ROCK STARS: Johannes Walther, p. 12

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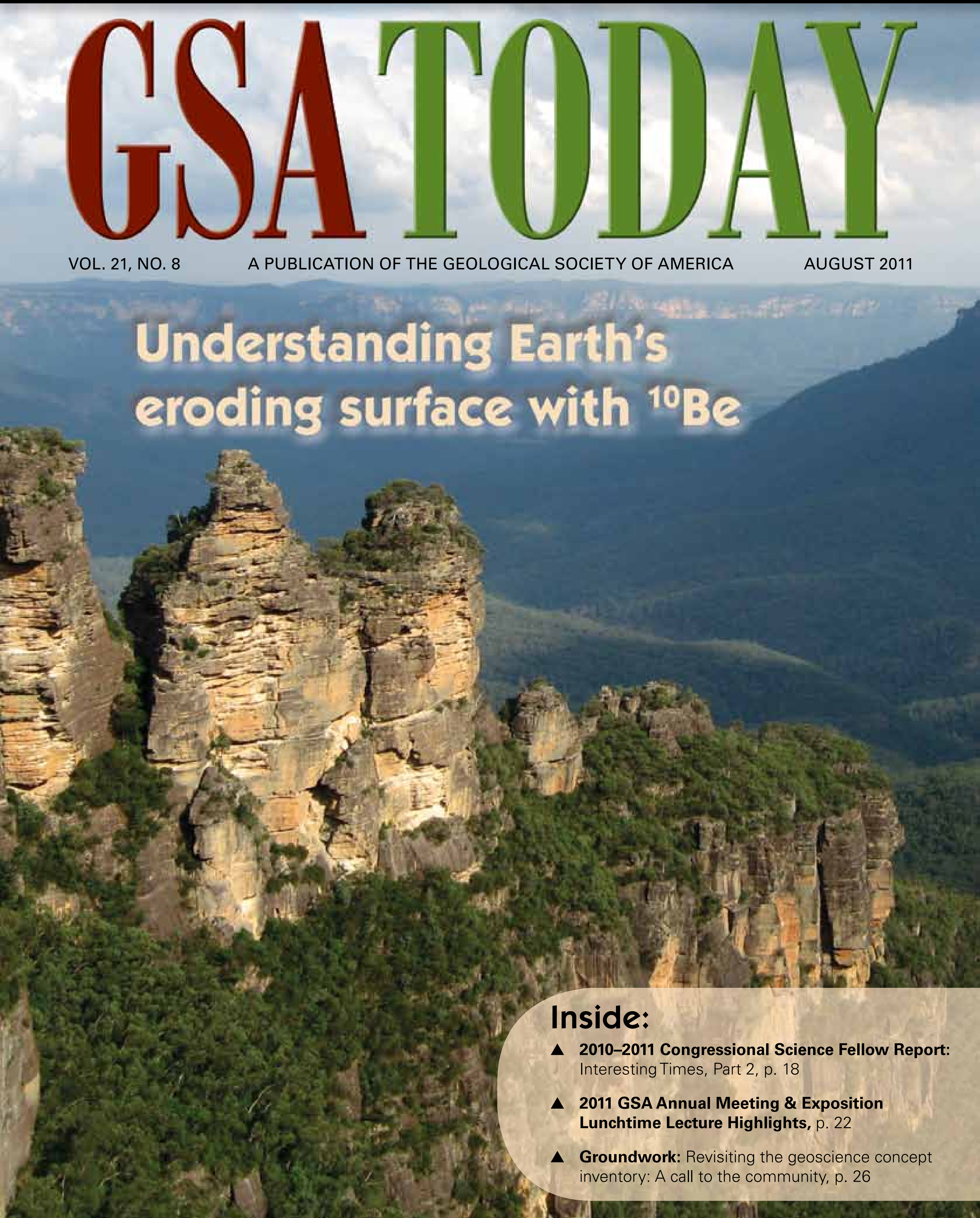

Understanding Earth's eroding surface with ^{10}Be

Inside:

GSA TODAY

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***GSA TODAY* STAFF**

Executive Director and Publisher: John W. Hess

Science Editors: Bernie Housen, Western Washington Univ. Geology Dept. (ES 425) and Advanced Materials Science and Engineering Center (AMSEC), 516 High Street, Bellingham, WA 98225-9080, USA, bernieh@wwu.edu; R. Damian Nance, Ohio University Dept. of Geological Sciences, 316 Clippinger Laboratories, Athens, OH 45701, USA, nance@ohio.edu

Managing Editor: K.E.A. "Kea" Giles, kgiles@geosociety.org, gsatoday@geosociety.org

Graphics Production: Margo Sajban

Advertising (classifieds & display): Ann Crawford, +1-800-472-1988 ext. 1053; +1-303-357-1053; Fax: +1-303-357-1070; advertising@geosociety.org; acrawford@geosociety.org

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SCIENCE ARTICLE

Cover: The Three Sisters are iconic sandstone towers exposed above the Jamison Valley in the Blue Mountains, Australia. Erosion in the mountains is dominated by stream channels cutting through exposed joints and preferential erosion of weaker shale units interbedded within the Triassic-aged sandstone. Photo by Eric Portenga. See related article, p. 4–10.

Erratum

On p. 12 of the July 2011 *GSA Today*, the affiliation for newly elected GSA Fellow R. Laurence Davis was listed as the College of Mt. St. Joseph; however, R.L. Davis is at the University of New Haven. *GSA Today* regrets this error.

Understanding Earth's eroding surface with ^{10}Be

Eric W. Portenga, *Dept. of Geology, University of Vermont, 180 Colchester Ave., Burlington, Vermont 05405, USA, eporteng@uvm.edu;* ***Paul R. Bierman,*** *Dept. of Geology and Rubenstein School of the Environment and Natural Resources, University of Vermont, 180 Colchester Ave., Burlington, Vermont 05405, USA, pbierman@uvm.edu*

ABSTRACT

For more than a century, geologists have sought to measure the distribution of erosion rates on Earth's dynamic surface. Since the mid-1980s, measurements of in situ ^{10}Be, a cosmogenic radionuclide, have been used to estimate outcrop and basin-scale erosion rates at 87 sites around the world. Here, we compile, normalize, and compare published ^{10}Be erosion rate data (n = 1599) in order to understand how, on a global scale, geologic erosion rates integrated over 10^3 to 10^6 years vary between climate zones, tectonic settings, and different rock types.

Drainage basins erode more quickly (mean = 218 m Myr^{-1}; median = 54 m Myr^{-1}) than outcrops (mean = 12 m Myr^{-1}; median = 5.4 m Myr^{-1}), likely reflecting the acceleration of rock weathering rates under soil. Drainage basin and outcrop erosion rates both vary by climate zone, rock type, and tectonic setting. On the global scale, environmental parameters (latitude, elevation, relief, mean annual precipitation and temperature, seismicity, basin slope and area, and percent basin cover by vegetation) explain erosion rate

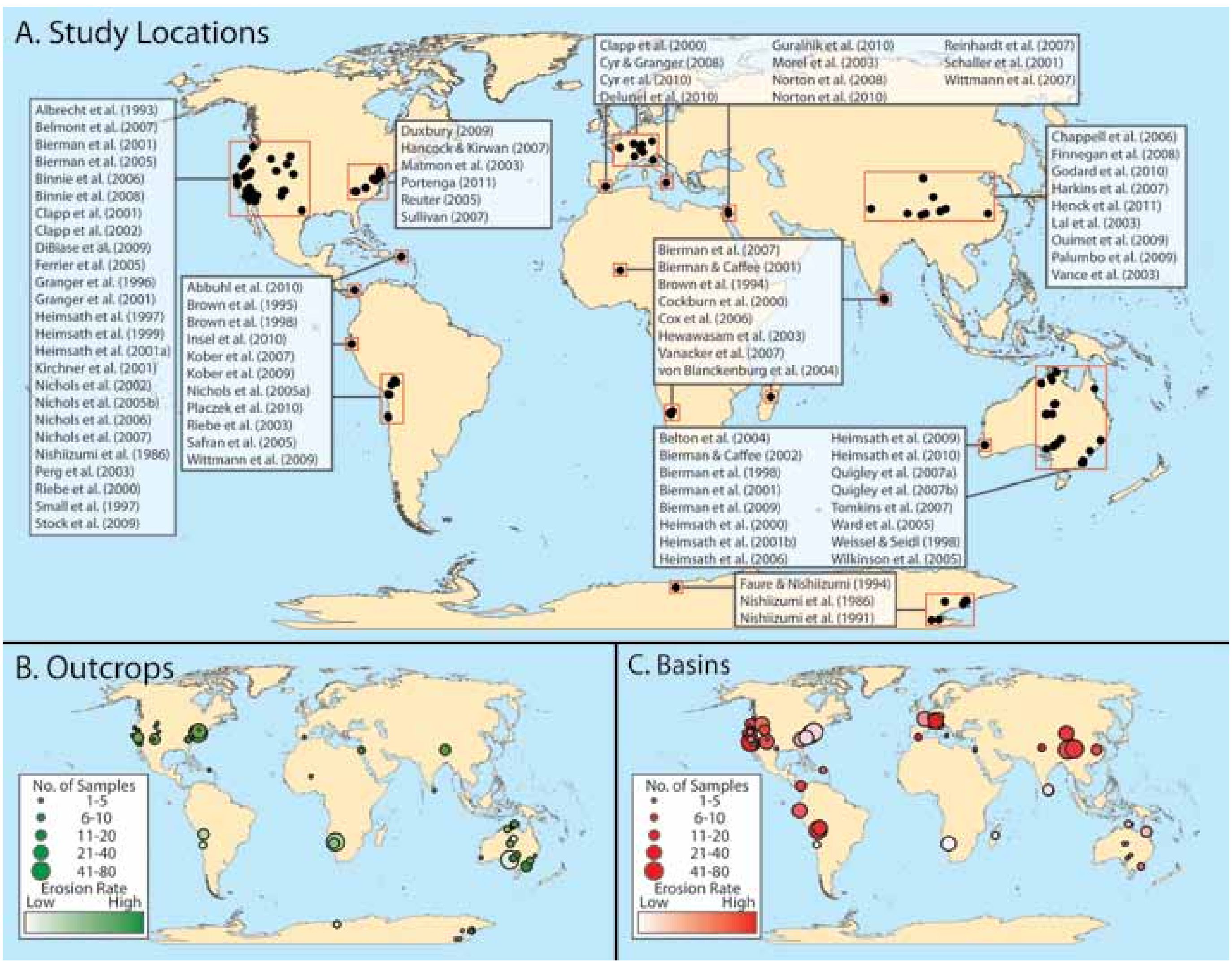

Figure 1. Geographical distribution of cosmogenic ^{10}Be erosion rate data (see supplemental data Tables DR1–DR3 [see text footnote 1]). (A) Location of studies compiled in this paper. (B) Distribution of outcrop samples and (C) drainage basin samples. Symbols sized to reflect the number of samples per study and colored to indicate relative erosion rate. Note: Citations included within this figure are listed with the supplemental data text.

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variation better when they are combined in multiple regression analyses than when considered in bivariate relationships. Drainage basin erosion rates are explained well by considering these environmental parameters (R^2 = 0.60); mean basin slope is the most powerful regressor. Outcrop erosion rates are less well explained (R^2 = 0.32), and no one parameter dominates. The variance of erosion rates is better explained when subpopulations of the global data are analyzed. While our compilation is global, the grouped spatial distribution of cosmogenic studies introduces a bias that will only be addressed by research in under-sampled regions.

INTRODUCTION

Accurate global mapping, understanding, and prediction of geologic or background erosion rates is important because erosion is the means by which sediment is generated, fresh rock is exposed to CO_2-consuming weathering reactions, soil is created, landforms change over time, and mass is moved from the continents to the oceans and eventually recycled via the process of subduction and volcanism. Earth's ability to support billions of inhabitants depends critically on the resiliency of the soil system and the purity of surface waters, both of which erosion affects directly. Thus, measuring the rate and spatial distribution of erosion on millennial time scales is fundamental to understanding how landscapes evolve through time and for placing human environmental impacts in context (Hooke, 1994, 2000).

