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SCIENCE

Cover: Landslides triggered by Hurricane Maria in Sept. 2017 in the municipality of Utuado, Puerto Rico. Photo taken by Erin Bessette-Kirton during helicopter reconnaissance on 29 Oct. 2017. See related article, p. 4–10.

GSA 2019 Annual Meeting & Exposition

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Landslides Triggered by Hurricane Maria: Assessment of an Extreme Event in Puerto Rico

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ABSTRACT

Hurricane Maria hit the island of Puerto Rico on 20 September 2017 and triggered more than 40,000 landslides in at least three-fourths of Puerto Rico's 78 municipalities. The number of landslides that occurred during this event was two orders of magnitude greater than those reported from previous hurricanes. Landslide source areas were commonly limited to surficial soils but also extended into underlying saprolite and bedrock. Slope failures occurred before, during, and after flooding, and many transitioned into long runout debris flows. Steep slopes in hilly and mountainous regions were particularly impacted by landslides due to antecedent soil moisture levels that were 11%–13% higher than average and rainfall totals of at least 250 mm within a 48 h period. High landslide densities were especially widespread across some geologic formations (e.g., granodiorite of the Utuado batholith); however, bedrock geology alone did not determine the location and distribution of landslides caused by Hurricane Maria. While rainfall data collected during Hurricane Maria were inconsistent, satellite-based soil moisture data were correlated with the distribution of landslides. In the future, the use of soil moisture data could enable assessments of regional landslide susceptibility prior to hurricanes or extreme precipitation events.

INTRODUCTION

Hurricane Maria struck Puerto Rico on 20 September 2017 as the strongest hurricane to make landfall on the island since 1928 (National Weather Service, 2017a). Maria produced heavy rainfall and flooding across most of Puerto Rico and triggered widespread landslides throughout mountainous areas. Landslides damaged and destroyed structures and roads (Puerto Rico Highway and Transportation Authority, 2017, personal commun.; U.S. Geological Survey, 2017a), in some cases isolating communities for days and weeks (e.g., Radebach, 2017; Schmidt and Hernández, 2017). Slope failures caused at least three fatalities (Hennessy-Fiske, 2017; Irizarry Álvarez, 2017), although Kishore et al. (2018) believe that the death toll from Hurricane Maria was underestimated by more than 4000 deaths, some of which could have been related to landslides. Landslides were also partly responsible for damage to the communications and electrical power transmission infrastructure that left much of the island without power for more than six months.

Landslides occur frequently in the mountainous regions of Puerto Rico (e.g., Monroe, 1964, 1979; DeGraff et al., 1989; Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1998; Pando et al., 2005; Lepore et al., 2012). Most noteworthy was the 7 October 1985 Mameyes disaster, which killed at least 129 people and is recognized as the deadliest landslide in North American history (Campbell et al., 1985; Jibson, 1992). Hurricanes and tropical cyclone systems (henceforth referred to collectively as TCs) routinely affect Puerto Rico (Hernández Ayala and Matyas, 2016) and are capable of producing landslide-triggering rainfall (e.g., Campbell et al., 1985; Jibson, 1989; Larsen and Torres-Sánchez, 1992). Landslides have been associated with at least 17 major disaster declarations in Puerto Rico since 1960 (Federal Emergency Management Agency, 2018), and, on average, 1.7 major landslide-triggering storms (TCs and non-TC systems) affect Puerto Rico annually (Pando et al., 2005). The frequency of such events constitutes a hazard to ~1 million U.S. citizens that reside in the predominantly rural interior of the island, much of which is characterized by rugged mountainous terrain (Martinuzzi et al., 2007). Puerto Rico's vulnerability to extreme rainfall events is sobering given projections of increasingly frequent extreme TCs in the Atlantic Ocean Basin (Knutson et al., 2010).

As a step toward reducing landslide risk during extreme, island-wide precipitation events, we evaluated the extent and characteristics of Maria-induced landslides throughout Puerto Rico. Herein, we present an assessment of island-wide landslide density, which we compare, in conjunction with rainfall data, to TCs that have affected Puerto Rico since 1960. Additionally, we discuss the conditions specific to landsliding in Puerto Rico and examine the impact of environmental variables (e.g., rainfall, soil moisture, and geology) on observed variations in island-wide landsliding. An improved understanding of causative factors specific to landslides in Puerto Rico is important for revised susceptibility analyses and risk management in anticipation of future storms capable of producing widespread landsliding.

SETTING

Puerto Rico (18° 15′ N, 66° 30′ W) is the easternmost of the Greater Antilles and covers an area of 8750 km^2 (Fig. 1A). Two-thirds of the island is mountainous, with the east-west–trending Cordillera Central range spanning most of the island and reaching a maximum elevation of

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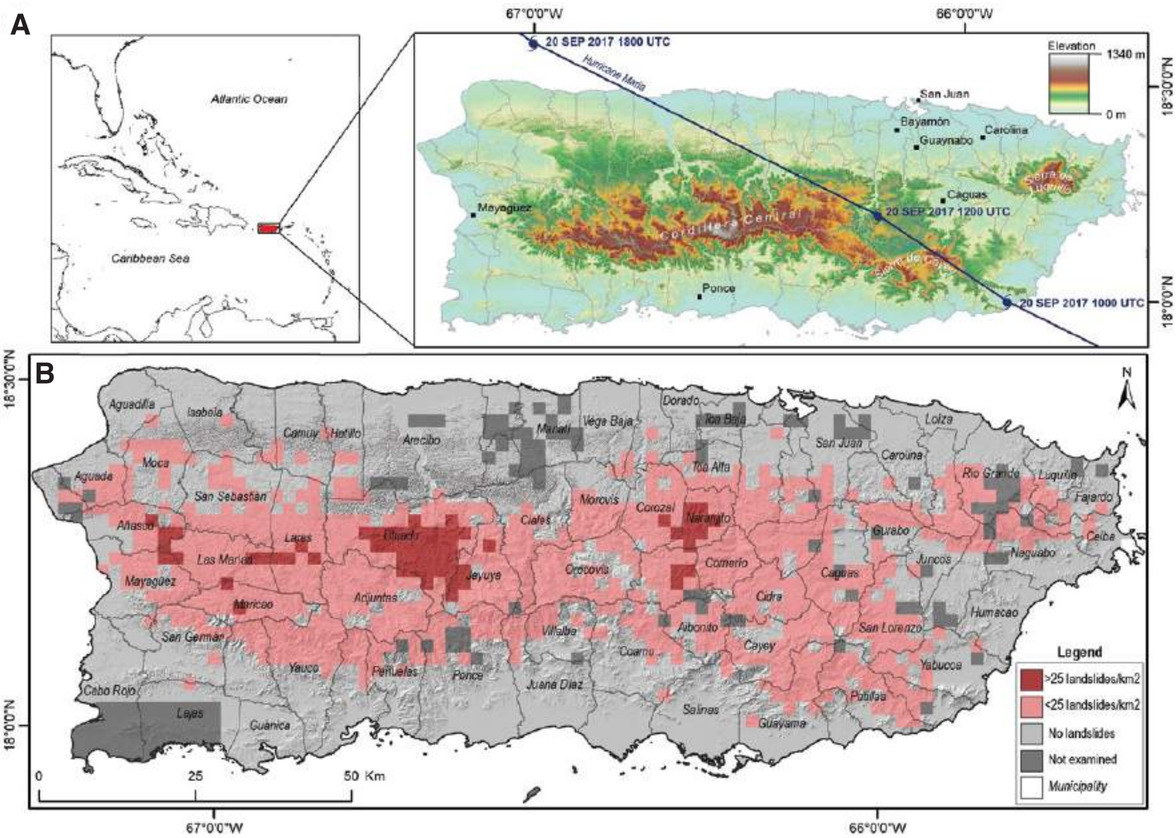

Figure 1. (A) Topographic map of Puerto Rico showing the storm track of Hurricane Maria. (B) Relative density of landslides mapped from the rapid classification of satellite and aerial imagery and site visits following Hurricane Maria (updated from Bessette-Kirton et al., 2017).

1340 m (U.S. Geological Survey, 2017c; Fig. 1A). Broad lowlands and coastal plains ring most of the island. Present-day tectonic uplift resulting from the convergence of the North American and Caribbean plates is one of the main drivers of the rugged topography that is expressed across much of the island (Taggart and Joyce, 1991; Brocard et al., 2015, 2016). The average annual rainfall varies dramatically across micro-climate zones, with the highest annual rainfall usually reported around the Sierra de Luquillo (Fig. 1A) in the northeastern part of the island (Ravalo et al., 1986; Daly et al., 2003). High rainfall, temperature, and humidity contribute to widespread saprolite formation (Murphy et al., 2012).

Puerto Rico is part of an extinct volcanic island arc that lies along the North America–Caribbean plate boundary and is underlain by a faulted basement assemblage of Upper Jurassic ocean crustal fragments and Cretaceous to Eocene volcaniclastic and intrusive units (Jolly et al., 1998). This arc complex is unconformably overlain by a cover sequence of Oligocene–Pliocene carbonates and associated siliciclastic deposits (Monroe, 1976; Ortega-Ariza et al., 2015).

HURRICANE MARIA

Hurricane Maria made landfall along the southeast coast of Puerto Rico as a Category 4 hurricane at 6:15 a.m. local time (Atlantic Standard Time [AST]) on 20 September 2017 (Pasch et al., 2018) and moved across Puerto Rico with a west-northwest trajectory (Fig. 1A). Rainfall data from Hurricane Maria vary both in absolute magnitude and spatial distribution. Estimates of average island-wide rainfall from the National Hurricane Center (NHC; Pasch et al., 2018), the National Centers for Environmental Prediction (NCEP; National Weather Service, 2018), and the PERSIANN-Cloud Classification System (CCS; Center for Hydrometeorology and Remote Sensing, 2018) range from 280 to 543 mm, while maximum rainfall values range from 353 to 1431 mm (see [A] in the GSA Data Repository[1] for a summary of rainfall data). Doppler estimates are not available due to the destruction of radar during the storm (National Weather Service, 2017b). Although rainfall estimates from Hurricane Maria vary, multiple data sets indicate that at least 250 mm of rain fell across Puerto Rico's mountainous terrain, much of which had received 254–381 mm of rainfall from Hurricane Irma two weeks prior to Maria (5–7 September 2017; Cangialosi et al., 2018).

