Wignall, 2001; Keller, 2005). These hothouse pulses coincide with peaks in extinction intensity, and all but the oldest pulses are associated with a LIP trigger and related feedbacks (Table 1). Integration of numerous parameters with Earth's biogeochemical record led us (Kidder and Worsley, 2004, 2010) to suggest that a hothouse climate is not just a greenhouse intensification, but that it functionally differs from a greenhouse in ways that leave recognizable geological evidence. Our hothouse model explains the systemic interplay among factors including warmth, rapid sea-level rise, widespread ocean anoxia, ocean euxinia that reaches the photic zone, ocean acidification, nutrient crises, latitudinal expansion of desert belts, intensification and latitudinal expansion of cyclonic storms, and more. Similarly, Emanuel (2002) noted that distinct climate states are governed by critical feedbacks and interplay among factors such as large-scale atmospheric circulation, clouds, water vapor tropical cyclones, oceanic thermohaline circulation, and atmospheric CO_2.

Can rapid human climate-warming activities force the current icehouse climate into a hothouse climate? The intervals characterized by the two best-known Cenozoic LIPs shed light on the potential climate impact of LIPs as compared with human emissions. We assume that warming and cooling feedbacks (Table 2) are built into these examples, and suggest that the warming effects of the Columbia River Basalts and Ethiopian Highlands LIPs (Table 1) were weakened by icehouse preconditions.

Trajectories of human CO_2 atmospheric inputs needed to reach and/or surpass our suggested boundaries for icehouse, greenhouse, and hothouse climates are also explored. If human fossil fuel emissions can substitute for the LIP emissions that appear to have triggered hothouses under suitable ancient preconditions, a hypothetical range of human-induced climate maxima can be

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TABLE 1. HEATT EPISODES (AND TWO NON-HEATTS), LIPs, AND SELECTED HOTHOUSE-RELATED EFFECTS

HEATT and extinction age (Ma)	LIP and age of peak eruption (Ma)	Approximate extinction intensity (%) (1)	Transgression (3rd Order)	Warming	Anoxia	Euxinia (sub-photic)	Euxinia (photic zone)	$\delta^{13}C$	$\delta^{34}S$ (sulfate)	$\delta^{15}N$ <2‰
Mid-Miocene Climate Optimum no HEATT	Columbia River Basalt (15.6–16.0) (2)	5	y(3)	y(4)	y(4)					
No HEATT	Ethiopian Highlands (29–31)	5								
Paleocene-Eocene Thermal Maximum (55)	NAIP (58–62)	5	y	y	lim	y	y	n		y(5)
End-Cretaceous (65)	Deccan Traps (66)	30	y	y	lim	y	y	n		y
Cenomanian-Turonian OAE 2 (93)	Ontong Java II (86–94)	10	y	y	y	y	y	p/n	p	y
Early Aptian OAE 1a (120)	Ontong Java I (119–125)	5	y	y	y	y	y	p/n		y
Toarcian-Pliensbachian (183)	Karoo-Ferrar (179–183)	10	y	y	y	y	y	n	p(6)	y
End-Triassic (200)	CAMP (200)	30	y	y	y	y	y	n	p/n	y
End-Permian (251)	Siberian Traps (249–251)	55	y	y	y	y	y	n	p	y
Hangenberg (359)	East European Platform (365)	20	y(7)		y(7)	y(7)	y(7)	p(8)		
Frasnian-Famennian (374)	Viluy Traps (ca. 373) (9)	25	y	y	y	y	y	p/n	p	y
Late Ordovician (444)		30	y	y	y		y	n		y
SPICE (499)		40	y(10)	y(11)	y(10)	y(10)		p(10)	p(10)	
Botomian (ca. 520)	Antrim (ca. 510)	40	y		y			n	p	
Ediacaran (542)		?	y		y			n		y

Note: HEATT—haline euxinic acidic thermal transgression; LIP—large igneous province; OAE—oceanic anoxic events; NAIP—North Atlantic igneous province; CAMP—Central Atlantic magmatic province. See Kidder and Worsley (2010) or Large Igneous Provinces Commission website (www.largeigneousprovinces.org) for more complete coverage of LIPs. Symbols are defined as follows: y—yes; p—positive; n—negative; lim—limited. Most information listed in the boxes is referenced in Kidder and Worsley (2010) except for some new references which are keyed to numbers in parentheses as follows, including new age dates on the Viluy LIP: (1) Rohde and Muller (2005); (2) Barry et al. (2010); (3) John et al. (2011); (4) Kender et al. (2009); (5) Knies et al. (2008); (6) Owens et al. (2010); (7) Marynowski and Filipiak (2007); (8) Kaiser et al. (2006); (9) Courtillot et al. (2010); (10) Gill et al. (2011); (11) Elrick et al. (2011).

TABLE 2. EXAMPLES OF WARMING AMPLIFIERS AND COOLING FEEDBACKS TO WARMING

	Estimated time scale (yr)
Warming Amplifiers	
Methane release from tundra, peat, seabed	10^2–10^4
Polar cloud heat retention plus polar precipitation	10^2
Increased mid-latitude insolation as desert belts expand	10^2
Warm-brine sinking	10^2
Polar upwelling of desert-belt generated brine	10^2
High absolute humidity and poleward atmospheric latent heat transport across cloud-free mid-latitudes	10^2
Lower polar albedo with loss of sea ice plus development of polar forests (sea ice was already gone preceding most ancient HEATT episodes)	10^2–10^4
Seafloor geothermal heating-driven polar upwelling via haline mode overturn	10^4
"Tropical" cyclone effects (upwelling, stratospheric water injection, increased poleward heat transport)	10^2–10^4
Cooling Feedbacks to Warming	
Increased silicate weathering and carbonate burial (carbonate burial hampered in acidic oceans)	10^6–10^7
Burial of organic matter in black shales	10^5–10^6

inferred from considering CO_2 emission levels in scenarios such as those of (1) human actions to mitigate climate change, (2) forced mitigation by societal collapse of human economies, and (3) successful rapid exhaustion of fossil-fuel resources.

DEFINING ICEHOUSE, GREENHOUSE, AND HOTHOUSE CLIMATES

Figures 1 and 2 distinguish icehouse, greenhouse, and hothouse climate states. Icehouses have major polar ice caps that calve marine icebergs. A cool greenhouse can have small polar ice caps and Alpine glaciers, but no ice sheets that calve icebergs. Glaciations in the Late Devonian, Late Eocene, and just prior to the Late Ordovician icehouse were probable cool greenhouse climates. A warm greenhouse may have seasonal sea ice as the only polar ice. Thermohaline circulation (Figs. 1 and 2) reflects differing climate states. The "thermal mode" (Zhang et al., 2001) describes the strong pole-driven sinking cold icehouse brines. They acknowledged the weaker polar sinking of brines in the greenhouse climate of the Late Permian as modeled by Hotinski et al. (2001). The "haline mode" describes sinking warm brine driven by evaporation (Zhang et al., 2001). Kidder and Worsley (2004) suggested that such evaporation-driven sinking of brines would be most effective where evaporation in embayments and larger restricted settings (e.g., Mediterranean Sea, Persian Gulf) would feed brines into the deep ocean when pole-driven sinking ceased. Such basins would generate warm brines with increasing potency as transgression expands their surface area (Kidder and Worsley, 2010). Although Zhang et al. (2001) suggested the haline mode was unstable, Kidder and Worsley (2010) proposed that peak LIP forcing can sustain the haline mode.

Other critical changes from icehouse to greenhouse to hothouse (Figs. 1 and 2) include reductions in pole-equator thermal contrast, planetary windbelt velocity, wind shear, and wind erosive power (Kidder and Worsley, 2010). Oceanic anoxia and euxinia expand as climate warms (e.g., Wignall, 2001; Kidder and Worsley, 2004; Wignall et al., 2010), and euxinia moves into the photic zone (e.g., Kump et al., 2005; Kidder and Worsley, 2010) in hothouses. Tropical cyclonic storms strengthen, extend to high

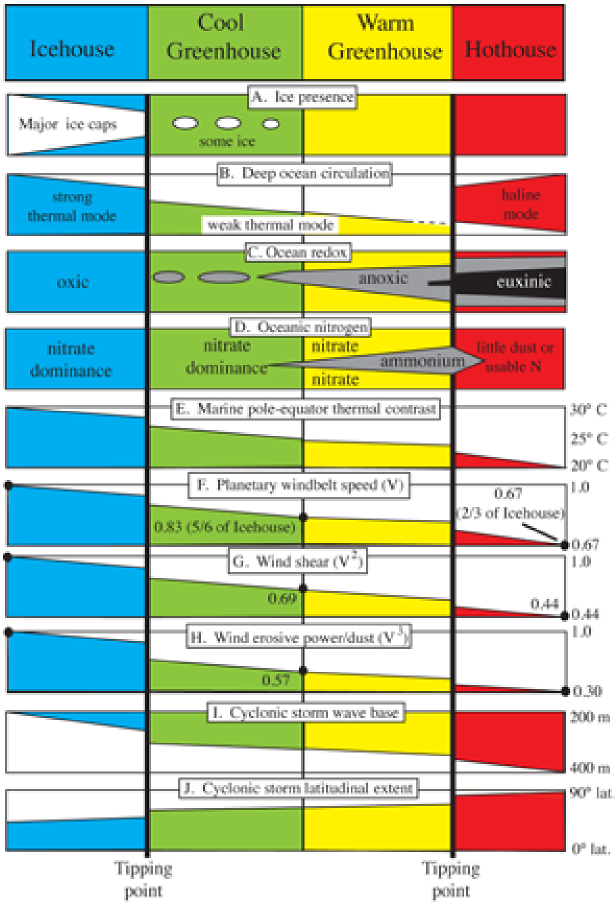

Figure 1. Factors useful in distinguishing icehouse, cool greenhouse, warm greenhouse, and hothouse. Boxes A–D are conceptual. Boxes E–H are based on semiquantitative estimates developed in table 2 of Kidder and Worsley (2010). Approximations in Boxes I and J are supported by modeling of Korty et al. (2008) and by Fedorov et al. (2010), respectively. See text for explanation.