Yet, geoscientists are largely lacking the data to develop a global model that can predict, with accuracy or precision, the background rate and spatial distribution of erosion on Earth's dynamic surface. It is even more difficult to predict how erosion rates respond to changes in boundary conditions including tectonic and climatic forcing. Understanding how rates of erosion are related to complex, non-linear feedbacks between multiple Earth systems including the solid Earth (tectonic regime), the climate (precipitation and temperature), and the biosphere (vegetation) is prerequisite to developing such a model.

Throughout the twentieth century, geologists used a variety of tools to measure rates of erosion (e.g., Saunders and Young, 1983). The most common approach equated sediment yield with erosion rate (Dole and Stabler, 1909; Judson, 1968). Such an approach presumes that human impact is inconsequential and that short-term measurements of sediment flux are representative of long-term flux rates, but both assumptions have been repeatedly questioned (e.g. Kirchner et al., 2001; Trimble, 1977; Wilkinson, 2005), and various modeling approaches have been implemented (Syvitski et al., 2005) to overcome the limitations of sediment yield data.

Geologic erosion rates are useful for placing human impact on the sedimentary system and global environment in context. Until recently, no one method of measuring geologic erosion rates directly was globally applicable. The development of Accelerator Mass Spectrometry (AMS) allowed rapid, high-precision, low-detection limit measurement of in situ–produced cosmogenic radionuclides (Elmore and Phillips, 1987), the concentration of which reflects near-surface residence time and thus the pace of surface processes (Bierman and Nichols, 2004). In situ–produced ^{10}Be, extracted from purified quartz, is now routinely used to estimate how quickly outcrops and drainage basins erode over geomorphically meaningful time scales (e.g., Bierman and Caffee, 2001; Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996; Nishiizumi et al., 1986; Schaller et al., 2001; Small et al., 1997).

The method relies on the observation that cosmic rays interact with Earth's surface, producing ^{10}Be, an otherwise exceptionally rare isotope. The production of ^{10}Be occurs predominantly within a few meters of Earth's surface and decreases exponentially with depth. Thus, the concentration of ^{10}Be in outcropping rock or in fluvial sediment reflects near-surface residence time. Cosmogenic rate estimates reflect the time it takes to erode several meters of rock or sediment, typically 10^3 to 10^6 years, the integration time being inversely proportional to the erosion rate. In bedrock outcrops, erosion rates are inferred, assuming erosion occurs steadily through time. Sampling river sand presumes that stream networks mix and deliver sediment from the entire basin. Because soils are typically well-stirred by physical and biological processes, shallow, human-induced soil erosion does not typically affect cosmogenic estimates of basin-scale erosion rates.

Many local and regional-scale cosmogenic studies (now 87) indicate that individual environmental parameters can influence millennial-scale erosion rates, although the results are not uniform. Parameters considered in the past include latitude, elevation, relief, seismicity, basin slope and area, percent basin cover by vegetation, and mean annual precipitation and temperature. In order to understand the relationship between erosion rates and environmental parameters, we compiled all publicly available outcrop and drainage basin erosion rates inferred from measurements of ^{10}Be (Fig. 1). After standardizing the data for changes in ^{10}Be half-life (Nishiizumi et al., 2007), production rate (Balco et al., 2008), and scaling schemes (Lal, 1991) used over the past 24 years, we compared erosion rates and a variety of environmental parameters, both individually and using multivariate statistical methods. The result is a description, at a global scale, of the relationship between these parameters and the erosion rate of both outcrops and drainage basins. Such relationships are important for understanding the behavior of Earth's sedimentary system over a variety of spatial and temporal scales as geologists attempt to make sense of human impacts on erosion and sediment generation (Hooke, 1994; Montgomery, 2007; Wilkinson, 2005).

We recognize that a spatial bias introduced to our analyses is due to the small number of studies carried out in South America, Africa, the Middle East, and the polar latitudes as well as the fact that the number of samples from each study varied in size. Our compilation and analyses are carried out using available data, however, and further sampling in under-studied regions can only improve our understanding of how different factors control erosion rates.

METHODS

We compiled all publicly available in situ ^{10}Be erosion rate data (Fig. 1; Tables DR1–DR3[1]). We included only unshielded outcropping bedrock samples collected from horizontal or subhorizontal surfaces and modern stream sediment samples from drainage basins that did not experience extensive recent glacial cover. For each sample, we collected data necessary to recalculate erosion rates (Table DR1). In some cases, information was provided in the original publications; in other cases, we contacted authors directly. Samples in this compilation required recalculation because constraints on production rates, neutron attenuation path length, and

[1]GSA supplemental data item 2011216, reference list for text Figure 1, erosion rate recalculation methods, ArcGIS data extraction methods, statistical methods, results of statistical analyses (including Figs. DR1–DR4), and bedrock and drainage basin erosion rate data tables (Tables DR1–DR5), is online at www.geosociety.org/pubs/ft2011.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

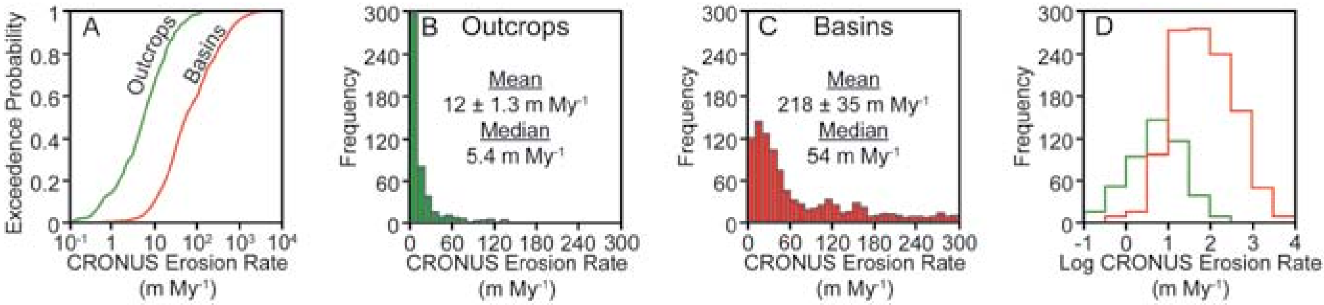

Figure 2. Erosion rate data. (A) Exceedance probability for compiled erosion rates. (B) Histogram of outcrop erosion rates. (C) Histogram of drainage basin erosion rates. (D) Histograms of erosion rates after being log-transformed (base 10) showing normally distributed datasets for statistical analyses; outcrops are green lines and drainage basins are red lines.

the ^{10}Be half-life have improved over time and values used in individual studies varied widely.

We used the CRONUS online calculator for erosion rate estimates (Balco et al., 2008; http://hess.ess.washington.edu/). Effective elevation, or the production-rate weighted average elevation for a basin, and effective latitude were determined (see supplemental data methods section [footnote 1]), enabling us to use the CRONUS calculator for determining drainage basin erosion rates. CRONUS-calculated erosion rates for outcrops and basins strongly and significantly correlate to their original published erosion rates (Figure DR1).

We compared erosion rates for outcrops and drainage basins to latitude (°N or °S), elevation (meters above sea level [masl]), mean annual precipitation (MAP; mm yr^{-1}) and temperature (MAT; °C), seismicity (peak ground acceleration [PGA; see supplemental data {footnote 1}], where seismically active sites have PGA >2), basin area (km^2), mean basin slope (°), and percent basin coverage by vegetation. These parameters are used because they are the most commonly analyzed metrics in cosmogenic erosion rate literature to date. We extracted data from global datasets using ArcGIS (Table DR4). Not all global coverages extend to Antarctica. Antarctic climate data were modified from Monaghan et al. (2006), and because seismicity data were not available for Antarctica, those sites are excluded from some of our analyses. See the supplemental data for details regarding these parameters.

We used a variety of statistical methods (see supplemental data [footnote 1]). These parametric statistical tests assume a normal sample distribution. Because both outcrop and drainage basin erosion rate distributions are highly skewed (Fig. 2), we log-transformed (base 10) all erosion rate data before performing statistical tests; this transformation produced a more normally distributed dataset. Bivariate analyses were carried out for numeric parameters, and we completed analyses of variance and Student's *t*-Tests for nominal data. We also performed forward stepwise regressions for each global dataset and for each subgroup of nominal data categories. Parameters were entered into the regression based on their ability to statistically improve the regression. If a variable did not significantly improve the regression, it was omitted.

RESULTS

Outcrop Erosion Rates

Outcrops (n = 450) erode at an average rate of 12 ± 1.3 m Myr^{-1}. The median erosion rate is 5.4 m Myr^{-1}, reflecting the highly skewed distribution (Fig. 2B). In bivariate global comparisons (Fig. DR2), outcrop erosion rates are unrelated to absolute latitude, elevation, or seismicity. Globally, outcrop erosion rates co-vary weakly with relief and MAP; the highest outcrop erosion rates occur where MAT is ~10 °C.

Analysis of variance (ANOVA) shows that outcrops in seismically active regions erode similarly (14 ± 1.6 m Myr^{-1}; n = 55) to those in seismically inactive areas (13 ± 1.4 m Myr^{-1}; n = 395) but that outcrop erosion rates differ by lithology and climate (Fig. 3). Erosion rates of sedimentary (20 ± 2.0 m Myr^{-1}; n = 118) outcrops are faster than metamorphic outcrops (11 ± 1.4 m Myr^{-1}; n = 102) and igneous outcrops (8.7 ± 1.0 m Myr^{-1}; n = 230), which are statistically similar. The average outcrop erosion rate in temperate climates (25 ± 2.5 m Myr^{-1}; n = 85) is significantly higher than those in any other climate zone except for erosion rates in tropical zones. Outcrops in polar climates erode most slowly (3.9 ± 0.39 m Myr^{-1}; n = 31). Median values show similar trends (Fig. 4).

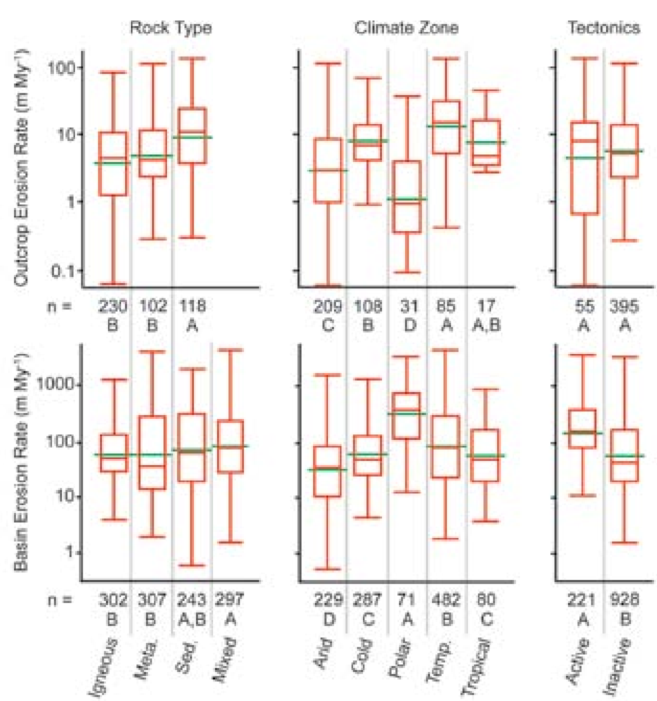

Figure 3. Analysis of variance (ANOVA) for the log-transformed CRONUS erosion rates on outcrop and drainage basin samples categorized by rock type, climate zone, and tectonic regime. Letters below each box-plot represent the results from paired Student's *t*-Tests—categories linked by a similar letter are similar at p <0.05. Green lines are means; red lines are medians. Box defines 25th and 75th percentiles. Whiskers represent data range, excluding statistical outliers.