LANDSLIDE DISTRIBUTION AND CHARACTERISTICS

To rapidly assess the areas that were most severely impacted by landslides, we used post-hurricane satellite (DigitalGlobe Inc.) and aerial imagery (Sanborn and Quantum Spatial; Vexcel Imaging, 2017) collected between 26 September and 8 October 2017 to map landslide density. A few of the landslides that we mapped

[1] GSA Data Repository item 2019079, (A) summaries of published rainfall and soil moisture data from Hurricane Maria and (B) database of past hurricanes and tropical storms in Puerto Rico with landslide occurrences described when applicable, is available online at www.geosociety.org/datarepository/2019.

may have occurred during Hurricane Irma, but an absence of imagery during the interim precluded us from differentiating between landslides that occurred during each hurricane. We divided the island into a 2 km × 2 km grid and classified each grid cell as either having no landslides (NLS), 1–25 landslides/km^2 (low landslide density, LLD) or more than 25 landslides/km^2 (high landslide density, HLD). With the intent of rapidly preparing a product to aid emergency response agencies, we visually examined each grid, but did not map individual landslides. Landslide scars were readily visible in imagery because of defoliation from strong winds during Hurricane Maria, and because of the sharp color contrast between exposed soil and rock and the remaining vegetation (Fig. S1 [see footnote 1]). See Bessette-Kirton et al. (2017) for further description of the mapping procedure. We validated and updated our preliminary density map (Bessette-Kirton et al., 2017) by helicopter and on the ground, covering a distance of 1950 km between 26 October and 6 November 2017.

From our mapping, we estimated that more than 40,000 landslides resulted from Hurricane Maria. Landslides occurred in at least 59 of Puerto Rico's 78 municipalities (Fig. 1B). Many of the other 19 municipalities have such low relief that landsliding is unlikely. Five HLD clusters, ranging in size from 12 to 132 km^2, occurred in the north-central and northwestern reaches of the Cordillera Central. Landsliding in the municipalities of Utuado and Naranjito was particularly severe, with ~38% and 45% of each municipality, respectively, classified as having HLD. All five HLD clusters were located ~10–20 km north of the Cordillera Central divide (Fig. 1). Areas along the southern flank of the Cordillera Central, which have some of the highest relief and steepest slopes on the island, generally had lower landslide densities.

During field work, we observed a variety of landslide failure modes and material types and properties. Most landslides were shallow, translational failures in soil or saprolite, generally measuring decimeters to a few meters deep (e.g., Fig. S1A [see footnote 1]). We also observed deeper (up to ~30 m) complex failures (e.g., Fig. S1B) in soil, saprolite, and rock, and rock falls and rock slides. Many landslides transitioned into debris flows (e.g., Figs. S1C and S1D), and coalescence and subsequent channelization of debris flows (e.g., Fig. S1D) was common. Landslides that partly reactivated preexisting landslides were also common. Crosscutting relationships between debris flow and flood deposits indicated that landsliding occurred before, during, and after extreme flooding (e.g., Fig. S1C). Landslides continued to occur during storms in the days and weeks following Maria.

ASSESSMENT OF CONTRIBUTING FACTORS

Our evaluation of landslide distribution shows that while landslides occurred throughout most of Puerto Rico's mountainous interior, landsliding was particularly severe in five distinct areas (Fig. 1B). We examined rainfall, soil moisture, and geology in NLS, LLD, and HLD areas as a first-order attempt to understand the differences between severely impacted areas and neighboring areas in which landslides were less spatially dense.

Elevated pore-water pressure from rainfall is the most common trigger for landslides (Terzaghi, 1950). Because subsurface-water pressure is not commonly measured, rainfall is often used as a proxy. During Hurricane Maria, rainfall amounts reported by the NHC and NCEP data sets for NLS areas were 7%–12% less than the average island-wide rainfall (Fig. 2). The average island-wide rainfall reported by the PERSIANN-CCS data set was about equal to rainfall in NLS areas (Fig. 2). All three data sets showed that rainfall in LLD and HLD areas was greater than average (4%–19% increase; Fig. 2), but differences in the spatial distribution of rainfall resulted in inconclusive differences between LLD and HLD areas.

Variability between rainfall data sets calls into question the validity of using island-wide rainfall estimates for localized

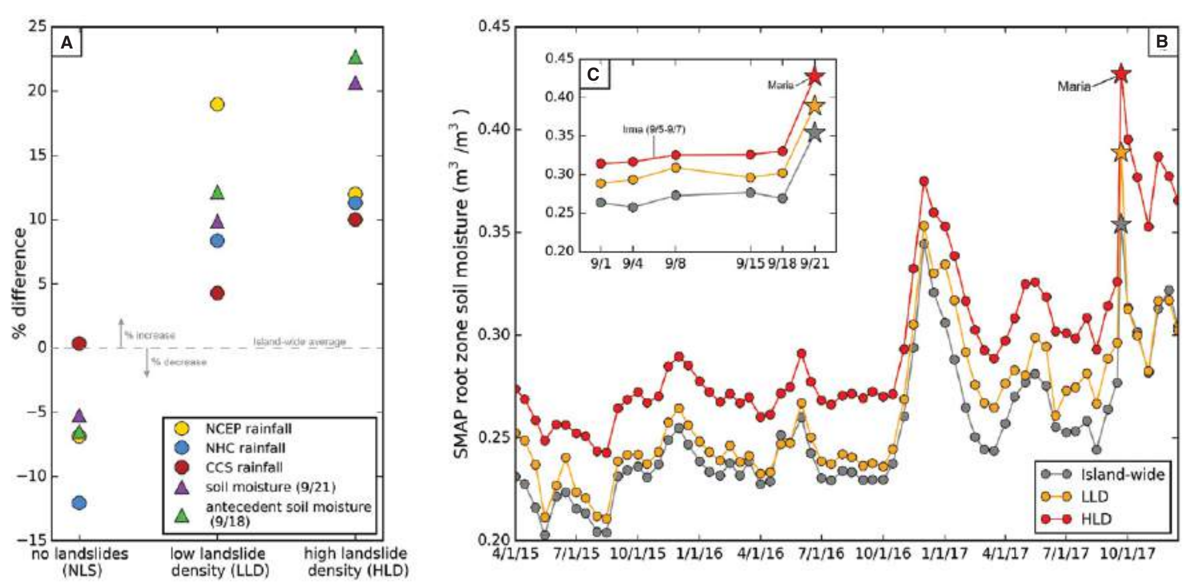

Figure 2. (A) Deviation from average island-wide rainfall and soil moisture in areas with no, low, and high landslide densities. (B) Soil Moisture Active Passive (SMAP) root zone soil moisture (Reichle et al., 2018) measurements from April 2015–December 2017 (Hurricane Maria shown with stars). (C) Antecedent SMAP root zone soil moisture measurements during the two weeks preceding Hurricane Maria, including the passage of Hurricane Irma. SMAP data were averaged across the entire island and in areas with low landslide density (LLD) and high landslide density (HLD). CCS—PERSIANN-Cloud Classification System; NCEP—National Centers for Environmental Prediction; NHC—National Hurricane Center.

areas (Fig. S2 [see footnote 1]). Collecting accurate rainfall data during hurricanes is intrinsically difficult due to high winds and the inability to measure sideways rainfall. During Hurricane Maria, these complications were compounded by damage to rain gages (at least 14 of the U.S. Geological Survey's 24 gaging stations; U.S. Geological Survey, 2017b) and the failure of two Federal Aviation Administration Doppler radars (Buchanan, 2017; National Weather Service, 2017b). Additionally, localized effects, such as orographically enhanced rainfall, may have produced pockets of heavy rain that were not accurately represented by any of the existing data sets.

Soil moisture is a better proxy for pore-water pressure than rainfall because it is a subsurface hydrologic response variable. We found that soil moisture measurements from NASA's Soil Moisture Active Passive (SMAP) mission (see [A] in the GSA Data Repository [see footnote 1]) differentiated between LLD and HLD areas more effectively than did rainfall data. We compared landslide density to SMAP's 9 km × 9 km gridded global estimates of root zone (0–100 cm) volumetric water content before (9:30 a.m. AST on 18 September 2017) and after (9:30 p.m. AST on 21 September 2017) Hurricane Maria (Reichle et al., 2018; Fig S3 [see footnote 1]). These estimates rely on remotely sensed measurements of brightness temperatures and the solution of a water and energy balance (see [A] in the GSA Data Repository for details [see footnote 1]). Both antecedent and post-event root zone SMAP measurements showed that soil moisture was 10%–23% greater than the island-wide average in areas where landslides occurred (LLD and HLD areas) and 5%–7% less than the island-wide average in NLS areas (Fig. 2A). Additionally, the difference in deviation from the mean between LLD and HLD areas for antecedent and post-event root zone soil moisture measurements (11%) was nearly twice as large as the spread between LLD and HLD areas for rainfall (3%–6% increase and 7% decrease).

SMAP measurements from the two years prior to Hurricane Maria (Fig. 2B) show that soil moisture across Puerto Rico immediately before Maria (18 September 2017) was 10% above the average island-wide soil moisture during the period of record (April 2015–December 2017). Additionally, the antecedent soil moisture in LLD and HLD areas was 13% and 11% above average, respectively. SMAP data showed that prior to the passage of Hurricane Irma, the average island-wide soil moisture was already higher than normal, and rainfall from Irma only caused a slight increase in island-wide soil moisture (Fig. 2C). The increase in soil moisture caused by heavy rainfall during Hurricane Maria was unprecedented (41%–48% above average) during the time period for which SMAP data are available. However, increased antecedent soil moisture prior to Hurricane Maria evidently influenced the susceptibility to landsliding in LLD and HLD areas. This finding, along with the physical relation between increased pore-water pressure and decreased effective material strength (Terzaghi, 1950), may make soil moisture a useful tool for estimating differential susceptibility to landsliding prior to future storms with predicted heavy and widespread rainfall. Although the resolution of soil moisture data is coarse (9 km × 9 km), and the data for Puerto Rico are primarily derived from a land-surface model without local calibration, our preliminary assessments indicate that SMAP data could be a useful component of landslide forecasting across widespread areas prior to future hurricanes.