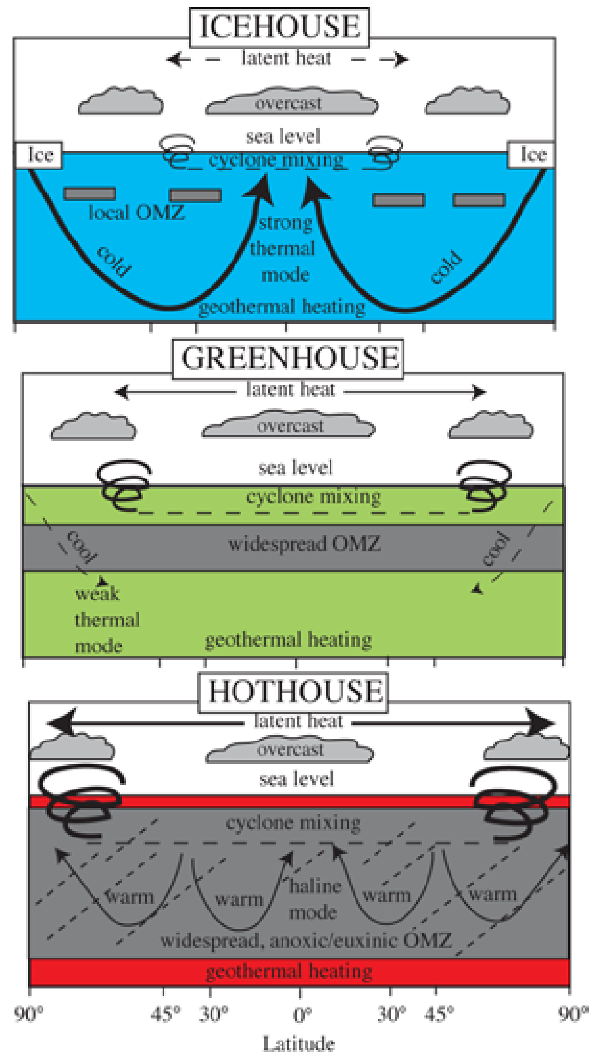

Figure 2. Schematic view of some aspects of icehouse versus greenhouse versus hothouse after Kidder and Worsley (2010). Key factors in the progressive steps from icehouse to hothouse include shifting deep-ocean circulation from thermal to haline mode, expansion of anoxia and euxinia, weakening of planetary windbelts and hence wind-driven upwelling and eolian dust transport to oceans. Also critical is increased cyclonic storm mixing that develops as tropical storms expand their reach to high latitudes and into deeper waters. OMZ—oxygen minimum zone.

latitude, and reach perhaps twice as deeply as those in modern oceans (e.g., Emanuel, 2005; Kidder and Worsley, 2004, 2010; Korty et al., 2008). "Tropical" cyclones that reach polar latitudes help maintain moist and mild climates there by drawing up warm waters via upwelling, thus promoting heat-trapping cloud cover.

Increased polar precipitation generates freshwater runoff (e.g., Kidder and Worsley, 2004, 2010; Sluijs et al., 2011) that can hamper thermal-mode polar deep-water formation. Models for a cap of low-salinity water are consistent with such weakening as polar rainfall and humidity increase in a warming world (e.g., Manabe et al., 1994; Abbot and Tziperman, 2009). Support for such conditions in the geologic record includes a temperate, moist, mid-Pliocene Arctic Ocean (Ballantyne et al., 2010; Fedorov et al., 2010); a warm mid-Miocene Climate Optimum with no coastal ice sheets (e.g., Tripati et al., 2009); a warm Southern Ocean sea surface from mid-Jurassic to Early Cretaceous (Jenkyns et al., 2011); and high-paleolatitude fossil forests at a number of geologic intervals (e.g., Retallack and Alonso-Zarza, 1998; Taylor et al., 2000; Jahren, 2007).

HEATT EPISODES

Kidder and Worsley (2010) proposed that hothouse climates develop via HEATT (haline euxinic acidic thermal transgression) episodes (Fig. 3). The rapid transgression (Table 1; Fig. 3) occurs with deep-ocean warming fed by desert-belt sinking of warm brine, and thermal expansion of ocean water raises relative sea level by up to 20 m. The LIP trigger rapidly emits substantial amounts of carbon dioxide (Fig. 4), but not enough to produce the negative $\delta^{13}C$ excursions (Table 1) that typify most HEATTs (e.g., Erwin, 1993, and references therein). Further warming feedbacks (Table 2) collectively force Earth from HEATT-susceptible warm greenhouse preconditions to a hothouse climate (Kidder and Worsley, 2010).

DID ICEHOUSE PRECONDITIONS WEAKEN THE IMPACT OF TWO CENOZOIC LIPs?

The cooling influences of both collisional orogenesis and the Antarctic circum-polar current and perhaps other icehouse-

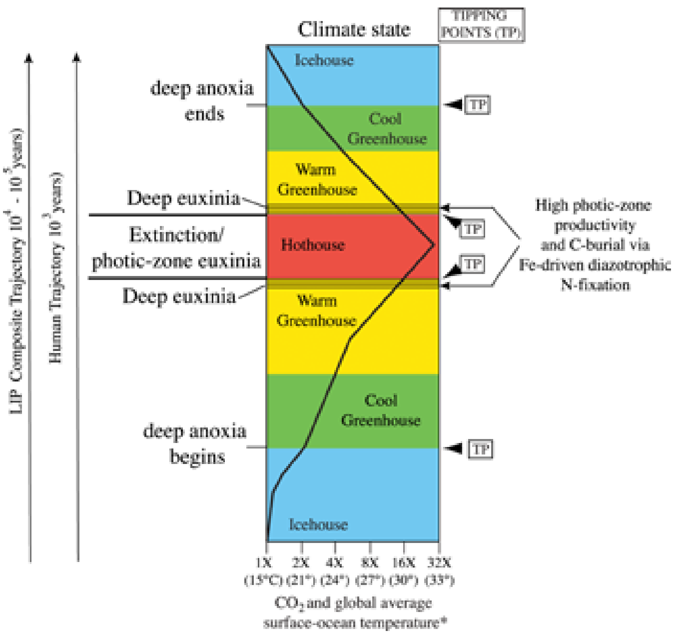

Figure 3. Progression of developments during a HEATT episode after Kidder and Worsley (2010). Icehouse climate sensitivity of Park and Royer (2011) has been adopted. Carbon dioxide thresholds needed for achieving cool greenhouse, warm greenhouse, and hothouse planetary states are suggested using the 280 ppm preindustrial level and today's solar constant. High productivity of diazotrophs and green-algal phytoplankton coupled with increased carbon-burial rate and efficiency as anoxia expands hampers achievement of the HEATT peak unless warming factors and feedbacks can overcome that obstacle. Similar carbon-burial rate after the HEATT peak accelerates cooling from hothouse to warm greenhouse.