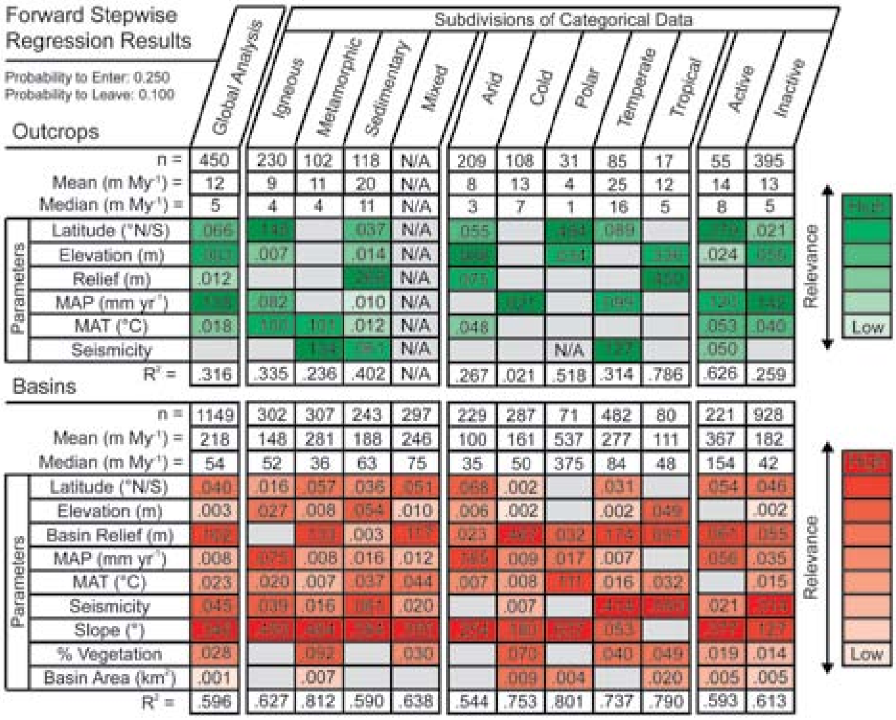

Figure 4. Forward stepwise regressions for outcrop and drainage basin datasets considered globally and by subdivisions of categorical data. Colored boxes indicate parameters that significantly explain erosion rate variance. The number in each colored box is the amount of the overall R^2 value contributed by the corresponding parameter. The R^2 value listed at the bottom of each column represents the total amount of variation in the data that is explained by the significant parameters. Regressions use log-transformed CRONUS erosion rates. Mean and median values calculated from CRONUS erosion rates.

A forward stepwise regression shows that 32% of the variation in the global population of outcrop erosion rates can be described by five parameters; MAP is the most important regressor (Fig. 4). For individual climate zones, lithologies, and seismic regimes, the relevant parameters and their weighting vary greatly (Fig. 4; Table DR5).

Drainage Basin Erosion Rates

On average, sampled drainage basins erode at 218 ± 35 m Myr^{-1} (n = 1149). The distribution is highly skewed, with a median erosion rate of 54 m Myr^{-1} (Fig. 2C). At the global scale, basin slope yields the strongest bivariate correlation, with erosion rates (R^2 = 0.33, Fig. 5; Fig. DR3). Basin relief, mean elevation, and seismicity also have significantly positive, bivariate correlations. MAT has a very weak negative correlation. There is no significant bivariate correlation between basin erosion rates and latitude, MAP, or basin area (Fig. DR3).

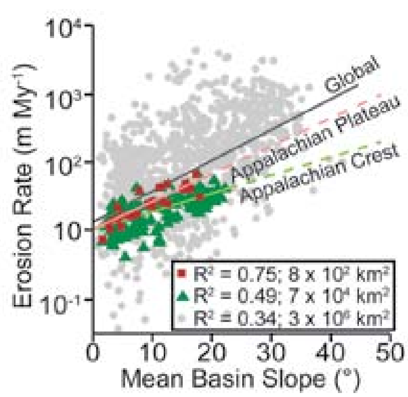

Figure 5. Mean basin slope and erosion rate co-vary. Correlation is scale-dependent and decreases with increasing area included in the sample: Appalachian Plateau within the Susquehanna River Basin (red squares; Reuter, 2005); Appalachian Mountains crest data (green triangles; Matmon et al., 2003; Reuter, 2005; Sullivan, 2007); and global data set (gray circles; references in Table DR1 [supplemental data; see text footnote 1]).

Analysis of variance (Fig. 3) indicates that the average erosion rate for seismically active basins (367 ± 55 m Myr^{-1}; n = 221) is significantly higher than in seismically inactive basins (182 ± 30 m Myr^{-1}; n = 928). The average drainage basin erosion rate in polar climates (537 ± 125 m Myr^{-1}; n = 71) is higher than in all other climate zones. Arid region drainage basins erode most slowly (100 ± 17.3 m Myr^{-1}; n = 229). Results are less clear for lithology. On average, metamorphic terrains erode more rapidly than other lithologies, but this is not reflected in ANOVA results on log-transformed data (Fig. 3).

Forward stepwise regressions of basin erosion rates show that all nine parameters together significantly describe 60% of variability in the global data set (Fig. 4). For nearly every basin-scale subcategory, basin slope is the most significant regressor (Fig. 4). The remaining parameters are highly variable in terms of their regression power. Basin area, MAT, and elevation have low weights for nearly all subcategories in which they appear.

DISCUSSION

While summaries of ^{10}Be erosion rate data have been presented in the past (e.g., Bierman and Nichols, 2004; von Blanckenburg, 2005), our compilation of 1599 measurements of in situ–produced ^{10}Be provides the first broad, standardized view of pre-human, geologic erosion rates (Figs. 1 and 2). Compiled outcrop erosion rates are slow and do not exceed 140 m Myr^{-1}, similar to rock weathering rates measured in the past (Saunders and Young, 1983). Some cosmogenic studies in tectonically active zones (i.e., Binnie et al., 2006, 2008; DiBiase et al., 2009) indicate drainage basin erosion rates higher than previously reported (Saunders and Young, 1983).

Spatial Distribution of Existing Samples

Our compilation is global; however, large portions of Earth remain unsampled, meaning that the data are not randomly distributed (Fig. 1). Drainage basin cosmogenic data represent only 2.3% of the world's land area. Latitudes with large sample populations, between 30°–50° north and south, correspond to Europe, the United States, and Australia—easily accessible locations. There are sampling gaps between 50°–70° latitude, both north and south. Low latitude samples are also rare. Exceptions include large sample populations from basins and outcrops in Namibia and the Bolivian Andes (i.e., Bierman and Caffee, 2001; Cockburn et al., 2000; Insel et al., 2010; Kober et al., 2007, 2009; Safran et al., 2005; Wittmann et al., 2009). Refining the relationships presented in this study will happen only when these large spatial data gaps are filled.

Both outcrop and drainage basin erosion rates have highly skewed distributions (Fig. 2), with most samples indicating relatively slow rates of erosion. This skewed distribution probably reflects the rapidity of erosion in tectonically active zones where mass is supplied to orogens by plate convergence and removed by rapid erosion of threshold slopes (Montgomery and Brandon, 2002; Zeitler et al., 2001). In contrast, slower, isostatically driven rock uplift supplies mass for erosion in the tectonically stable zones that make up most of the world (Hack, 1975, 1979).

Studies with a large number of samples in one region (i.e., Bierman and Caffee, 2002; DiBiase et al., 2009; Henck et al., 2011; Ouitmet et al., 2009; Safran et al., 2005; Schaller et al., 2001) are helpful in creating large sample populations for statistical analyses; however, sample adjacency leads to biases in data interpretation because of the scale dependence of correlation. For example, outcrops in “cold” climates come from numerous locations geographically ($n = 108$), and the stepwise multivariate regression accounts for only 2% of the variability of erosion rates, whereas 52% of variability of erosion rates in “polar” climates is explained (Fig. 4). This high correlation is most likely the result of all 31 polar outcrop samples coming from a single, small geographic area.

Most ^{10}Be measurements have been done in quartz-rich rocks and sediment because quartz retains in situ ^{10}Be and has a simple composition, so nuclide production rates are easily calculated. Not all rocks are quartz-bearing; thus, the global data set does not represent all lithologies. Beryllium-10 can be extracted from other minerals (Ivy-Ochs et al., 2007; Nishiizumi et al., 1990), expanding the area where erosion rates can be measured. Application of other isotope systems (such as ^{21}Ne, ^{3}He, and ^{36}Cl) offers the potential to better constrain the effect of lithology on erosion rates (Kober et al., 2009); however, uncertainties in cross calibration of production rates between different isotope systems could introduce biases into the data analysis.

Basins Erode More Rapidly Than Outcrops

Average outcrop erosion rates are more than fifteen times slower (12 m Myr^{-1}) than those inferred from drainage basin studies (218 m Myr^{-1}). Comparison of median and outcrop drainage basin rates (5.3 vs. 54 m Myr^{-1}, respectively) shows a similar relationship. Within each seismic regime, climate zone, and lithology, drainage basins erode more rapidly than outcrops (Fig. 4). There are 22 sites or regions where both outcrop and basin erosion rates have been measured (Fig. DR4). At 12 of these, statistical analyses indicate that drainage basins erode more rapidly than outcrops; at the other 10 sites, drainage basin and outcrop erosion rates are statistically inseparable. In no case, does a Student’s *t*-Test indicate that outcrops erode more rapidly than the adjacent basins. These results suggest that soil cover, even if it is quite shallow, speeds the rate of rock weathering (Heimsath et al., 1997, 1999).

Outcrop and drainage basin erosion rates are controlled by different processes and occur in different physical, chemical, and hydrological environments. Outcrops are situated above the landscape and exposed to a limited suite of what must be largely ineffective subaerial erosion processes that both physically and chemically wear away exposed rock. The stability of outcrops is likely due to the dry microclimate they create as precipitation rapidly runs off exposed rock surfaces. The conversion of bedrock to regolith results from linked chemical and physical processes that include hydrolysis, weathering induced by organic acids, and the ability of soil to hold water in contact with rock between precipitation events. A mantle of soil appears to create conditions favorable for the conversion of bedrock to soil (Heimsath et al., 1997, 1999).

Influence of Spatial Scale on Erosion Rate Correlation

Scale appears to determine which environmental parameters are related to outcrop and drainage basin erosion rates because correlations observed on the local scale are often not observed or are much weaker on the global scale. For example, in Australia, the lowest measured outcrop erosion rate from sampling sites on Australia’s Eyre Peninsula and in central Australia correlate well with MAP ($R^2 = 0.98$; Bierman and Caffee, 2002). On the global scale, however, this relationship is much weaker (Fig. DR2E). Drainage basin erosion rates have previously been shown to correlate well with average basin elevation in individual studies (Heimsath et al., 2006; Palumbo et al., 2009). This bivariate relationship is weak at the global scale ($R^2 = 0.14$; Fig DR3B), and elevation is at most a lightly weighted regressor in all of the multivariate regressions (Fig. 4), suggesting that, on a global scale, elevation is not an important control on erosion rates.

Mean basin slope is the one parameter that is significantly related to drainage basin erosion rates at both the local (e.g., DiBiase et al., 2009; Matmon et al., 2003; Ouimet et al., 2009; Palumbo et al., 2009; von Blanckenburg et al., 2004) and global level. However, scale remains important. For example, mean basin slope produced the strongest bivariate correlation (Fig. 5) with drainage basin erosion rates at the global scale (total basin area = 3.3×10^6 km^2, $R^2 = 0.34$). The regression explains more variability if only the Appalachian Mountain crest data are included (6.9×10^4 km^2, $R^2 = 0.49$) and gets even better if the data included are restricted to the Appalachian Plateau (786 km^2, $R^2 = 0.75$). Although bivariate analysis may be useful at local and regional scales, such regressions are of lesser value at global scales. Multivariate analysis is needed because many environmental metrics, such as slope, relief, elevation, and MAP, spatially co-vary.

