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Views on grand research challenges for Quaternary geology, geomorphology and environments

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Introduction

This missive presents one view of the grand challenges, broadly for disciplines within the geosciences, atmospheric, and ocean sciences, biosciences, chemistry, physics, engineering, and archaeology concerned with Quaternary geology, geomorphology, and associated environmental changes. This area of inquiry encompasses the global earth system on 10^{-3}–10^{6} year timescales addressing pressing questions such as tectonic and climatic dynamics, hominid evolution, and past, current, and future sustainability. Outlining "grand challenges" for this interdisciplinary science is a daunting task. Though often attempted, no one scientist or group of scientists has the depth of knowledge or insights to fully justify research challenges for a scientific discipline at a particular time. This effort, like many preceding, has unintentional biases based on limited scientific knowledge, reach, and vision, particularly in reference to the range of influencing disciplines. Often advances in a discipline do not originate at the center of inquiry but by those at the margins who bring new perspectives, knowledge, and computational and analytical prowess. Many future frontiers may remain unrealized because the spark of creativity has yet to leap a disciplinary boundary.

A revolution has occurred in the geosciences in the past 25 years with mounting evidence that human activity has and is altering the climate system, challenging the sustainability of the planet (cf. IPCC, 2014). The need to better understand current and future climate dynamics has propelled the international scientific community to study past periods of pronounced climate change, like the transition from glacial to interglacial conditions. The Quaternary, the past 2.6 million years, and more resolutely the past 25 ka is an enduring focus of climate change research because of the wealth of proxy climatic data and identifiable boundary conditions for Earth System Models (ESM) (cf. Ruddiman, 2014). Thus, for many in the community the grandest challenge is a better understanding of the sensitivity and the variable response of the past, present, and future state of the climate system to internal (e.g., greenhouse gases) and external (e.g., solar variability) drivers of planetary change; and the proportional response of and complex feed backs from the biosphere, hydrosphere, cryosphere, lithosphere, pedosphere, and anthrosphere.

As a scientific community we pass on a research legacy, an enduring grand challenge, to future generations to better understand anthropogenic climate change to curtail, adapt, and mitigate unintended harm done for continued sustenance of life on this planet. What follows is an outline of six "grand challenges" that are not necessarily definitive directions, but serve as examples of research frontiers that have and will continue to motivate scientists. This journal welcomes science from these, others and future frontiers, particularly those that are unidentified or unintentionally neglected in this contribution.

Understanding Quaternary Environments for the Evolution and Migration of Hominids

Quaternary geology and geomorphology is a central discipline for understanding the progression and mechanisms of climate variability and associated changes in glacial, periglacial, fluvial, lacustrine, marine, and eolian systems in the past 2.6 million years (cf. Wright and Frye, 1965; Flint, 1971; Ehlers, 1996). This research coupled with paleo-genomics (e.g., Jobling et al., 2014; Ermini et al., 2015) and an expanding archaeological record (e.g., Madsen et al., 2014; Bretzke and Conard, 2015) informs the community on the paleoenvironments associated with and timing of hominid evolution (e.g., Scholz et al., 2011) and the spread of our genus across the planet. Outstanding questions remain on the paleoenvironmental context for the evolution of Hominids in East African during the past 800 ka, particularly with groups near large lake and river systems. There is a pressing need to define the multiple pathways and timing for dispersal of our ancestors across Africa, into the Middle East, Europe, and Asia (cf. Pearson, 2013).

In the Americas, the evidence for human migration is much later than in Asia or Europe, post the last glaciation. However, there is recent compelling archaeological evidence for a pre-Clovis culture, 14.5–15 ka old (e.g., Gilbert et al., 2009; Waters et al., 2011; Sistiaga et al., 2014) and possibly older (Lahaye et al., 2013). Large unknowns persist on the routes and timing of human migrations southward into the Americas (cf. Pitblado, 2011; Lahaye et al., 2013). Equally compelling questions remain on the associated paleoenvironmental and paleoclimatic conditions conducive for human migration from Subarctic Asia through North and South America.

Interglacial Climate Variability and Mechanisms of Climate Change on a Warmer Planet

A clear interdisciplinary focus is elucidating the timing and mechanisms for climate variability in the past 130 ka to place in context the ongoing changes in climate dynamics with the rise of greenhouse gases (cf. Bradley, 2015). The calibration and refining of Earth System models (ESM) to boundary conditions of past periods in the Quaternary is an ongoing effort to improve the predictive capabilities for future climate simulations (cf. Schmidt et al., 2014; Ziemen et al., 2014; Moberg et al., 2015). The integration of Quaternary proxy climatic data with ESMs on the global and the regional scale is needed to provide insight into non-linear response of climate dynamics on various spatial scales, for areas affected by monsoonal systems, and varying modes of ocean circulation, like the El Nino Southern Oscillation or the North Atlantic Oscillation. New knowledge is needed globally on the state of glaciers, ice sheets, northern tree line, tropics, and subtropics and arid lands during past interglacial periods such as the Eemian, ca. 130 ka ago (Dahl-Jensen et al., 2013; Nikolova et al., 2013) and during a shorter warm period centered around 80 ka, when sea level appears to be near current levels (Dorale et al., 2010). Additional insights are critical for the non-analogous climate response of Southern Hemisphere glaciers, lakes, rivers, and eolian systems, particularly in areas influenced by monsoonal variability, which was potentially intensified by ice sheet-induced cooling of the Northern Hemisphere oceans (Kanner et al., 2012; Rhodes et al., 2015).