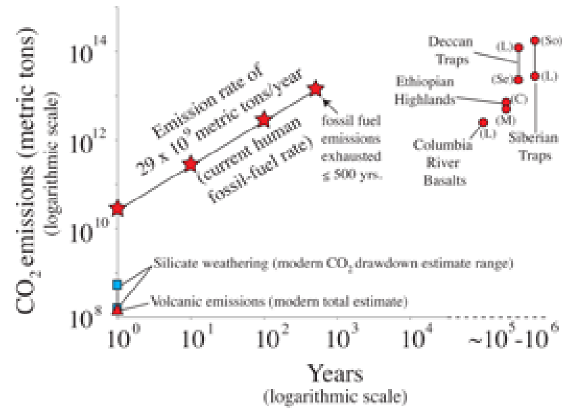

Figure 4. Some CO_2 inputs and outputs to/from Earth's atmosphere. Extrapolated human carbon dioxide emission rates (red stars) (www.eia.gov; U.S. Energy Information Administration, 2010) as compared to selected LIP emission estimates over an assumed duration of 10^5 yr. LIP CO_2 rates were calculated from LIP volume estimates multiplied by 14×10^6 metric tons of CO_2 emitted for each cubic kilometer of basalt (Self et al., 2006). Sources of volume estimates are labeled as follows: L—Large Igneous Province Commission website (www.largeigneousprovinces.org); C—Courtillot et al. (1999); M—Mohr (1983); Se—Self et al. (2006); So—Sobolev et al. (2011). This calculation does not consider amplification by contact metamorphism or clathrate release. Rates of silicate weathering drawdown (blue squares) are from Hilley and Porder (2008). Average annual volcanic emissions (red triangle) are from Williams et al. (1992). Values from Gaillardet and Galy (2008) for silicate weathering drawdown (5.1×10^8 metric tons of CO_2/yr) and volcanic plus metamorphic release (3.0×10^8 metric tons of CO_2/yr) are consistent with values shown in this diagram.

precondition hurdles may have hampered the warming influence of the small Columbia River Basalts (CRB) LIP and the larger Ethiopian Highlands (EH) LIP (Table 1). Larger and older LIPs dwarf these examples in CO_2-emission potential, but both Cenozoic LIPs are closer to potential volumes of human CO_2 emissions (Fig. 4).

Increased silicate weathering during the Himalayan continental collision has long been considered as a stimulus for the onset and sustenance of the enduring (ca. 35 Ma) Cenozoic icehouse (e.g., Chamberlin, 1899; Raymo, 1991). Likewise, Gondwanaland's collision with Laurasia to form Pangea may have triggered and helped to sustain the even longer-lasting (ca. 70 Ma) late Paleozoic icehouse (Kidder and Worsley, 2010). Temporal correlation of these prolonged orogenies with icehouse climate (Kidder and Worsley, 2010) is prima facie evidence for orogenically driven CO_2 drawdown and carbon burial. Climate cooling via Himalayan silicate weathering has been challenged by reports of high rates of metamorphic degassing of CO_2 in orogenic systems (e.g., Evans et al., 2008; Skelton, 2011). Such arguments against orogenically driven cooling need to offer an alternative mechanism for CO_2 drawdown to explain Cenozoic cooling. That organic carbon burial in the Bengal Fan outstrips estimates of Himalayan silicate weathering (France-Lanord and Derry, 1997) points to carbon burial as the bottom line in cooling. Other aspects of Himalayan orogenesis that favor carbon burial (e.g., nutrient release via silicate weathering, stimulation of iron-dust delivery to oceans, and ocean upwelling by monsoonal winds) need more thorough tracking to better account for the overall impact of the Himalayas on the carbon cycle.

You et al. (2009) noted global average temperature during the Middle Miocene Climate Optimum (MMCO) was ~3 °C warmer than at present, suggesting the MMCO as an analog to predicted warming over the next century. Deep ocean Miocene warming by <2 °C (Zachos et al., 2001) is consistent with a global average model temperature increase of ~1.5 °C (Herold et al., 2012) and a rise in atmospheric CO_2 during the MMCO coincided with the eruption of the CRB LIP (Zachos et al., 2001; Kender et al., 2009; You et al., 2009; Barry et al., 2010). The CO_2 increase may have been only ~50 ppm (Tripati et al., 2009) to 100 ppm (Kürschner et al., 2008) higher than pre-MMCO levels. CO_2 emissions from this LIP were probably insufficient to force a hothouse climate, but the CRB probably emitted as much CO_2 as human fossil-fuel burning will release in the next century (Fig. 4). Miocene Earth-cooling preconditions may have offset the CRB emissions in pulses distributed over >400,000 yr (Self et al., 2006; Barry et al., 2010). The Miocene atmospheric CO_2 gain of 50–100 ppm has already been surpassed by the 110 ppm increase since the nineteenth century.

The larger Ethiopian Highlands (Afar) LIP has an estimated eruptive volume 2×–3× larger than the CRB (Fig. 4). Despite the correspondingly larger volume of calculated CO_2 emissions (Fig. 4), the EH LIP failed to warm climate even at its eruptive peak, which occurred just after the establishment of the Antarctic ice cap. This volcanism began ca. 31 Ma, peaked at ca. 30 Ma, and then declined to lower levels of activity that persist today as part of the Red Sea system (e.g., Courtillot et al., 1999). This LIP volcanism followed sharp cooling at the end of the Eocene that lasted from ca. 34 to 33 Ma (Zachos et al., 2001) as the Antarctic ice cap formed and expanded. That sharp Oi-1 cooling episode

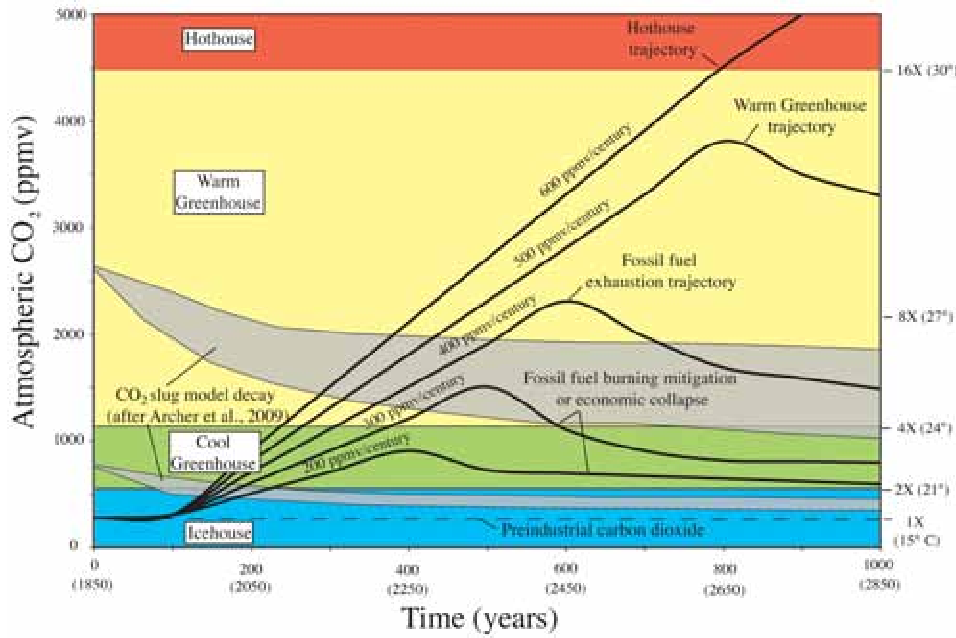

Figure 5. Projected examples of a range of future carbon dioxide emission scenarios plotted against the backdrop of climate state thresholds taken from Figure 3. The carbon dioxide trajectory curves begin with an assumed rate increasing CO_2 by 200 ppmv/century (our modern rate of 2 ppm/yr). The other curves show the hypothetical effect of increasing that rate by increments of 100 ppmv/century when plotted against the icehouse, greenhouse, hothouse thresholds developed herein. We assume various reasons for initiation of curve declines (e.g., human intervention, economic collapse, exhaustion of fossil fuels). Atmospheric declines in CO_2 with time approximate model results of Archer et al. (2009) that show increasing residence time of CO_2 as the size an instantaneous slug (injection) increases. The starting point for the Archer et al. (2009) CO_2 injections is arbitrarily placed at 1850 so as to distinguish those slugs from the slower rates of human injection shown by the trajectory curves. We follow the suggestion of Park and Royer (2011) that temperature sensitivity to CO_2 doublings is more substantial in icehouses (6–8 °C) than in warmer climate states (3–4 °C). We adopt the low end of both sensitivity ranges in this figure.

(Zachos et al., 2001) was followed by warming of deep ocean waters by ~2–3 °C from ca. 33 to 32 Ma. This warming occurred *before* the EH LIP eruptions. Warming did not intensify with the onset of the LIP, suggesting that it could not disrupt the icehouse precondition established with the formation of the Antarctic ice cap. A likely supporting cooling factor was the thermal isolation of Antarctica via development of the circum-polar Antarctic current as the Tasmanian Gateway opened and deepened (Kennett et al., 1974; Katz et al., 2011). An ocean-isolated polar continent is a unique configuration for the Phanerozoic. Its cooling effect plus that of the Himalayan cooling influence discussed earlier may have weakened the climate impact of both the CRB and EH eruptive pulses at their respective rates and magnitudes of CO_2 emission.

TIPPING TOWARD A HOTHOUSE?

