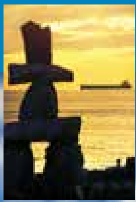

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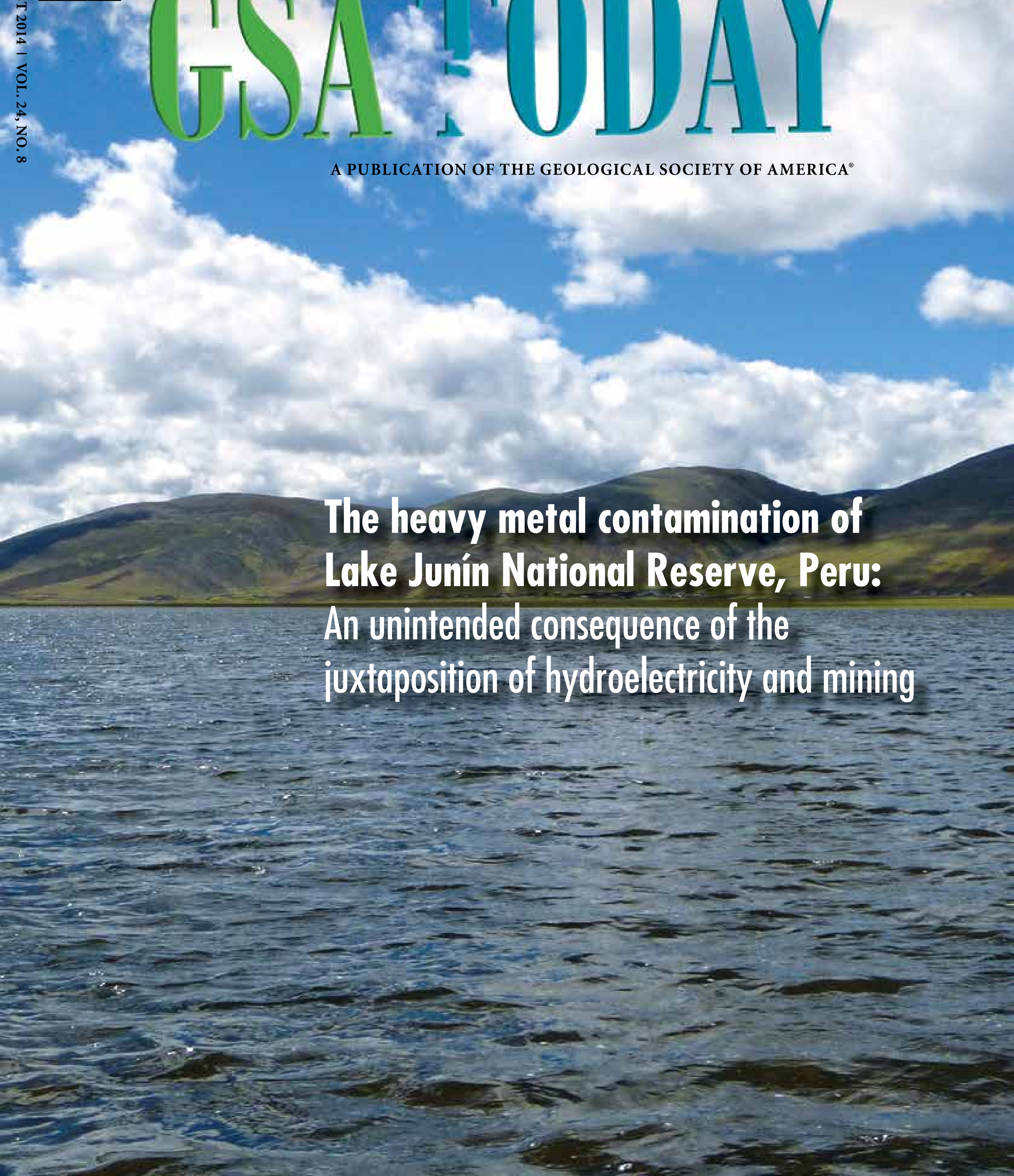

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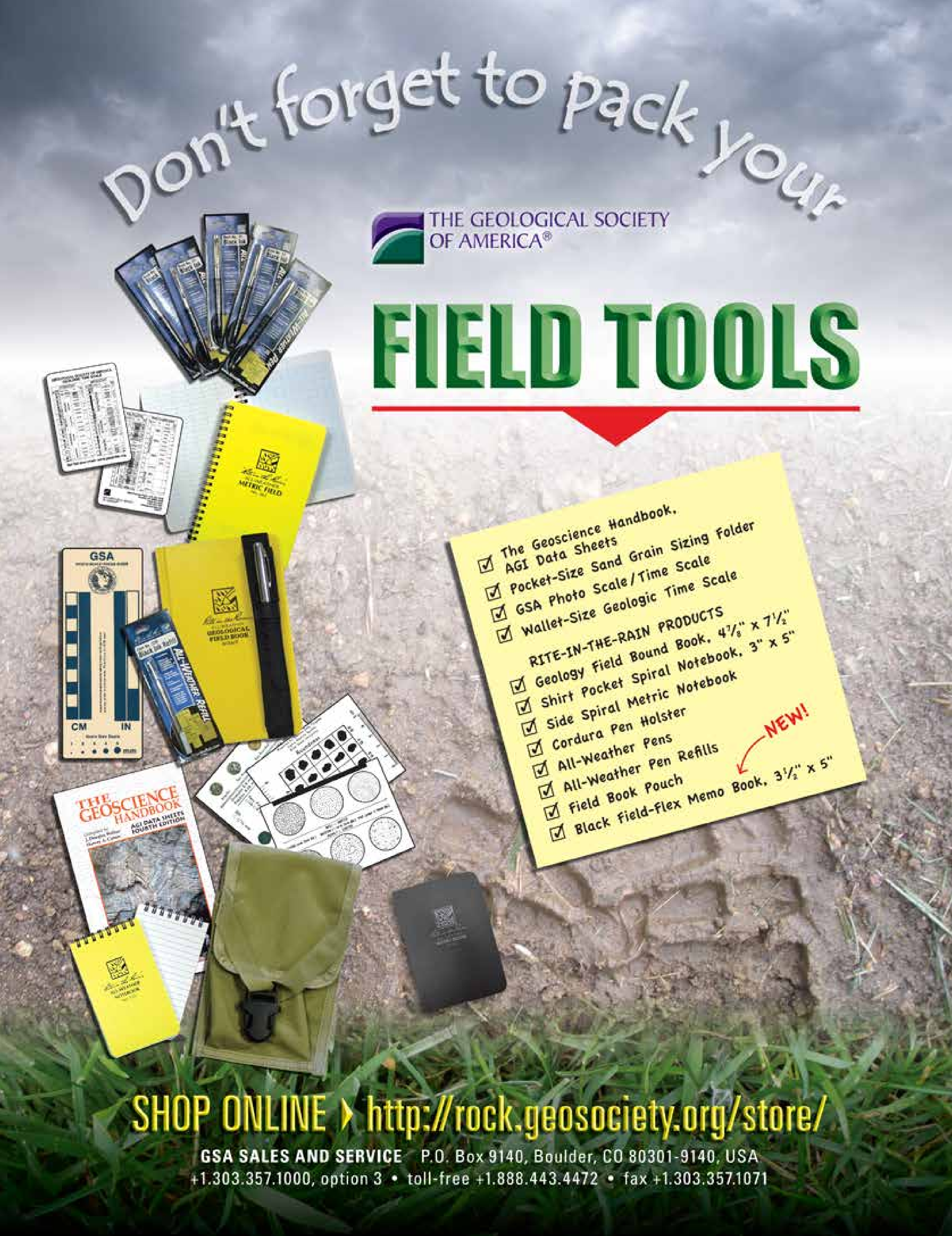

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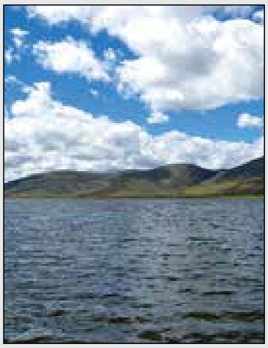

Cover: Northeastern shoreline of Lake Junín Peru; the pristine water surface belies a high level of heavy metal contamination of surface sediments. Photo by Donald T. Rodbell. See related article, p. 4–10.

GROUNDWORK:

GSA News

The heavy metal contamination of Lake Junín National Reserve, Peru: An unintended consequence of the juxtaposition of hydroelectricity and mining

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ABSTRACT

Hydraulic engineering is increasingly relied upon to provide the necessary dry-season discharge for Peru's hydroelectricity generation. Redirecting stream flow can yield unintended consequences, however, and here we document the wholesale contamination of the Lake Junín National Reserve by acid mine drainage from the Cerro de Pasco mining district. Since construction of the Upamayo Dam in 1932, the Río (river) San Juan, which drains the Cerro de Pasco region, has been seasonally redirected into Lake Junín. As a result, the upper several decimeters of sediment in the lake contain peak concentrations of Cu, Zn, and Pb of ~6000 ppm, ~50,000 ppm, and ~2000 ppm, respectively, with the latter two greatly exceeding the United States Environmental Protection Agency (EPA) limits for the entire 150 km^2 lake basin. That the source of the contamination to Lake Junín is acid mine drainage from Cerro de Pasco is supported by spatial gradients in metal concentrations, authigenic calcite (marl) concentrations, and the isotopic record of Junín water. Today, the upper 50 cm of sediment in Lake Junín contain ~60,400, 897,600, and 40,900 metric tons of Cu, Zn, and Pb, respectively, which is equivalent to ~5.1 years' worth of Zn extraction and ~0.7 years' worth of Pb extraction from mining operations at Cerro de Pasco at current rates.

INTRODUCTION

About 60% of Peru's electricity is generated by hydropower (World Bank, 2013), which during the dry season relies heavily on glacial meltwater to augment stream flow. During the austral winter months (June, July, and August [JJA]), precipitation in the high Andes is <5% of the annual total, and it has been estimated for one drainage basin in north-central Peru that during these months ~40% of river discharge comes from glacial meltwater (Mark et al., 2005). The ongoing reduction in ice cover in Peru that began early in the twentieth century has reduced the aerial extent of glacial ice in some areas by ~30% (Vuille et al., 2008). Climate models project that warming will be pronounced in the highest elevation regions of the tropical Andes (Bradley et al., 2006), and thus acceleration in ice loss is likely. In order to maintain dry season river discharge and energy generation for a growing Peruvian population, the hydropower industry in Peru has turned to hydraulic engineering, including dam construction, to ensure river discharge and hydroelectric production. This study highlights an unintended consequence of early dam construction in the Cerro de Pasco region of the central Peruvian Andes, a region that has been a focal point of Peruvian mining operations for centuries.

When Francisco Pizarro conquered the Incan Empire in 1533, he found a longstanding legacy of metallurgy and mining activity spanning almost a millennium (Abbott and Wolfe, 2003). Pre-colonial mining occurred in Cerro de Pasco, with the earliest evidence for anthropogenic lead enrichment by aerosolic fallout in nearby lakes at ca. 600 CE (Cooke et al., 2009). The Cerro de Pasco mining district is among the most extensively worked mining districts in Peru, and during the last five years of the eighteenth century, silver output in Cerro de Pasco surpassed even that of Potosí, Bolivia (Hunefeldt, 2004).

The Peruvian War of Independence (1809–1824) temporarily crippled the silver industry at Cerro de Pasco, and the final battles for independence took place among the silver mines themselves. In the first two decades after independence, Cerro de Pasco produced 65% of Peruvian silver, and to support the mining industry, a central railway was constructed between Lima and La Oroya in the late nineteenth century (Klarén, 2000), which was later extended to Cerro de Pasco. The railroad also allowed for the transition to copper production in 1897 (Becker, 1983). An American engineer, A. William McCune, explored the Peruvian cordillera searching for copper, and he found plenty of it among the exhausted silver ores of Cerro de Pasco (Becker, 1983). McCune helped organize a syndicate (1900–1901) that included J.P. Morgan to finance the Peruvian copper venture. Named the *Cerro de Pasco Investment Corporation*, and later the *Cerro de Pasco Copper Corporation*, the company constructed the first copper smelter in 1906. The volume of ore production at Cerro de Pasco soon justified construction of a large central smelter, completed in 1922, and by 1931 the Cerro smelter held monopoly over the refining of all nonferrous metals in Peru (Becker, 1983).

In order to generate hydroelectricity for Cerro de Pasco's operations, the Upamayo Dam was constructed in 1932 (Shoobridge, 2006). The Upamayo Dam is located in the uppermost reach of the Río Mantaro, immediately downstream of the confluence

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Figure 1. Location of Lake Junín in the central Peruvian Andes. Red dots in Lake Junín are short-core locations; red dots outside of Lake Junín drainage basin denote the location of lakes with published records of aerosolic metal contamination (Cooke et al., 2009; Bird et al., 2011a); purple dots along Río San Juan mark the location of modern alluvium collected in July 2013.

between the Río San Juan, which drains southward from Cerro de Pasco, and the outflow of Lake Junín, the largest lake entirely within Peru (Fig. 1). Cerro's operations grew to include lead and zinc by 1952 (Klarén, 2000), but political turmoil disrupted production during the second half of the twentieth century, when in 1968 a bloodless coup d'état against President Belaúnde led to rule by a military junta that lasted until 1975. In 1971, the Cerro de Pasco Copper Corporation was nationalized under the name *Centromín* (Klarén, 2000). Deregulation in the 1990s allowed for the reacquisition of the mining operations at Cerro de Pasco by the Peruvian based company Compañía Minera Volcán S.A. (Gurmendi, 2006).