An examination of mapped rock formations in mountainous areas indicated that geologic material did not consistently correlate with landslide density. Twelve of the island's 145 rock formations (Bawiec, 1998) had >10% HLD by area. Landslides were observed nearly everywhere in half of these 12 formations and had HLD classification in ≥11% of their areas. In contrast, the other six formations had HLD in ≥14% of their areas but also had no observed landslides in ≥11% of their areas. Similar variability is also apparent when grouping geologic formations by terrane (Fig. S4 [see footnote 1]). For example, the intrusive igneous rock terrane had the two formations with the highest proportion of HLD area, both of which also had landslides across nearly their entire areas (granodiorite-quartz diorite of the Utuado batholith [Ku] and hornblende quartz diorite porphyry [Thp]; Fig. 3). However, two similar formations both lacked landslides and had large areas of high density landslides (diorite [TKdi] and rhyodacite porphyry [Trhp]; Fig. 3). Finally, the San Lorenzo Formation granodiorite (Ksl) had no HLD areas and lacked landslides in 53% of its area, yet the formation is essentially equivalent to the Ku granodiorite (Bawiec, 1998), which displayed the greatest areal percentage of HLD (63%).

To the extent of the resolution of our data, these variations in landslide density cannot be attributed to differences in rainfall or slope. Instead, it appears that relations between geologic formation and landslide density were largely due to soil moisture variability. For example, Ksl occurs in the eastern quarter of the island where soil moisture was relatively low (0.25–0.26 m^3/m^3), whereas Ku occurs where soil moisture was relatively high (Fig. S5 [see footnote 1]). Individual formations with large HLD areas (Fig. 3) also reveal trends between landsliding and soil moisture (Fig. S5) when considering formations that cover large areas of Puerto Rico (necessitated by the gross resolution of SMAP data). The three formations that are most widespread from east to west (basaltic breccia and basalt lava [Kln], hornblende quartz diorite porphyry [Thp], and diorite [TKdi]; spanning east-west distances of ~60, 70, and 160 km, respectively) display strong positive correlations between soil moisture and landslide density (Fig. S5). We conclude that landslide densities were not strongly controlled by variable susceptibility to landsliding among the geologic formations, but by variable soil moisture.

Although we have identified spatially averaged correlations between landslide density and soil moisture, the resolution of our island-wide data sets and our method of grid analysis do not allow for differentiation of contributing factors at a scale sufficient for detailed analyses. For example, our analysis of island-wide geology (1:100,000 scale) does not account for localized variations in geologic units that may affect rock weathering rates and soil formation, and therefore landslide susceptibility. The resolution of our 2 km × 2 km grid framework is compatible with island-wide rainfall and soil moisture data sets but is likely less useful for comparison with higher resolution data sets (<4 km^2). While our rapidly produced landslide density map allowed for the analysis of contributing factors on a regional scale, a detailed inventory would be invaluable for more localized assessments of landslide susceptibility.

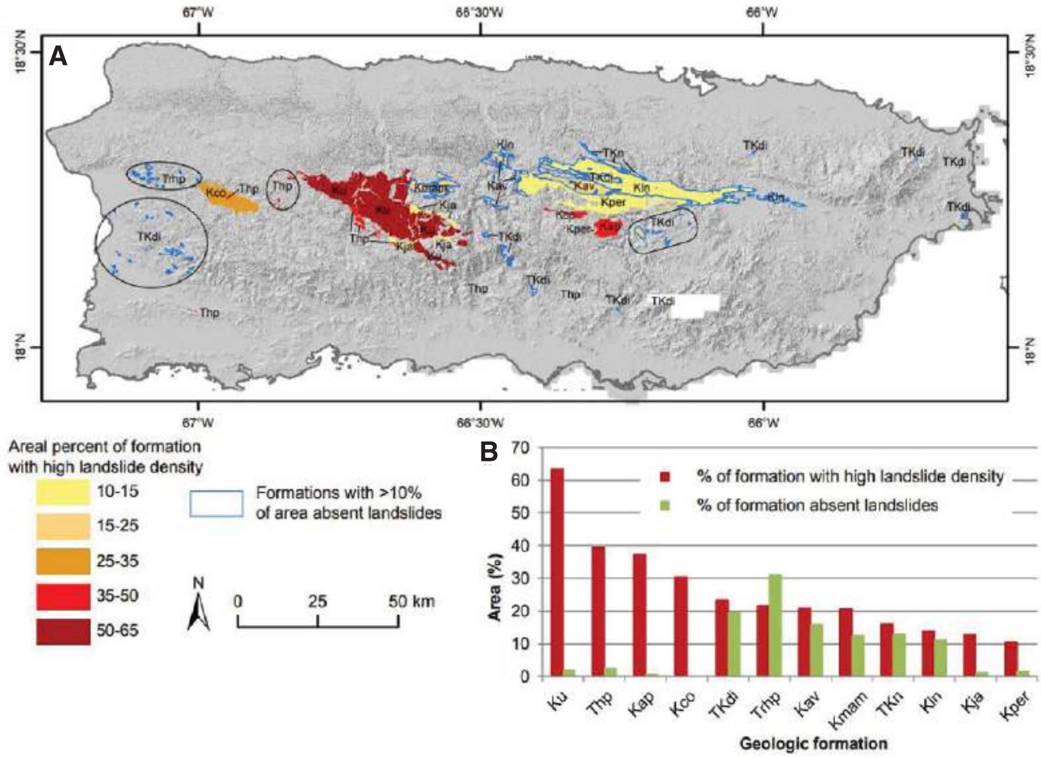

Figure 3. Landslide density distributions and geologic formations. (A) Map showing geologic formations with >10% by area high landslide density and with >10% by area absent landslides. (B) Chart showing formations with >10% by area with high landslide density. Ku—granodiorite; Thp—hornblende quartz diorite; Kap—basalt lava and tuffaceous sandstone; Kco—basaltic lava and volcanic breccia; TKdi—diorite; Trhp—rhyodacite porphyry; Kav—andesitic lava; Kmam—andesite lava and volcanic sandstone and siltstone; TKn—crystal tuff and tuffaceous clastics; Kln—basaltic breccia and basalt lava; Kja—amphibolite; Kper—basalt lava and tuff, volcanic sandstone (Bawiec, 1998).

COMPARISON WITH PAST EVENTS

To place Hurricane Maria in the context of previous landslide-generating TCs, we compiled rainfall data and information on the extent and characteristics of landslides from 72 TCs that affected Puerto Rico between 1960 and 2017 (see [B] in the GSA Data Repository [see footnote 1]). Based on this information, we classified the extent of landsliding as either none, isolated, frequent, or widespread for each TC (Table S2 [see footnote 1]; see Table 1 for classification criteria). In addition to reporting maximum rainfall (Fig. 4A), we calculated the average rainfall in mountainous terrain (mean mountain rainfall [MMR], Fig. 4B) for 56 TCs for which data were available. We used contoured rainfall maps (National Centers for Environmental Prediction, 2018) to extract the average rainfall in areas with slopes >20° for each historical TC to compare with all three rainfall data sets from Hurricane Maria. On average, Hurricane Maria produced more rain than any other TC to affect Puerto Rico in the 58-year record (Fig. 4). Our calculated MMR values for Hurricane Maria range from 287 to 579 mm, and although these values vary by as much as a factor of two, even the minimum is nearly twice as large as the median MMR for all previous widespread landsliding events (152 mm).

Although TC-triggered widespread landsliding occurs frequently in Puerto Rico, the number and spatial extent of landslides triggered by Hurricane Maria were unprecedented in comparison to previously documented events. For example, Hurricane Hugo (1989) and the precursor to Tropical Storm Isabel (1985) both produced large amounts of rain but only triggered landslides that were confined to localized areas (Jibson, 1989; Larsen and Torres-Sanchez, 1992). Other TC-triggered landslide events have not been documented systematically, and typically refer to "numerous" landslides in one or more municipalities or regions of Puerto Rico (Table S2 [see footnote 1]). Based on our island-wide landslide density map (Fig. 1B), we estimate that the number of landslides triggered by Hurricane Maria (at least 40,000) was approximately two orders of magnitude greater than the hundreds of landslides reported from previous detailed inventories.

CONCLUSIONS

Although landsliding is frequent on steep hillslopes in Puerto Rico, the abundance and widespread extent of landslides that occurred during Hurricane Maria were unprecedented in comparison to previously recorded hurricane or tropical storm-triggered landsliding events. Hurricane Maria provided a unique data set to examine the characteristics and contributing factors of landslides with variable failure types and material properties as a means of improving future hazard assessments throughout Puerto Rico.

While we have shown that the average rainfall from Hurricane Maria in mountainous areas was greater than that of any other hurricane or tropical storm in Puerto Rico since 1960, we also found that inconsistencies among rainfall data sets and the coarse resolution of available data did not allow for a meaningful assessment of the correlation between rainfall amount and landslide distribution. Satellite-based SMAP measurements from both before and after Hurricane Maria showed larger differences between low and high landslide density areas, indicating that, unsurprisingly, soil moisture

TABLE 1. CRITERIA USED TO CLASSIFY THE OCCURRENCE OF LANDSLIDES DURING 72 HURRICANES AND TROPICAL STORM SYSTEMS THAT IMPACTED PUERTO RICO BETWEEN 1960 AND 2017

Landslide Classification	Classification Criteria
None	No landslides reported in available sources.
Isolated	Fewer than 10 landslides reported.
Frequent	More than 10 landslides reported; reports are generally localized. This category includes events reported in Larsen and Simon (1993) and Pando et al. (2005), which classify all reported landslide events as "moderate to extensive" with "tens to hundreds of landslides" if the event is not documented in any other source.
Widespread	Hundreds of landslides reported; landslides reported in many municipalities or large regions. This category includes any event that the Federal Emergency Management Agency declared as a major disaster or emergency because of landslides (Federal Emergency Management Agency, 2018).