Forcing a hothouse requires melting of all polar ice and the breakdown of the thermal mode of oceanic deep-water circulation. Only then can desert-belt evaporation drive the haline mode. Modern polar glaciers are melting unexpectedly rapidly, particularly when water drains beneath them (e.g., Overpeck et al., 2006; Chen et al., 2009). This water accelerates melting and lubricates glacial flow, speeding outlet glaciers toward the sea. The predicted rapid breakup of Antarctic ice shelves (Mercer, 1970) has been under way since the 1990s. Removal of this ice-shelf barrier allows seaward acceleration of glacial flow (e.g., Overpeck et al., 2006). However, as long as sufficient seasonal sea ice forms and evaporative katabatic winds from ice caps are maintained, polar sinking of brines will sustain the thermal circulation mode. Sinking boreal brines will diminish with the loss of the Greenland ice sheet and perennial Arctic sea-ice, leaving the colder and concurrently weakening austral system as the only significant cold-brine generator. The modern circum-polar current that thermally isolates Antarctica from warm surface currents favors a dry polar climate with little cloud cover (Fig. 2), resulting in significant radiative heat loss, which helps keep the polar climate colder than a moist polar atmosphere characterized by higher relative overcast (Fig. 2).

GEOLOGICAL UPTAKE AND EMISSION OF CARBON DIOXIDE

Geological uptake and emission of CO_2 are difficult to measure precisely. Modern volcanic CO_2 is apparently emitted more slowly than silicate weathering draws down CO_2 (Fig. 4), but both sets of estimates are difficult to project because of the very short baseline from which to extrapolate. Nevertheless, geologically rapid injection of CO_2 into the atmosphere by LIPs and associated feedbacks (Table 2) probably overwhelms cooling feedbacks sufficiently to force climate from a greenhouse to hothouse state in some cases.

The CO_2 contribution of LIPs with known volumes can be crudely estimated (Fig. 4) via the Self et al. (2006) suggestion that each cubic kilometer of basalt erupted releases 14 million metric tons (T) of CO_2 to the atmosphere. Self et al. (2006) proposed that much LIP activity may occur as short (10–50 yr) pulses, separated by long intervals. Barry et al. (2010) suggest that eruptive pulses during the 420 ka of the most voluminous phase of CRB outpourings were separated by hiatuses averaging 4 ka.

Atmospheric retention of 15%–35% of a slug (instantaneous model injection) of CO_2 for at least 10,000 yr (Archer et al., 2009) is governed by factors such as seawater uptake, reaction with seawater carbonates, and silicate weathering. Therefore, if successive LIP basalt eruptions average <10^4 yr in recurrence frequency (Barry et al., 2010), total atmospheric CO_2 will build with each successive eruption. The two CO_2 slugs of Archer et al. (2009) are portrayed in Figure 5. The smaller (1000 Pg of carbon) slug represents past human CO_2 emissions plus those expected by the end of the twenty-first century. The larger (5000 Pg C) slug is that expected from burning "the entire reservoir" of fossil fuels. A warming ocean's ability to absorb CO_2 weakens, and its $CaCO_3$ will likely dissolve more slowly than model predictions (e.g., Hay, 2011). Silicate weathering rates can increase in warm, CO_2-rich atmospheres (e.g., Walker and Kasting, 1992; Lenton and Britton, 2006). Still, Lenton and Britton (2006) suggested that >1 million years are needed to return atmospheric CO_2 to the levels present before an emission slug.

Self et al. (2006) proposed that silicate weathering of LIP basalts would minimize warming by quickly drawing down CO_2. However, silicate-weathering rates are probably too slow to draw down atmospheric CO_2 rapidly enough to negate warming effects (e.g., Lenton and Britton, 2006; Archer et al., 2009). Furthermore, much of the LIP basalt will be buried beneath the youngest basalt flows, allowing chemical weathering of only a small fraction of the basalt. Nevertheless, geologically rapid cooling is evident during at least some waning HEATT episodes such as the Cenomanian/Turonian OAE. We suggest that such cooling may be biologically driven as diazotrophic (N-fixing) cyanobacteria capitalize on iron-rich anoxic waters. These and associated green-algal phytoplankton will stimulate a pulse of organic carbon burial and cooling as euxinia reverts to anoxia as sulfide in the ocean's water column is buried (Fig. 3). For example, rapid cooling during the Cenomanian/Turonian OAE (e.g., Jenkyns, 2003) was probably driven by rapid organic carbon burial during waning of a HEATT episode driven by the oceanic Ontong-Java LIP (Table 1) that would weather slowly underwater (e.g., Berner, 2004). However, rapid organic matter burial in the absence of carbonate burial in acidic oceans may only compensate for the temporary loss of carbonate burial and may not greatly increase carbon burial. See Kidder and Worsley (2010) for further discussion of anoxia, euxinia, and N-fixing as applied to onset and decline of hothouse climates.

HOW MUCH CAN HUMANS FORCE CLIMATE?

Human fossil-fuel emissions (even without factors such as methane release, forest destruction, and cement production) can rival, in centuries, the CO_2 that LIPs emit over 10^4–10^5 yr or more (Fig. 4). Continued current rates of CO_2 emission from fossil fuel burning will, in ~100 yr, match the CO_2 release from the entire CRB LIP (Fig. 4). Fossil fuels would be exhausted before their emissions approach the totals of larger LIPs such as the Deccan Traps or the Siberian Traps (Fig. 4). This crude order-of-magnitude discussion shows that human rates of CO_2 emissions outstrip LIP volcanic emission rates by two orders of magnitude and outcompete silicate-weathering rates and organic matter burial feedback, even during the ongoing Himalayan orogeny.

Figure 5 projects CO_2 trajectories against the backdrop of icehouse-greenhouse-hothouse boundaries shown in Figure 3. Direct human input of CO_2 to the atmosphere will diminish sharply with mitigation, societal collapse, or fossil fuel exhaustion. Feedbacks such as methane emissions will likely amplify warming if they are fast enough, but the hothouse trajectory would probably require more than methane (e.g., Cui et al., 2011; Kump, 2011). Although the maximum potential human emissions of CO_2 will surpass those of the CRB, the duration will be so short in comparison (Fig. 4) that some positive feedbacks in the Earth system (Table 2) may not have time to establish a hothouse. For example, the rapidly initiated PETM did not develop as fully as other HEATTs (Kidder and Worsley, 2010), probably because its trigger was not sustained even amid HEATT-favoring preconditions. Even the 20,000-yr warm-up modeled by Cui et al. (2011) is probably short compared to older HEATTs. So, even if a human-induced hothouse is unlikely, a warm greenhouse may develop as high CO_2 emission rates overwhelm the "protection" exercised by the present icehouse precondition. Pushing the planet from a cool greenhouse to a warm greenhouse will require melting of all Antarctic ice. We speculate that the circum-polar current may hamper this melting, given the failure of the CRB and EH LIPs to melt the smaller-than-modern Antarctic ice cap. Long residence times modeled for atmospheric CO_2 (Archer et al., 2009) would sustain warmth, allowing slow-acting factors such as deep-ocean circulation to adjust. However, such long residence times were in force during and after the CRB and EH LIP eruptions. Furthermore, warming feedbacks (Table 2) would have been active during the CRB and EH eruptions. The higher-than-modern rates of atmospheric CO_2 increase needed to reach a warm greenhouse in centuries (Fig. 5) would require those feedbacks. Figure 5 suggests that, as Earth warms, it becomes increasingly insensitive to CO_2 forcing as atmospheric CO_2 levels rise. For example, doubling CO_2 from 280 to 560 ppm yields an approximate global average temperature increase of 6 °C (Fig. 5). Note that sensitivity to CO_2 doublings is higher in icehouses than in warmer climates (Park and Royer, 2011). Doubling CO_2 at higher values (e.g., 2200–4400 ppm) raises global average temperature by ~3 °C. Even though the rate of warming slows, the higher CO_2 levels ensure that warmth will probably persist for millennia (Archer et al., 2009; Fig. 5).

Finally, humans may not burn all fossil fuels. A hopeful reason is that energy and carbon strategies will reduce atmospheric CO_2 emissions. A pessimistic view is that calamities such as floods, droughts, crop losses, cyclones, and sea level that rises tens of meters will displace populations. Human migrations, conflicts, and economic crises will sharply curtail fossil fuel emissions.

CONCLUSIONS

Humans can raise global atmospheric CO_2 to levels known from much warmer ancient climates (e.g., Hay, 2011; Kiehl, 2011). Conditions in some of those warm climates will probably be achieved if current levels of carbon emissions continue, although precise prediction of the degree and rate of warming is difficult. A cool greenhouse similar to the MMCO in which the tropics and deep sea warm, most northern ice melts, and perhaps half of the Antarctic ice disappears appears possible within centuries. A warm greenhouse is also possible, although reaching it faces steeper precondition hurdles.