Correlation of Physical and Environmental Parameters to Erosion Rates

Compiling and analyzing the global ^{10}Be dataset shows that the most successful understanding of erosion rates, in the absence of site-specific studies, will come from multivariate analyses of drainage basin data (Fig. 4; Table DR5). In general, analysis of data by climatic, tectonic, or lithologic subpopulations provides better correlation (higher R^2 value) because of the autocorrelation of erosion rates within similar process domains. Multivariate analysis explains almost twice as much variance in drainage basin erosion rates as in outcrop erosion rates, suggesting that there are other, unconsidered parameters controlling outcrop erosion rates (such as rock strength, structure, and joint spacing). Collecting such data along with samples for cosmogenic analysis would likely improve the understanding of controls on exposed bedrock erosion rates.

Some physical drainage-basin metrics, such as relief and slope, are clearly related both to each other and to drainage basin erosion rates. On the global scale, relief and slope both produced significant bivariate correlations with drainage basin erosion rates. In the multivariate analyses, slope was the predominant regressor in nearly every subdivision of categorical data (Fig. 4), as well as for the global basin-scale multivariate regression. Relief is unimportant for most categories of outcrops, except for sedimentary rocks and tropical climate zones. The lack of a relationship between watershed area and ^{10}Be-estimated drainage basin erosion rates is important because it indicates that changes in the sediment delivery ratio do not affect estimation of erosion rates cosmogenically; this finding stands in stark contrast to estimates made on the basis of sediment yield (Trimble, 1977; Walling, 1983).

Seismicity, a proxy for tectonics, is positively related to drainage basin erosion rates in bivariate regression, multivariate regressions, and in the comparison of tectonically active and inactive basins (Fig. 4; Fig. DR4). This relationship has previously been observed (i.e., von Blanckenburg, 2005) and likely reflects tectonic weakening of rocks through seismic shaking, deformation, fracturing, and perhaps base-level lowering (Riebe et al., 2001b). Multivariate regressions for both outcrops and basins in tectonically active areas show high R^2 values.

Although individual climate metrics are weakly related to erosion rates (Fig. 4), consistent with the findings of Reibe et al. (2001a), erosion rates of both outcrops and basins vary significantly by climate zone (Fig. 3). MAP is frequently cited as a parameter controlling erosion rates and a relationship is often observed in local and regional studies of both outcrop and drainage basin erosion (e.g., Bierman and Caffee, 2002, 2001; Henck et al., 2011; von Blanckenburg et al., 2004). Although MAP may produce a strong correlation at the local scale, the weak correlations observed globally and with multivariate analyses suggest MAP does not play an important role in explaining erosion rates for most basins. MAT is a significant regressor for polar basins; otherwise, its weighting is usually low (Fig. 4). MAT carries high weighting for some subcategories of outcrops. Latitude, a climate proxy, is significant in most basin subcategories. The percentage of a drainage basin covered with vegetation is generally unimportant.

IMPLICATIONS FOR LANDSCAPE EVOLUTION

The greater than ten-fold offset between rates of outcrop erosion and those of drainage basins suggests that ridgelines, where outcrops are most common, erode less rapidly than surrounding basins. Taken at face value, the offset between outcrop and drainage basin erosion rates is consistent with increasing relief, which may be driven by base-level changes (Riebe et al., 2001b), the result of Pleistocene sea-level changes, or by repeated climate swings (Peizhen et al., 2001). By collecting from the tops of bedrock outcrops, geologists sample the most stable portions of the landscape; perhaps then, it is no surprise that isolated outcrops erode more slowly than basins as a whole. However, this erosion rate offset cannot continue forever because ridgelines will eventually be consumed from their margins by the more rapidly eroding basins.

Cosmogenic data show that millennial-scale erosion rates differ between climate zones. Substituting time for space, glacial-interglacial climate cycles probably changed erosion rates and thus the flux of sediment shed off the landscape. Erosion rates are generally high for both outcrops and basins in temperate and cold climate zones, peaking where the MAT is ~10 °C (Figs. DR2–DR3). Temperatures in these climate zones fluctuate throughout the year, with numerous freeze-thaw cycles that may facilitate frost cracking on outcrops and cryoturbation on basin hillslopes (Delunel et al., 2010; Hales and Roering, 2007). This hypothesis is testable. Paleoerosion rates should be higher than modern rates in warmer climate locations that cooled significantly during the Pleistocene.

CONCLUSIONS AND FUTURE PROSPECTS

Compiling more than 20 years of cosmogenic analyses clearly shows their value in measuring background rates of erosion around the world, understanding how such rates are related to environmental parameters, and laying the groundwork for predicting long-term sediment generation rates at a variety of spatial scales. Yet, the same compilation demonstrates spatial biases in the existing data set, providing both justification and guidance for filling these data gaps. Multivariate regressions, using widely available environmental data, explain much of the variance in drainage basin erosion rates. Outcrop erosion rates are less well explained, suggesting that important controlling parameters, such as fracture density, joint spacing, bedrock structure, and rock strength and chemistry, need to be measured and considered in any predictive model.

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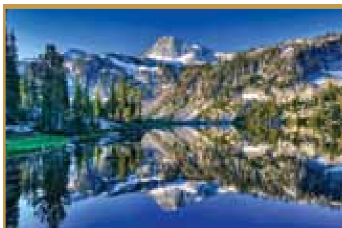




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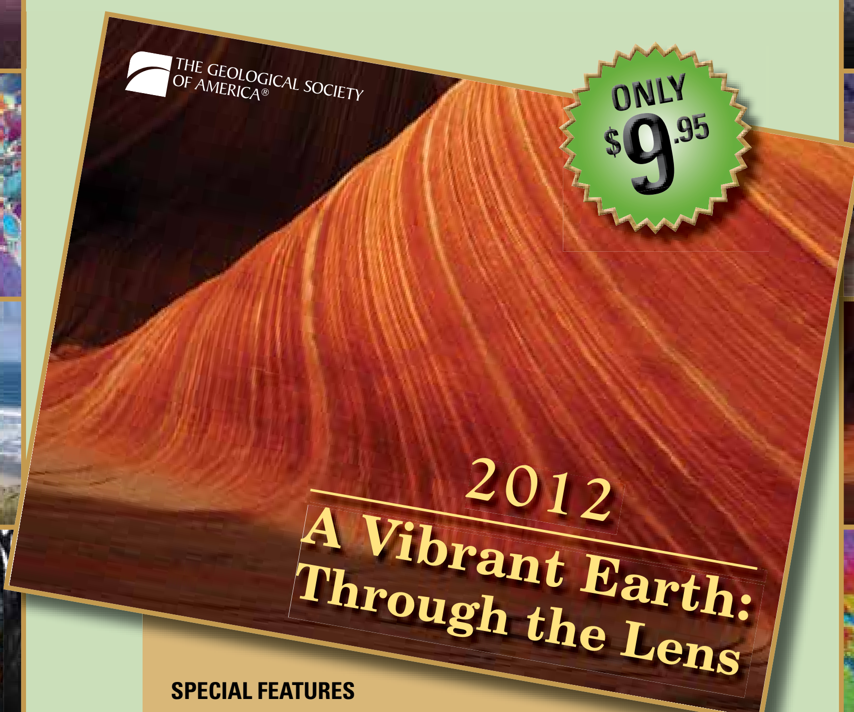

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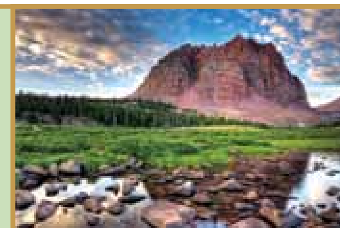
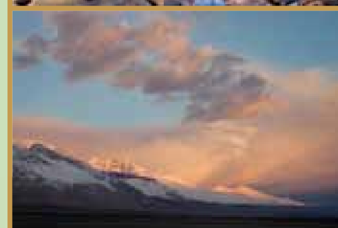
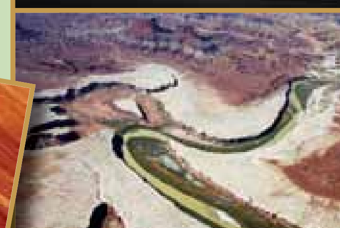

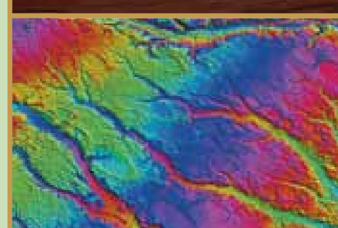


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ROCK STARS

Walther as young professor in Jena 1895 around the time of publication of his facies law.

Johannes Walther (1860–1937): More than the law of facies correlation

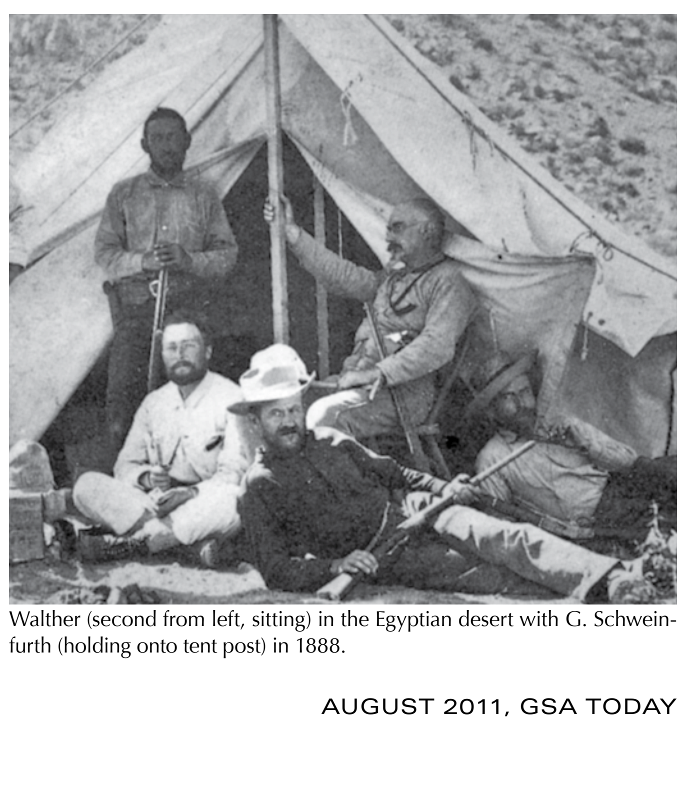
Eberhard Gischler, *Institut für Geowissenschaften, Goethe-Universität, Altenhöferallee 1, D-60438 Frankfurt am Main, gischler@em.uni-frankfurt.de*

Most geologists know of the German geoscientist Johannes Walther as the author of the law of facies correlation, published in German in 1894 and translated into English and explained by Gerard Middleton in 1973. The law explains that sedimentary facies seen conformably overlying each other in outcrops were formed at the same time beside each other. More than 100 years later, this law is central to facies stratigraphy and especially to sequence stratigraphy, both scientifically and practically (petroleum geology). Other than his facies law, not much is known about the life and career of this extremely productive geoscientist, particularly outside of Germany. A closer look shows that Walther accomplished much more than the formulation of his facies law, contributing significantly to marine geology, paleoecology, and paleoclimatology.

Several circumstances contributed to Johannes Walther's successes, including an early interest in the natural sciences, the influence of Ernst Haeckel from his teenage years, lots of reading, intensive traveling and field work, networking, the realization of the potential of marine geology, and dedication that at times turned into ambition.