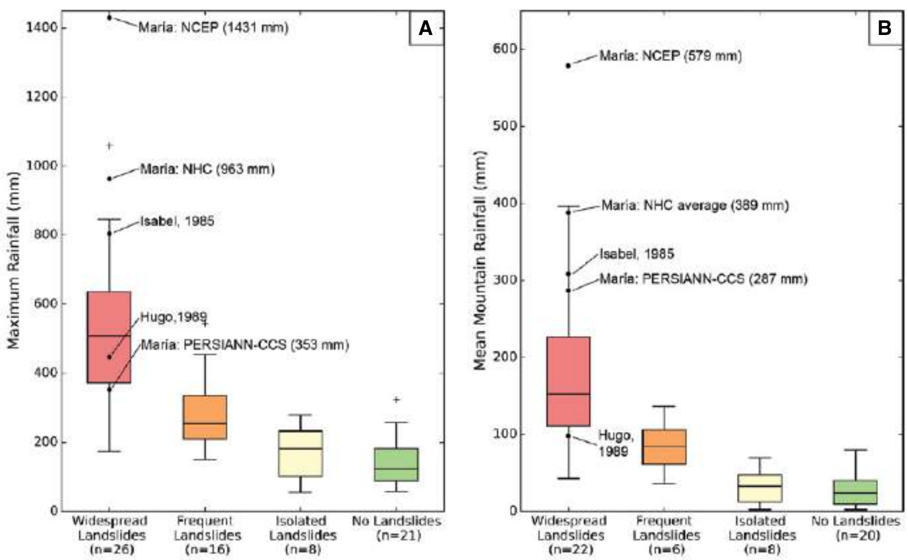

Figure 4. Distribution of (A) maximum rainfall and (B) mean mountain rainfall for widespread, frequent, isolated, and no landslide-triggering hurricanes and tropical cyclones that affected Puerto Rico between 1960 and 2017 (see [B] in the GSA Data Repository [see text footnote 1]). Rainfall data for Hurricane Maria are from the National Hurricane Center (NHC), National Centers for Environmental Prediction (NCEP), and the PERSIANN-Cloud Classification System (CCS). See (A) in the GSA Data Repository (see text footnote 1) for detailed information on rainfall data sets.

was an important factor in landslide susceptibility. Additionally, above-average antecedent soil moisture levels may have contributed to unprecedented widespread landsliding throughout mountainous areas of Puerto Rico, demonstrating that SMAP data could be used in the future to assess landslide susceptibility prior to hurricanes and tropical storms. We did not observe variable inherent susceptibility to landsliding for geologic bedrock units. Inconsistent correlations between landsliding and underlying bedrock formations likely resulted from differences in soil moisture. While a detailed landslide inventory is necessary for the analysis of localized landslide susceptibility, the rapid quantification of landslide density proved to be advantageous for systematically assessing the impact of widespread landsliding during an extreme precipitation event.

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GSA 2019
22–25 September
Phoenix, Arizona, USA

Important Dates

25 June	**Abstracts deadline**
Early July	Student volunteer program opens
19 August	Early registration deadline
19 August	GSA Sections travel grants deadline
26 August	Registration and student volunteer cancellation deadline
28 August	Housing deadline for discounted hotel rates

Registration

Register today for best pricing!

community.geosociety.org/gsa2019/attend/registration

Deadline: 11:59 p.m. MDT, 19 Aug.

Cancellation deadline: 11:59 p.m. MDT, 26 Aug.

Student Volunteers

Please wait to register for the meeting until you sign up as a volunteer, unless you want to reserve a space in a Field Trip or Short Course. Sign-up will open in early July. Details are online at **community .geosociety.org/attend/registration/volunteers.**

Meet With Us on Social Media

(follow hashtag #GSA2019)

- **twitter.com/geosociety**
- **instagram.com/geosociety**
- **facebook.com/GSA.1888**
- **community.geosociety.org**

Travel & Transportation

Photo © Visit Phoenix/Jill Richards.

There are several ways to navigate the city, including public transportation and transportation services such as taxis, rental cars, charter services, Uber, Lyft, and zTrip.

Phoenix Sky Harbor International Airport (PHX)

Sky Harbor, dubbed "America's Friendliest Airport," is the main airport for the Greater Phoenix area. Sky Harbor serves more than 100 domestic and international destinations, with 1,200 daily flights. The airport is located in the middle of Greater Phoenix, less than ten minutes from downtown.

Phoenix Light Rail

- Need to get from the airport to your downtown hotel? It will cost you US$2 if you take Phoenix's Valley Metro light-rail system (an all-day pass is US$4).
- Getting from the airport to downtown affordably is just one of the light rail's perks. The 26-mile line links Phoenix to the neighboring communities of Tempe and Mesa, and includes stops at attractions such as the Phoenix Art Museum, the Heard Museum, Chase Field, Talking Stick Resort Arena, and Tempe's Mill Avenue District.
- The light rail's quiet, air-conditioned trains run 18–22 hours per day, seven days a week, and stop every 12–20 minutes.
- There are 35 stations along the line, and they are adorned with US$8 million worth of public art. The artwork at each station reflects the character of the community where it is located.
- Convenient transportation to the airport comes by way of PHX Sky Train. This driverless people mover transports Valley Metro light-rail passengers to the airport from the 44th Street/ Washington Street station.

Phoenix Transit Bus

For citywide and regional route information and schedules, call +1-602-253-5000 or go to **ValleyMetro.org.** You can also use NextRide for bus arrival times. Phone +1-602-253-5000, say "next ride," and then say or enter the bus stop number. Or text 64274 and enter NXRD and the bus stop number. You'll receive a text message with the arrival time of the next bus.

Phoenix Dial-A-Ride

This service is available seven days a week for people with disabilities. Hours: 5 a.m.–10 p.m. To reserve your ride, call +1-602-253-5000. For more info, visit **ValleyMetro.org/accessibility.**

TRAVEL GRANTS

You still have time to apply for grants. Various groups are offering grants to help defray your costs for registration, field trips, travel, etc., at the GSA Annual Meeting. Check out the meeting website for application and deadline information. Note: Eligibility criteria and deadline dates may vary by grant. The deadline to apply for the GSA Student Travel Grant is 19 Aug.

Learn more at **community.geosociety.org/gsa2019/ attend/registration.**

"It was my first meeting, but I was highly impressed and the organization was excellent. All my expectations were surpassed."

—Feedback from GSA 2018 Indy

Childcare by KiddieCorp

Location: Phoenix Convention Center

Hours: Sun.–Wed., 7 a.m.–6 p.m. daily

Ages: Six months to 12 years

Cost: US$10 per hour per child for children two years or older and US$12 per hour per child for children under two with a one-hour minimum per child. At least one parent must be registered for the meeting. This is a discounted rate; GSA subsidizes 85% of the total cost for this service to attendees.

Late pick-up fee: US$5 per child for every five minutes the parent is late.

More info: www.kiddiecorp.com/parents-guide/

Register securely at https://form.jotform.com/KiddieCorp/gsakids

Reserve childcare in advance: To ensure that the center is properly staffed and to facilitate planning of games and other activities for the children, advance registration is required. On-site registration may be possible, at a slightly higher cost, if space is available. The deadline for advance childcare registration is **23 Aug.**

Cancellations: For a full refund, cancellations must be made to KiddieCorp prior to 23 Aug. Cancellations made after 23 Aug. will incur a 50% fee. No refunds after 4 Sept.

About: KiddieCorp is a nationally recognized company that provides onsite children's activities for a comfortable, safe, and happy experience for both kids and parents. Childcare services are a contractual agreement between each individual and the childcare company. GSA assumes no responsibility for the services rendered.

Contact: KiddieCorp
+1-858-455-1718
info@kiddiecorp.com

Hotels

Reservation deadline: 28 August

community.geosociety.org/gsa2019/attend/travel/hotels

GSA has negotiated special hotel rates for GSA 2019 attendees. We appreciate your support by staying in the official GSA hotels; your patronage enables GSA to secure the meeting space at a greatly reduced cost, which in turn helps lower the cost of the meeting and your registration fees.

Orchid.Events (OE) is GSA's only official housing company for this meeting. To be included in the GSA room block and receive GSA rates, you must make your reservation through OE. Reservations are taken on a first-come, first-served, space-available basis. We recommend that you make your reservation early for the best opportunity to get the hotel of your choice.

Reservation Options

Online: Start at **community.geosociety.org/gsa2019/attend/travel/hotels**

Phone: 7 a.m.–6 p.m. MST, Mon.–Fri.: +1-855-657-0547 (U.S. toll-free); +1-801-433-0661 (international)

Print: Download the form and fax (+1-801-355-0250; do not mail after faxing) or mail to Orchid.Events, 175 S. West Temple, Suite 30, Salt Lake City, UT 84101, USA

Critical Dates

19 Aug.: Last day to cancel rooms without a penalty

28 Aug.: Reservations must be received by this date in order to guarantee rooms at special meeting rates

12 Sept.: All changes, cancellations, and name substitutions must be finalized through OE

After 12 Sept.: You must contact the hotel directly with any changes or for new reservations

Roommates & Rides

Use the GSA Travel & Housing Bulletin Board at **community.geosociety.org/gsa2019/attend/travel/rooms-rides** to share housing, airport shuttles, and/or carpool. You can also use this service to make arrangements to meet up with your colleagues.