Abrupt Climate and Environmental Change

Studies of ice cores from Greenland that span the last glacial period revealed astonishing, abrupt transitions, spanning a few years, from warm to pronounced cooling periods, like during the Younger Dryas chronozone (Steffensen et al., 2008). Equally astonishing is that these rapid climate changes may be forced by mechanisms operating on comparatively gradual timescales that trigger a rapid change in system state (i.e., threshold response). The inferred driver for these rapid climate changes during the last glacial period is ice sheet modulation of Atlantic meridional overturning circulation and associated effects on CO2 levels (Clement and Peterson, 2008; Landais et al., 2015).

Pressing questions remain if abrupt shifts in the climate system can occur during interglacial conditions. Two time periods in the Holocene at ca. 8.2 ka and 4–5 ka appear to be intervals of rapid climate change, though the 8.2 ka event is associated with the last global effects of the retreating Laurentide ice sheet (Alley et al., 1997; Barber et al., 1999). Less is known about the 4–5 ka period, which may herald dramatic changes in global hydrology with lasting aridfication of East and North Africa (e.g., Forman et al., 2014; Bloszies et al., 2015) and possible desertification in eastern China (e.g., Yang et al., 2015). North American research on fluvial systems document an episode of incision, 3.5–6 ka, a possible hydrologic response to episodes of mid-Holocene drought (Counts et al., 2015) or a more complex hydrologic response involving sediment supply and changes in climate (Springer et al., 2009; Stinchcomb et al., 2012). Refining the timing and spatial extent of this incision could yield new insights into how drainage basins respond to abrupt climate change. Climatic variability in the past 5000 years on decadal to century timescales remains insufficiently understood with many past climate "surprises," such as sustained multi-decadal long mega-droughts during the Medieval Climate Anomaly in the central USA that exceeded historic drying (e.g., Cook et al., 2007; Stahle et al., 2007). Understanding extreme climate variability for our current interglacial, the Holocene, and associated atmosphere-vegetation-landscape feedbacks in semiarid and temperate areas is critical knowledge for assessing the potential threshold response of earth systems as our planet warms into the twenty-first century.

Earth Surface Processes in the (Paleo-) Critical Zone

A clear research focus within the community is within the so called "Critical Zone" (CZ) which is defined as the, "heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources" (National Research Council, 2001). Quantifying and modeling the modern CZ is a central challenge for achieving a sustainable planet because the CZ responds to climatic, anthropogenic, and tectonic forcings (Brantley et al., 2007). The CZ and, in particular, Earth's surface and soil is a product of multiple environmental factors that have varied over time, creating a "polygenetic paleosol" (Richter and Yaalon, 2012). This CZ history influences the current and future state of Earth's surface and global carbon cycle; thus, reconstructing this history and its effects on earth's surface is necessary to predict future changes. In this regard, advances in Quaternary geology, geomorphology and environmental reconstruction research that emphasize modern and paleo-CZs stand to make major contributions.

Reconstructions of past CZs in the Middle to Late Quaternary have been achieved by use of optical and cosmogenic radionuclide dating providing estimates of soil production, denudation rates, residence times, and dates of burial (cf. Ahr et al., 2013; Reusser et al., 2015). For example, luminescence dating along the Colorado Front Range show periods of CZ stability, burial and pedogenic rejuvenation over the past 18 ka (Leopold et al., 2011). Measurement of *in situ* cosmogenic ^{10}Be of river sediment on the southeastern Piedmont USA provides background (pre-European settlement) erosion rates that are 100-fold lower than post-settlement erosion rates (Reusser et al., 2015). Grand challenges remain to explore the effects of soil production and erosion rates on influx and storage (residence times) of sediment and carbon in depositional environments under a range of geographic and environmental constraints.

There is compelling research in the modeling of the CZ in the past and into the future with parameterization for earth surface processes, land use changes and pedogenesis (e.g., Nordt et al., 2012, 2013; Nordt and Driese, 2013; Pelletier et al., 2015). Challenges remain on quantifying non-linear, threshold-response interactions, particularly with extreme states, amongst such factors as topography, vegetation, land use, and sediment flux. Research on paleo-CZ has focused on development of transfer function for geochemical proxies from surface soils applied to buried soils that has yielded unique information on past climatic components, such as growing season temperature and mean annual precipitation (e.g., Nordt and Driese, 2010; Klopfenstein et al., 2015). Challenges remain to refine, test, and develop geochemical proxies linked to a wide variety of current pedogenic environments, recognize non-analogous conditions in the paleo-record and forward judicious interpretations of past critical zones.