Johannes Walther was a child of the monarchy. He was born in 1860 in Neustadt, Thuringia, then located in the dukedom of Saxony-Weimar-Eisenach (1871–1918 part of the German empire). Johannes' father was the local minister who had a keen interest in the natural sciences and planted this seed in his son's mind. At age 12, young Johannes met the geology professor Adolf von Koenen (1837–1915) of Göttingen, who took him along when mapping the Thuringian Rhön Mountains. At age 15, Johannes started to visit university classes of the famous and, later in life, controversially disputed biologist Ernst Haeckel (1834–1919) at the nearby university in Jena. Haeckel was a prominent follower of Darwin who spread evolutionary theory in Germany and the continent. These experiences were the sparks that inspired Johannes' interest in studying biology and geology. However, a major problem for him was an unidentified illness that included severe headaches that prevented him from passing the abitur, the precondition to university studies. Haeckel's intervention with the Duke of Saxony-Weimar-Eisenach allowed Walther to study natural sciences at the university in Jena without the school-exit exam. He started his studies in 1879, concentrated on biology, and finished in 1882 with a Ph.D. in zoology under Haeckel and the anatomist Oscar Hertwig (1849–1922). During his time in Jena, Walther also met his lifelong friend, Carl Duisberg (1861–1935), a chemist who would later become an influential industrialist and the head of Bayer and IG Farben. It is noteworthy that Walther did not join a student dueling corporation, which was quite common during those days, but was one of the cofounders of the student society of natural sciences at the university in Jena.

Because the geosciences in Jena were represented only by one professor of mineralogy, Walther left for Leipzig, where he studied under geologists Hermann Credner (1841–1913), Ferdinand von Richthofen (1833–1905), and Ferdinand Zirkel (1838–1912) and the marine zoologist Carl Chun (1852–1914). Walther continued his geoscientific studies in Munich with the paleontologist Carl von Zittel (1839–1904) and the geologist Carl Wilhelm von Gümbel (1823–1898). In the letters to his friend Duisberg during these early postdoctoral years, Walther



Walther (second from left, sitting) in the Egyptian desert with G. Schweinfurth (holding onto tent post) in 1888.

Walther as a postdoc during field work in Tunisia in 1884.

explained how he spent his time visiting classes, but also dedicated quite some time to reading geoscientific literature, and regularly went on field trips. It is also interesting to learn that Walther engaged in networking in that he visited most of the well-known geologists and paleontologists of his time in Germany, Austria, and Switzerland. The letters to Duisberg show a young man who was absolutely dedicated to his science, but who also confessed that sometimes his ambition left hardly any time for activities other than in the geosciences. Whereas his friend Duisberg married and founded a family early on, Walther would marry only in 1899, at the age of 39, when he had been a tenured professor for five years.

It was during the early postdoctoral years that Walther also started his first research project, which led him to Anton Dohrn's (1840–1909) marine research station in Naples, Italy. It must have been the collective influence of Haeckel, who studied the radiolaria of the Challenger Expedition (1872–1876); of Chun as the leader of the Valdivia Deep Sea Expedition (1898–1899); and of Gümbel, who investigated the sediments of the Gazelle Expedition (1874–1876), that got Walther interested in marine geology. As a postdoc, Walther also visited Sir John Murray in Edinburgh, who had published the scientific results of the Challenger Expedition, thereby establishing oceanography as a science.

In the Gulf of Naples, Walther investigated fauna, flora, and sediments of shallow seamounts by dredging from a small vessel. He made the first sediment maps of these areas, described the distribution of modern carbonate-producing fauna and flora, and identified the importance of coralline algae as reef builders. He also realized the significance of bioerosion and made quantitative taphonomic experiments with crustaceans, mollusks, and echinoderms in aquaria. At the same time, he investigated Mesozoic and Cenozoic limestones in the Mediterranean realm, in the Calcareous Alps, and tried to compare modern and ancient facies. Guidance during his studies in the Alps was given to him by Edmund Mojsisovics von Mojsvár (1839–1907), an Austrian paleontologist and biostratigrapher who had intensively studied the Triassic reefs of the Dolomites. Walther's postdoctoral years lasted from 1882 through 1886 and found their end in habilitation, a precondition in several European countries in order to be appointed to a professorship. Walther's habilitation thesis of 1886 was a paleontological gem. It focused on the taxonomy, functional morphology, and paleoecology of Jurassic crinoids and included comparative taxonomic, embryologic, ecologic, and taphonomic studies of modern crinoids from the Mediterranean. The combination of geology and biology and the use of the actualistic method was characteristic of Walther and can be found in many of his publications. Another typical attribute was his artful illustrations in many papers, which can be seen as a parallel to his mentor Haeckel, who is famous for his scientific artwork.

After habilitation, Walther returned to Jena as a lecturer without salary at the university. In 1890, he was bestowed with the title of professor and was given tenure in 1894. From 1886 to 1906, when he left Jena for a chair at the university in Halle, Walther traveled extensively and conducted field work in Africa, Arabia, central Asia, North America, and several European countries. It has to be kept in mind that at the time international travel without airplanes lasted weeks to months. Field work was performed using the railway, horses, donkeys, or camels to get around. During his career, Walther would visit all continents except for Antarctica. His interest in marine geological studies led him to the coral reefs of the Sinai and southern India, where he identified the importance of antecedent topography for Quaternary reef building and where he developed the concept that a reef limestone consists of a framework with interstitial sediment. He estimated the ratio of framework and detrital sediment to be 2:3.

Walther's field work locations were ideal in that he could study modern and recently uplifted fossil reefs nearby. During these studies, Walther also became interested in the adjacent deserts as sedimentary environments. An early supporter of this path was the world traveler Georg Schweinfurth (1836–1925) whom Walther accompanied during several expeditions. Walther detailed the importance of wind for sediment transport and redeposition, and he used his modern observations to identify deserts in the fossil record. Along these lines, he also realized that climate in the geologic past must have changed repeatedly. As he could not call on the universal model of plate tectonics, Walther was trying to explain the spatial distribution of paleoclimate indicators by polar wandering. He also discussed Alfred Wegener's (1880–1930) hypothesis of continental displacement, but concluded that evidence for the theory must first be found on the bottom of the world oceans. The evidence was indeed found there, but not until the 1960s.

After Walther accepted the chair of geology and paleontology at the university in Halle, more time had to be spent on administration and development and extension of the geological institute and museum. Still, Walther continued his research and did field work in the Mediterranean, Asia, north Africa, North America, and Australia. His Australia trip had to be cut short owing to the outbreak of World War I. After the war, Walther saw the demise of the monarchy and the development of the Weimar Republic (1919–1933); as an emeritus, he experienced the early rise of National Socialism and the Third Reich.

During his tenure in Halle from 1906–1928, Walther fought for geology to be introduced to school education, acted as dean of the faculty of natural sciences, and, from 1924–1932, was the president of the Scientific Academy Leopoldina. During his last years, Walther published several articles on Johann Wolfgang Goethe (1749–1832), who was one of his heroes—yet another parallel to his mentor Haeckel.

Walther died from a stroke in 1937 at age 76. His legacy includes 110 scientific publications in journals, 10 textbooks, 25 doctoral students, five of whom later became university professors, and, to close the circle, his universally known law of facies correlation.

The "Rock Stars" series is produced by the GSA History and Philosophy of Geology Division Editorial Committee chaired by Robert N. Ginsburg.

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EarthTrek™, the global citizen science program coordinated by GSA in partnership with organizations across North America and around the globe, is now heading into its third year. During that time it has provided scientists with invaluable data as well as introduced many members of the public to the wonders of scientific field work.

EarthTrek is different from most “citizen science” programs in that it only works with real research programs—that is, people are collecting data that will be used for research outcomes rather than just collecting data as a way to learn about science. For example, more than 860 graveyards have been visited by EarthTrek participants, who in turn have collected thousands of measurements for scientists studying the weathering rates of gravestones around the planet. A report from the first year of data collection highlights the scientific findings, such as positive/negative weathering profiles.

Other projects include Operation RubyThroat, which records sightings of ruby-throated hummingbirds in order to understand their migration patterns in North and Central America; the Garlic-Mustard Field Survey, which tracks infestations of garlic-mustard weeds; and Quake-Catcher Network, for which participants have logged thousands of hours of seismic data.

EarthTrek is an excellent way for scientists to engage the public and have them assist in collecting data for projects on global, regional, or local levels. Projects can be short term (days) or long term (up to three years). Scientists work with EarthTrek staff to develop sound scientific protocols, then EarthTrek calls on its participants to become involved. The data can be logged online and fed directly into existing databases, or EarthTrek can assist in the development of databases to collect data. The scientists can concentrate on the data aspects while EarthTrek manages the people! In turn, EarthTrek asks that the scientists provide regular feedback that can be communicated to participants.

This successful collaboration carries a minimal cost to scientists, ranging from free to a small fee for development of databases if required. It is certainly a very cost-effective way to meet the “broader impacts” aspects of a National Science Foundation proposal.

EarthTrek is a wonderful way for the public to become involved in real scientific research. Participants—called “EarthTrekkers”—learn about science by following the protocols and collecting data. They can take online exams, watch videos on protocols, and even ask questions in the online forums. They are also rewarded for their participation with points, icons, pins, and stickers. These rewards bring people back because it shows they are being recognized for their contributions. They also get an opportunity to see the results of their work when reports are released on the projects for which they have collected data.

An emerging aspect of EarthTrek is the release of some project information for teachers to use with their students for simple data manipulation or even to develop layers in GIS programs. It is a valuable way for students to learn to work with real “warts and all” data.

EarthTrek is now looking to expand its project base and is calling for scientists who would like to have the public help collect data for their research to contact the EarthTrek Program Director, Gary Lewis, at glewis@geosociety.org to talk through the possibilities.

Collecting gravestone weathering data for EarthTrek’s Gravestone Project; photo by G. Lewis.

For more information, go to
www.goEarthTrek.com.

2011 GSA SECTION MEETING MENTOR PROGRAM HIGHLIGHTS

MENTORING TOMORROW'S GEOSCIENCE LEADERS

The Geological Society of America runs two mentoring luncheons at its spring Section Meetings: The Roy J. Shlemon Mentor Program in Applied Geology and the John Mann Mentors in Applied Hydrogeology Program. These popular events, supported by the GSA Foundation through gifts from Roy J. Shlemon and John Mann, are designed to extend the mentoring reach of individual professionals from applied geology. This spring, Shlemon Program funds provided mentor experiences to 397 students via 47 mentors; the Mann Program funds provided mentor experiences to 205 students via 26 mentors. Both mentors and students leave these events expressing feelings of personal and professional growth.

Students have commented:

- "I learned things that I didn't even know I needed to know! I now have much more perspective about the professional world."
- "This was VERY valuable to undergrads. Entering the job world and leaving the academic world is very scary. This lunch has made me much less apprehensive of the future. Thank you very much."
- "I found this experience educational on so many levels. I learned something valuable from each mentor."
- "It was awesome to hear the personal experiences and suggestions. This lunch was the most beneficial part of the meeting."

GSA's Education & Outreach Department, which facilitates the mentor programs, gratefully acknowledges the following mentors for their gifts of time and insight.

The Roy J. Shlemon Mentor Program in Applied Geology

NORTHEASTERN/NORTH-CENTRAL SECTION JOINT MEETING

Katharine Lee Avary, Consultant

Joe Biaglow, Greenfields Environmental Corp.

Gabriela Depine, Shell Exploration and Production Co.

Maurice Deul, Consultant

Raymond Follador, ARK Resources Inc.

Michael Forth, A&A Consultants Inc.

Michael Goodman, Chevron USA Inc.

Steve Gridley, United Environmental Group Inc.

Jim Hamel, Hamel Geotechnical Consultants

Michael Jarvis, Talisman Energy USA Inc.

Connie Jump, Chevron USA Inc.

William Kelly, New York State Geologist & Director of the New York State Geological Survey (retired)

James Kilburg, Shaw Environmental & Infrastructure Inc.

Dan Martt, American Geotechnical & Environmental Services Inc.

Dan Neilans, Alpha Natural Resources

Susan Price, Murphy Risk Services

Iain Prince, Shell Exploration and Production Co.

Alex Prvanovic, American Geotechnical & Environmental Services Inc.

Douglas Reif, CNX Gas Company LLC

Richard Ruffolo, GAI Consultants

David Saja, The Cleveland Museum of Natural History

Daniel Sanger, Pennsylvania Soil and Rock Inc.

Dan Sellers, Rex Energy Corp.