GSA 2019
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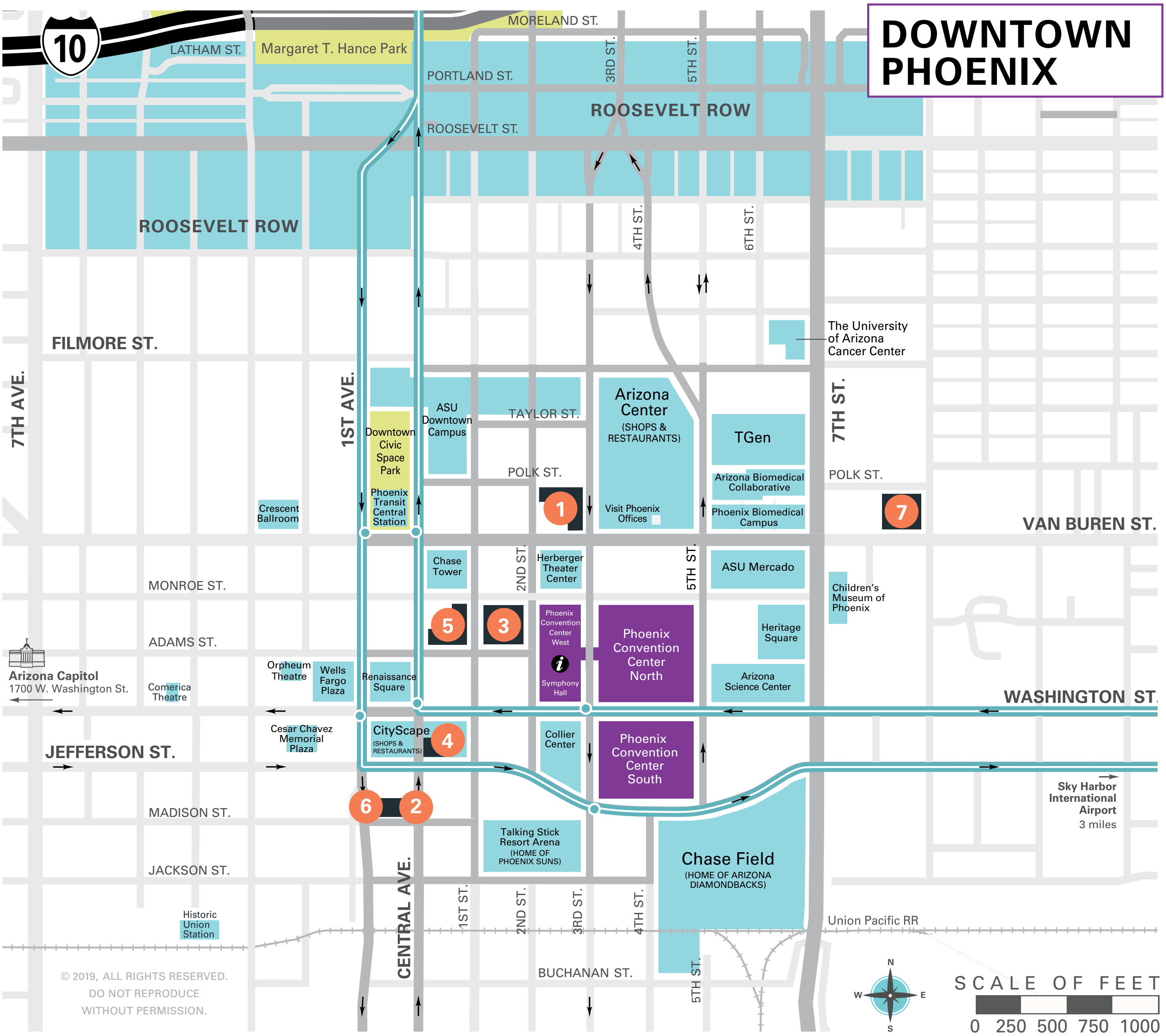
Hotel Rates

Hotel	Rate (Single/ Double)	Each Additional Adult (3rd & 4th Person)	Distance to PCC	Parking (24-hr)**
Sheraton Grand Phoenix (HQ Hotel)	US$199	US$20	1 block	Self US$25; Valet US$35
Courtyard by Marriott Downtown Phoenix	US$189	US$0	3 blocks	Valet US$33
Hyatt Regency Phoenix	US$199	US$20	across the street	Self US$23; Valet US$33
Kimpton Hotel Palomar Phoenix	US$179	US$20	3 blocks	Self US$25; Valet US$33
Renaissance Phoenix Downtown Hotel	US$199	US$20	1 block	Valet US$35
Residence Inn by Marriott Downtown Phoenix	US$209	US$10	3 blocks	Valet US$33
SpringHill Suites by Marriott Phoenix Downtown*	US$159	US$0	3 blocks	Complimentary

*Breakfast included in rate (check hotel website for specifics regarding breakfast menu)
**Parking rates subject to change; additional fees for oversized vehicles
PCC—Phoenix Convention Center
Note: Rates are in U.S. dollars and do not include the current applicable tax of 12.75%. Complimentary basic Internet will be provided in all guest rooms booked through GSA/OE.

VISITPHOENIX®

Downtown Phoenix Hotel Map



HOTELS		SINGLE/DOUBLE
1	Sheraton Grand Phoenix (HQ)	$199
2	Courtyard by Marriott Phoenix Downtown	$189
3	Hyatt Regency Phoenix	$199
4	Kimpton Hotel Palomar Phoenix	$179
5	Renaissance Phoenix Downtown Hotel	$199
6	Residence Inn by Marriott Phoenix Downtown	$209
7	Springhill Suites by Marriott Phoenix Downtown	$159

LEGEND

- LIGHT RAIL ROUTE
- LIGHT RAIL STATION
- VISITOR INFO CENTER
- CONVENTION CENTER
- POINT OF INTEREST
- HOTELS
- PARK

Submitting an Abstract

Abstract submission deadline: Tuesday, 25 June, 11:59 p.m. PDT
Submission fee: US$50 for professionals; US$25 for students
Begin at **community.geosociety.org/gsa2019/abstracts**
For detailed guidelines on preparing your submission, please view "preparing an online submission" at **https://gsa.confex.com/gsa/2019AM/categorypreparation.cgi.**

TWO-ABSTRACT RULE

- You may submit two volunteered abstracts, *as long as one of the abstracts is for a poster presentation*.
- Each submitted abstract must be different in content.
- If you are invited to submit an abstract in a Pardee Keynote Symposium or a topical session, the invited abstracts do not count against the two-abstract rule.

POSTER PRESENTERS

- You will be provided with one horizontal, free-standing 8-ft-wide by 4-ft-high display board and Velcro for hanging your display at no charge.
- Each poster booth will share a 6-ft-long by 30-inch-wide table.
- Electricity is available for a fee.
- Wi-Fi will be available in the poster hall area.
- Posters should be on display from 9 a.m. to 5:30 p.m. on Sunday, with authors present 3:30–5:30 p.m. On Monday through Wednesday, posters should be on display from 9 a.m. to 6:30 p.m., with authors present 4:30–6:30 p.m.
- Want to present your poster digitally? As a poster presenter, you will be given the opportunity to present your poster in a digital format. Information on this will be provided in the acceptance notices. Presenters are responsible for all fees associated with this type of presentation.

ORAL PRESENTERS

- The normal length of an oral presentation is 12 minutes plus three minutes for questions and answers.
- You *must* visit the Speaker Ready Room at least 24 hours before your scheduled presentation.
- All technical session rooms will be equipped with a PC running Windows 7/MS Office 2016.
- **Presentations should be prepared using a 16:9 screen ratio.**

ABSTRACTS SUBMISSION CODE OF ETHICS

Working together as a community of geoscientists, we will continue to advance the finest science in a respectable, professional manner. Authors will display integrity in disseminating their research. Presentations will adhere to the content and conclusions of abstracts, as submitted and reviewed. Listed co-authors will have made a bona fide contribution to the project. Conversely, the presenter should remain gracious by offering collaborators the opportunity for recognition as a co-author. All co-authors must be aware of their inclusion and have accepted that recognition. Presenters must be diligent in preparing a polished product that conveys high quality scholarship. Submission of an abstract implies a sincere intent to attend the meeting.

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Request an Annual Meeting Press Release

Each year, GSA works to highlight scientific presentations from the Annual Meeting that may be of wider interest beyond the GSA community. If you are presenting new research that you would like to share with science journalists and the audiences they write for, please let us know well in advance of the meeting. Submit a press release request at **https://bit.ly/2VAEvHr.**

"I just loved it so much!! This was my first GSA and I had such a blast! I learned so much and met so many great people, everything was very well organized!"
—Feedback from GSA 2018 Indy

Pardee Keynote Symposia

Joseph Thomas Pardee (1871–1960)

Pardee Keynote Symposia are named in honor of GSA Fellow and benefactor Joseph Thomas Pardee (1871–1960) via a bequest from Mary Pardee Kelly. Pardee is perhaps best known for his work on Glacial Lake Missoula. These symposia consist of invited presentations covering a broad range of topics.

P1. Digital Learning Innovation in the Geosciences

Cosponsors: *GSA Geoscience Education Division; American Geophysical Union; National Association of Geoscience Teachers; National Earth Science Teachers Association*
Discipline: Geoscience Education
Advocate: Ariel D. Anbar

New technologies for data visualization and discovery, and new education technologies, are transforming geoscience education, enabling active modes of discovery-based learning at scale. Interactive simulations, immersive and extended-reality environments, adaptive and personalized learning platforms, and digital tutoring are examples of technologies that enable rich, active learning experiences in and out of traditional classrooms. This symposium includes presentations, panel discussion, and a hands-on showcase to explore the state of the art and future frontiers.

P2. Grand Ideas, Grand Events: Geoscience Research, Geoscience Education, and Human Connections to Grand Canyon at its Six Millionth, 150th, and 100th Anniversaries

Cosponsors: *GSA History and Philosophy of Geology Division; National Association of Geoscience Teachers; GSA Geoscience Education Division*
Disciplines: History and Philosophy of Geology, Geoscience Education, Geoscience Information/Communication
Advocates: Steven Semken; Eleanour Snow; Karl E. Karlstrom; Laura J. Crossey

In commemoration of the concurrent 150th anniversary of John Wesley Powell's first expedition and the 100th anniversary of Grand Canyon National Park this year, this symposium presents historical and modern perspectives on understanding and sustaining the iconic geological landscapes of Grand Canyon that encode nearly two billion years of earth history. Presenters will highlight the importance of Grand Canyon to the indigenous people who have long inhabited it, the generations of geoscientists who explore and study it, the expert interpreters and educators who teach from it, and the millions who visit to experience and learn from this singular place.