We suspect it will be difficult for humans to force Earth from the current icehouse to a hothouse. The likely cool greenhouse in which about half of Antarctica is still ice-covered means devastation from the tens of meters sea level is likely to rise (e.g., Ward, 2010), and poleward shifting of warm climate belts. Although a hothouse may not occur because economic crises or intentional climate-mitigating efforts by humans or fossil-fuel exhaustion limit greenhouse gas emissions, even a cool greenhouse climate will severely disrupt many societies and economies.

Feedbacks (Table 2) and still-unknown amplifiers will ultimately control just how far humans can force climate toward a hothouse. Uncertainties over these feedbacks should not distract us from the likelihood that a cool greenhouse seems imminent within perhaps a century or two. Long atmospheric CO_2 residence times will probably keep Earth from returning to an icehouse for centuries to millennia unless active removal of CO_2 from the atmosphere is undertaken.

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- **Coal Division** *Gilbert H. Cady Award.* Submit three copies of the following to Jack C. Pashin, Energy Investigations Program, Geological Survey of Alabama, P.O. Box 869999, Tuscaloosa, AL 35486-6999; jpashin@gsa.state.al.us: (1) name, office or title, and affiliation of the nominee; (2) date and place of birth; (3) education, degree(s), honors, and awards; (4) major events in his or her professional career; and (5) a brief bibliography noting outstanding achievements and accomplishments in coal geology that warrant recognition.

Deadline: 2 April

- **Quaternary Geology and Geomorphology Division** *Farouk El-Baz Award for Desert Research.* Submit nominations of colleagues who have demonstrated excellence in desert geomorphology research to Jim O'Connor, U.S. Geological Survey, 2130 SW 5th Ave., Portland, OR 97201, USA; oconnor@usgs.gov. Nominations should include (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. Please submit via e-mail; hardcopy submission must be previously approved.

THE GEOLOGICAL SOCIETY OF AMERICA®

STUDENT GRANTS, AWARDS & SCHOLARSHIPS

Deadline: 15 March

- **Antoinette Lierman Medlin Scholarship in Coal Geology:** GSA's Coal Geology Division offers two scholarships: (1) Financial support of ~US$2,000 for one year for full-time students involved in coal geology research; and (2) a field study award of ~US$1,500. In addition, recipients may receive a stipend to present their results at the 2012 or 2013 GSA Annual Meeting. Students may apply for both awards but may receive only one. To apply, send five copies of the following to Margo Corum, USGS Eastern Energy Resources Science Center, 12201 Sunrise Valley Dr., Reston, VA 20192-0002, USA; mcorum@usgs.gov: (1) a cover letter indicating the award(s) sought; (2) a concise (five or fewer double-spaced pages, incl. references) statement of objectives and methods and an explanation of how the scholarship funds will be used to enhance the project; and (3) a letter of recommendation from the student's advisor that includes a statement of financial need and the amount and nature of other available funding for the research/field study.

Deadline: 1 May

- **History and Philosophy of Geology Student Award:** The GSA History and Philosophy of Geology Division offers a US$1,000 award for proposals from students for presentations at a future GSA Annual Meeting. The topic of the proposed presentation may be, but is not limited to, (1) the history of geology; (2) a literature review of ideas for a technical work or thesis/dissertation; or (3) some imaginative aspect of the history of geology we have not thought of before. The application and guidelines are online at **http://gsahist.org/HoGaward/awards.htm.** If you have questions, please contact the Division secretary-treasurer, Jane P. Davidson, jdhexen@unr.edu.

2012 JOHN C. FRYE ENVIRONMENTAL GEOLOGY AWARD

Deadline: 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 one of the state geological surveys. **Please send nominations to** GSA Grants, Awards, and Recognition, P.O. Box 9140, Boulder, CO 80301-9140, USA. Learn more at www.geosociety.org/awards/fryhow.htm.

THE GEOLOGICAL SOCIETY OF AMERICA®

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 Web site, and 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 continue to shape GSA's future by voting on the nominees listed here.

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Elections begin 10 March; ballots must be submitted electronically or postmarked by 8 April 2012.

Students and Early Career Scientists, IGC Travel Grant and Mentoring Program

Brisbane, Australia
5–10 August 2012

The Geological Society of America is accepting applications for the 34th IGC Students and Early Career Scientists Travel Grant and Mentoring Program. This program is organized in collaboration with the U.S. National Committee for Geological Sciences (National Academy of Sciences). To be eligible, applicants must be U.S. residents or citizens and be enrolled in or employed at a U.S. institution. Early career scientists are defined as those within seven years of receiving their Ph.D. Each award is anticipated to be a maximum of US$3,000.

Applications open 12 Dec. at **www.geosociety.org/grants/travel.htm.** In addition to the online form, the following supplemental information is required: a cover letter addressing reasons for attending the meeting and a prioritized budget of expenses; proof of abstract submission and a copy of the submitted abstract; and two letters of reference.

The online application and supplemental material must be received electronically no later than **17 Feb. 2012**. Applicants will be notified of the results by 15 Apr. 2012.

Questions?
Please contact Jennifer Nocerino,
jnocerino@geosociety.org.

Sponsored by: Board on International Scientific Organizations U.S. National Committee for Geological Sciences; AGI American Geosciences Institute; The Geological Society of America®; GSA Foundation

Welcome New GSA Members!

The following individuals submitted their applications for GSA membership between February and July 2011 and were approved by GSA Council during the 2011 GSA Annual Meeting & Exposition in October.

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Michael A. Maguigan
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Marko Manojlovic
Matthew J. Manor
Karen Marchal
Andre Marconato
Nicole L. Marin
Thomas Mark
Michael Martin
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Nathan Mathabane
Maren G. Mathisen
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Jason McAnulty
Lee McAuliffe
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Graham A. Meese
Esmel H. Meledje
Fanyu Meng
Audrey Mennenga
Matthew Mercuri
Ross G. Merieski
Christopher K. Mew
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Matthew C. Meyer
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Laura C. Sorey
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Kyra J. Soto
Edward G. Southwick
Katherine G. Sowards
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Jordyn A. Spizale
Ian Springer
Max Stafford-Glenn
Adrian C. Stanciu
Chris Stanford
Benjamin R. Staudt
Victoria A. Stempniewicz
Benjamin T. Stencil
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Molly M. Stetz
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Adam Storey
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Erin M. Weber
Mary Weber
Nicole L. Webster

2012

SOUTH-CENTRAL
8–9 March
Alpine, Texas, USA
Local Committee Chair: Kevin Urbanczyk
Early reg. deadline: 6 Feb. 2012

NORTHEASTERN
18–20 March
Hartford, Connecticut, USA
Local Committee Chair: Jean Crespi
Early reg. deadline: 13 Feb. 2012

CORDILLERAN
29–31 March
Querétaro, Mexico
Local Committee Chair: Luca Ferrari
Early reg. deadline: 27 Feb. 2012

SOUTHEASTERN
1–2 April
Asheville, North Carolina, USA
Local Committee Co-Chairs: Blair Tormey; Cheryl Waters-Tormey
Early reg. deadline: 27 Feb. 2012

NORTH-CENTRAL
23–24 April
Dayton, Ohio, USA
Local Committee Chair: Charles Ciampaglio
Early reg. deadline: 19 Mar. 2012

ROCKY MOUNTAIN
9–11 May
Albuquerque, New Mexico, USA
Local Committee Chair: Laura Crossey
Abstracts deadline: 14 Feb. 2012
Early reg. deadline: 9 Apr. 2012

GSA Section Meeting Schedule

Randol L. Wehrbein
Fu Wang Wei
Jeremy H. Wei
Jin Weimin
Beau W. Weise
Rachel B. Weiss
Earl L. Wells
Shane Wells
Cody C. Wendt
Quinn C. Wenning
Merissa A. Wert
Bradley G. West
Joline C. Whalen
Ashley L. White
Elizabeth J. White
Shawna E. White
Amie Whitlock
Sheila Wilhelmi
Christie L. Wilkins
Drew J. Williams
Michelle Williams
Jake T. Willingham
Ashley Willis
Sarah J. Wilson
Denny Wind
Emily J. Wivell
James R. Woodburn
Elliott C. Woods
Danielle R. Worthen
Quinn Wrenholt
Zachary Wright
Rosemarie Wrigley
Guangliang Wu
Nanping Wu
Zhongwei Wu
Michael P. Wuttke
Nurul S. Yahaya
Jaclyn M. Yamrich
Marcella Yant
Evan M. Young
Michael Youtz
Stephanie Zaborac-Reed
Justin Zabrecky
Yulliana Zazueta
Anthony Zepeda
Yushi R. Zhao
Lu Zhu
Alice Zicht
Margaret A. Zimmer
Valerie L. Zimmer
Stefano Zincone
Lucas Zoet