Brian Shaffer, Alpha Natural Resources

Abdul Shakoor, Consultant & Kent State University

Gregory Walsh, U.S. Geological Survey

William Zempolich, Chevron USA Inc.

SOUTHEASTERN SECTION MEETING

Katharine Lee Avary, Consultant

Richard Kolb, Duncklee & Dunham PC

Craig Sprinkle, CH2M HILL

John Stewart, Kleinfelder

Ronald Wallace, Georgia Environmental Protection Division

Brad Worley, NCDOT Geotechnical Engineering Unit

Continued next page

The Roy J. Shlemon Mentor Program in Applied Geology *(continued)*

SOUTH-CENTRAL SECTION MEETING

Kelly Haggar, Riparian Inc.

Art Johnson, Hydrate Energy International

Barry Levine, City of Memphis Division of Public Works

Shane Matson, Spyglass Energy Group

Charles Wickstrom, Spyglass Energy Group

ROCKY MOUNTAIN/CORDILLERAN SECTION JOINT MEETING

Jeffrey Bader, AECOM

Paul Inkenbrandt, Utah Geological Survey

Phil Johnson, Cotton, Shires and Associates Inc.

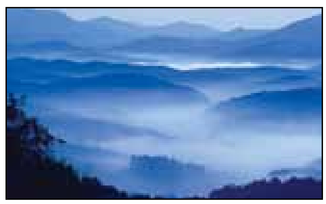
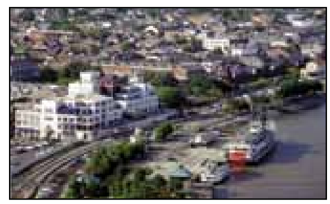
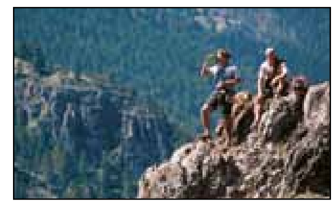
Alexander Seyfarth, Bruker AXS

Roy Shlemon, Consultant

Wes Thompson, BIO-WEST Inc.

Lillian D. Wakeley, U.S. Army Engineer R&D Center

Kate Zeigler, Zeigler Geologic Consulting

From left to right. Holtwood Gorge, Susquehanna River, Pennsylvania; photo courtesy Frank J. Pazzaglia. Grandfather Mountain; image courtesy North Carolina Tourism. Aerial moonwalk over New Orleans; photo by Richard Nowitz courtesy New Orleans Convention and Visitors Bureau. Logan Canyon; photo by Donna Barry.

The John Mann Mentors in Applied Hydrogeology Program

NORTHEASTERN/NORTH-CENTRAL SECTION JOINT MEETING

Joe Biaglow, Greenfields Environmental Corp.

Robert Blauvelt, GEI Consultants, Inc

G. Patrick Bowling, Pennsylvania Dept. of Environmental Protection

Paul Doss, Consultant & University of Southern Indiana

John Dougherty, CDM

Mark Eisner, Advanced Land and Water Inc.

Gary Fleeger, DCNR Bureau of Topographic and Geologic Survey

John Graves, U.S. Environmental Protection Agency

Laurie Scheuing, Consultant

Stephen Urbanik, New Jersey Dept. of Environmental Protection

SOUTHEASTERN SECTION MEETING

J. Wright Horton, U.S. Geological Survey

Darren Lockhart, The EI Group Inc.

Craig Sprinkle, CH2M HILL

John Stewart, Kleinfelder

Ronald Wallace, Georgia Environmental Protection Division

SOUTH-CENTRAL SECTION MEETING

Dan Larsen, Consultant & University of Memphis

Barry Levine, City of Memphis Division of Public Works

Thomas Marshall, Iowa Geological and Water Survey

Dale Nyman, Consultant

Charles Thibault, Consultant

ROCKY MOUNTAIN/CORDILLERAN SECTION JOINT MEETING

George Condrat, Loughlin Water Associates LLC

Victor Heilweil, U.S. Geological Survey

Daniel Horns, Utah Valley University

Paul Inkenbrandt, Utah Geological Survey

Robert Oaks Jr., Classic Geological Studies Corp.

Wes Thompson, BIO-WEST Inc.

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For more information about these and other GSA mentor programs and to volunteer to be a mentor at a future GSA meeting, go to **www.geosociety.org/mentors/** or contact Jennifer Nocerino, jnocerino@geosociety.org.

Larry Meinert

Interesting Times—Part 2

My previous column was titled "Interesting Times…" because of the 2010 elections and the wholesale changes in U.S. government that resulted. A footnote was added prior to publication of the original article that even more dramatic changes had transpired due to the tragic shooting on 8 Jan. 2011 of Congresswoman Giffords and members of her staff. There have been countless inquiries to Giffords' office in general and to me personally about the congresswoman's health and miraculous continuing recovery. I can only say that I am truly humbled by the outpouring of goodwill from people worldwide as they expressed their heartfelt condolences and best wishes. This event has changed the lives of many people, including of course the staff, who have continued to carry on the good work of the office and the spirit of Congresswoman Giffords.

Her recovery continues to be an inspiration. I have talked to her during some of our weekly staff conference calls and can report that her recovery is amazing. I have no special insight beyond what her doctors have reported—it is a long road to recovery, and she is making great strides.

I had the privilege of attending the launch of space shuttle mission 134, the second to last shuttle launch, crowning a very successful 30-year program of space exploration. As the public knows, this mission was commanded by Congresswoman Giffords' husband Mark Kelly, and the congresswoman was able to attend the launch. This was my first opportunity to witness a space shuttle launch, and given that this is close to the end of a very successful NASA program, I was honored to be able to experience firsthand the roar of the engines as this glorious tribute to science and engineering blasted into space.

When I returned to Washington and the legislative cycle of budget hearings and budget cutting, I had the opportunity to experience what few in the congressional arena get to do. I was offered the chance to work on both sides of the Capitol. I initially interviewed widely for my congressional fellowship in both the Senate and House and for both member offices and committee staff. There are many reasons for choosing any of these attractive possibilities. I chose Giffords' office in the House for the reasons outlined in my previous *GSA Today* column (v. 21, no. 3, p. 18–19). In May, I had the pleasure of joining the staff of Senator Coons, the newly elected senator taking over the seat of Vice President Biden. One of the reasons I chose this office is that Senator Coons sits on several committees of interest to geologists, including the Senate Energy and Natural Resources Committee.

The contrast between the House and Senate paints a fairly complete picture of the vision of the founding fathers in designing a balance of powers within the legislative branch. The House reflects majority rule, and I had the rich opportunity to experience the transition from the majority to the minority—a huge difference indeed. The minority party can only introduce bills and have them move forward with the concurrence of the majority party. In this era of partisanship, that does not often happen. The Senate is different on several levels. Although there currently is a Democratic majority, the Senate operates by consensus, and it is not an exaggeration that a single senator has the power to affect the path of the entire country. Thus, being in a Senate office is an opportunity to be involved at an entirely different level than in the House.

My portfolio continues to focus on energy and natural resources. As I write this column, we are preparing for hearings on several bills concerning U.S. energy policy. I attended a briefing on U.S. energy options during which Texas state geologist Scott Tinker outlined the various possibilities for energy use for the coming decades. To many people's consternation, the discussion in the Senate Energy and Natural Resources Committee focused more on the procedural points of finding authorization offsets rather than the merits of the various energy bills. It would take several pages to explain the details of such offsets, but suffice it to say that some people view this as political demagoguery rather than an expedient path toward solving the nation's problems. At the same time, the offsets are pieces of the complex puzzle that has also included policy debates about suspending congressional earmarks, changing entitlements, and raising the debt ceiling as the country wrestles with long-term fiscal discipline.

As Congress moves toward solutions to important energy problems, it is clear that geologists have a central role to play in the discussion, and I am honored to be the GSA-USGS Congressional Fellow at this pivotal time in U.S. legislative history. In my next column, I will report on how U.S. energy policy has evolved in the 112th Congress.

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

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USGS science for a changing world

2011–2012 GSA-USGS Congressional Science Fellow Named

Kelly A. Kryc

Kelly Kryc brings an interdisciplinary background spanning the physical and life sciences to the 2011–2012 GSA-USGS Congressional Science Fellowship. Her experience encompasses two decades of academic research and non-profit sector program management.

Kryc's research focused on interpreting the geochemical record of terrigenous provenance and biological export production to understand Holocene climate change in Antarctica. She earned a B.A. with honors in geology and marine science from Middlebury College (1994), an M.S. in oceanography from the Graduate School of Oceanography at the University of Rhode Island (1998), and a Ph.D. in earth science from Boston University (2002). She subsequently conducted post-doctoral research at Stanford University. Her field research in Antarctica included one season collecting samples in the Dry Valleys and three research cruises coring the East Antarctic Margin.

More recently, Kryc embarked on a career in science program management, which cultivated her abilities to tackle complex issues through strategic planning and adaptive management. Her first position was as the assistant director of Ocean Drilling Programs at the Joint Oceanographic Institutions (now Ocean Leadership) in Washington, D.C., providing scientific direction and leadership of the U.S. Implementing Organization. She subsequently accepted a position as the executive program associate at the Integrated Ocean Drilling Program–Management International office in Washington, D.C., facilitating long-range planning activities. Most recently, she served as a program officer with the Marine Microbiology Initiative at the Gordon and Betty Moore Foundation, which broadened her expertise to include the life sciences. Kryc left the Foundation in late 2010 to start her own consulting business providing long-range strategic planning guidance to non-profit organizations. In addition to her professional activities, Kryc is committed to advancing geoscience literacy in the United States and serves as a member of the National Advisory Committee for the Centers for Ocean Sciences Education Excellence (COSEE).

Kryc notes that she is honored by her selection to serve as the 2011–2012 GSA-USGS Congressional Science Fellow. She is excited by the potential to contribute the skills she has, and those she hopes to develop, in multiple policy areas. Among these, climate change and energy independence stand out for their urgency, and for the critical need in these areas for substantive and accessible science to support public policy.

Donna L. Russell, *Director of Operations*

GSA Foundation's Silent Auction

GSA Foundation's 2010 Silent Auction in Denver, Colorado, USA.

Silent Auction Donation Suggestions

- Geological Specimens
- Gift Certificates
- Geological Books
- Maps
- Wine
- Beer
- Unopened CDs and DVDs
- Artwork
- Jewelry
- Unusual Collectibles
- Seasonal Decorative Items
- Geological Tools
- Field Supplies
- Software
- Field Gear

The GSA Annual Meeting in Minneapolis, Minnesota, USA, will be here before we know it (9–12 October), and the Foundation staff is already at work planning the annual Silent Auction. We hope you will stop by our Auction in the Foundation booth and browse through all the great items we will have available for bid.

The auction is a good place to find those special holiday gifts, and at the same time support the GSA Foundation. All proceeds go to the Foundation's Greatest Needs Fund, which supports research grants, student travel grants (domestic and international), education & outreach programs, GSA publications, and other funding projects for the Society.

Would You Like to Donate to the Auction?

Your items will be on display in the Foundation booth at the annual meeting—Come watch the bidding! All donations to the Silent Auction are tax-deductible based upon the retail value of the donated item. The Foundation will also accept cash donations to support the auction.

Please mail donations directly to the attention of Donna Russell or Geni Klagstad at the GSA Foundation, 3300 Penrose Place, P.O. Box 9140, Boulder, CO 80301, USA, by 1 Sept. 2011. For further information, contact Donna at drussell@geosociety.org, +1-303-357-1054; or Geni at gklagstad@geosociety.org, +1-303-357-1010.