P3. Geoscience Communication in the Modern Age

Cosponsors: *GSA Geology and Society Division; GSA History and Philosophy of Geology Division; National Association of Geoscience Teachers; GSA Geoscience Education Division*
Disciplines: Geoscience Information/Communication, Geoscience Education, Geoscience and Public Policy
Advocates: Iain Stewart; Callan Bentley; Mika McKinnon

Geoscience communication takes many forms, sharing information critical to society from scientist practitioners to decision makers and the public, as well as more creative interpretations by communicators seeking connection. This symposium celebrates excellence in several important domains of modern geoscience communication: popular writing (both fiction and nonfiction), visual art, photography, music, film, mainstream media, and social media, as well as research into effective science communication. We examine inspiring examples from accomplished communicators and gain insight into how best to help society enjoy a sustainable future on planet Earth (and beyond!).

P4. Fostering an Inclusive Academic Culture for the Twenty-First Century: Advancing Policies, Departments, and Supporting Faculty to Address the Needs and Challenges for Building a Healthy Geoscience Enterprise

Cosponsors: *GSA Geology and Society Division; American Geophysical Union; American Geosciences Institute*
Disciplines: Geoscience and Public Policy, Geoscience Education
Advocates: Pranoti M. Asher; Christopher Keane; Heather R. Houlton; Lexi Shultz

As society increasingly relies on geoscientists for resources and hazards mitigation, the profession must remain on the leading edge of innovation to solve complex challenges. Geoscience departments and academic leaders play a critical role in recruiting and training these future innovative geoscientists, as well as promoting an inclusive culture to support the academic enterprise that extends beyond our departments. Panelists who have championed non-traditional policies for faculty advancement, bolstered inclusive departmental cultures, and initiated practices that highlight the successes of their departments will discuss their strategies and how to overcome common challenges.

P5. Extreme Impacts of Global Climate Change: Effective Communication for Geoscientists, Educators, Policy Makers, and the Press

Cosponsors: *GSA Quaternary Geology and Geomorphology Division; GSA Energy Geology Division; GSA Environmental Engineering and Geology Division; GSA Geology and Health Division; GSA Geology and Society Division; GSA History and Philosophy of Geology Division; GSA Hydrogeology Division; International Union for Quaternary Research (INQUA)*
Disciplines: Geoscience Education, Geoscience Information/Communication, Geoscience and Public Policy
Advocates: Jennifer L. Pierce; George T. Stone

Fires, floods, and melting ice—can't we talk about something nice? Scientific data overwhelmingly demonstrate recent global temperature increases—due largely to combustion of fossil fuels—disrupt Earth's hydrologic, biologic, atmospheric, and geologic systems, thereby driving extreme impact events resulting in destruction of life and property. Despite this, effectively communicating the causes and risks of climate change and changing how people think about climate change remains a challenge. Why? In this interactive session, we combine up-to-date science on extreme events such as wildfires, hurricanes, sea-level rise, and arctic warming with compelling presentations on climate communication and education.

P6. Understanding the Neoproterozoic Earth-Life System

Disciplines: Paleontology, Paleoecology/Taphonomy, Geochemistry, Precambrian Geology
Advocates: Qing Tang; Huan Cui; Feifei Zhang

This session aims to boost discussion and interdisciplinary collaboration by bringing together a trans-disciplinary group of innovative thinkers to present advances on biological, geochemical, sedimentologic, and climatic evolution in the Neoproterozoic in order to better understand the Neoproterozoic Earth-life system.

Feed Your Brain—*Lunchtime Enlightenment*

Donald Siegel

Sunday, 22 Sept., noon–1:30 p.m.
GSA Presidential Address: Donald Siegel, "The Future of the Geosciences in the Twenty-First Century: A Speculation for Your Consideration."

Scott W. Tinker

Monday, 23 Sept., 12:15–1:15 p.m.
Scott W. Tinker, "Switch is Back! Energy Poverty, the Energy Transition, and Modern Energy Education."

Katharine Hayhoe
Photo credit Artie Limmer, Texas Tech Univ.

Tuesday, 24 Sept., 12:15–1:15 p.m.
Katharine Hayhoe, 2019 Michael T. Halbouty Distinguished Lecturer, "Climate Change: The Threat Multiplier."

Meghan Kish

Wednesday, 25 Sept., 12:15–1:15 p.m.
Meghan Kish, "Your Park. Your Science. Our Future: Inspiring Geoscience and Other STEM Careers Via Collaboration with the NPS."

Scientific Field Trips

Trip descriptions and leader bios are online at **community.geosociety.org/gsa2019/learn/field.**

2. **Pluton Construction in the Sierra Nevada Viewed Using the StraboSpot Field Data System.** Wed.–Sat., 18–21 Sept. US$278. **Cosponsors:** *GSA Structural Geology and Tectonics Division; GSA Mineralogy, Geochemistry, Petrology, and Volcanology Division*. **Leaders:** Allen F. Glazner, University of North Carolina; Basil Tikoff; John M. Bartley; Greg M. Stock; Drew S. Coleman.

3. **What Is the Age of the Mazatzal Orogeny? Evidence for Mesoproterozoic ca. 1.47–1.45 Ga Regional Deformation in the Type Area of the Mazatzal Orogeny.** Thurs.–Fri., 19–20 Sept. US$265. **Cosponsors:** *GSA Structural Geology and Tectonics Division; GSA Mineralogy, Geochemistry, Petrology, and Volcanology Division*. **Leader:** Michael F. Doe, MF Doe Geoscience LLC.

5. **Unraveling Volcanic and Related Processes Using Remotely Sensed Data Sets: Perspectives from a Miocene-Aged Volcanic Terrain in Northwest Arizona.** Thurs.–Sat., 19–21 Sept. US$448. **Cosponsor:** *GSA Planetary Geology Division*. **Leaders:** Nicholas P. Lang, Mercyhurst University; Susanne McDowell; Cole A. Nypaver; Briana D. Li-Vidal; Brandt M. Gibson.

6. **Volcanology and Associated Hazards of the San Francisco Volcanic Field.** Thurs.–Sat., 19–21 Sept. US$335. **Leaders:** Nancy Riggs, Northern Arizona University; Michael H. Ort; Charles Connor; Fabrizio Alfano; Michael Conway.

7. **Back to the Jurassic: Architecture of Eolian, Wadi, Microbialite, and Disturbed Facies, Carmel Formation and Navajo Sandstone, Kane County, Southwest Utah.** Wed.–Fri., 18–20 Sept. US$426. **Cosponsor:** *Pacific Section SEPM (Society for Sedimentary Geology)*. **Leaders:** Mario V. Caputo, San Diego State University; Thomas B. Anderson.

8. **Exploring Arizona Earth Fissures: An Anthropogenic Geologic Hazard.** Fri., 20 Sept. US$200. **Leaders:** Lorraine K. Carnes, Arizona State University; Joseph P. Cook.

9. **Classic Springs and Karst Systems of Northern Arizona.** Fri.–Sat., 20–21 Sept. US$235. **Cosponsors:** *GSA Hydrogeology Division; GSA Karst Division*. **Leaders:** Abraham E. Springer, Northern Arizona University; Benjamin W. Tobin.

10. **Journey to the Grand Canyon: A Geologic and Hydrologic Excursion across Arizona's Magnificent Heartland.** Fri.–Sat., 20–21 Sept. US$660. **Leaders:** Wayne Ranney; Marvin Frank Glotfelty.

12. **Middle Proterozoic Rocks of the McDowell Mountains, Arizona, USA—Journey into the Magmatic Gap.** Sat., 21 Sept. US$105. **Cosponsor:** *McDowell Sonoran Conservancy*. **Leader:** Steve Skotnicki.

13. **An Educator's Look at Phoenix-Area Geology.** Sat., 21 Sept. US$204. **Cosponsors:** *National Association of Geoscience Teachers (NAGT); NAGT Geo2YC Division; National Earth Science Teachers Association (NESTA)*. **Leaders:** Callan Bentley, North Virginia Community College; Merry Wilson, Scottsdale Community College; Carla McAuliffe; Aida Awad.

14. **Tectonic Development of the Colorado Plateau Transition Zone, Central Arizona: Insights from Lower Crustal and Mantle Xenoliths and Volcanic Host Rocks.** Sat., 21 Sept. US$240. **Cosponsors:** *GSA Geochronology Division; GSA Mineralogy, Geochemistry, Petrology, and Volcanology Division; GSA Structural Geology and Tectonics Division*. **Leaders:** Alan D. Chapman, Macalester College; Nancy Riggs; Mihai N. Ducea.

15. **The Co-Evolution of Verde Valley and the Verde River, Central Arizona.** Sat., 21 Sept. US$96. **Cosponsor:** *GSA Quaternary Geology and Geomorphology Division*. **Leaders:** Philip A. Pearthree; P. Kyle House; Kelin Whipple; Joseph P. Cook.

16. **Geoarchaeology of Prehistoric Agriculture, Soils, and Floodplain Dynamics on the Lower Salt and Middle Gila Rivers, Arizona.** Sat., 21 Sept. US$342. **Leaders:** Gary Huckleberry, University of Arizona; Kyle Woodson; Jonathan Sandor.

17. **Lava and Pyroclastic Flows of the Miocene Goldfield-Superstition Volcanic Province, Central Arizona.** Sat., 21 Sept. US$170. **Cosponsors:** *GSA Mineralogy, Geochemistry, Petrology, Volcanology Division; Arizona Geological Society; Cereris Resource Development (Ft. Worth, Texas)*. **Leaders:** R.V. Fodor, North Carolina State University; Michael T. Mohr; Brian A. Dombroski.