The location of the Upamayo Dam and the small reservoir upstream from it has resulted in the discharge of Río San Juan waters, once destined for the Río Mantaro, directly into Lake Junín. This redirecting of the Río San Juan into Lake Junín began in 1932 and is most prevalent during the dry season (JJA) when the level of Lake Junín typically drops by ~2 m (Pedersen et al., 1999). This paper documents the impact of acid mine drainage from Cerro de Pasco into Lake Junín, which in 1974 was designated a Peruvian National Wildlife Reserve.

METHODOLOGY

Six sediment cores (0.6–1.3 m long) were acquired with a Verschuren surface corer (Verschuren, 1993) between 2002 and 2008 from various locations in Lake Junín (Fig. 1). Results from the 2002 core are reported by Veliz (2001). Surface sediment and water samples were acquired in 2013 from three locations along the Río San Juan between Cerro de Pasco and the Upamayo Dam. Sediment cores were subsampled in the field at 0.5- and 1.0-cm increments and transported to the sediment core laboratory at Union College (Schenectady, New York, USA) for analysis of exchangeable (adsorbed) metals. All sediment samples were freeze-dried and disaggregated in an agate mortar and pestle, and between 50 and 100 mg of sample was then placed in 14 ml Falcon™ test tubes. To each sample we added 9.5 ml of milliQ deionized water and 1.0 ml high-purity (70%) HNO_3. Samples were then shaken horizontally for 12 h, refrigerated vertically for 24 h, and returned to room temperature for 1 h. Subsequently, 1.0 ml of sediment-free supernatant was extracted and diluted with 9 ml of milliQ deionized water; these samples were analyzed for Mn, Fe, Co, Cu, Zn, Sr, Ba, and Pb by a Perkin Elmer Sciex ELAN 6100 DRC inductively coupled plasma–mass spectrometer (ICP-MS). A blank solution was prepared with each batch of samples, and blanks and standards were analyzed by ICP-MS at regular intervals throughout sample runs, which ranged from ~50–150 samples. Here we focus on Cu, Zn, and Pb; concentration data for all metals are available in the GSA Supplemental Data Repository[1] (Table S1).

We measured weight percentage total carbon (TC) and weight percentage total inorganic carbon (TIC) by coulometry. For the measurement of TC, we combusted samples at 1000 °C using a UIC 5200 automated furnace and analyzed the resultant CO_2 by coulometry using a UIC 5014 coulometer. Similarly, we measured TIC by acidifying samples using a UIC 5240 acidification module and measured the resultant

[1]GSA supplemental data item 2014200—concentration data for metals, total carbon, total $CaCO_3$, total organic carbon, oxygen and carbon isotope data, and age model data for each core—is online at www.geosociety.org/pubs/ft2014.htm. You can also request a copy from GSA Today, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

CO_2 by coulometry. We calculated weight percentage total organic carbon (TOC) from TOC = TC − TIC; weight percentage TIC was converted to % calcite based on stoichiometry. All coulometry data are available in the GSA Supplemental Data Repository (Table S2; see footnote 1).

Age models (Fig. 2 and Table S3 [see footnote 1]) for sediment cores were developed from a combination of radiocarbon dates on plant macrofossils and correlation of the significant rise in anthropogenic Pb to the ^{210}Pb-dated record of aerosolic Pb deposition since 1625 CE in regional glacial lakes within ~25 km of Lake Junín (Cooke et al., 2009; Bird, 2009). In addition, we correlated the δ^{18}O record of marl in one Junín core (Core B, Fig. 1) with the ^{210}Pb-dated δ^{18}O record of marl in nearby Laguna Pumacocha (Fig. 1) (Bird et al., 2011a).

We determined the history and source of metal deposition in Lake Junín by comparing sediment cores from within Lake Junín with those from nearby lakes that are not connected hydrologically to Junín. The downcore variation in metal concentration is the simplest means of comparison, but because the concentration of any particular metal is inversely affected by the deposition rate of all other metals and non-metals (e.g., clastic sediment, organic matter, and marl), a more rigorous metric is to calculate the deposition rate, or *flux*, of each metal analyzed. Flux is the product of dry sediment bulk density (mg cm^{-3}), sedimentation rate (cm yr^{-1}), and the concentration of a particular metal (ppm). The units of flux are thus mass of metal X per unit area of lake floor per year (e.g., µg cm^{-2} yr^{-1}), and the flux of any component to a lake is independent of the changing rates of deposition of all other components.

DATA AND DISCUSSION

Downcore Trends

There are consistent downcore trends in metal concentrations in surface cores throughout Lake Junín. Baseline (pre–twentieth century) concentrations of all metals are low, and concentrations rise abruptly in the upper several decimeters of all cores. For example, background levels of Cu, Zn, and Pb in Core B are <1 ppm, <10 ppm, and <1 ppm, respectively (Fig. 3). Concentrations of these metals rise abruptly in the early twentieth century to >450 ppm, >30,000 ppm, and >150 ppm, respectively. In cores acquired near the northern end of Lake Junín (2008 Cores C and G), peak concentrations of Cu, Zn, and Pb reach ~6000 ppm, ~50,000 ppm, and ~2000 ppm, respectively. These concentrations are similar to those measured on surface sediments in Lake Junín by Pedersen et al. (1999). Our best dated core (2008 Core B) reveals that metal concentrations began to increase as early as ca. 400 CE, consistent with evidence of pre-Incan smelting by the Tiwanaku and Wari Empires on the Altiplano of southern Peru and Bolivia (Cooke and Abbott, 2008). However, metal concentrations in Lake Junín during this time are ~1/100th of the concentration of metals in sediments deposited during the twentieth century.

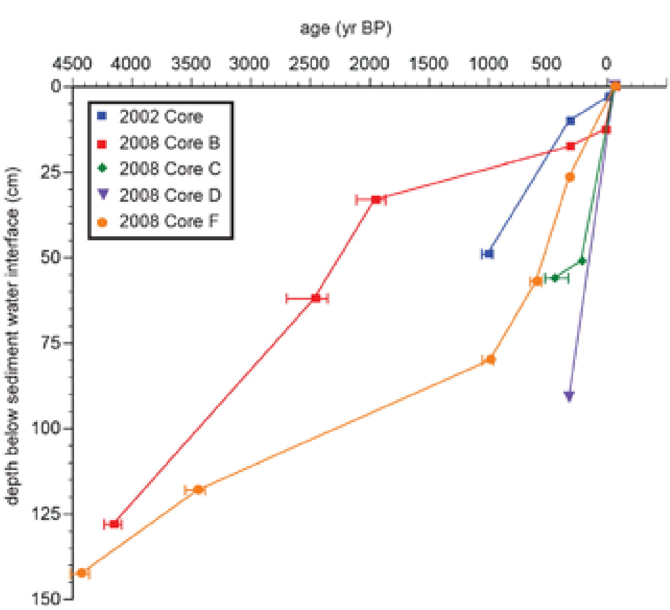

Figure 2. Age-depth models for sediment cores used in this study.

The concentration of authigenic calcite (marl) in Junín sediments declines abruptly when metal concentrations increase (Fig. 3). For much of the past 12,000 years, Lake Junín has been generating calcite at ~0.85 mm yr^{-1} (Seltzer et al., 2000), and calcite represents ~80%–100% of the mass of Holocene sediment until the twentieth century. This calcite is produced both organically as mollusk shells and ostracode carapaces and inorganically as a precipitate on the leaves of the submerged macrophyte *Chara*. The abrupt decline in calcite concentration may record the acidification of Lake Junín water by acid mine drainage to the point that HCO_3^- and Ca^+ remain soluble and no longer precipitate calcite. Alternatively, the inverse relationship between organic carbon (from algal remains and plant macrofossils) and calcite concentration (Fig. 3) may indicate that lake eutrophication resulted in the post-depositional dissolution of authigenic calcite in the lake sediments. This latter scenario is apparently responsible for the decline in $CaCO_3$ concentrations in Minnesota lakes; there, Dean (1999) concluded that organic carbon concentrations in excess of 12% generate enough carbonic acid in sediment pore water to dissolve all contemporaneously deposited marl. Because the pH of Lake Junín (7.7–8.5; Flusche et al., 2005) is not anomalously low for calcite precipitation, it is possible that lake eutrophication was the cause of the abrupt decline in $CaCO_3$ concentrations. Of course, some combination of acid mine drainage and lake eutrophication is possible, and an influx of nutrients may have occurred simultaneously with the introduction of heavy metals into the lake.

A comparison between the δ^{18}O record from Junín marl and that from nearby Laguna Pumacocha confirms that the introduction of heavy metals to Lake Junín was associated with a significant input of river water (Fig. 3). The δ^{18}O record from both lakes shows that they generally track one another over the Holocene, reflecting regional changes in the isotopic composition of precipitation (Vuille et al., 2012). However, beginning ca. 1920 CE, the Pumacocha record reveals a positive shift of 1.0‰ that is consistent with other regional isotopic records from ice cores and speleothems (Bird et al., 2011b), whereas the Junín record shifts abruptly 2‰ in the negative direction (Fig. 3). This discrepancy can be explained by an increase in the seasonal discharge of the Río San Juan directly into Lake Junín as a result of the construction of the Upamayo Dam (Fig. 1) in 1932 CE. The introduction of isotopically δ^{18}O-depleted river water into evaporatively δ^{18}O-enriched Lake Junín would result in a lake-wide isotopic

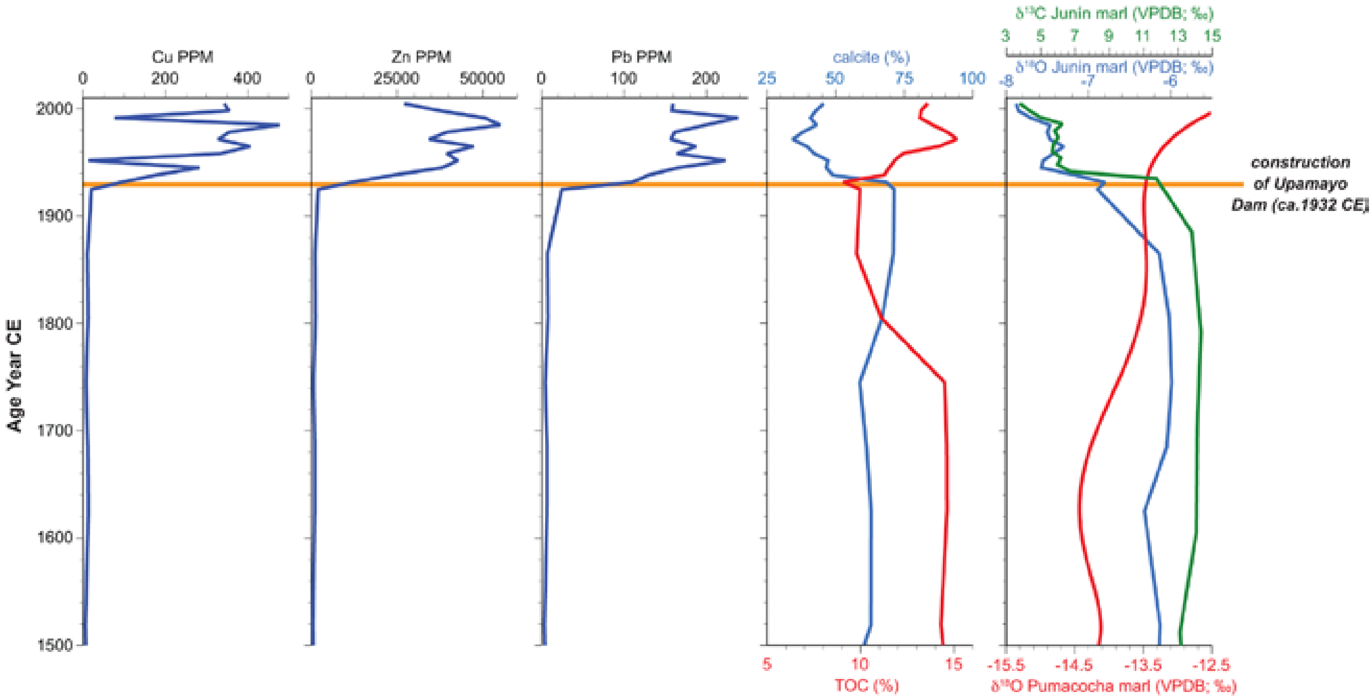

Figure 3. Downcore variation in Cu, Zn, Pb, calcite, and $\delta^{18}O$ and $\delta^{13}C$ of marl in Lake Junín short core B (Fig. 1). Smoothed record of $\delta^{18}O$ of marl in Laguna Pumacocha (Fig. 1) (Bird et al., 2011a) reveals isotopic composition of regional precipitation; simultaneous isotopic depletion of Lake Junín and increase in metal concentrations records the influx of isotopically light acid mine drainage from the Cerro de Pasco region via the Río San Juan due to construction of the Upamayo Dam ca. 1932 CE. VPDB—Vienna Pee Dee Belemnite.

depletion of marl. Further, an abrupt decrease from ~11–5‰ in the $\delta^{13}C$ of marl occurred at the same time as the negative shift in oxygen values (Fig. 3). This may also reflect the influx of Río Santa water into Lake Junín, which for much of the Holocene had been accumulating authigenic calcite with $\delta^{13}C$ values that are highly enriched (between 8 and 14‰) as a result of degassing (Seltzer et al., 2000). Increased Río Santa inflow may also have contributed isotopically light carbon from flooded soils and wetlands into Lake Junín.