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Sheryl Barker
Vincent Beck
Kareen Borders
Michelle L. Bresett
John M. Brown
Sharon N. Feldstein
Kevin Ford
Neal F. Garner
James A. Gulick II
Alireza Hajian
Shannon M. Hendricks
Laura R. Hickey
Laura K. Hollister
Lynne W. Hope
Jennifer E. Judkins Jr.
Penny Kelly
Linda M. Khandro
Eugene A. Kindt
Kimberly S. Kirchoff-Stein
Michael P. Klimetz
Debra S. Kogelman
Jon M. Krawiec
Monica M. Kuhlman
Laurie Lee
David B. Markham
Argie J. Miller
Michele Rue
Paul H. Ruscher
Chris A. Stanton
Kevin Swanson
Margo Rae Ungricht
Constance A. Ward
Mardes J. York

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Roger A. Anderson
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Stuart L. Ashley
Gail T. Bansak
James M. Baumgras
Paul C. Benoit
Madeline J. Bryant
Todd Carefoot
Shelia B. Cassidy
Nathan A. Collins
Ray Covington
Steven D. Curry
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Harry de Lahunta
Aileen Fell
Linda Fountain
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Ken C. Gourley
Robert W. Gowland
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Robert Hergenrother
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Robert Kass
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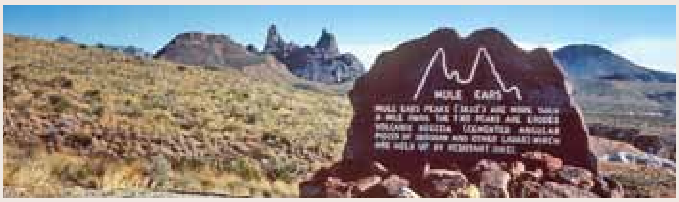
D. Peter Reedy
Luke Rosier
Van Sauvé
William Shaw
Mary Sheahan
Robert J. Stirnkorb
Sandra B. Sylvester
Dale E. Thomas
Mark E. Thomas
Piers Tonge
James P. Tuthill
Theresa E. Tweet
Roger W. Vaught
Clint C. Whitmer
Kasun T. Wickramanayake
Molly J. Wicks
Edward A. Wiese
Michael Wolfe

▸▸ 2012 Section Meeting Mentor Programs ◂◂

Plan now to attend a Shlemon and/or a Mann Mentor luncheon at your 2012 Section Meeting to chat one-on-one with professional geoscientists. These volunteers will answer your questions and share insights on how to get a job after graduation.

Lunches served at these events are FREE. Students will receive lunch tickets with their registration badge. These events are very popular, and space is limited, so try to arrive early to ensure your participation.

The John Mann Mentors in Applied Hydrogeology Program is designed to acquaint undergraduate, graduate, and recent graduate students with careers in applied hydrogeology through mentoring opportunities with practicing professionals. The Roy J. Shlemon Mentor Program in Applied Geoscience is designed to acquaint advanced undergraduate and beginning graduate students with careers in applied geoscience. For further information, contact Jennifer Nocerino at jnocerino@geosociety.org.



SOUTH-CENTRAL SECTION MEETING
8–9 March • Alpine, Texas, USA
Shlemon Mentors Luncheon: Thurs., 8 March
Mann Mentors Luncheon: Fri., 9 March

Big Bend, Alpine, Texas. Photo courtesy USGS.

NORTHEASTERN SECTION MEETING
18–20 March • Hartford, Connecticut, USA
Shlemon Mentors Luncheons: Sun. & Mon., 18 & 19 March
Mann Mentors Luncheon: Tues., 20 March

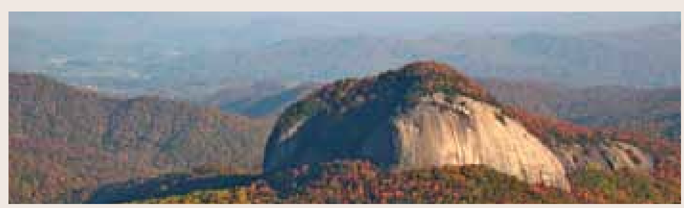
Boudins in metaigneous rocks, Tolland, Connecticut. Photo by Tim Byrne.

CORDILLERAN SECTION MEETING
29–31 March • Querétaro, México
Shlemon Mentors Luncheon: Thurs., 29 March
Mann Mentors Luncheon: Fri., 30 March

Spectacular skies over Querétaro, México. Photo by Michelangelo Martini.

SOUTHEASTERN SECTION MEETING
1–2 April • Asheville, North Carolina, USA
Shlemon Mentors Luncheon: Sun., 1 April
Mann Mentors Luncheon: Mon., 2 April

Looking Glass Rock. Photo courtesy Blair Tormey.



NORTH-CENTRAL SECTION MEETING
23–24 April • Dayton, Ohio, USA
Shlemon Mentors Luncheon: Mon., 23 April
Mann Mentors Luncheon: Tues., 24 April

Wright Flyer with crowd. Photo courtesy Dayton Montgomery County and Visitors Bureau.

ROCKY MOUNTAIN SECTION MEETING
9–11 May • Albuquerque, New Mexico, USA
Shlemon Mentors Luncheon: Thurs., 10 May
Mann Mentors Luncheon: Fri., 11 May

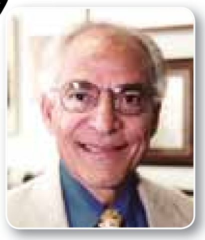
Petroglyph National Monument. Credit: Petroglyph National Monument.

▸▸ STUDENTS—*Mark Your Calendars!* ◂◂

GSA Foundation Update

Donna L. Russell, Director of Operations

The Farouk El-Baz Student Award Fund



Farouk El-Baz

Established in 2007, the purpose of the Farouk El-Baz Student Award Fund is to encourage and promote desert research throughout the world. Up to two students are awarded US$2,500 each, based on a proposal for arid land research and a recommendation from an advisor. Disbursements of income from the Fund are awarded annually. A special Committee, appointed by the GSA International Section, selects the recipients.

Here are the recipients of the El-Baz Student Award since 2008:

2011 Recipients

Jessica R. Norman
University of South Florida
For "The role of biogenic versus lithogenic carbon in pedogenic carbonate formation."

Ahmed El-Sayed Gaber
Tohoku University
For "Assessing the natural resources at some localities in Egypt by using the optical / microwave remote sensing and 3D GPR."

2010 Recipients

Justine R. Cullen
University of the Fraser Valley
For "Determining an optimal protocol for optically-stimulated luminescence of sand dunes in the drylands of central Canada."

Stefan Thomas Knopp
University of Calgary
For "Near-surface diagenetic processes and their implication for landscape evolution in desert environments."

2009 Recipients

Christopher J. Hein
Boston University
For "Sea Level Changes and the Regressive Wadi Infilling of a Pharaonic Harbor."

Sarah W. Keenan
University of Bristol
For "Rare earth elements and rates of fossilization in dinosaur bones from various depositional environments of the late Cretaceous of Montana."

2008 Recipients

Alexander Rohrmann
University of Arizona
Alexander was the first recipient of the Farouk El-Baz Student Research Award, to encourage and promote desert research.

Amanda J. Williams
University of Nevada
For "Biological Soil Crusts in the Mojave: (An interdisciplinary approach to develop a predictive model)."

To donate to the El-Baz Student Award Fund or other Foundation Funds please use the coupon below:

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NOTICE

of Spring 2012 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.

GSA Council will meet next on Saturday, 28 April, 1–4:30 p.m. and Sunday, 29 April, 8 a.m.–noon. The GSA corporate meeting will be Saturday, 28 April, 4:30–5 p.m. All meetings will be held at GSA Headquarters, 3300 Penrose Place, Boulder, Colorado, USA.

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GSA CONNECTION

Helps you keep on top of GSA meetings and geoscience news

If you currently aren't receiving the monthly GSA e-newsletter GSA Connection, you may be missing out. Sign up for our monthly electronic newsletter, which contains the most recent information for the section meetings, along with other GSA highlights. Please be assured, we do not sell e-mail addresses or use them for marketing outside of GSA.

To sign up, here's all you do:

1. On the GSA Home page, look below the "Quick Links" box and click on the link that says "Sign up for GSA e-News" (just below "Stay Informed" header);
2. That brings you to a page where you enter your e-mail address;
3. After submitting your e-mail address, you will receive an e-mail with a link to your own personal subscriber page;
4. Follow that link and place a check in the box next to GSA Connection, then scroll down, and hit Submit.

Philmont Scout Ranch Volunteer Geologist Program

Cimarron, New Mexico, USA

Sponsored by the Rocky Mountain Association of Geologists

Volunteer to teach and demonstrate area geology in back-country New Mexico!

Philmont Scout Ranch is one of three national high-adventure bases owned and operated by the Boy Scouts of America. Located in the southern Sangre de Cristo Mountains of northern New Mexico, Philmont is a 137,000 acre ranch dedicated to outdoor activities. The twelve-day backpacking experience serves over 27,000 high-school-age boys and girls from all over the USA as well as several foreign countries.