INDUSTRY TRACKS Look for these icons, which identify trips in the following areas:

Economic Geology | Engineering | Hydrogeology and Environmental Geology

18. **Dust on a Dangerous Highway: Exploring Linkages between Landscape and Dust Emissions along Interstate-10 near Casa Grande, Arizona.** Sat., 21 Sept. US$112. **Cosponsor:** *GSA Quaternary Geology and Geomorphology Division*. **Leaders:** Mark R. Sweeney, University of South Dakota; Eric V. McDonald, Desert Research Institute.

19. **Accessible Field Geology of Petrified Forest National Park.** Wed.–Thurs., 25–26 Sept. Apply at **https://theiagd.org/gsa-2019/.** **Cosponsors:** *The International Association for Geoscience Diversity; GSA Geoscience Education Division; GSA Diversity in the Geosciences Committee*. **Leaders:** Christopher L. Atchison, University of Cincinnati; William G. Parker; Nancy Riggs; Steven Semken; Steven Whitmeyer.

20. **Catalina-Rincon Metamorphic Core Complex, Tucson, Arizona.** Wed.–Fri., 25–27 Sept. US$385. **Leaders:** George H. Davis, University of Arizona; George E. Gehrels; Jon Spencer.

21. **A River is Born: Highlights of the Geologic Evolution of the Colorado River Extensional Corridor and its River: A Field Trip Honoring the Life and Legacy of Warren Hamilton.** Wed.–Sat., 25–28 Sept. US$488. **Cosponsors:** *GSA Quaternary Geology and Geomorphology Division; GSA Structural Geology and Tectonics Division*. **Leaders:** Keith A. Howard, U.S. Geological Survey; P. Kyle House; Philip A. Pearthree; Barbara E. John; Ryan S. Crow.

22. **Sonoran Desert Landforms via Mountain Biking.** Thurs., 26 Sept. US$250. **Leaders:** Ronald Dorn, Arizona State University; Ian Walker, Arizona State University; Steve Skotnick, Hydrosystems Inc.

23. **The 2010 Schultz Fire—Immediate, Ongoing, and Long-Term Geomorphic, Ecological, and Societal Impacts of a Small, High-Severity Wildfire.** Thurs.–Fri., 26–27 Sept. US$248. **Cosponsors:** *Grant Meyer; GSA Quaternary Geology and Geomorphology Division; Stephen Slaughter; GSA Environmental and Engineering Geology Division*. **Leaders:** Ann M. Youberg, University of Arizona; Luke McGuire.

24. **Geology and Paleontology of the Mid-Pleistocene El Golfo Badlands, Sonora, Mexico.** Thurs.–Fri., 26–27 Sept. US$340. **Leaders:** Fred W. Croxen, Arizona Western College; Christopher A. Shaw.

25. **The Rise and Fall of a Laramide Deposystem: Structural Inversion and Regional Drainage Reversal across the Plateau Transition Zone in Eastern Arizona.** Thurs.–Fri., 26–27 Sept. US$370. **Leader:** Andre R. Potochnik, Grand Canyon Conservancy.

26. **Exploring Superimposed Laramide Contraction, Porphyry Copper Systems, and Cenozoic Extension in the Globe-Superior-Ray–San Manuel Area, East-Central Arizona.** Thurs.–Sat., 26–28 Sept. US$595. **Cosponsor:** *GSA Mineralogy, Geochemistry, Petrology, and Volcanology Division; GSA Structural Geology and Tectonics Division*. **Leaders:** Mark D. Barton, University of Arizona; Eric Seedorff, University of Arizona; Daniel Favorito; Roy Greig; Carson A. Richardson.

27. **The "Holey" Tour: Ron Greeley's Introductory Planetary Geology Field Trip.** Thurs.–Sat., 26–28 Sept. US$475. **Cosponsors:** *GSA Planetary Geology Division; Arizona State University School of Earth and Space Exploration*. **Leaders:** David A. Williams, Arizona State University; Steven D. Kadel; R. Scott Harris.

28. **Mesozoic to Cenozoic Sedimentation, Tectonics, and Metallogeny of Sonora, Mexico.** Thurs.–Mon., 26–30 Sept. US$850. **Leaders:** Jason B. Price, California Institute of Technology; Thierry Calmus, Lucas Ochoa-Landin, Scott Bennett.

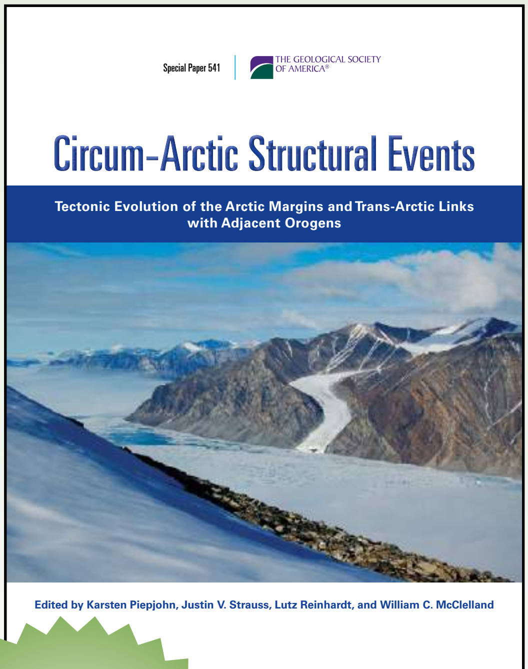
29. **Volcanic and Marine Stratigraphy along the El Alamo Canyon, Santa Rosalia Basin, Baja California.** Thurs.–Wed., 26 Sept.–2 Oct. US$1,250. **Cosponsor:** *Geophysics Institute, UNAM, Campi Morelia*. **Leader:** José Luis Macías, National Autonomous University of Mexico (UNAM).

30. **Walk in the Footsteps of the Apollo Astronauts.** Fri.–Sat., 27–28 Sept. US$265. **Cosponsors:** *USGS; Flagstaff Festival of Science; Flagstaff Lunar Legacy; Lowell Observatory*. **Leaders:** R. Greg Vaughan, Astrogeology Science Center; Kevin Schindler; Jeanne Stevens; Ian Hough.

32. **A Comparison of Two Caves in Southern Arizona: Colossal Cave and Kartchner Caverns.** Thurs., 26 Sept. US$90. **Cosponsors:** *Kartchner Caverns State Park; Colossal Cave Mountain Park*. **Leaders:** Sarah Truebe, University of Arizona; Lauren Hohl.

"I especially enjoyed the wide selection of field trips and the ancient Earth and planetary sessions."
—Feedback from GSA 2018 Indy

Explorations from *Aquifers to the Arctic*



SPECIAL PAPER 541

Circum-Arctic Structural Events: Tectonic Evolution of the Arctic Margins and Trans-Arctic Links with Adjacent Orogens

Edited by Karsten Piepjohn, Justin V. Strauss, Lutz Reinhardt, and William C. McClelland

The circum-Arctic region has received considerable attention over the past several decades with vigorous debate focused on topics such as mechanisms for opening the Eurasian and Amerasian basins, the importance of plume-related magmatism in the development of the Arctic Ocean, and mechanisms for ancient terrane translation along the Arctic margins. In recognition of the 25th anniversary of the Circum-Arctic Structural Events program, an international polar research effort organized and led by Germany's Bundesanstalt für Geowissenschaften und Rohstoffe, this volume presents results from 18 major field expeditions involving over 100 international geoscientists from a broad spectrum of disciplines, focusing on the Proterozoic to Cenozoic tectonic evolution of the circum-Arctic region with correlations to adjacent orogens.

SPE541, 686 p., ISBN 978-0-8137-2541-3
$120.00 | **member price $84.00**

New in the GSA Store

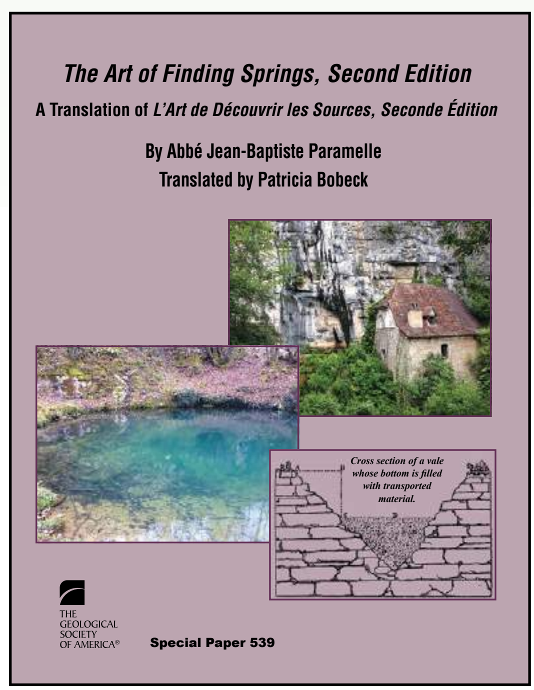
SPECIAL PAPER 539

The Art of Finding Springs, Second Edition: A Translation of *L'Art de Découvrir les Sources, Seconde Édition*

By Abbé Jean-Baptiste Paramelle; translated by Patricia Bobeck

Jean-Baptiste Paramelle (b. 1790) published *The Art of Finding Springs* in 1856 as a "how-to" manual—a compilation of observations and experiences gained during his career in water exploration. Between 1832 and 1853, Paramelle had found groundwater (his "springs") in more than 10,000 places in France; his observational method was a scientific advance over water-finding methods used earlier in the nineteenth century. The 32 chapters of this volume, carefully translated from its original French by Patricia Bobeck, include topics such as definitions of landforms, rock types, advice on how to observe geology and landforms in the field, discussion of the water cycle and spring formation, how to determine the depth and volume of groundwater, where to look and where not to look for groundwater, and more.

SPE539, 127 p., ISBN 978-0-8137-2539-0
$58.00 | **member price $40.00**



IN PRESS

Waterfall Gullfoss, Iceland, by Brennan T. Jordan.