Spatial Trends

The spatial distribution of heavy metals in Lake Junín sediments further confirms that the source of these contaminants is indeed the Río San Juan (Fig. 4). Although San Juan discharge may well have seasonally entered Lake Junín prior to the construction of the Upamayo Dam, construction of the dam increased this discharge substantially. The average concentration of Cu and Pb from ca. 1850 CE to present decreases markedly with increasing distance from the confluence of the Río San Juan with Lake Junín (Fig. 4). In the most distal (southerly) cores, the concentration of these metals approaches that of Cu and Pb in the three nearby lakes that are not hydrologically linked to Cerro de Pasco or any other mining district (Fig. 1; Cooke et al., 2009; Bird et al., 2011a). Metal concentrations in these latter lakes, therefore, provide a record of regional background deposition by aerosolic input only, and this, in turn, confirms the point-source origin of much of the metal contamination to Lake Junín. The concentration of Zn does not show a similar decline with increasing distance from the Río San Juan (Fig. 4), and this may reflect a complex process of Zn recycling between sediment pore waters and lake water, as discussed by Pedersen et al. (1999). Pedersen et al. report Zn concentrations in interfacial pore waters in Lake Junin that are an order of magnitude higher than Zn concentrations both in the superjacent water column and in subjacent pore waters 10 cm below the sediment-water interface. Apparently, Zn can be recycled from the sediment to the water column by oxidation of labile organic compounds at the sediment-water interface (Pedersen et al., 1999). Presumably, this recycled Zn may then be resorbed onto organic compounds that can be deposited further into the lake basin, and this may explain the increasing trend in Zn concentration with increasing distance from the confluence of the Río San Juan.

In general, the average flux of Cu, Zn, and Pb reveals lower input rates of these metals with increasing distance from the confluence of the Río San Juan (Fig. 4). The decline in Zn flux with increasing distance from the Río San Juan confluence seems to be at odds with the lack of any similar trend in Zn *concentration*. It is possible that reduced Zn flux with increasing distance into Lake Junín may be compensated for by a reduction in the deposition rate of other components of the lake sediment, thus allowing for Zn *concentration* to remain high in the more distal samples. That Cu and Pb do not also show this trend may stem from their very high concentrations in proximal samples, which are 2–4 times as high as samples from even moderately distal sites (Fig. 4). Pedersen et al. (1999) estimated a diffusive efflux rate for Zn from surface sediments into the overlying water column of ~25 µg cm^{-2} yr^{-1}, which is of the same order of magnitude as the average flux of Zn since 1850 CE for the more distal sites in Lake Junín. Recycled Zn, therefore, may be the major source of Zn to distal sites.

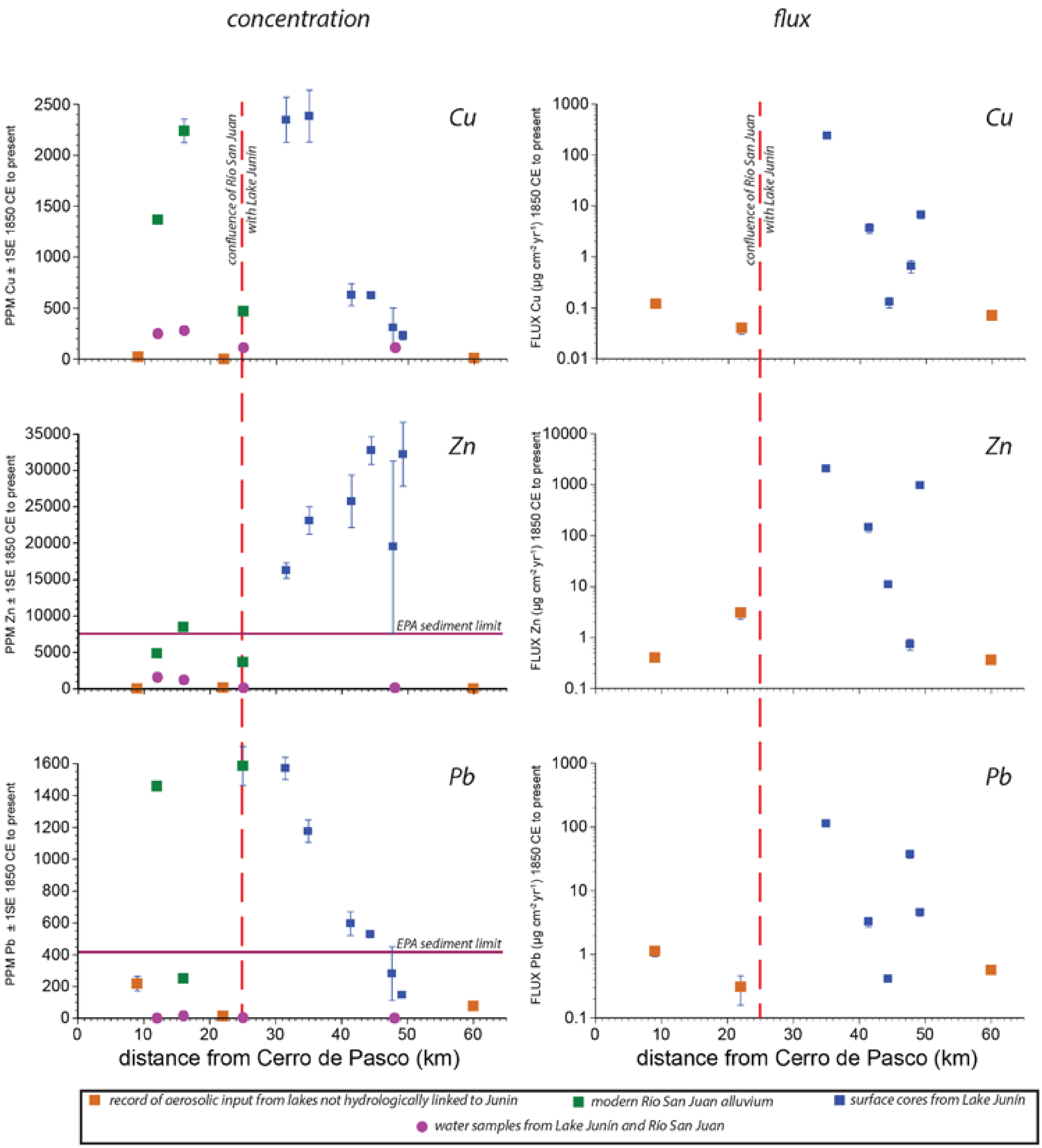

Figure 4. Variation in Cu, Zn, and Pb in Lake Junín with increasing distance from Cerro de Pasco plotted as both mean concentration (ppm) and mean flux (µg cm^{-2} yr^{-1}) for the period 1850 CE to present. Distance is radial distance and does not reflect the true thalweg distance of Río San Juan. Río San Juan enters Lake Junín ~25 km south of Cerro de Pasco (Fig. 1). Also plotted are the mean concentration and flux of Cu, Zn, and Pb to three lakes (Lagunas Chipian, Pumacocha, and Llamacocha; Fig. 1) (Cooke et al., 2009; Bird et al., 2011a) that are not hydrologically linked to any mining districts, and, thus, these lakes can only receive aerosolic inputs of metals. The concentrations of Cu, Zn, and Pb for three samples of modern alluvium collected from the channel of the Río San Juan and four samples of modern river and lake water are plotted for comparison. Metal concentration limits for sediments from the U.S. Environmental Protection Agency (U.S. EPA, 1993) are plotted for Zn and Pb; those for Cu are 4300 ppm and are off scale.

Magnitude of Contamination

Comparison between the average Cu, Zn, and Pb concentration in sediment deposited since 1850 CE with limits set for sediments by the EPA (U.S. EPA, 1993) reveals the relative magnitude of the contaminant threat posed by these metals (Fig. 4). Whereas only peak concentrations of Cu in the most proximal cores (Cores G and C, Fig. 1) exceed the EPA limit of 4300 ppm, and mean Cu concentrations (1850 CE to present) are considerably lower than this level, average concentrations of Zn and Pb exceed EPA limits for these metals of 7500 and 420 ppm, respectively, nearly everywhere in Lake Junín. Peak concentrations of Zn and Pb within proximal cores in Lake Junín exceed EPA limits by one order of magnitude, and the peak in Zn concentration within cores (~50,000 ppm) is nearly uniform throughout the lake basin.

Comparison between the concentration of Cu, Zn, and Pb in the modern alluvium of the Río San Juan between Cerro de Pasco and Lake Junín (Fig. 1) and the concentration of these elements in proximal cores reveals that some progress may have been made in reducing the output of Zn from tailings piles and tailings ponds (Fig. 4). The concentration of Zn in modern alluvium is much lower than the average Zn concentration in Junín sediment deposited since 1850 CE anywhere in the lake. The concentrations of Cu and Pb, however, show mixed results, and some samples of modern alluvium are as concentrated in these elements as the most contaminated sediment in Lake Junín. Pedersen et al. (1999) and Martin et al. (2001) noted that alluvium ponded on the upstream side of the Upamayo Dam is subjected to seasonal exposure and inundation. During the dry season, when these sediments are exposed and unsaturated, sulfide oxidation and the resultant acidification of pore waters occurs; these workers report pore water pHs as low as 3.2 in this location. These acidic conditions remobilize Cu, Zn, and Pb from both sulfide minerals and secondary oxidation products (Pedersen et al., 1999), and the redissolved metals are then flushed into Lake Junín during the subsequent wet season when rising lake levels inundate these deposits. Thus, the alluvium derived from the mine tailings of Cerro de Pasco and ponded behind the Upamayo Dam serves as a long-term source of metal contamination to Lake Junín. The pumping of metals from these deposits into Lake Junín would be dramatically reduced if these deposits were permanently submerged with anoxic lake water (Martin et al., 2001).

To fully appreciate the scale of the contamination of Lake Junín that has resulted from decades of uncontrolled acid mine drainage from Cerro de Pasco, we consider the total mass of Cu, Zn, and Pb in the upper 50 cm of lake sediments (Table 1). We calculate the average concentration of these metals in the upper 50 cm of our six sediment cores and take this to be an approximation of the average concentration of Cu, Pb, and Zn for the upper 50 cm of the lake basin. The resultant mass of Cu, Zn, and Pb in Lake Junín's uppermost 50 cm is 60,425, 897,588, and 40,900 metric tons, respectively. The average annual production of Zn and Pb from 2009 to 2011 from the mining operations at Cerro de Pasco are 177,000 and 53,333 metric tons, respectively (Volcan, 2013) (Table 1). Thus, at current rates of extraction, there are 5.1 years' worth of Zn and 0.7 years' worth of Pb stored in the upper 50 cm of Lake Junín.

The concentration of Cu, Zn, and Pb in water samples from the Río San Juan and Lake Junín are lower than sediment samples from the same sampling locations (Fig. 4). Concentrations of Cu, Zn, and Pb in water samples range from 111 to 282 ppm, 123 to 1603 ppm, and 3 to 18 ppm, respectively, and all exceed maximum contaminant levels (MCLs) set by the U.S. EPA (EPA, 2009) and Peru's Permissible Maximum Limits (LMPs; Ministerio del Ambiente, 2010) for effluent discharge from mining activities by ~2 orders of magnitude or more. The aforementioned recycling of Zn from lake bottom sediments into the water column contributes a significant source of dissolved Zn in Lake Junín (Pedersen et al., 1999). It would seem, then, that until a concerted effort focuses on preventing the remobilization of metals from the ponded sediment behind the Upamayo Dam and a sufficient thickness of uncontaminated sediment buries the heavily contaminated sediments of Lake Junín, the influx of metals to Junín waters will continue, and concentrations will exceed MCLs and LMPs for the foreseeable future.

Table 1. Mass of Cu, Zn, and Pb in upper 50 cm of sediment in Lake Junin relative to annual output from mining activities in Cerro de Pasco

Core	Average Cu in upper 50 cm (ppm)	Average Zn in upper 50 cm (ppm)	Average Pb in upper 50 cm (ppm)
F	220	8511	223
C	1805	17977	1009
G	2448	16104	1560
2002	192	12827	162
B	75	10226	48
D	94	6162	270
average concentration in upper 50 cm of sediments in Lake Junin (ppm)	806	11968	545
average dry bulk density of sediment (g cm^{-3})		1	
surface area of lake (km^2)*		150	
surface area of lake (cm^2)*		1.5E + 12	
volume of sediment (cm^3)		7.5E + 13	
mass of sediment (g)		7.5E + 13	
mass of metal (g)	6.0E + 10	9.0E + 11	4.1E + 10
mass of metal (metric tons)	60,425	897,588	40,900
Cerro de Pasco mining output (metric tons; average 2009–2011)†	n/a	177,000	55,333
2009–2011 average mining output from Cerro de Pasco in upper 50 cm of Lake Junin mud (per year)	n/a	5.1	0.7

Note: n/a—not applicable.
* Does not include area of fringing wetlands.
† From Volcan (2013).

CONCLUSIONS

By virtue of the construction and location of the Upamayo Dam, much of the history of mining at Cerro de Pasco has been unwittingly recorded in the sediments of Lake Junín. Though Lake Junín and its surrounding wetlands were designated as a national reserve in 1974 to protect the rich avian life that the lake supports, decades of mine runoff from Cerro de Pasco have made the sediments of Lake Junín among the most polluted in Peru. The Upamayo Dam, which was constructed for hydroelectricity generation, is not the source of these contaminants, and were it not for the dam, the bulk of the metal pollution would have been destined for the Río Mantaro and the upper Amazon Basin. If this had been allowed to occur, the concentration of metals in the upper Amazon Basin would have been lower than that present in Lake Junín due to the dilution of metals over thousands of kilometers of river bottom. Among the biggest challenges that will face any attempt to mitigate the environmental disaster that has befallen Lake Junín are finding ways to stop the recycling of Zn from the lake bottom and the remobilization of all metals from the seasonally exposed and submerged deposits that are trapped behind the Upamayo Dam. As future hydraulic engineering projects are developed in Peru and elsewhere, it would behoove all not to repeat the mistakes that are recorded in the mud of Lake Junín.