Digging Up the Past

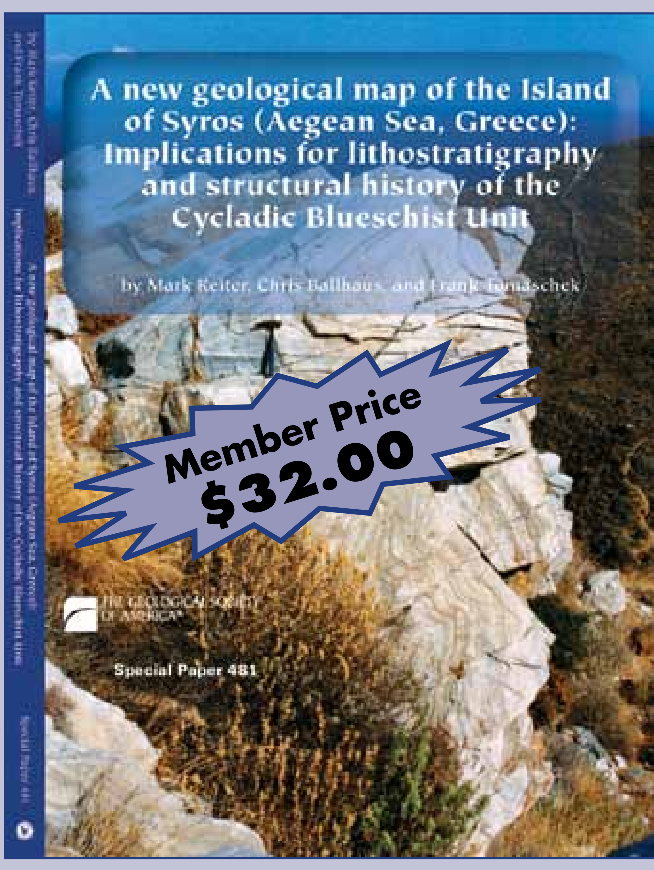
Most memorable early geologic experience:

In 1959, working as USGS field assistant to retired Yale Professor, Chester Longwell, in South Nevada, thus connecting with early geologic exploration of the West.

—Peter W. Lipman

A new geological map of the Island of Syros (Aegean Sea, Greece): Implications for lithostratigraphy and structural history of the Cycladic Blueschist Unit

By Mark Keiter, Chris Ballhaus, and Frank Tomaschek



Syros Island, in the heart of the Cycladic archipelago, has been a key area for the study of high-pressure rocks throughout the past decades. Excellently preserved blueschist- to eclogite-facies lithologies offer a unique opportunity to study processes of burial and exhumation in a young orogen. The authors present a new, highly detailed geological map of Syros and review the current state of research concerning this interesting island.

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ARCHEAN to ANTHROPOCENE

the past is the key to the future

2011 GSA Annual Meeting & Exposition
Minneapolis, Minnesota, USA

Events & Deadlines

CALENDAR

Early registration deadline:
Tues., 6 Sept.

Housing deadline:
Tues., 6 Sept.

Registration cancellation deadline:
Mon., 12 Sept.

Pre-Meeting Field Trips:
Tues.–Sat., 4–8 Oct.

Short Courses & Workshops:
Fri.–Sun., 7–9 Oct.

NEW TIMES!

Exhibits Opening:
Sun., 9 Oct., 2–6:30 p.m.

Presidential Address & Awards Ceremony:
Sun., 9 Oct., 6:30–8:30 p.m.

Awards & Welcoming Reception:
Sun., 9 Oct., 8:30–9:30 p.m.

TECHNICAL PROGRAM

Oral Sessions:
Sun.–Wed., 9–12 Oct.

Poster Sessions
(posters are to be hung all day; authors present a.m. or p.m.):
Sun.–Wed., 9–12 Oct.

EXHIBIT HALL HOURS

Sun., 9 Oct., 2–6:30 p.m.

Mon.–Tues., 10–11 Oct., 9 a.m.–6 p.m.

Wed., 12 Oct., 9 a.m.–2 p.m.

Lunchtime Lectures:
Sun.–Wed., 9–12 Oct., 12:15–1:15 p.m.

Private Alumni Receptions:
Mon., 10 Oct.; evening times vary

Group Alumni Reception:
Mon., 10 Oct., 7–9:30 p.m.

Post-Meeting Field Trips:
Thurs.–Sat., 13–15 Oct.

Lunchtime Lecture Highlights

The GSA Lunchtime Lecture series offers four one-hour presentations (one for each day of the meeting) by high-profile speakers on broad topics relevant to geoscience and society. Bring your lunch and prepare to be challenged and inspired! So far, GSA has confirmed the following two speakers; days and times will be listed on the meeting website, www.geosociety.org/meetings/, and in the September issue of *GSA Today*.

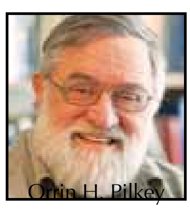
John F.H. Thompson

Mineral Resources—21st Century Challenges for Earth Scientists

2011 Michel T. Halbouty Distinguished Lecturer

John F.H. Thompson, Vice President Technology and Development, Teck Resources Limited

John Thompson obtained his B.A. from Oxford University and then moved to Canada, where he completed his M.Sc. and Ph.D. degrees at the University of Toronto, working on magmatic sulfides deposits in the Caledonides and Appalachians. In 1982, he joined the BP Minerals group in Australia to work in mineral exploration, subsequently moving to an international exploration role with the group, based in UK. In 1988, he moved to Salt Lake City initially with BP Minerals and later with Kennecott–Rio Tinto. In 1991, Thompson became director of the Mineral Deposit Research Unit (MDRU) at the University of British Columbia, managing exploration-related research for more than 20 companies. In 1998, he joined Teck Corporation as chief geoscientist and in late 2005 was appointed vice president of technology and development for Teck Resources Limited. In this role, he manages R&D and evaluation activities related to corporate development, operations, and new projects.



Orrin H. Pilkey

Mathematical Modeling is Damaging our Science

Orrin H. Pilkey, James B. Duke Professor Emeritus of Earth Sciences, Nicholas School of the Environment, Duke University

Orrin Pilkey is a marine/coastal geologist currently concerned with the global view of barrier island evolution and the impact of sea-level rise on coastal civilizations. He has received a number of awards, including the Shepard Medal for excellence in marine geology and the GSA Public Service Award. He has co-authored numerous books, including *Useless Arithmetic*, a critical review of mathematical modeling in the earth sciences; *The Rising Sea*; and *The World's Beaches*.

Lecture synopsis: Mathematical modeling requires the development of simplifying assumptions in order to make a very complex natural world simple enough to model. Unfortunately, these simplifications have in some instances become accepted real-world principles, trapping our science in an "expected universe," where field work is structured to verify the reality of the "model world" rather than exploring the uncertainty and variability in the "real world." This is a precarious approach to science, and those who study natural processes in the field must take care to avoid following a path guided entirely by questions framed by modelers.

PRESIDENTIAL ADDRESS & AWARDS CEREMONY

Sunday, 9 Oct., 6:30–8:30 p.m.

Minneapolis Convention Center, Ballroom A

Please join us SUNDAY evening (note new day) when GSA President John Geissman gives his Presidential Address and salutes this year's awardees. The citations and responses for the 2011 recipients of the Penrose Medal, the Arthur L. Day Medal, the Young Scientist Award (Donath Medal), the President's Medal of the Geological Society of America, the GSA Public Service Award Medal, the Bromery Award for the Minorities, the GSA Distinguished Service Award, the Subaru Outstanding Woman in Science Awardee, and the American Geological Institute (AGI) Medal in Memory of Ian Campbell will be presented, and the John C. Frye Environmental Geology awardee, the GSA Division awardees, the ExxonMobil Field Camp Excellence Award, and the newly elected GSA Fellows will also be announced. A reception will immediately follow the ceremony.

Attention GeoCorps™ America Alumni and Current Participants!

The second annual GeoCorps Alumni Reception will take place in October at the 2011 GSA Annual Meeting & Exposition in Minneapolis, Minnesota, USA. Please watch the GeoCorps website for further details.

www.geosociety.org/geocorps/

2011 Short Courses

Don't Forget to Sign up for a GSA Short Course!

These courses fill up quickly—early registration is recommended.
If you register after 6 Sept., you will need to pay an additional US$30. To sign up, go to **www.geosociety.org/meetings/2011/reg.htm.**

Earn continuing education credits (CEUs)!
All short courses offer CEUs, and most are at low or no cost. For full course descriptions, go to **www.geosociety.org/meetings/2011/courses.htm.**

Questions?
Contact Jennifer Nocerino, jnocerino@geosociety.org.

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Positions Open

ENVIRONMENTAL GEOBIOLOGY
KANSAS STATE UNIVERSITY

The Department of Geology at Kansas State University invites applications for a tenure-track assistant professorship for the fall of 2012, in the field of Environmental Geobiology. For details of this advertisement, please visit our website at http://www.ksu.edu/geology. Questions about this position may be directed to Dr. Saugata Datta at sdatta@ksu.edu or +1-785-532 2241. Kansas State University is an equal opportunity/affirmative action employer and actively seeks diversity among its employees. A successful pre-employment background check is required before a job is offered.

EARTH SYSTEMS SCIENTIST
STRUCTURAL GEOLOGY/TECTONICS
TENURE-TRACK POSITION
DEPT. OF EARTH AND ENVIRONMENTAL SCIENCES
BOSTON COLLEGE

The Department of Earth and Environmental Sciences at Boston College invites applications for a tenure-track position in the area of Structural Geology/Tectonics to start in Fall 2012. The successful candidate will be expected to develop an externally-funded research program integrated with excellence in teaching within the geological sciences and environmental geoscience curriculum at both the undergraduate and graduate levels. Teaching responsibilities include courses in structural and field geology as well as others in the candidate's area of expertise. Specific research subfields of the successful applicant could include crustal dynamics, thermochronology, tectonic history of orogenic belts, tectonic-climate interactions, paleoseismology, and/or active deformation/geodesy. The department is equipped with a mineral separation laboratory including Wilfley table, heavy liquids separation lab, Franz magnetic separator, and stereomicroscope. Other labs in the department include state-of-the art petrographic microscopes, a laser Raman microspectroscopic imaging system, and an isotope ratio mass spectrometer for light stable isotope analyses. Information on the department, its faculty and research strengths can be viewed at www.bc.edu/eesciences. Applicants should send a curriculum vita, statements of teaching and research interests, and the names and contact information of at least three references as a single PDF-file-mail attachment to tectonics-position@bc.edu. Review of applications will begin on 28 October 2011. Department faculty will be available at the GSA and AGU fall meetings to meet with applicants. Boston College is an academic community whose doors are open to all students and employees without regard to race, religion, age, sex, marital or parental status, national origin, veteran status, or handicap.

APPLIED GEOPHYSICS, TENURE-TRACK
DEPT. OF GEOLOGICAL SCIENCES AND GEOLOGICAL ENGINEERING
QUEEN'S UNIVERSITY

The Department of Geological Sciences and Geological Engineering at Queen's University, seeks individuals with outstanding research and teaching capabilities to apply for a tenure-track position, starting on 1 January 2012 or 1 July 2012, as an Assistant Professor in Applied Geophysics. The successful candidate will hold a P.Eng., or will be eligible to apply for a P.Eng., immediately by virtue of having graduated from an accredited engineering program. The candidate will build on the existing applied geophysics program which is focused in the Geological Engineering program, but is of interest to students in Geological Sciences and other departments at Queen's. The candidate is expected to carry on an active, externally funded research program of international caliber and to supervise graduate students at the M.Sc. and Ph.D. levels. A willingness to engage in collaborative research with departmental colleagues will also be considered in the selection process. For more information about faculty research interests, the full range of undergraduate and graduate teaching programs, and our laboratory facilities, visit www.geol.queensu.ca.

The University invites applications from all qualified individuals. Queen's University is committed to employment equity and diversity in the workplace and welcomes applications from women, visible minorities, aboriginal peoples, persons with disabilities, and persons of any sexual orientation or gender identity. All qualified candidates are encouraged to apply; however, Canadians and permanent residents will be given priority.

Academic professionals at Queen's University are governed by the Collective Agreement between the Queen's University Faculty Association (QUFA) and the University, which is posted at http://www.queensu.ca/vpac/FacultyRelations/CollectiveAgreements.html. Remuneration will be in accordance with the Collective Agreement, which considers qualifications and experience.