There is a significant stock of buried carbon in Quaternary peat lands and sediments which may stay sequestered or be released as climate warms. Only recently has the carbon sequestered in Quaternary buried soils been systematically study. In the Holocene and Late Pleistocene the burial of soils, particularly by eolian activity have sequestered large carbon pools and with anthropogenic disturbance may become labile (Marin-Spiotta et al., 2014). Much like quantifying erosion rates, there is a pressing need to quantify the landscape scale variations in carbon storage due to soil burial, erosion, and exhumation (Chaopricha and Marin-Spiotta, 2014).

The Human Imprint on the Earth System

Evidence is mounting that human activities continue to affect earth surface processes with non-analog responses compared to Holocene landscape dynamics (Steffen et al., 2015). The Quaternary sciences have anchored this ongoing discussion by investigating the meaning, the initiation and the effects of the Anthropocene; a proposed new geologic epoch dominated by human impacts on earth systems (Crutzen, 2002; Zalasiewicz et al., 2008, in press; Lewis and Maslin, 2015). There is a robust dialog on how and to what extent humans have altered earth surface processes from sediment source to sink in the past decades to millennia in Asia, Europe, Australia, Africa, and the Americas and affected the global greenhouse gas inventory, ecosystem services, and modulated climate variability.

Land-use practices, especially agricultural expansion, across continents since the middle Holocene has been implicated in lowering biodiversity and providing new sources for atmospheric CH_4 and possible CO_2 (Ruddiman, 2007). These changes at the catchment scale also significantly altered upland and hillslope soil erosion rates through increased mass wasting (Notebaert et al., 2011; Reusser et al., 2015), flooding and fluvial sediment storage (Notebaert and Verstraeten, 2010; Hoffmann et al., 2013), regional hydrology (e.g., Contreras et al., 2013; Stinchcomb et al., 2013) and the overall sediment budget. Using empirical Holocene records to tune land surface and hydrological models that predict water and sediment flux; and the sensitivity of landscapes to change remains a challenge.

In turn, the growing foot-print of urbanization since the Nineteenth century has degraded biodiversity of riparian and adjacent environments and enhanced hydrological variability (Walsh et al., 2005; Wohl, 2015). Further advances in geomorphic and hydrologic data collection and modeling are needed to better understand processes that influence variability in sediment, water, and nutrient flux for natural and human-altered landscapes. Pressing questions remain on the role of human activities in desertification in past 5 ka in East and North Africa, across northern Asia and with more recent extreme hydrologic variability in the Americas. Studies show that there is a close correspondence between rapid changes in climate, flooding, and civilization (Macklin et al., 2013; Munoz et al., 2015). Continuing to resolve the timing in these changes will yield new insights into climate-human-water interactions. Although strides have been made toward quantifying anthropogenic impact (e.g., Ackermann et al., 2014; Notebaert and Berger, 2014; Stinchcomb et al., 2014; Vanmaercke et al., 2015), challenges persist in separating natural from anthropogenic drivers in landscape change.

Quaternary Tectonic Framework and Seismic Hazards

Knowledge of Quaternary geology and geomorphology also yield significant insights in tectonic and volcanic processes for many fault zones and serve to quantify seismic hazards to safe guard urban population centers (cf. Yeats et al., 1997; McCalpin, 2009). The advances in paleoseismology in the past two decades has provided a deeper time perspective on earthquake generation, spanning centuries to multiple millennia, to place in context the shorter seismological and differential-GPS and satellite-based measurements of vertical and horizontal crustal movements. Studies have focused on addressing fault segmentation and geometry changes, recurrence intervals, and inferring earthquake magnitude in a variety of tectonic settings from active and passive plate margins to interplate areas. There remains too many fault systems in proximity to growing cities in Asia, the Caribbean, and Central, and South America in which little is known about seismic source zones, segmentation, slip-rates, and earthquake recurrence. Examples of critical areas of research include the North Anatolian Fault in Turkey, Longmenshen Belt in central China, fault systems in Hispaniola and the San Ramon Fault within the Santiago, Chile metropolitan area. Also, recent research has begun to address the paleo-tsunami record around the Pacific Ocean, with more studies needed (cf. Nelson et al., 2015).

Conclusion

It is an opportune time to pursue research in the geosciences, particularly focused on the Quaternary, earth surface processes, and environmental change. Scholarship that addresses these grand challenges should yield needed insights on the origins of our genus and specie, the response of earth systems to past, current, and future climate variability and anthropogenic-sourced change, and how expanding urban populations can sustainably interface with tectonic hazards and rapidly changing hydrologic conditions. An enduring need is the synthesis of proxy environmental information across Quaternary archives such as speleothems, glacial, marine, lacustrine, fluvial, and eolian records to better understand the components of climate variability and the complex response of earth systems. We hope this missive feeds new ideas and alternative and contradictory viewpoints that will motivate research beyond this limited view. These research challenges are not static but as John Bardeen said Science is a field which grows continuously with ever expanding frontiers."

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