ACKNOWLEDGMENTS

This work was supported by the Faculty Research Fund of Union College and by National Science Foundation grants ATM-0502464 and EAR-1003711 to DTR. We are grateful to Matt Manon of the Union College Geology Department for analytical assistance and to two anonymous reviewers for their efforts to improve the manuscript.

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GSA 2014

19-22 October | Vancouver, BC, Canada

Neighborhood Spotlights

CHINATOWN

From www.tourismvancouver.com: Few neighborhoods in Vancouver embody the city's history, diverse cultures, and vibrant future like Chinatown. Located on the eastern side of downtown Vancouver, the bustling district is North America's third largest Chinatown by population, after those in San Francisco and New York. Its roots trace to the late 1800s, when early Chinese immigrants, who arrived to work on British Columbia's railroads and in the mines, were settled in a ghetto on the edge of the city. With time, the neighborhood grew into a proud center of Chinese culture, home to traditional restaurants, markets, temples, and gardens, as well as a booming business district. Today, Chinatown reflects this rich heritage but is also in the midst of a renaissance, with trendy bars and restaurants reclaiming historic spaces. While you're in Vancouver for the meeting, you're invited to explore the classical Chinese Gardens, enjoy traditional dim sum, and visit an authentic Chinese market.

Tourism Vancouver/Coast Mountain Photography.

Wikipedia Commons. Photo by Robert Werner.

YALETOWN

From yaletowninfo.com: Founded in the 1890s as the rail yard and industrial neighborhood, Yaletown has now become Vancouver's trendy and upscale renovated district. This fresh urban neighborhood is an easy walk from the center of downtown Vancouver or a quick ferry ride from Granville Island. Yaletown's converted heritage buildings are home to some of the city's top fashion and design shops, as well as cutting-edge restaurants, bars, and boutique hotels. This revitalized area is also well known for its coffee shops and dog-friendly spaces. Take one of the many walking tours to discover all of Yaletown while you're in Vancouver for the meeting.

GSA Career Enhancement Programs

(Previously called mentor programs)

SATURDAY

Geoscience Career Workshop: Launch Your Job Search

This workshop, which runs from 1 p.m. to 5 p.m., will help students successfully prepare for a career in the geosciences. It will cover constructing effective cover letters, résumés, and CVs. Professionals will meet with the group and offer tips and suggestions for navigating their company hiring process.

SUNDAY

Geoscience Careers in Industry Program

This free program connects students and private sector industries in a day of progressive sessions aimed at building a stronger career pipeline. Students will gain important skills toward preparing to enter the workforce, learn career advice from industry professionals, and have the opportunity to present their research to industry representatives.

9 a.m.–noon: Geoscience Careers in Industry: Student Research Highlight Session
Noon–1:30 p.m.: Geology in Industry Career Pathways Luncheon
1:30–4 p.m.: Geoscience Careers in Industry: Professional Practice Session
4:30–5:30 p.m.: Geoscience Careers in Industry: Evening Reception

Women in Geology Career Pathways Reception

This informal gathering, from 5 p.m. to 6:30 p.m., begins with remarks from a few key women speakers who will address issues faced by women in geology. A reception follows, providing time for networking, sharing ideas, and getting to know other women geoscientists and geosciences educators. *Appetizers provided.*

MONDAY

Geology in Government Career Pathways Luncheon

This popular program provides a FREE lunch from 11:30 a.m. to 1 p.m. for undergraduate and graduate students with a panel of mentors representing a variety of government agencies. These mentors will answer questions, offer advice about preparing for a career in government, and comment on the prospects for current and future job opportunities with their agencies. Also, come learn more about GSA's GeoCorps™ program!

TUESDAY

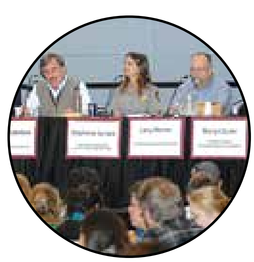
Student Networking Luncheon

This light lunch from 11:30 a.m. to 1 p.m. is sponsored by AGI, GSA, SEG and the SEG Foundation, and ConocoPhillips. The program provides undergraduate and graduate students with an exciting opportunity to network with more than 40 geoscience professionals. The mentors will answer questions, offer advice about career plans, and comment on job opportunities within their fields. Please pre-register (see contact info. below).

John Mann Mentors in Applied Hydrogeology Program

This program underwrites the cost for 25 students to attend the Hydrogeology Division Luncheon and Awards Presentation and meet some of geoscience's most distinguished hydrogeologists. Students eligible for this honor are those who have (1) indicated a professional interest in hydrology/hydrogeology on their GSA membership application, and (2) registered for the Annual Meeting by 15 September. The first 25 students who respond on 16 September to an e-mail invitation based on these criteria will receive FREE tickets for the luncheon.





CONTACT

GEOSCIENCE CAREERS IN INDUSTRY PROGRAMS:
Tahlia Bear, tbear@geosociety.org, **community.geosociety.org/gsa2014/science/careers/careersprog.**

CAREER PATHWAY AND MENTOR PROGRAMS:
Jennifer Nocerino, jnocerino@geosociety.org, **community.geosociety.org/gsa2014/science/careers/mentors.**

TO SPONSOR ONE OF THESE EVENTS, CONTACT
Debbie Marcinkowski, dmarcinkowski@geosociety.org.

Don't forget to sign up for a

GSA Short Course

These courses fill up quickly—early registration is recommended.

If you register after 15 Sept., you will need to pay an additional US$30. **Earn continuing education credits (CEUs)!** All short courses offer CEUs, and most are at low or no cost.

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

For full course descriptions and to sign up, go to **community.geosociety.org/gsa2014/science/courses.**

ON TO THE FUTURE

GSA's On To the Future (OTF) initiative is again providing partial travel scholarships to 125 students and recent graduates underrepresented in the geosciences to experience their first GSA Annual Meeting. With generous support from donors and supporters, GSA is committed to financially assisting diverse students reach their professional goals.

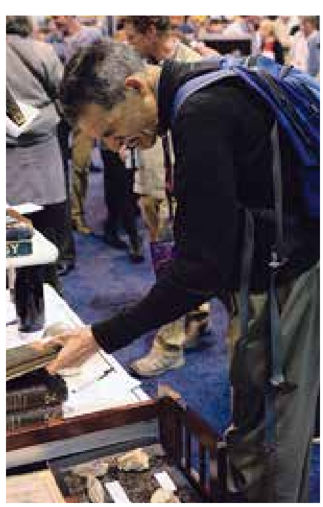
If you would like to serve as an OTF Conference Mentor to one of the scholars, contact Tahlia Bear at tbear@geosociety.org.

To learn more or to support the OTF Program, go to **community.geosociety.org/OTF/home/.**

2014 GSA ANNUAL MEETING & EXPOSITION

Find Treasures at the GSA Foundation's Silent Auction

Thanks to everyone who supported the GSA Foundation's 2013 Silent Auction in Denver. We had an amazing event! Funds raised helped support *On To the Future*, GSA's Diversity in the Geosciences project to bring 125 students from underrepresented geosciences groups to their first annual meeting. The remarkable attendance at the anniversary event helped increase awareness of the Foundation's fundraising mission in support of Society-wide projects and programs.



Donate to the Foundation's Silent Auction

We're seeking items that broadly pertain to the geosciences:

- Geo-gifts, jewelry, and apparel donations are great for our pre-holiday meeting;
- Help us build our "well-equipped geoscientist" with tools, field gear, supplies, software;
- Donate geologic specimens, gems, and fossils;
- Contribute to our selection of wine and wine accessories;
- Give gift certificates (i.e., Amazon, special events, trips, restaurants); and
- Remember that GSA meeting attendees love books.

Proceeds from this year's Silent Auction will help support GSA's Diversity Committee's projects.

Visit us in Vancouver. Browse! Bid! Buy!

Contact: GSA Foundation Silent Auction, Ann Crawford, acrawford@geosociety.org, +1-800-472-1988 ext. 1053.

Mentoring Tomorrow's Geoscience Leaders

The Geological Society of America (GSA) is proud to provide mentoring programs at all its meetings. At the Section Meetings, students are invited to participate in both 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.

Mentors and students meet in a relaxing, informal setting to discuss applied geology or hydrogeology careers over a free lunch. The mentors, who come as volunteers, are professionals in these fields (check out the "Mentor Hall of Fame" at www.geosociety.org/mentors/hof.htm).

This spring, the Shlemon Program funds, in addition to financial assistance from the GSA Northeastern Section, provided lunches and a place to converse to 370 students and 46 mentors; the Mann Program welcomed 172 students and 22 mentors. Both mentors and students leave these events expressing feelings of personal and professional growth. New friendships are made and professional contacts are established that will last well into the future.

GSA's Education & Outreach Program gratefully acknowledges the following mentors for their individual gifts of time and for sharing their insight with GSA's student members. To learn more about these programs, or to be a mentor in the future, please contact Jennifer Nocerino, jnocerino@geosociety.org.

The Roy J. Shlemon Mentor Program in Applied Geology

Helping Mentor Students Since 2000

SOUTH-CENTRAL SECTION

Angela Chandler, Arkansas Geological Survey

Thomas Ewing, Frontera Exploration Consultants

Joseph Hannibal, Cleveland Museum of Natural History

Mark Hudson, U.S. Geological Survey

Marilyn Suiter, National Science Foundation

Kenzie Turner, U.S. Geological Survey

NORTHEASTERN SECTION

Samuel Baughman II, Lancaster Geology

Gale Blackmer, Pennsylvania Geological Survey

Bob Bond, Langan

Ted Daeschler, Academy of Natural Sciences

Mark Eisner, Advanced Land and Water Inc.

Peter Gale, New England Research

Don Geddes, American Water Engineering

Christopher Gellasch, Uniformed Services University of the Health Sciences

Daniel Goode, USGS Pennsylvania Water Science Center

Susan Hagar, ARCADIS U.S. Inc. Corporate

Denise Hills, Geological Survey of Alabama

Kathy Horvath, Environmental Cleanup and Brownfields

Karen Jennings, Coastal Resources Inc.

Pierre Lacombe, U.S. Geological Survey

Tim Peck, USACE–Baltimore

Bob Stewart, Jr., ExxonMobil Exploration Company

Cynthia Stine, Pennsylvania Dept. of Environmental Protection

Marilyn Suiter, National Science Foundation

Lori Summa, ExxonMobil Upstream Research Company

Kristin Wilson, Wells National Estuarine Research Reserve

Katrina Withers, ExxonMobil Upstream Research Company

SOUTHEASTERN SECTION

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Adam Karst, Iluka Resources Inc.

Richard Kolb, Duncklee & Dunham

John Miller, University of North Carolina–Asheville

Malcolm Schaeffer, HDR Engineering Inc.

Ronald Wallace, Georgia EPD

NORTH-CENTRAL SECTION

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Jessica Ball, Geological Society of America

Shane Butler, Illinois State Geological Survey

Kathleen Cameron, University of Nebraska–Lincoln

Charles Joyce, SCS AQUATERRA

Robert Rohlfs, Leggette, Brashears & Graham Inc.

JOINT ROCKY MOUNTAIN/ CORDILLERAN SECTION

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David Coles, Coles Environmental Consulting Inc.

John Gillespie, Sundance Energy LLC

Jeanne Godaire, U.S. Bureau of Reclamation

Jeffrey Knott, California State University–Fullerton

Karl Osvald, Bureau of Land Management

Michael Stickney, Montana Bureau of Mines and Geology

2014 SOUTH-CENTRAL SECTION

Looking south from Mount Sequoyah (el. 6,003 feet/1,830 meters) in the Great Smoky Mountains National Park. Photo by Brian Stansberry, used with permission from Wikimedia Commons.

2014 NORTHEASTERN SECTION

Cucumber Falls in Ohiopyle State Park, Ohiopyle, PA. Photo by Frank Kovalchek, used with permission from Wikimedia Commons.

2014 SOUTHEASTERN SECTION

Blue Ridge Mountains, Shenandoah National Park, VA. Photo by Amrinder Arora, used with permission from Wikimedia Commons.

2014 NORTH-CENTRAL SECTION

Chimney Rock National Historic Site, Morrill County, Nebraska. Photo by Mike Tigas, used with permission from Wikimedia Commons.

2014 JOINT ROCKY MOUNTAIN/ CORDILLERAN SECTION

Grinnell Glacier 2009, Glacier National Park, Montana, used with permission from Wikimedia Commons.

The John Mann Mentors in Applied Hydrogeology Program

Helping Mentor Students Since 2004

SOUTH-CENTRAL SECTION

Brian Hunt, Barton Springs/Edwards Aquifer Conservation District

Kyle Murray, Oklahoma Geological Survey

Darrell Pennington, FTN Associates Ltd.

Darcia Routh, Arkansas Dept. of Health

NORTHEASTERN SECTION

Eric Dieck, Langan Engineering and Environmental Services

Mark Eisner, Advanced Land and Water Inc.

Frank Getchell, Leggette, Brashears & Graham Inc.

Daniel Goode, USGS Pennsylvania Water Science Center

Susan Hagar, ARCADIS U.S. Inc. Corporate

Lewis McCaffrey, Drrokk LLC

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Richard Kolb, Duncklee & Dunham

David Nelms, U.S. Geological Survey

Ronald Wallace, Georgia EPD

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Carrie Jennings, Minnesota Dept. of Natural Resources

Andrew Phillips, Illinois State Geological Survey

Robert Rohlfs, Leggette, Brashears & Graham Inc.

JOINT ROCKY MOUNTAIN/ CORDILLERAN SECTION

Troy Benn, DNRC–Water Resources, Bozeman

Kyle Blasch, USGS Wyoming–Montana Water Science Center

Kevin Dennehy, U.S. Geological Survey

Betsy Hovda, Montana Dept. of Environmental Quality

THE GEOLOGICAL SOCIETY OF AMERICA®

GSA Today Reader Survey Results

In April, GSA invited members to participate in a reader survey to comment on the content and delivery of *GSA Today*. The last reader survey was conducted in 2007, so we were eager to check in with members again in 2014 to assess service against the ever-changing information milieu.