Fifty-four positions are open again this year, to be filled on a first-come, first-served basis. Volunteers will receive a sign-up packet with scout applications (you have to be a scout, at least for the summer!), medical forms, and brochures in May 2012. Students who would like to volunteer must show proof of enrollment in a graduate-level program.

The 2012 season begins on 16 June; last week of the program begins on 12 August.

For more information and to sign up, contact Ed Warner, P.O. Box 480046, Denver, CO 80248-0046, USA, +1-303-331-7737, ewarn@ix.netcom.com. Alternate contact: Bob Horning, P.O. Box 460, Tesuque, NM 87574, USA, +1-505-820-9290, rrhorning@gmail.com. Learn more about the geology of the area at http://pubs.usgs.gov/pp/pp_505/html/pdf.html.

Positions Open

HYDROGEOLOGIST, GEOHYDROLOGY SECTION, KANSAS GEOLOGICAL SURVEY–THE UNIVERSITY OF KANSAS, LAWRENCE

Full-time position to lead KGS High Plains aquifer activities. Position can be an unclassified-professional rank of research associate or a faculty-equiv. rank of assistant or associate scientist. Master's or doctorate with experience in regional-scale hydrogeology and project leadership. Field experience and publications involving hydrogeologic processes of relevance for the High Plains aquifer desirable. Individual expected to develop research program of national stature and relevance to Kansas. The Geohydrology Section has 8 full-time professionals with additional support personnel. Emphasis on state-of-the-science field studies and complementary theoretical research. Scientist-rank positions are sabbatical-eligible. Complete announcement/application info. at www.kgs.ku.edu/General/jobs.html. First consideration deadline: 9 Mar. 2012. For further information contact Jim Butler (jbutler@kgs.ku.edu) or Brownie Wilson (bwilson@kgs.ku.edu). KU is an EO/AA employer

TECTONICS, DYNAMICS, SURFICIAL PROCESSES WESTERN WASHINGTON UNIVERSITY

Western Washington University invites applications for a tenure-track Assistant Professor whose interdisciplinary research and teaching specialties connect tectonics/structural geology and surface processes. The appointment will begin effective 16 Sept. 2012. The ideal candidate will enhance our existing strengths in field geology, geomorphology, geophysics, and tectonics, and contribute to the development of emerging departmental directions in engineering geology and geohazards research. Some examples of desirable research directions include influences of tectonic processes on landform evolution, rock/soil mechanics, or surficial deformation/seismic hazards associated with active plate margins. Candidates must have a Ph.D. in an appropriate Earth Science field at the time of appointment; teaching/research specialty in tectonics + surface processes; ability to teach Structural Geology, Introduction to Geology, and Field-based courses (such as a portion of Field Geology or a section of a field-taught Structure course); ability to develop high-quality undergraduate teaching program; ability to establish externally-supported research program; ability to involve students in research; ability to contribute to graduate (MS) degree program; and excellent understanding of fundamental physical principles and processes and a demonstrated ability to apply that understanding in field-based and quantitative ways to important problems in the Earth sciences. Preferred qualifications include post-doctoral experience; college-level teaching experience; ability to teach GIS, Engineering Geology, or Geophysics/Geodynamics; and ability to work with a diverse student body. Interested candidates must apply online. To see full position description and log in to WWU's Electronic Application System for Employment (EASE), please go to https://jobs.wwu.edu/JobPostingsBrowse.aspx?CatID=85. Applications need to include a cover letter outlining your teaching and research experience and accomplishments with specific reference made to the required and preferred qualifications described above. The application should also include a C.V., graduate school transcripts, statements describing teaching and research philosophy and effectiveness, as well as goals and plans for teaching and research at WWU. The names and contact information for letters of reference from four persons familiar with the candidate's research and teaching must be provided; one of these references must be from outside the applicant's current institution. Review of all application materials will begin on 17 Feb. 2012; position is open until filled. Questions regarding this position should be directed to the search committee chair, Elizabeth Schermer (schermer@geol.wwu.edu), or the Geology Department chair, Bernie Housen (bernieh@wwu.edu). WWU is an EO/AA employer and encourages applications from women, minorities, persons with disabilities, and veterans.

ASSISTANT OR ASSOCIATE PROFESSOR GEOLOGICAL ENGINEERING UNIVERSITY OF UTAH

The Department of Geology & Geophysics at the University of Utah is inviting applications for a tenure-track faculty position in Geological Engineering beginning fall semester 2012. Applicants must have a Ph.D. and an established and productive research program in a field of geological engineering. Examples of appropriate research areas include, but are not limited to, landslides and slope stability, geological hazard mapping and risk assessment, earthquake engineering, reservoir engineering, rock mechanics, and petrophysics. The position requires teaching capstone undergraduate design and other courses in support of the ABET accredited Geological Engineering Program. For further details and to apply please go to: http://utah.peopleadmin.com/postings/11278.

The University of Utah is an Equal Opportunity/Affirmative Action employer and educator. Minorities, women, and persons with disabilities are strongly encouraged to apply. Veterans preference. Reasonable accommodations provided. For additional information: www.regulations.utah.edu/humanResources/5-106.html.

The University of Utah values candidates who have experience working in settings with students from diverse backgrounds, and possess a strong commitment to improving access to higher education for historically underrepresented students.

ASSISTANT PROFESSOR OF GEOLOGY UNIVERSITY OF ARKANSAS AT LITTLE ROCK

The University of Arkansas at Little Rock Department of Earth Sciences invites applications for a tenure-track assistant professor position in either Mineralogy/Petrology or Environmental Geology/Geochemistry. We seek a broadly trained scientist who will complement existing faculty strengths.

We expect faculty to develop and maintain an innovative, extramurally funded research program, to supervise student research projects, and to publish results in refereed journals. The successful applicant should have a Ph.D. degree at the time of employment and demonstrated potential to perform teaching duties. Teaching duties will include introductory geology and courses in the candidate's specialty.

The Department of Earth Sciences, with over 70 undergraduate geology majors, offers a B.S. in Geology, a Graduate Certificate in Geospatial Technology, and participates in college graduate programs. Research facilities include geochemical instrumentation, mineral separation equipment, and a state-of-the-art spectroscopy and microscopy facility (http://ualr.edu/nanotechnology/).

Submit applications electronically in PDF format to jbconnelly@ualr.edu. Please use the subject line Assistant Professor Geology-R97703-01. Applications should include a cover letter, curriculum vitae, statement of teaching and research interests and goals, and contact information for at least three professional references. The position begins 15 Aug. 2012. Review of applications will begin 1 Dec. 2011 and will continue until the position is filled. For more information, please contact Dr. Jeffrey Connelly, Chair, Department of Earth Sciences, jbconnelly@ualr.edu.

The University of Arkansas at Little Rock is an equal opportunity, affirmative action employer and actively seeks candidacy of women, minorities and individuals with disabilities. Persons hired must provide proof of legal authority to work in the United States. Under Arkansas law, all applications are subject to disclosure.

TENURE-TRACK POSITION IN LITHOSPHERIC GEODYNAMICS

The Center for Earthquake Research and Information (CERI) at the University of Memphis invites applications for a tenure-track position with tenure in the Department of Earth Sciences at the Assistant Professor level to begin August 2012. We seek an individual with research interests in the field of lithospheric dynamics. We are particularly interested in scientists who study lithospheric processes using an integrated approach combining numerical models with geological and geophysical data. Applicants must have a Ph.D. at the time of employment, and show a demonstrated record of research productivity or strong promise in research. The successful candidate is expected to build a vigorous, externally funded research program, mentor M.S. and Ph.D. graduate students, and teach graduate courses in her or his specialty. CERI faculty are engaged in a variety of regional, national, and international research projects in seismology, geodesy, geology, geophysics, and earthquake hazards (www.ceri.memphis.edu). The U.S. Geological Survey also maintains an office at CERI. More information about this position can be obtained by contacting the chair of the search committee, M. Beatrice Magnani (mmagnani@memphis.edu).

Applicants should submit a full curriculum vitae, a letter expressing their research and teaching interests, and the names and addresses (with phone numbers and e-mail) of at least three references using the University of Memphis workForum online application system (http://workforum.memphis.edu). To receive full consideration, applications should be submitted by 1 Feb. 2012. The University of Memphis is an Equal Opportunity/Affirmative Action employer.

Opportunities for Students

M.Sc. student opportunities: Caribbean climate change of the last two millennia, University of Puerto Rico 2012. The Departments of Geology and Marine Sciences, University of Puerto Rico at Mayagüez (http://geology.uprm.edu/) are seeking 1–2 M.Sc. candidates for an NSF-funded project to use a network of speleothems and Cariaco Basin data in an international collaboration. A degree in physical sciences is preferred, as well as experience with scientific programming and instrumentation, and field collection and laboratory analysis. Being bilingual (Spanish/English) is an asset but not required.