Applications should include a complete and current curriculum vitae, letters of reference from three (3) referees of high standing, a statement of teaching experience, a statement of research interests and future plans, and samples of research writing. Please arrange to have applications and supporting letters sent directly to Dr. D.J. Hutchinson, Head, Department of Geological Sciences and Geological Engineering, Queen's University, Room 240 Bruce Wing, Kingston Ontario Canada K7L 3N6.

Applications will be accepted until 26 August 2011, or until a suitable candidate is identified. Review of applications will commence shortly thereafter, and the final appointment is subject to budgetary approval.

DEVON ENERGY CORPORATION
CHAIR OF BASIN RESEARCH
OKLAHOMA STATE UNIVERSITY

The Boone Pickens School of Geology at Oklahoma State University (OSU) is extending its search for the endowed Devon Energy Corporation Chair of Basin Research. This Chair will be filled at the level of Professor, will carry tenure in the School of Geology, and will be filled by January or August 2012. Applicants must have a Ph.D. degree in geology or related field and have an outstanding record of research, commensurate with the rank of tenured full professor and a demonstrated record of funding. The specific field of study is open but special consideration will be given to geoscientists with interests in one or more of the following research areas: reservoir characterization and modeling, unconventional petroleum reservoirs, depositional and/or diagenetic systems, geochemistry of petroleum systems, and/or origin and migration of basinal fluids. Preference will be given to candidates with a close working relationship with the petroleum industry. The applicant must be committed to excellence in teaching both undergraduate and graduate students, will be expected to supervise M.S.- and Ph.D.-level graduate students and develop courses in his/her specialty.

The successful candidate will join a faculty of twelve geoscientists and will take a leadership role as part of campus and industry research groups in a department that has close ties to the petroleum industry. The school's teaching and research facilities include state-of-the-art geophysical field and laboratory equipment and software, the Devon Visualization Laboratory, and a wide range of petrographic and geochemical instrumentation. The School also maintains a field camp in Cañon City, Colorado, USA.

Candidates should submit a letter of application, including (1) a discussion of research interests, (2) approach to teaching, (3) curriculum vitae, and (4) the names, addresses, e-mail addresses, and phone numbers of three references to: Devon Chair Search, Boone Pickens School of Geology, 105 Noble Research Center, Oklahoma State University, Stillwater, Oklahoma 74078-3031, phone: +1-405-744-6358, Fax: +1-405-744-7841. Screening of candidates will begin on 17 Oct. 2011 and continue until the position is filled.

More information on OSU and the Boone Pickens School of Geology can be found on the web http://osu.okstate.edu and http://geology.okstate.edu respectively. Inquiries about this position may be directed to Dr. Todd Halihan (todd.halihan at okstate.edu) or Dr. Jay Gregg (jay.gregg at okstate.edu). Committed to health and safety, Oklahoma State University maintains a tobacco-free work environment. Oklahoma State University is an Affirmative Action/Equal Opportunity/E-Verify employer committed to diversity.

Revisiting the Geoscience Concept Inventory: A call to the community

J.C. Libarkin*, E.M.G. Ward, *Dept. of Geological Sciences, Geocognition Research Lab, Michigan State University, 206 Natural Science, East Lansing, Michigan 48824, USA;* ***S.W. Anderson,*** *MAST Institute, University of Northern Colorado, 1210 Ross Hall, Campus Box 123, Greeley, Colorado 80639, USA;* ***G. Kortemeyer,*** *Lyman Briggs College, Michigan State University, East Lansing, Michigan 48825, USA; and* ***S.P. Raeburn,*** *Division of Science & Mathematics Education, Michigan State University, 103 N Kedzie Lab, East Lansing, Michigan 48824, USA*

ABSTRACT

The use of concept inventories in science and engineering has fundamentally changed the nature of instructional assessment. Nearly a decade ago, we set out to establish a baseline for widespread and integrated assessment of entry-level geoscience courses. The result was the first Geoscience Concept Inventory (GCI v.1.0). We are now retiring GCI v.1.0 and rebuilding the GCI as a more community-based, comprehensive, and effective instrument. We are doing this in the hopes that GCI users, many of whom have expressed a need for a revised and expanded instrument, and the geoscience community at large will view it as a springboard for collaborative action and engagement. If we work together as collaborators, the geosciences have the potential to evaluate learning across our community and over time.

INTRODUCTION

The Geoscience Concept Inventory (GCI; Fig. 1) was developed to diagnose conceptual understanding and assess learning in entry-level geoscience courses. The GCI has become a staple in many classroom-based research studies, is being revised for use in pre-college settings, and has been shown to discriminate between experts and novices. Although a valuable research tool, the GCI is in need of an expansion that can only be accomplished by a community of geoscientists and educators working together. This paper is a call for that collaboration.

The GCI holds a unique place in the concept inventory world for several reasons. First, the GCI is the only concept inventory to generate a bank of correlated concept inventory questions for higher education science (Libarkin and Anderson, 2006). Through this correlation, users of the GCI can create course-specific subtests rather than being tied to a single set of questions.

Second, the GCI contains single response, two-tier, and multiple-response multiple-choice questions. Two-tier questions offer added insight into student thinking by requesting an explanation for student responses (Treagust, 1988). Multiple-response questions, essentially a set of true/false items, are generally more difficult than typical single-response items and are cognitively similar to free response questions, offering deeper insight into cognition (Kubinger and Gottschall, 2007).

Third, GCI questions were developed from ideas that both experts and novices found important for entry-level geoscience courses. A review of textbooks provided initial ideas about important concepts for inclusion on the GCI, while open-ended interviews with students provided additional topics (Libarkin and Anderson, 2005). For example, in-depth interviews suggest that students conflate gravity and magnetism and inflate the importance of magnetic fields on the movement of large objects. Addressing this mixing and mis-scaling is important for student understanding of geomagnetism and its effects, a discovery that only became apparent after considering the student perspective.

THE NEED TO REVISE AND EXPAND THE GCI AS A COMMUNITY

The original GCI questions were piloted with up to 5,000 students enrolled at >40 institutions nationwide, with the current version in use by >200 faculty and researchers. The GCI has been used to estimate learning in geoscience courses, including evaluation of specific instructional approaches (e.g., Kortz et al., 2008) and analysis of learning (e.g., Petcovic and Ruhf, 2008). In ongoing work, GCI scores have been shown to correlate strongly with geological mapping ability. This suggests that the GCI, a measure of very foundational knowledge, can be used as a skills measure to predict performance on an expert task. While we are encouraged that GCI v.1.0 was useful in these studies, we acknowledge that the instrument ingrains our own biases and limitations. As many of our colleagues have stated, the GCI is both an effective instrument for gauging learning in entry-level geoscience courses *and* a test in need of revision.

The diversity of geoscience courses at all levels should be reflected in the assessment instruments used to evaluate learning nationwide. Expansion to more complex, wider ranging questions will allow replicable assessment in advanced courses and across geoscience programs. A critical need for questions targeted toward upper-level courses requires community

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*libarkin@msu.edu

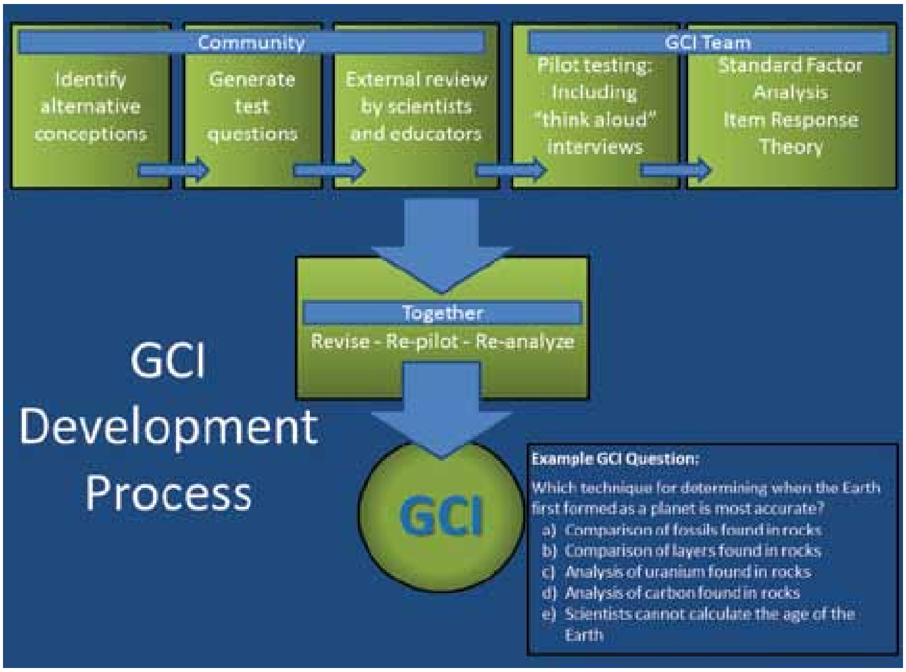

Figure 1. Development cycle for the Geoscience Concept Inventory (from Ward et al., 2010) and an exemplar GCI question.

effort. Experts knowledgeable about issues students have understanding complex ideas, such as feedback in global systems, are needed to write, review, and test new questions.

The current effort to revise and expand the GCI is a community endeavor. This interdisciplinary and collaborative approach addresses the limitations that are otherwise inherent in any tool generated for an entire field by a single development team: (1) education technology specialists with expertise in online assessment, together with geocognition researchers, oversee question dissemination, community feedback and question submission, and online data collection; (2) self-selected geologists, science educators, and instrument developers participate as reviewers and authors of new questions; and (3) the GCI development team analyzes student response and interview data to establish instrument validity and reliability.

We have been collecting comments from users and have been reevaluating the GCI from the perspective of existing standards for instrument design (e.g., Moreno et al., 2006). Based on this examination, we have generated a revised version of the GCI. This version, GCI v.2.1, is available through the GCI WebCenter at http://gci.lite.msu.edu/. We invite the community to contribute to its on-going use and development through:

1. **Reviewing GCI questions.** Reviews and comments on existing questions and those proposed for inclusion are needed.
2. **Proposing new areas for GCI development.** The existing GCI covers only limited topics, and inclusion of questions from atmospheric sciences, geophysics, planetary science, and other fields is needed.
3. **Becoming authors of the GCI.** Contributors become co-authors of the instrument. Guidelines are available at the GCI WebCenter (http://gci.lite.msu.edu/; Libarkin and Ward, 2011). Revisions initiate expert review and statistical analysis of student responses. The development of new GCI questions takes at least six months from submission to validation, with continual change in response to community needs.
4. **Assessing student learning.** Online testing can generate a national sense of student learning, as well as link learning to instruction. The GCI is being migrated to a new system (LectureTools) that will offer auto-feedback of results, analysis of overall course performance, and summary of student conceptual difficulty. Anonymous data collected from courses across our community will also be accessible.

We encourage anyone with a stake in teaching and learning to become involved with the GCI as a reviewer, developer, or user. This involvement is vital for any assessment initiative that serves an entire community. Careful consideration of evidence, such as that offered by the GCI, is a first step to answering calls for overall improvement of instruction (e.g., COSEPUP, 2006). The quality of assessment can only rise to the level of the tools used, and everyone has a stake in ensuring that assessment instruments continually improve. We invite our community to join us as co-authors of the GCI.

ACKNOWLEDGMENTS

We thank all GCI users and colleagues who graciously provided constructive feedback, encouraged us in this new initiative, and are poised to become co-authors on a community GCI. The GCI was funded by the U.S. National Science Foundation (NSF) through grants DUE-0127765, DUE-0350395, DGE-9906479, DUE-0717790, and DUE-0717589. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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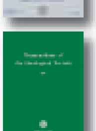
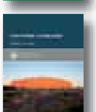

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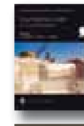
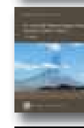
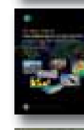
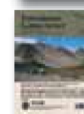


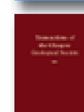

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