The response rate to the online survey was 19.2% and although not a perfectly constructed statistical sample, responders fairly represented membership demographics in terms of employment sector, disciplinary interests, and location. Responders were skewed toward older age groups and longer membership terms in comparison with GSA's general membership.

Some highlights to come out of the survey regarding content:

- 50% read at least half of each issue;
- 86% rate the content overall as "good" or "excellent";
- Roughly two-thirds report that the lead science articles compare favorably with *Geology* and *GSA Bulletin* articles; and
- A vast majority of respondents (82%–96%) "agree" or "strongly agree" with positive statements that *GSA Today* is relevant, reliable, credible, and serves to keep members current and informed.

Notable points concerning delivery:

- 83% reported that they normally access *GSA Today* in print and that they receive their copy in a timely fashion, and almost 50% keep, file, or pass on to others their print copies after use;
- When asked about accessing Annual Meeting information, 47% reported finding the Annual Meeting information in print to be valuable and 42% reported they could just as easily access needed Annual Meeting information online;
- When asked if they would like to have an option to "opt-out" of receiving *GSA Today* in print, 40% reported they would like to have that option, 41% reported they do not want the option, and 19% didn't know.

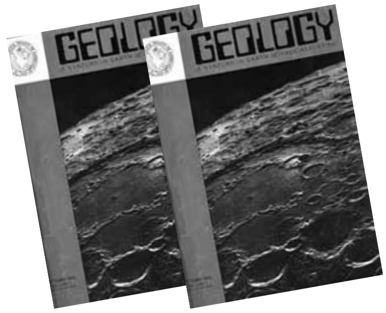
You can view the numerical results of the survey at **https://www.surveymonkey.com/results/SM-Z3M5FJK8/.**

Overall, members across the demographic spectrum give *GSA Today* a good look each month. A wide majority accesses the magazine in print format and also rates its content very favorably. Respondents value and most often read the lead science article, but the range of content offers something of interest to most member audiences.

Verbatim remarks to the final three survey questions generally reinforce the numerical data recorded and also offer a wealth of comments, ideas, and suggestions.

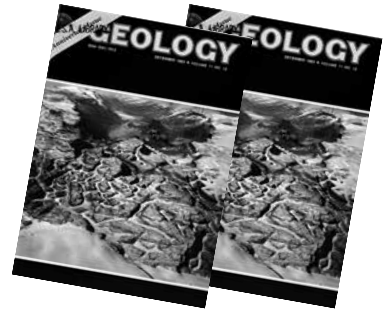
Thank you to everyone who took the time to respond! We are considering your thoughtful suggestions and ways to enhance *GSA Today* as the mouthpiece of your Society.

Congratulations to Robert Mahon at the University of Wyoming–Laramie, who won a US$50 gift card for his participation in the survey.



Geology—Past & Future

REVISITED



Editor's note: The following is the sixth installment of our encore presentation of articles that highlighted the 10th anniversary of the first issue of *Geology*, as published in *Geology* in Dec. 1983 [v. 11, no. 12, p. 679–691, doi: 10.1130/0091-7613(1983)11<679:GAF>2.0.CO;2]. Each section was written by a different author (author affiliation notations are as originally published in 1983). See the August 2013 *GSA Today* (v. 23, no. 8, p. 18–19) for the first installment and table of contents. In this issue: article 12: **"Hydrogeology,"** by Mary P. Anderson; and article 13: **"Mineral Deposits,"** by Brian J. Skinner.

Hydrogeology

Mary P. Anderson, *Department of Geology, University of Wisconsin, Madison, Wisconsin 53706, USA*

Since the beginning of hydrogeology as a science, dating from the publication of Darcy's Law in 1856, concern has been focused successively on defining basic concepts, on well hydraulics, and on regional flow system analysis. Ten years ago, attention was shifting from emphasis on the mechanics of flow to emphasis on solute transport, particularly as related to the movement of contaminants in groundwater. In the early 1970s the new frontier was clearly recognized to be solute transport and the chemistry of groundwater. For example, the 1973 Meinzer Award was given to William Back and Bruce Hanshaw for comparison of the chemical hydrogeology of Florida and Yucatan.

The general expectation in the early 1970s was that contaminant transport could be readily quantified by solving the advection-dispersion equation. Although a macroscopic viewpoint in which volume-averaged parameters are measured had been the key to quantifying the flow problem, it would prove to be inadequate for quantifying contaminant transport. By the mid-1970s many realized that the solution to the contaminant-transport problem would require carefully controlled long-term field experiments for the purpose of examining the influence of aquifer heterogeneities on the dispersion process and determining the kinds of chemical reactions that occur in the subsurface. But it was not until the early 1980s that there was a general call for a series of such field experiments. Another concern emerging in the early 70s was that predictions based on deterministic models were misleading. As a result, attempts to incorporate stochastic principles into groundwater modeling became more apparent, and R.W. Nelson's earlier efforts in the 60s to solve the inverse problem for flow were resuscitated. This attention to stochastic hydrology was highlighted in a remarkably prescient Penrose Conference, "Geostatistical Concepts and Stochastic Methods in Hydrogeology," held in 1977, during which the application of stochastic approaches to the flow problem, as well as to the contaminant transport problem, were explored.

The major challenges to hydrogeologists in the coming decade will arise in the areas of (1) stochastic hydrology, particularly as related to parameter estimation techniques and the complementary problems of modeling spatial variability and quantifying the dispersion process; (2) the hydrogeology of fractured rocks, particularly as related to disposal of high-level radioactive waste; (3) the chemistry of groundwater, particularly as related to organic chemicals. I predict that we are only several years away from resolving the remaining questions about the dispersion process, but at least a decade away from achieving a consensus on the appropriate way to tackle flow through fractured rocks. The inverse problem is a devilish one and will be troublesome for a long time; there has not been a great deal of progress toward the development of practical application techniques since the 1977 Penrose Conference. Significant breakthroughs in quantifying chemical reactions in the subsurface have been made during the last few years, and I expect that steady progress will continue because the urgency of this problem is recognized by governmental agencies. However, given the variety of organic chemicals and hydrogeologic settings, deciphering the chemistry of organics in the subsurface is likely to remain a fertile area for research for the foreseeable future.

Send brief comments to gsatoday@geosociety.org. Should this article spark a longer comment, please consider writing a *GSA Today* Groundwork or science article; learn more at www.geosociety.org/gsatoday/.

Mineral Deposits

Brian J. Skinner, *Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06511, USA*

Ten years ago Paul Barton and I reviewed contemporary perceptions of the ways mineral deposits form. We focused on the way ore minerals are transported and deposited from solution. Our emphasis was chemical because ore chemistry had been the focus of remarkable advances during the preceding two decades. We paid less attention to the question of where mineral deposits are located within tectonic frameworks, but we did recognize the great importance of the question. We made no attempt to predict what the next major advances might be, but the emphasis given certain observations indicates what such predictions would probably have been.

First, in view of the plate-tectonic revolution, we would have predicted major advances in understanding the tectonic settings of certain classes of mineral deposits. Certain associations such as porphyry coppers and subduction zones had already been noted. By 1983 all young deposits—that is, Phanerozoic-age deposits—are routinely considered in terms of a plate-tectonic framework, and the concept is becoming increasingly helpful in prospecting. Bold thinkers now try to place Proterozoic deposits into a plate tectonic framework, and a few very bold thinkers even use the concept for Archean deposits.

Second, the discoveries of brines laden with heavy metals such as copper, lead, and zinc in the Salton Sea and Cheleken geothermal fields and the discovery of an active ore-forming site on the bed of the Red Sea would have led us to predict the discovery of more sites of present-day hydrothermal ore deposition, such as the remarkable "smokers" along the East Pacific Rise. There are, no doubt, many chapters of this story still to come, but it is already clear that "smokers" mark the sites where one class of volcanogenic massive sulfide deposits are currently forming.

In the next decade, I predict that at least three topic areas will see major advances. The first will again be sites of modern hydrothermal ore-forming processes. None of the discoveries along the East Pacific Rise matches, in all details, a major class of mineral deposit on land. Although the mid-ocean ridge deposits are volcanic-associated massive sulfide and formed as a result of submarine volcanism, there are bigger and richer deposits in the geologic record that may reflect different tectonic settings, such as back-arc basins and along the flanks of magmatic arcs. Sea floor exploration should turn up even more spectacular new settings of active mineral deposition. Development of geothermal power offers a good possibility for chance discovery of some other class of active ore-depositing system, too. It is a long shot, but a real one, for the next decade.

The second topic area concerns the movement of aqueous fluids in and out of sedimentary basins and formation of mineral deposits by those fluids. Certain important classes of deposits—for example, the Mississippi Valley-type deposits and sediment hosted, stratiform deposits of lead, zinc, and copper—clearly are the results of evolutionary processes in sedimentary basins. As drillers seek smaller and deeper oil and gas pools, they should find evidence bearing on deposit formation as a natural result of basin development. Perhaps we may be lucky enough to find deposits actually forming. The key technique in unlocking the story will probably be stable-isotope geochemistry.

The third major topic area concerns why styles and rates of deposit formation have varied through geologic time. The missing link may be the interaction of climate and tectonics and the control of each by unappreciated processes in the core and mantle. Earth is running down. Present calculations suggest that the mantle is cooling at a rate of about 100 °C/b.y., and this must influence styles and rates of tectonism. Tidal drag is slowly lengthening the day; interactions with the biosphere have brought slow changes in the atmosphere and possibly the hydrosphere and lithosphere too. Somewhere in this complex network of interactions are the answers to why and how mineral-depositing processes have changed through time and are still changing. Some obvious answers, such as an increasing level of oxygen in the atmosphere, have already been realized. The decade ahead will produce a great many more.

GSA Foundation Update

P. Geoffrey Feiss, GSA Foundation President

As GSA enters the membership renewal season, it is a great time to join thousands of fellow GSA members who make a gift to the GSA Foundation as part of the renewal process. These statistics demonstrate the generosity of GSA members, and the effectiveness of giving through the membership renewal process:

Total number of donors in 2013: .... 4,134 (including more than 1,000 student members!)

Total giving via membership renewal: ....US$203,024

Percent of GSA members who made a gift: 14%

Average amount of each gift: ....US$49.11

The GSA Foundation invites you to be part of this generous community! You may direct your support to a wide range of funds that help GSA advance its programs and priorities. As you navigate the GSA Foundation giving page, **gsafweb.org/makeadonation.html,** you may select from numerous options:

Greatest Needs: Flexible • Efficient • Strategic

This choice could also be called "Greatest Opportunities." Designating gifts to this fund gives GSA the ability to respond to new opportunities and expand effective programs. These resources are critical to helping GSA advance its strategic priorities.

On To the Future: Engage Diverse Students in the Annual Meeting

Your support of On To the Future program (OTF) will ensure that its second year in Vancouver, B.C., Canada, is as successful as the inaugural program in Denver. You can help 125 students from underrepresented backgrounds attend the annual meeting and advance GSA's strategic commitment to increasing the diversity of membership in the society and the profession.

Other Priorities

You may also use the website drop-down menu to select from a wide array of established Foundation funds that support GSA programs and priorities:

Research Grants (drop-down: GEOSTAR)

More than 9,400 GSA members have benefited from GSA research grants. In place since 1933, GSA's research grants program has distributed over US$11 million to master's and doctoral thesis research in the geological sciences for graduate students at universities in the United States, Canada, Mexico, and Central America.

Divisions and Sections

All sections and most divisions have a fund that supports travel grants. Use the drop-down menu to designate your gift to your Section, Division, or both!

Meetings

Your support will enhance GSA's Annual Meeting experience for thousands of student and professional members.

Endowed Research Grants

The GSA Foundation also accepts donations for numerous endowed funds for research and awards. You can see the full list of giving opportunities by scrolling through the drop-down menu.