The position starts immediately, 2012, and will run at least two years. Candidates should send a complete CV, a statement of interest, copies of academic certificates, and names and emails of three referees to Dr. Thomas Miller by email: thomase.miller@upr.edu.

GROUNDWORK

Furthering the Influence of Earth Science

Geological Time Conventions and Symbols

Nicholas Christie-Blick, *Dept. of Earth and Environmental Sciences and Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA; ncb@ldeo.columbia.edu*

All science involves conventions. Although subordinate to the task of figuring out how the natural world functions, such conventions are necessary for clear communication, and because they are a matter of choice rather than discovery, they ought to reflect the diverse preferences and needs of the communities for which they are intended.

A short article published recently in both *Pure and Applied Chemistry* and *Episodes* (Holden et al., 2011a, 2011b) sets out to rationalize the definition and symbols for units of time for use in nuclear chemistry and the earth and planetary sciences. Given that the authors are members of a task group established jointly by the International Union of Geological Sciences (IUGS) and the International Union of Pure and Applied Chemistry (IUPAC), and that publication was approved by both bodies, one might reasonably assume that the recommendations reflect a workable consensus. Regrettably, they don't. They will be widely ignored in North America. How could the peer review system fail so badly in this case? What needs to be done?

The present state of affairs can be traced to the decision of the task group to depart from its stated mission of "updating the recommendations on radioactive decay constants (and half-lives) for geochronological use" in order to impose a controversial agenda with respect to time concepts. This course was pursued even after it became clear in 2009 that a consensus was lacking because the hard work of developing that consensus had never been undertaken.

At stake is whether a necessary distinction exists between the concepts of geohistorical dates (points in geological time) and spans of time. The task group argues that they are one and the same; the symbols "a" (for "annus" [year]) and ka, Ma, and Ga (for 10^3, 10^6, and 10^9 years, respectively) will suffice for both purposes. However, the distinction has proven vital for communication among earth scientists for more than thirty years (references in Aubry et al., 2009; Christie-Blick, 2009). According to that well-established convention, the symbols ka, Ma, and Ga refer explicitly to points in time in powers of 10^3 years before present. Spans of time require a different abbreviation or symbol: m.y. or Myr in the case of millions of years, for example.

The critical issue is not whether a single set of symbols will work or whether language will become unnecessarily cumbersome to avoid confusion. It is whether the adoption of two sets of *symbols,* not *units,* is in fact "inconsistent both internally and with respect to SI (*Le Système international d'unités*)" (Holden et al., 2011a, 2011b), because that is the justification being offered in support of a change. This assertion cannot be sustained. No one objects to the storming of the Bastille on 14 July 1789 (a date) or to the construction of Stonehenge from 2600–1600 BC (an interval specified by two dates). In the case of the latter, we say that the job took 1000 years, not 1000 BC. The distinction between geohistorical dates and spans of geological time is conceptually analogous. There is no internal inconsistency, and the International System of Units (SI) rules don't apply to dates in either case because points in time are not units, even if they are specified in years (Aubry et al., 2009). The year, moreover, is not a part of the SI. It cannot be a "derived unit of time," the designation proposed by the task group, because under SI conventions "derived units are products of powers of base units" (BIPM, 2006). The base unit for time is the second. The task group is thus intent on fixing a problem that doesn't exist and in a manner that is at odds with their stated goal of "adherence to SI rules."

Following an airing of these issues in 2009 (Aubry et al., 2009; Christie-Blick, 2009; Renne and Villa, 2009), the task group's recommendations were considered first by the International Subcommission on Stratigraphic Classification (ISSC) and then by the International Commission on Stratigraphy (ICS) of the IUGS at its Prague workshop in late May–early June 2010. The ISSC voted to reject the task group's recommendations by a margin of 16 to 2, although many voting members did not register an opinion. After extended discussion at the ICS workshop, a straw poll of those present (about 40) was split approximately 50:50 (S.C. Finney, 2011, pers. commun. [e-mail dated 20 April]). In a closed session of the ICS Bureau on the final day of the meeting, the matter was discussed again in an attempt to reach a consensus. Finney notes that "a good many of the bureau members favored the Task Group's recommendation, but wanted flexibility in usage of the abbreviations Ma and myr at the author's discretion." (Here and below, the symbol myr is inappropriate because m is the SI prefix for 10^{-3} rather than 10^6.) Finney continues: "They were concerned that editors of journals and other publications might require that it be followed stringently."

The following motion was approved unanimously (17 votes) and confirmed without opposition in a formal e-mail ballot distributed to all members of the Bureau: "We neither accept nor reject the IUGS-IUPAC Task Group's recommendation to apply Ma, generally, as the unit of deep time. We accept the argument for Ma as a single unit for time but would recommend flexibility, allowing for the retention of Ma as specific notation for points in time (i.e., dates) and myr as a unit of time denoting duration. We agree with the spirit of this statement."

Although the situation cried out for continued dialogue to accommodate the range of opinion, in November 2010, the IUGS Executive Committee set aside the ICS's plea for flexibility and inexplicably voted "to authorize and endorse the IUGS-IUPAC

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task group publication and recommendation" (R. Calnan, 2011, pers. commun. [e-mail dated 10 May]). No response was received to repeated requests for clarification.

In parallel with these discussions, the task group's recommendations were considered also by the IUPAC. Consistent with standard protocol, in early 2009, the Interdivisional Committee on Terminology, Nomenclature and Symbols (ICTNS) sought 14 reviews and posted the manuscript for public comment on the IUPAC website (D.StC. Black, 2011, pers. commun. [letter dated 18 May]). On 5 July 2009, a revised manuscript was received by the ICTNS and sent back to the six reviewers who had expressed interest in seeing a revision. As an outspoken critic, I also received a copy. I responded on 6 July with a lengthy review within four hours of receipt. That the task group and ICTNS chose not to acknowledge any of my substantive criticisms is hard to square with David Black's assertion in his letter that "all the points raised by all the reviewers were addressed satisfactorily" in the second revision received in January 2011.

On the face of it, the evaluation was thorough; however, those participating on behalf of the IUPAC would not necessarily have been aware of (or cared about) concerns being raised by earth scientists. The IUGS Executive Committee proved unresponsive to the mixed signals received from its own advisory structure. The net result is a proposed convention that may appear to the casual observer to represent the consensus of a broad community of earth scientists and chemists but is nothing of the sort.

Ironically, the outcome is also unnecessary. An editorial in the 27 April 2011 issue of *New Scientist* closes with the following observation: "But it seems perverse to risk sowing confusion by choosing a symbol that is already widely used to denote a slightly different concept. By adopting another symbol, both systems could coexist in harmony." The task group and all of the organizations involved were presented with such a compromise (Aubry et al., 2009; Christie-Blick, 2009). That was to reserve the symbols a, ka, Ma, and Ga for geohistorical dates 10^0, 10^3, 10^6, and 10^9 years before present, and to express geohistorical time in years duration as yr, kyr, Myr, and Gyr (again adopting SI prefixes). The latter could then be used in the manner that the task group recommends, with no conflict, and with the outcome eventually to be determined by usage rather than by fiat.

The following steps are recommended: (1) Both the IUGS and the IUPAC should place an immediate moratorium on the proposed convention. (2) Professional societies and journals should maintain whatever conventions they currently use, as they see fit. (3) A new task group should be established, with broad disciplinary representation and with the explicit mission of seeking a true consensus on these and related matters.

ACKNOWLEDGMENTS

Helpful comments by Lucy Edwards, Stanley Finney, James Gehling, Brent Goehring, Sidney Hemming, Jerry McManus, Brian Pratt, John Van Couvering, Martin Van Kranendonk, and two anonymous reviewers are appreciated. David Black (IUPAC Secretary General) provided a comprehensive written response to my inquiries. I thank the editors of *GSA Today* for agreeing to consider a shortened version of this manuscript after the editors of both *Chemistry International* and *Episodes* declined to permit a critique of the IUPAC/IUGS review process.

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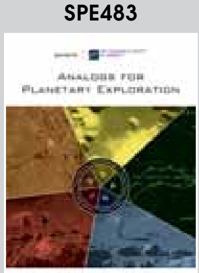

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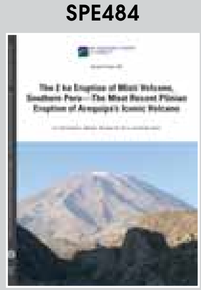

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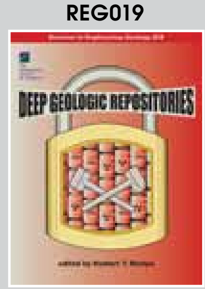

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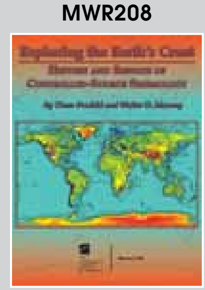

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