Penrose Circle

Penrose Circle donors make a special commitment to advancing GSA's mission via the following levels of support:

Penrose: ....US$500– $999

Topaz: .... US$1,000–$2,499

Ruby: .... US$2,500–$4,999

Emerald: .... US$5,000–$9,999

Diamond: ....US$10,000 or more

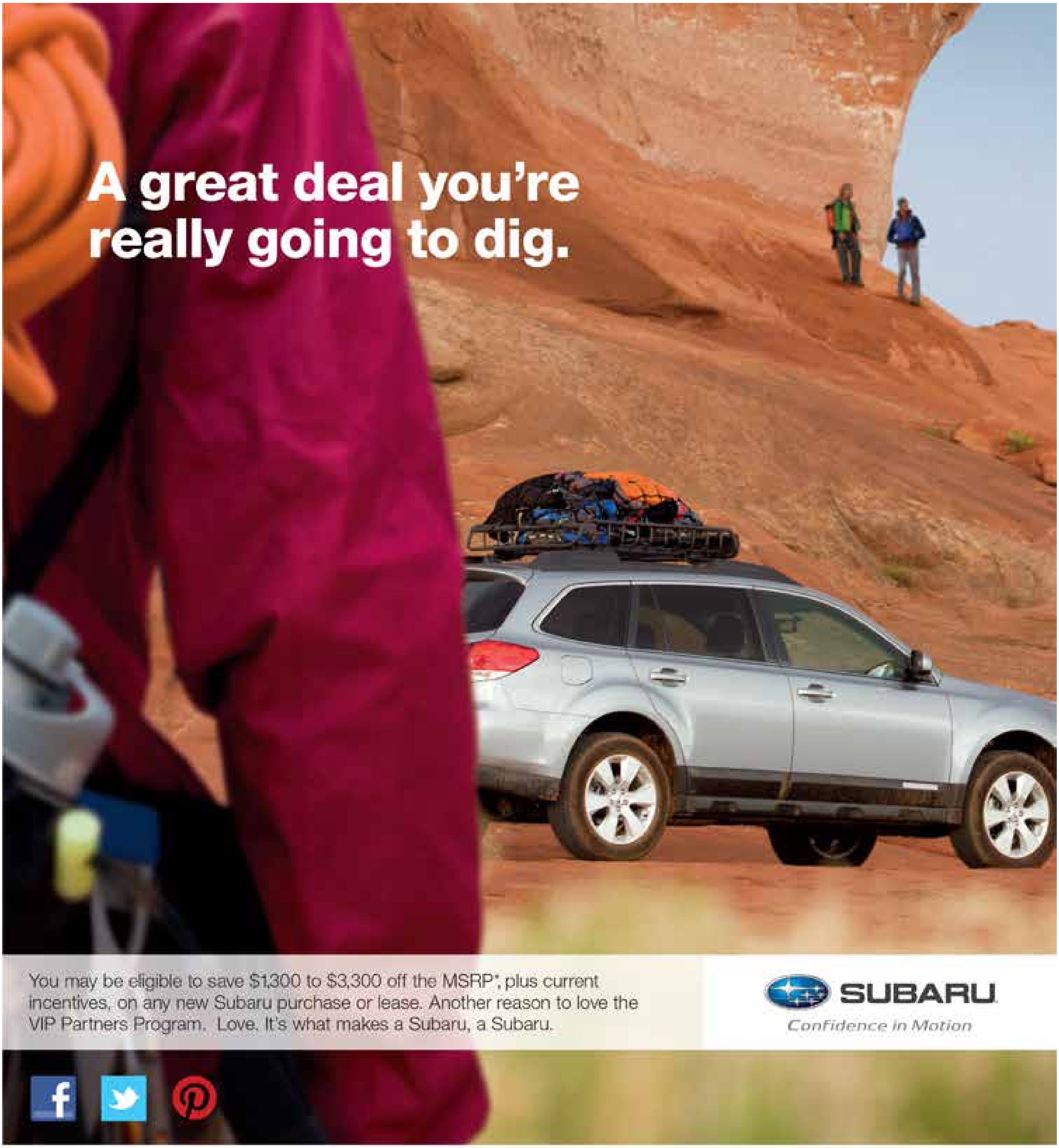
Pardee Coterie

Are you planning to include a gift to the GSA Foundation in your will or estate?

The Pardee Coterie recognizes donors who inform the GSA Foundation about their plans to support GSA through their will or trust. Estate gifts at all levels remain a transformative way to secure GSA's role in advancing the geosciences.

To make a contribution to the GSA Foundation via our secure site, please go to **gsafweb.org/makeadonation.html.**

If you have questions about giving to the GSA Foundation, please contact Chris Tallackson at +1-303-357-1007 or **ctallackson@geosociety.org.**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You may be eligible to save $1,300 to $3,300 off the MSRP*, plus current incentives, on any new Subaru purchase or lease. Another reason to love the VIP Partners Program. Love. It's what makes a Subaru, a Subaru.
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GSA's Distinguished International Lecture Series: Global Impact

Marjorie Chan stands where two oceans converge at Cape Leeuwin, the southwestern-most point of Australia. Photo by John W. Middleton.

As the 2014 GSA Distinguished International Lecturer, this has been the travel year of my life! It has been a privilege to represent the International Section (a regional organization within GSA) and be an ambassador for GSA to promote global interactions. I was graciously and warmly welcomed everywhere I visited. I found many enriching experiences, had the opportunity to taste and see different cultures, heard what others are doing, shared my own research, and developed potential collaborations for the future.

I saw the iconic sights of each city, and I was also able to experience the countries in a way that many tourists don't. There are so many highlights, including the Deccan Traps, Fort Golconda, and Taj Mahal of India; varied geology and Christchurch earthquake devastation in New Zealand; spectacular seaside cities of Australia; Mount Fuji (at a distance) and many shrines and temples of Japan; and the Three Gorges Dam, Great Wall, and the Terracotta Warriors of China. The short, partial-day field trips were especially fun. It was go, go, go—moving every two days or so—always an adventure, with something new to look forward to each day.

The GSA Distinguished International Lecturer program is only two years old, initiated through a generous endowment to the GSA Foundation from a geologic pioneer and role model to many women in our profession: Robbie Gries. Last year, Vic Baker from the University of Arizona was the inaugural Distinguished International Lecture speaker and traveled primarily to Europe. Thus, GSA requested that I go to Asia to cover another part of the globe. That was a perfect fit for me. As a third-generation Chinese American, I had never been to the country of my ancestors, and I was excited to see parts of Asia, with a few countries "down under" en route. I also anticipate a short trip to Korea this fall.

The University of Utah gave me a release from teaching for one semester so I could focus my travel during the spring 2014 semester. My husband accompanied me, and that was well worth us paying his expenses to make the travel a lot easier. We completed two separate trips that covered three months of international travel. On the first trip, I gave 27 lectures: six in India, six in New Zealand and 15 in Australia. On the second trip, I gave 24 lectures: three in Japan and 21 in China. My two lecture selections were "Mars for Earthlings: Using Earth Analogs to Decode the Sedimentary History of Mars," and "Eolian Explorations: "Dunes, Diagenesis, and Deformation." However, I also spoke about other hot topics in sedimentary geology, as well as graduate programs in the U.S. and the application process. In total, the lectures reached about 2,500 scientists, students, and public citizens.

Many partnering groups provided travel support and lodging, along with all of the individual host institutions. The major partner groups providing financial support were the University of Utah, the Geological Society of Australia, the Geoscience Society of New Zealand, the Sedimentological Society of Japan, the Geological Society of Japan, and the Exploration Technology Committee of the Japanese Association for Petroleum Technology.

The GSA lecture program (www.geosociety.org/Sections/International/LectureTour/) describes the tour talks and has links to my travel blog of short text and mainly pictures from every city

I enjoyed talking with many students at University of Delhi and especially encouraging some of the women geology students. Photo by John W. Middleton.

that I visited. If you missed it and/or want to see city and geologic scenes from the tour, they are in a continuous format (most recent to oldest) at http://geosociety.wordpress.com/category/international/.

The geology departments I visited were diverse and different in many ways. Some were doing so much with few resources, and others had booming programs with world-class facilities. An important point I saw clearly on my tours is the globalization of science. Certainly, international collaboration is an important part of how our discipline can move forward faster. Remarkable studies are being conducted all over the world, and I learned about many exciting research results from colleagues—ranging from sedimentary problems of dolomitization and opals to geophysical problems of earthquake liquefaction and reservoir induced seismicity. China in particular has made science a priority, and the government is heavily investing in science programs as well as instrumentation. One example is SinoProbe, a major earth-science effort to conduct deep exploration to understand the structure and evolution of China's continental lithosphere using multiple techniques. Some of their laboratories and equipment are truly impressive, the kind that many of us might only dream of. I wish the U.S. had a similar vision of investment in our sciences that have strong applications to societal needs and sustainable resources.

This large red banner across the entrance of Yangtze University greeted me, announcing the "Plan of World Famous Scientist Lecture: Marjorie A. Chan" (approximate translation of Chinese). Photo by John W. Middleton.

THE GEOLOGICAL SOCIETY OF AMERICA®

INTERNATIONAL SECTION

To me, one of the greatest successes of this tour was to be able to excite students and fuel their interest in geoscience while expanding their perspective to new ideas. I was particularly moved by the strong dreams of students in India. They had far-ranging interests and asked many questions on topics like Earth processes, unconventional resources, and extraterrestrial life. In every country I visited, I met bright and engaging young people who will be tomorrow's leaders.

I am a different person because of this GSA tour. Without doubt, meeting the many folks on this tour gave me a new perspective both personally and professionally. The field of geoscience is a "small world" where it often seems that there are much fewer than six degrees of separation. I know I will cross paths again with many of the individuals I interacted with on the trip. There were so many great people and experiences that all happened so quickly, and I am still trying to absorb all of it. Through this lecture program, GSA has made a difference, engaging and connecting across cultures and international boundaries. Most of all, it has been great to share and exchange ideas and enthusiasm for geoscience around the world.

Marjorie A. Chan, *2014 GSA Distinguished International Lecturer Professor of Geology, University of Utah*

Positions Open

RESEARCH SCIENTIST II
MARSHALL SPACE FLIGHT CENTER

The University of Alabama in Huntsville and NASA Marshall Space Flight Center are seeking a Laboratory Manager for the MSFC Noble Gas Research Laboratory (MNGRL) at Marshall Space Flight Center. The primary responsibilities of the successful candidate are operation and maintenance of our multi-collector noble-gas mass spectrometry facility. Other duties include preparation of geological samples for radioisotopic analyses, developing procedures for sample analysis, assistance in data collection and reduction for research staff and guest users, managing budgets and schedules for the facility, and development of future capabilities. The successful candidate must demonstrate competence in mass spectrometry and ultra-high vacuum laboratory operations and a commitment to producing excellent analytical results. It is anticipated that the successful candidate will also (to the degree feasible given the primary laboratory management responsibilities) participate in collaborative or independent research, as well as development of spaceflight capabilities.

Qualifications: (1) A M.S. in the physical sciences is required; Ph.D. and background in Planetary or Earth Science is preferred; (2) hands-on experience with noble-gas mass spectrometry and/or other high-resolution mass spectrometry techniques (e.g., ICP-MS, TIMS, etc.).

The MSFC Planetary Science group includes scientists and engineers from NASA's Marshall Space Flight Center and the University of Alabama in Huntsville (UAH). We study surface processes on the Moon, Mars, and asteroids, and are actively involved in planetary missions. Additional information about the MSFC Planetary Science group and the MNGRL Lab can be found on our website (http://planetary.msfc.nasa.gov/), or by contacting Dr. Barbara Cohen (barbara.a.cohen@nasa.gov).

Applications will be reviewed beginning 2 September until position is filled. Starting date is negotiable, with ability to start in fall 2014 preferred. This position is for an initial one-year term with the potential for continuation based on performance and the availability of funding. Expected salary is $67,151–$85,000 per year depending on qualifications.

Please complete the online application process and submit a resume, a statement about your qualifications and interests, and contact information for two references to the UAH Job Announcement http://uah.interviewexchange.com/jobofferdetails.jsp?JOBID=50487.

AN AFFIRMATIVE ACTION/EQUAL OPPORTUNITY EMPLOYER OF MINORITIES/FEMALES/VETERANS/DISABLED.

ASSISTANT PROFESSOR
SEDIMENTOLOGY/BASIN ANALYSIS
DENISON UNIVERSITY

Denison University invites applications for a tenure track position in the Dept. of Geosciences, to begin in August 2015. We seek a broadly trained scientist engaged in the study of Sedimentology and/or Basin Analysis. Successful candidates are expected to be outstanding teacher/scholars, and contribute to the continued growth of the Department and College. Candidates must have a Ph.D. at the time of appointment.

We require a colleague who is committed to teaching excellence in the liberal arts tradition, is field-based, has broad interests beyond their individual specialty, and will provide a balance of classroom, field, and laboratory experiences for our students. Candidates must have the desire and ability to teach courses at all levels of the curriculum. In addition, successful candidates are expected to maintain a vibrant, ongoing research program that actively incorporates undergraduate students.

Denison University is a highly selective, private residential liberal arts college enrolling approximately 2,100 undergraduate students from across the country and around the world. The college is located in the village of Granville, Ohio, 25 miles east of Columbus. For more information about Denison, visit our website at www.denison.edu.

All application materials will be handled electronically at https://employment.denison.edu. Applications must include (1) a letter of application addressing the position requirements listed above; (2) a curriculum vita; (3) academic transcripts of undergraduate and graduate course work (unofficial acceptable); (4) a statement of teaching philosophy and experience; and (5) a statement of your research program in a liberal arts context. In addition, please include the contact information for three persons who know you well, who will then be requested to upload reference letters. Completed application materials submitted by 27 October 2014 will receive full consideration, and evaluation will continue until the position is filled. We plan to meet with selected candidates at the 2014 GSA Annual Meeting in Vancouver, BC, Canada. Denison University is an Affirmative Action, Equal Opportunity Employer. To achieve our mission as a liberal arts college, we continually strive to foster a diverse campus community, which recognizes the value of all persons regardless of religion, race, ethnicity, gender, sexual orientation, disability, or socioeconomic background.

TENURE TRACK FACULTY POSITION
GEOBIOLOGY, MIAMI UNIVERSITY

The Dept. of Geology and Environmental Earth Science at Miami University invites applications for a tenure-track faculty position at the Assistant Professor level, beginning August 2015. Applicants must have a Ph.D. degree at the time of appointment. The successful applicant will be expected to teach effectively at the undergraduate and graduate levels, supervise student research at the undergraduate, M.S. and Ph.D. levels, initiate and maintain a vigorous, externally-funded research program, and provide service to the university.

We seek an outstanding candidate who is undertaking significant field and/or laboratory-based research in Geobiology. The particular research emphasis, for example paleobiology/paleontology, high-resolution biostratigraphy, paleobiogeochemistry, paleoecology, or paleoclimatology, should complement current program strengths indicated below. It is anticipated that this new position will enable us to address important questions pertaining to the interactions between life and Earth through geologic time.

The successful applicant will join an active department that consists of 13 faculty members, three research/technical staff members, 125 undergraduate and 35 graduate students. The department maintains active research programs in geomicrobiology, geomorphology, geophysics, hydrogeology, igneous petrology, isotope geochemistry, low-temperature geochemistry, mineralogy, paleoclimatology, sedimentology and stratigraphy, structural geology, tectonics, volcanology, and Quaternary geology. The department also maintains modern teaching, research, and instrumentation laboratories, and portable instrumentation in support of the above. Please visit www.miamioh.edu/geology for additional information.

Miami University's Oxford Campus, with nearly 15,000 undergraduate and over 1,800 graduate students, is located in a small-town setting adjacent to the Cincinnati and Dayton urban areas. More information on Miami and on the department may be obtained via www.miamioh.edu and www.miamioh.edu/geology.

Interested candidates should submit letter of application, curriculum vitae, statement of teaching philosophy, statement of research plans and unofficial copy of transcripts (submitted as "other") to **www.miamiujobs.com/applicants/Central?quickFind=53702**; candidates should arrange to have three letters of recommendation sent to **GeobioSearch@miamioh.edu.** Screening of applications begins 14 September 2014 and will continue until the position is filled. Appointment effective 17 August 2015.

Miami University, an equal opportunity/affirmative action employer with smoke- and tobacco-free campuses, is committed to a multicultural environment and strongly encourages applications from minorities, females, veterans and individuals with disabilities. Miami's Annual Security and Fire Safety Report with information on campus crime, fires, and safety may be found at www.MiamiOH.edu/campus-safety/annual-report/index.html. Hard copy available upon request. Employment will require a criminal background check according to University guidelines.

TENURE TRACK FACULTY POSITION
PETROLOGY, MIAMI UNIVERSITY

The Dept. of Geology and Environmental Earth Science at Miami University invites applications for a tenure-track faculty position at the Assistant Professor level, beginning August 2015. Applicants must have a Ph.D. degree at the time of appointment. The successful applicant will be expected to teach effectively at the undergraduate and graduate levels, supervise student research at the undergraduate, M.S. and Ph.D. levels, initiate and maintain a vigorous, externally-funded research program, and provide service to the university.

We seek a candidate who is undertaking significant field and/or laboratory-based research in igneous and/or metamorphic petrology. The particular research emphasis, for example igneous/metamorphic processes, crust-mantle evolution, experimental petrology, or ore-forming processes, should complement current program strengths indicated below.

The successful applicant will join an active department that consists of 13 faculty members, three research/technical staff members, 125 undergraduate and 35 graduate students. The department maintains active research programs in geomicrobiology, geomorphology, geophysics, hydrogeology, igneous petrology, isotope geochemistry, low-temperature geochemistry, mineralogy, paleoclimatology, sedimentology and stratigraphy, structural geology, tectonics, volcanology, and Quaternary geology. The department also maintains modern teaching, research, and instrumentation laboratories, and portable instrumentation in support of the above. Please visit www.miamioh.edu/geology for additional information.

Miami University's Oxford Campus, with nearly 15,000 undergraduate and over 1,800 graduate students, is located in a small-town setting adjacent to the Cincinnati and Dayton urban areas. More information on Miami and on the department may be obtained via www.miamioh.edu and www.miamioh.edu/geology.

Interested candidates should submit letter of application, curriculum vitae, statement of teaching philosophy, statement of research plans and unofficial copy of transcripts (submitted as "other") to **www.miamiujobs.com/applicants/Central?quickFind=53705**; candidates should arrange to have three letters of recommendation sent to **PetrologySearch@miamioh.edu.** Screening of applications begins 14 September 2014 and will continue until the position is filled. Appointment effective 17 August 2015.

Miami University, an equal opportunity/affirmative action employer with smoke- and tobacco-free campuses, is committed to a multicultural environment and strongly encourages applications from minorities, females, veterans and individuals with disabilities. Miami's Annual Security and Fire Safety Report with information on campus crime, fires, and safety may be found at www.MiamiOH.edu/campus-safety/annual-report/index.html. Hard copy available upon request. Employment will require a criminal background check according to University guidelines.

**LECTURER/ADJUNCT FACULTY
HYDROGEOLOGY
DEPT. OF GEOLOGICAL SCIENCES
THE UNIVERSITY OF TEXAS AT AUSTIN**

The Dept. of Geological Sciences at the University of Texas at Austin seeks to hire a one-year temporary teaching replacement in the field of Hydrogeology. Applicants are expected to teach an undergraduate introductory course in surface hydrology and hydrogeology, covering both physical and chemical aspects, for both geoscientists and engineers; the applicant can potentially teach a graduate course in the same field. Candidates should hold a Ph.D. in a relevant field (Earth Sciences of Hydrology/Hydrogeology) or have reached the ABD stage in their progress toward a degree. The position is for August 2014 to May 2015 and may be established as a lecturer or as visiting/adjunct faculty or scientist, as appropriate.

As part of the Jackson School of Geosciences (www.jsg.utexas.edu), the Dept. of Geological Sciences (www.geo.utexas.edu) has one of the largest combined graduate and undergraduate enrollments of any major Earth science program in the country and offers an undergrad specialization in Hydrogeology.

Review of applications will begin 1 July 2014 and will continue until the position is filled. Applicants should submit a letter of application, curriculum vitae, statement of teaching interests and contact information for at least three references. Submit a compiled electronic copy as a single pdf document to dgs@jsg.utexas.edu. Questions regarding the search may be addressed to Dr. Ginny Catania at gcatania@ig.utexas.edu.

Background check conducted on applicant selected.

The University of Texas at Austin is an Affirmative Action/Equal Opportunity Employer.

**FACULTY POSITION
GEOMICROBIOLOGY & BIOREMEDIATION
EARTH SCIENCES & BIOTECHNOLOGY
INSTITUTE, UNIVERSITY OF MINNESOTA**

The Dept. of Earth Sciences and The BioTechnology Institute (BTI) at the University of Minnesota seek applications for a tenure-track faculty position in the area of Geomicrobiology and Bioremediation. We are interested in a broad range of topics in geomicrobiology, microbiology, biogeochemistry, or related fields, with application in areas such as acid mine drainage bioremediation, dynamics of sulfate and nitrate removal, microbial bioremediation, biomining, and/or groundwater bioremediation. The appointment will be a 9-month (B-Term), tenure-track position at the assistant or associate professor level with responsibilities in research, teaching, and service. Rank will be determined based on qualifications. The Dept. of Earth Sciences, located in the College of Science and Engineering, will be the academic and teaching home, and the BioTechnology Institute, in the College of Biological Sciences, will be co-home for research activities.

This position is part of an interdisciplinary research cluster focused on the use of bioremediation to conserve our environment and advance industry. This cluster, one in a series supported by the Minnesota's Discovery, Research and InnoVation Economy (MnDRIVE) Initiative, focuses on using scientific discovery and innovation to enhance efficient environmental stewardship and to position the state as a leader in key industries.

Duties and Responsibilities: Applicants should have strong core fundamentals that allow them to easily move across disciplinary boundaries and become involved in interdisciplinary research opportunities at the Department, Institute, University, state and national levels. The successful candidate will develop an externally funded research program spanning basic and applied research aspects of bioremediation, teach undergraduate and graduate courses, and advise undergraduate and graduate students. The successful applicant will also complement current University of Minnesota research strengths in water, geomicrobiology, microbiology, geochemistry, and lake and river dynamics, and programs including the BTI, LacCore, the Water Resources Center, and the Saint Anthony Falls Laboratory.

Required Qualifications

- Ph.D. degree and a strong publication record in one or more of the areas listed above;
- Evidence of commitment to teaching and student learning; and
- Demonstrated ability in or strong potential for research that translates to Minnesota's environment and industries.

Preferred Qualifications

- Ability to communicate effectively with diverse audiences;
- Track record of interacting creatively, collaboratively, and productively with other scientists; and
- Postdoctoral or equivalent experience.

Materials Required

- A letter of intent;
- A CV with a list of publications;
- Statements of research and teaching interests; and
- Names and contact information of three referees who can address the candidate's teaching and research potential.

In support of our strong commitment to and respect for diversity and cultural competence, finalists invited for interviews will be asked to provide a statement describing interest, experience with, and commitment to diversity and inclusiveness.

Applications must be completed online at https://employment.umn.edu/applicants/jsp/shared/Welcome_css.jsp. **Search for requisition number 191508.**

Review of applications will begin 8 Sept. 2014. Applications will continue to be accepted until the position is filled. Expected appointment is fall 2015. Questions may be directed to Prof. Chris Paola at cpaola@umn.edu.

Find out what makes Minnesota a great place to work and live. Learn more about the University of Minnesota, and the Twin Cities at www1.umn.edu/faculty/.

The University of Minnesota provides equal access to and opportunity in its programs, facilities, and employment without regard to race, color, creed, religion, national origin, gender, age, marital status, disability, public assistance status, veteran status, sexual orientation, gender identity, or gender expression. The University supports the work-life balance of its faculty and especially encourages applications from women and members of under-represented groups. Any offer of employment is contingent upon the successful completion of a background check. Our presumption is that prospective employees are eligible to work here. Criminal convictions do not automatically disqualify finalists from employment. However, a criminal record, the age and time of the offense, the seriousness and nature of the violation, and any rehabilitation will be considered as it relates to your position.

**ASSISTANT PROFESSOR
STRUCTURAL GEOLOGY AND TECTONICS
UNIVERSITY OF MISSOURI**

The Dept. of Geological Sciences at the University of Missouri invites applications for a tenure-track, Assistant Professor position beginning in August 2015 in the broadly defined area of Structural Geology and Tectonics. The successful candidate's research will ideally complement and expand upon one or more of the areas of departmental expertise in solid-earth processes including geodynamics, igneous and metamorphic petrology, neotectonics, and seismology. Completion of the Ph.D. at the time of appointment is required. Applicants should be prepared to prove eligibility to work in the United States. The successful applicant will be expected to teach across the curriculum (i.e., introductory classes), advanced undergraduate courses, and graduate courses in his/her area of expertise. The applicant will also be expected to develop an active, externally funded research program and to direct graduate student research at the M.S. and Ph.D. levels.

Please apply online at http://hrs.missouri.edu/find-a-job/academic.

In addition to a curriculum vitae (CV), applicants should include a letter describing their geologic interests and qualifications for the position, a teaching portfolio, and a list of three references (including contact information). Items other than the CV should be uploaded in the Attachments section of the application system. Initial screening of applicants will begin 1 October 2014 and will continue until a suitable candidate is hired. Information about our department is available at **http://geology.missouri.edu.** The University of Missouri is an EO/AA/ADA employer.

HEAD OF EARTH & ENVIRONMENTAL SCIENCES AND PHYSICAL GEOGRAPHY
ASSOCIATE OR FULL PROFESSOR
IRVING K. BARBER
SCHOOL OF ARTS AND SCIENCES
UNIVERSITY OF BRITISH COLUMBIA
OKANAGAN CAMPUS, KELOWNA

We seek a candidate with demonstrated excellence in research and teaching, strong management skills, and proven ability to lead and motivate faculty, staff, and students. The position of Head will be available 1 July 2015 with a five-year renewable term.

Deadline for applications: 15 August 2014.

www.facultycareers.ubc.ca/17993

Inquiries: Associate Dean for Faculty, Irving K. Barber School of Arts and Sciences, Louise.Nelson@ubc.ca.

ASSISTANT PROFESSOR OF GEOSCIENCES
TOWSON UNIVERSITY

Applications are invited for a tenure-track, 10-month Assistant Professor of Geosciences position at Towson University in the Dept. of Physics, Astronomy and Geosciences starting fall 2015. A Ph.D. in a relevant area is required and postdoctoral experience is preferred. This position supports the Geology program and the interdisciplinary graduate and undergraduate programs in Environmental Science and Studies. Preference will be given to candidates with research and teaching interests in the areas of mineralogy, sedimentology and stratigraphy, shallow geophysics, solid earth geophysics, or hydrogeology. Candidates with background in climate change, engineering geology, or energy resources and whose interests overlap with the priorities already listed will also be considered. Teaching responsibilities include introductory courses and upper level electives related to the candidate's field of expertise. Research responsibilities include establishment of a productive research program that involves students and pursuit of external funding. Electronic applications should be submitted as a single PDF file that includes a cover letter, CV, and 2-page teaching and research statements. Three letters of reference should also be submitted separately by email. All materials should be sent to Dr. Steven Lev, GEOLsearch@towson.edu. Review of applications will begin on 3 October 2014 and will continue until the position is filled. Additional information can be found at www.towson.edu/physics.

PHYSICAL SCIENCE ADMINISTRATOR (PROGRAM DIRECTOR)
DIVISION OF EARTH SCIENCE
NATIONAL SCIENCE FOUNDATION

The National Science Foundation (NSF) is seeking candidate(s) for a Program Director within the Surface Earth Processes (SEP) Section, Division of Earth Science (EAR), Directorate for Geosciences (GEO), Arlington, Virginia. EAR supports proposals for research that will improve understanding of the structure, composition, and evolution and behavior of the Earth's materials. More information about EAR and their programs can be found at www.nsf.gov/div/index.jsp?div=ear. The individual selected for this position will serve as a Program Director in SEP and will be charged with maintaining a healthy balance of support for the needs of the research and education enterprise whether through program, division, directorate, Foundation, or interagency activities.

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Making things geological: 3-D printing in the geosciences

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INTRODUCTION

Geoscientists are some of most prolific producers of three-dimensional (3-D) data. These data do not belong in our computers—they belong in our hands. The power of computers to make accurate and speedy calculations on 3-D data sets is impossible for humans to match. Likewise, the power of the human mind and its sensory system to perceive qualitative aspects of physical objects is currently beyond computers. Three-dimensional printing, shorthand for a host of technologies more broadly described as "rapid prototyping," is transforming how scientists, engineers, doctors, and artists interact with and understand 3-D data and models by allowing those data to be touched and viewed from any angle under real-world conditions. Importantly, 3-D printing produces tangible objects that are obviously intuitive to students, non-geoscientists, and decision makers.

3-D PRINTING IS HERE

While some products result from a perfect mental vision, most manufacturing utilizes an iterative process. Human interaction with prototypes allows model qualities to be assessed in real-world situations. Computer-aided design (CAD) has yielded increasing design accuracy and has allowed design performance to be simulated computationally. However, the same fundamental need often still exists to validate models "in the *real* world."

Rapid prototyping technologies have developed to meet this challenge. These consist of a family of methods for producing physical models from digital designs (cf. Pham and Gault, 1998). Most commonly, these systems are additive, building an object by fusing together feedstock (e.g., plastic, metal, mineral) delivered to the print area as a powder, liquid, film, bead, or thread. The combination of 3-D printing with any of the multitude of 3-D scanning technologies, like computed tomography (CT) or photogrammetry, creates a 3-D photocopier (e.g., Rengier et al., 2010).

Rapid prototyping is being put to such disparate uses as producing art installations, fabricating aircraft parts, designing jewelry, reproducing paleontological specimens, engineering bone implants, making textiles, creating edible foods, and fulfilling the human need for self-defense (i.e., making weapons). This transformative technology has been widely covered in the popular press, resulting in broad public awareness.

Among geoscientists, paleontologists have been early adopters of this technology (e.g., Bristowe et al., 2004; Balanoff and Rowe, 2002; Pouech et al., 2010; Hasiotis et al., 2011; Hyatt and Rosiene, 2013)—seeking to digitally extract fossils from stubborn matrices or reconstruct disarticulated specimens. Other geoscientific uses have been reported mainly through meeting abstracts: printing CT, LiDAR, and seismic data to understand morphology and stratigraphy (Reyes et al., 2008); printing extraterrestrial topography (Horowitz and Schultz, 2012); and visualizing earthquake distribution (Lindqvist et al., 2012).

3-D PRINTING IS EASY

Reliable desktop 3-D printers cost less than US$3000, and feedstock is commodity priced (unlike 2-D printer ink). 3-D scanning has become easier and less-expensive as consumer-grade solutions have proliferated (e.g., Microsoft's Kinect sensor and free smartphone apps that use cloud services to stitch multiple images into a 3-D model). Free online services (e.g., thingiverse.com, tinkercad.com, 123Dapp.com) allow basic CAD modeling with options to export printable files or have a printing service deliver a completed model. These services provide free platforms for the distribution of models, often including social media and metrics for tracking views and downloads (i.e., impact). While academic and government institutions provide online warehouses of 3-D data and models (cf. DigiMorph.org, GB3D), a peer-review mechanism is sorely needed to ensure uniform standards of accuracy and printability while providing easy access and citability.

3-D PRINTING IS USEFUL

In the geosciences, we struggle with a fundamental problem—we love nature, but its aspects can be truly enormous or fantastically miniscule, very far away or exceedingly rare. Our burden is to overcome these conditions and communicate effectively about nature. With equal ease, 3-D printing can make hand-samples out of subduction zones and foraminifera, Martian topography, and seismic data.

Such models are immediately useful because much of what we need to communicate concerns shape and form (Fig. 1). For these purposes, we can produce inexpensive teaching models on demand, saving acquisition costs while bringing unique specimens to broader audiences. Three-dimensional printing makes the natural specimen the starting point. Digital models can be transformed (e.g., scaled, mirrored, distorted) by an instructor or a student to explore concepts like morphology, vertical exaggeration, or strain. With a little CAD work, we can make *flexible fossils* to more effectively communicate how organisms, extinct and extant, locomote.

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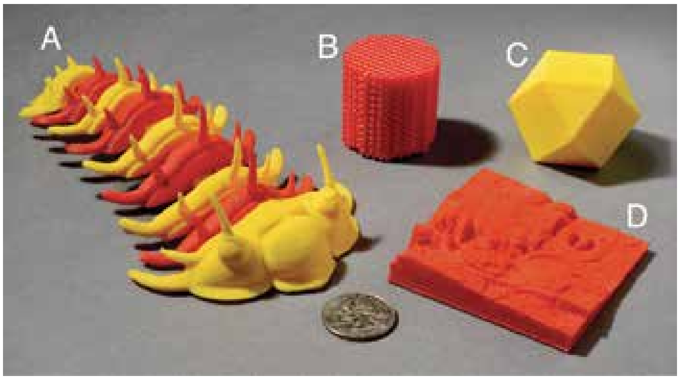

Figure 1. 3-D printed geological things. (A) Flexible fossil ("*Comura articulatum*," thingiverse.com). (B) "Artificial reservoir rock" with through-going porosity (GeoFabLab). (C) Crystal model (rhombic dodecahedron, 3Dlapidary.com). (D) Topography of Ames, Iowa, USA, near the football stadium (GeoFabLab). Models were printed in ABS (acrylonitrile butadiene styrene) plastic, the same material used to make LEGO®. Photograph by Bob Elbert.

Students might more easily develop a sense of scale from a *touchable topography*—that they themselves choose and print—that combines local elevation data showing natural and human features. By printing in multiple colors, geological attributes (like geologic formations or geophysical measurements) can be printed over elevation data as a way to better understand a new field area or check field results. Medical researchers already 3-D print hydroxyapatite for bone implants (e.g., Dorozhkin, 2010), and some researchers have 3-D printed using silica, marble, and gypsum feedstocks.

Destructive testing yields valuable information at the expense of repeatability. *Geo-clonin*g uses 3-D scanning or computational methods to create a digital model of a specimen that can be 3-D printed for analysis with traditional laboratory methods. Three-dimensionally printed river cobbles have been used to investigate weathering processes (Bourke et al., 2008). Others have used CT scanning and 3-D printing to reproduce pore networks (Otten et al., 2012). *Recombinant geology* involves modifying the intermediate digital model to test hypotheses about the original specimen. For example, parametrically modeled pelecypod shells have been 3-D printed to assess their burrowing functionality (Germann et al., 2014).

3-D PRINTING IS INCLUSIVE

Perhaps the most compelling reason to adopt 3-D printing into your teaching and research philosophies is that it will help you communicate more effectively. Some people do not "get" 3-D data on a computer screen, even with 3-D glasses or in 3-D visualization rooms. By printing 3-D data sets, we can interact with them in a more intuitive, more *human* way. Microfossils and pore networks can be scaled up to sizes more easily explored. A tangible model can help make the most of the short amount of time with a key decision maker at your company or funding agency. Visually impaired geoscientists may benefit greatly from having the opportunity to touch their data (Horowitz and Schultz, 2012).

With 3-D printers in our classrooms and laboratories, by taking them to conferences and K–12 science nights, we can help cement geoscience in the public's perception as a high-tech field and career. Students watch 3-D printers with a fervor usually reserved for athletic events. Let's capitalize on this passion and use 3-D printers in the same way we have used dinosaurs to sneak into young hearts and minds, making them more engaged with the geosciences and more aware of how much fun we have.

ACKNOWLEDGMENTS

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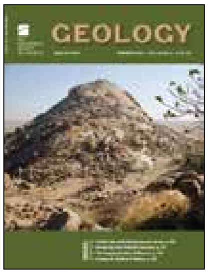

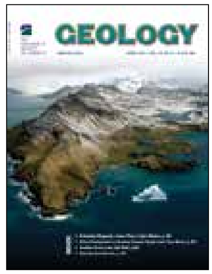

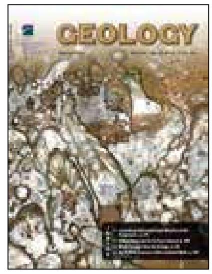

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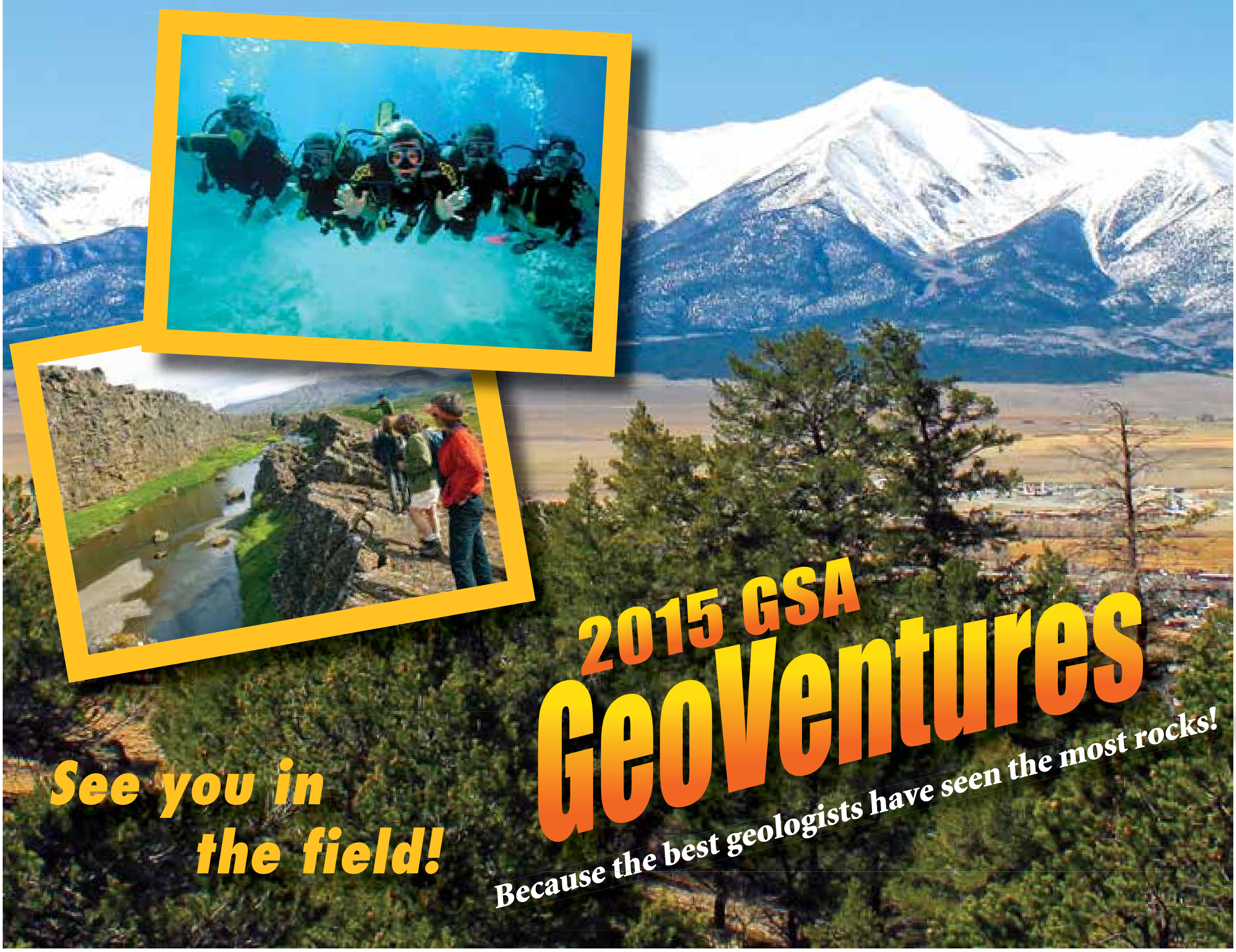

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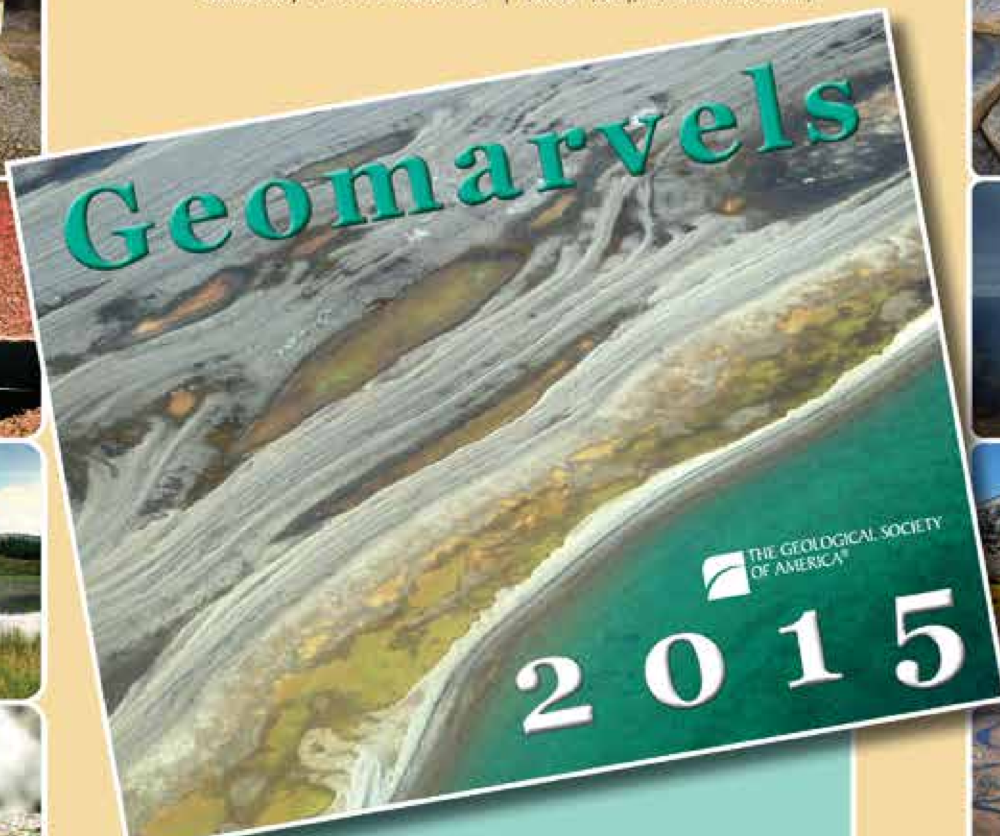

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