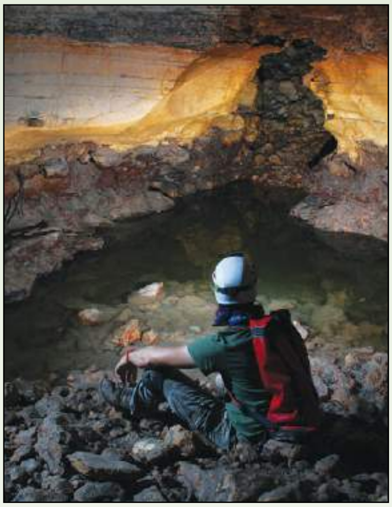
FIELD GUIDE 54

Iceland: The Formation and Evolution of a Young, Dynamic, Volcanic Island—A Field Trip Guide

By Brennan T. Jordan, Tamara L. Carley, and Tenley J. Banik

This field trip was created as a companion to the session "The Formation and Evolution of Iceland: Magmatic, Tectonic, and Geomorphological Processes," convened at the Geological Society of America 2019 Northeastern Section Meeting held in Portland, Maine, USA. This guide will be most valuable when used to supplement active exploration of the Icelandic countryside and its outcrops, and it is a useful resource for those seeking to learn more about Iceland's geology as seen in the field.

FLD054, ISBN 978-0-8137-0054-0



Seco Creek sinkhole, Edwards Aquifer, Texas, by Geary M. Schindel.

MEMOIR 215

The Edwards Aquifer: The Past, Present, and Future of a Vital Water Resource

Edited by John M. Sharp Jr., Ronald T. Green, and Geary M. Schindel

The Edwards is one of the great karstic aquifer systems of the world. It supplies water for more than 2 million people and for many agricultural, municipal, industrial, and recreational uses. Written by recognized experts of the Edwards, this memoir presents the current state of knowledge of the aquifer and addresses new and emerging challenges to its wise use. The volume also covers some of the new technologies that might be adopted to address current and future challenges.

MWR215, 27 chapters, ISBN 978-0-8137-1215-4

Monte San Vicino and the hamlet of Coldigioco, Italy, by Alessandro Montanari.

SPECIAL PAPER 542

PENROSE CONFERENCE VOLUME

250 Million Years of Earth History in Central Italy: Celebrating 25 Years of the Geological Observatory of Coldigioco

Edited by Christian Koeberl and David M. Bice

For more than 100 years, studies at the Umbria and Marche Apennines have led to new ideas and a better understanding of the past, such as the Cretaceous–Paleogene (K–Pg) boundary event, or the events across the Eocene–Oligocene transition from a greenhouse to an icehouse world. The Umbria-Marche Apennines are entirely made of marine sedimentary rocks, representing a continuous record of the geotectonic evolution of an epeiric sea from the Early Triassic to the Pleistocene. The book includes reviews and original research works accomplished with the support of the Geological Observatory of Coldigioco, an independent research and educational center, which was founded in an abandoned medieval hamlet near Apiro in 1992.

SPE542, 28 chapters, ISBN 978-0-8137-2542-0

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Cancellation deadline: 26 August

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GSA K–12 teacher members: You are welcome to take short courses without registering for the meeting or paying the nonregistrant fee.

Continuing Education Units (CEUs): Most professional development courses and workshops offer CEUs. One CEU comprises 10 hours of participation in an organized continuing education experience under responsible sponsorship, capable direction, and qualified instruction.

See **community.geosociety.org/gsa2019/learn/short** or contact Jennifer Nocerino, jnocerino@geosociety.org, for course abstracts and additional information.

The following short courses are open to everyone. Early registration is highly recommended to ensure that courses will run.

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501. **High Resolution Topography and 3D Imaging I: Introduction to Terrestrial Laser Scanning.** Fri., 20 Sept., 8 a.m.–5 p.m. US$52. Limit: 24. CEU: 0.8. **Instructor:** Chris Crosby, UNAVCO. **Cosponsor:** *UNAVCO.*

502. **Everything You Wanted to Know about Luminescence Geochronology—Mysteries of the "Illuminati" Revealed.** Fri., 20 Sept., 8 a.m.–5 p.m. US$150. Limit: 30. CEU: 0.8. **Instructors:** Ginni DeWitt, East Carolina University; Shannon Mahan, USGS (Denver); Michelle Nelson, Utah State University; and Tammy Rittenour, Utah State University. **Cosponsors:** *GSA Rocky Mountain Section; GSA Environmental and Engineering Geology Division; GSA Geoarchaeology Division; GSA Geochronology Division; GSA Quaternary Geology and Geomorphology Division.*

503. **3D Hydrogeological Modeling from Data to Model to Actual Use.** Fri., 20 Sept., 9 a.m.–4 p.m. US$114. Limit: 40. CEU: 0.6. **Instructor:** Tom Martlev Pallesen, I•GIS. **Cosponsor:** *I•GIS.*

504. **Field Safety Leadership.** Fri.–Sat., 20–21 Sept., 8 a.m.–5 p.m. US$25. Limit: 24. CEU: 1.6. **Instructors:** Greer Barriault, ExxonMobil; Kevin Bohacs, ExxonMobil (retired). **Cosponsor:** *ExxonMobil.*

505. **Geoheritage: Concepts and Methods for Sharing Earth's Legacy for Economic, Societal, and Scientific Advancement.** Fri., 20 Sept., 8 a.m.–5 p.m., and Sat. 21 Sept., 6:30 a.m.–4:30 p.m. US$150. Limit: 23. CEU: 1.7. **Instructors:** José Brilha, University of Braga, Portugal; Thomas Casadevall, U.S. Advisory Group for Geoheritage and Geoparks; Terri Cook, Down to Earth Writing and U.S. Advisory Group for Geoheritage and Geoparks. **Cosponsors:** *U.S. Geoheritage and Geoparks Advisory Group; Association of American State Geologists; Arizona Geological Survey; Geological Society of America; American Geosciences Institute; U.S. Geological Survey; National Park Service; National Association of Geoscience Teachers.*

506. **Introduction to Petroleum Structural Geology.** Fri.–Sat., 20–21 Sept., 8 a.m.–5 p.m. US$25. Limit: 30. CEU: 1.6. **Instructors:** J. Steve Davis, ExxonMobil Upstream Integrated Solutions Company; Kellen Gunderson, Chevron Energy Technology Company. **Cosponsors:** *ExxonMobil; Chevron Energy Technology Company; GSA Structural Geology and Tectonics Division; GSA Energy Geology Division; American Association of Petroleum Geologists Structural Geology and Geomechanics Division.*

507. **Structural and Stratigraphic Concepts Applied to Basin Exploration.** Fri.–Sat., 20–21 Sept., 8 a.m.–5 p.m. US$25. Limit: 30. CEU: 1.6. **Instructors:** Will Hoffman, ExxonMobil; Sarah Evans, ExxonMobil; Órla McLaughlin, ExxonMobil. **Cosponsors:** *ExxonMobil; GSA Sedimentary Geology Division.*

INDUSTRY TRACKS

GSA's short courses offer sessions relevant to applied geoscientists.
Look for these icons, which identify courses in the following areas:

Economic Geology | Energy | Engineering | Hydrogeology and Environmental Geology

508. **Sequence Stratigraphy for Graduate Students.** Fri.–Sat., 20–21 Sept., 8 a.m.–5 p.m. US$25. Limit: 55. CEU: 1.6. **Instructors:** Morgan Sullivan, Chevron; Bret Dixon; Independent Consultant; Casey Reid, ExxonMobil. **Cosponsors:** *ExxonMobil; Chevron.*

509. **Introduction to Drones (sUAS) in the Geosciences.** Sat., 21 Sept., 8 a.m.–5 p.m. US$120. Limit: 24. CEU: 0.8. **Instructor:** Greg Baker, University of Kansas. **Cosponsors:** *GSA Geoarchaeology Division; GSA Hydrogeology Division; GSA Quaternary Geology and Geomorphology Division; GeoAvatar LLC.*

510. **High Resolution Topography and 3D Imaging II: Introduction to Structure from Motion (SfM) Photogrammetry.** Sat., 21 Sept., 8 a.m.–5 p.m. US$52. Limit: 24. CEU: 0.8. **Instructors:** Chris Crosby, UNAVCO; Ramon Arrowsmith, Arizona State University. **Cosponsors:** *UNAVCO; OpenTopography.*

511. **An Introduction to Quantitative Topographic Analysis with the Topographic Analysis Kit (TAK) for TopoToolbox.** Sat., 21 Sept., 8 a.m.–5 p.m. US$83. Limit: 40. CEU: 0.8. **Instructors:** Adam Forte, Louisiana State University; Kelin Whipple, Arizona State University.

512. **Detrital Zircon Geochronology: Best Practices for U-Pb Data Acquisition, Reduction, Analysis, and Archiving.** Sat., 21 Sept., 8 a.m.–5 p.m. US$40. Limit: 40. CEU: 0.8. **Instructors:** George Gehrels, University of Arizona; Kurt Sundell, University of Arizona.

513. **Advances in Quantifying Sediment Budgets for River Systems.** Sat., 21 Sept., 8 a.m.–5 p.m. US$114. Limit: 25. CEU: 0.8. **Instructors:** Amy East, U.S. Geological Survey; Allen Gellis, U.S. Geological Survey; Andrew Ritchie, U.S. Geological Survey. **Cosponsor:** *GSA Quaternary Geology and Geomorphology Division.*

514. **Your Thesis is Software: Tools for the Geoscientist to Help Write Better Code, from Version Control to Test-Driven Development.** Sat., 21 Sept., 8 a.m.–5 p.m. US$30 students; US$120 professionals. Limit: 30. CEU: 0.8. **Instructor:** Simon Goring, University of Wisconsin–Madison. **Cosponsor:** *EarthRates RCN.*

515. **Forensic Geochemistry: Contaminant Sources/Release Ages and Aquifer Continuity in Soil/ Groundwater Systems using Stable Radiogenic Isotopes of Strontium (Sr) and Lead (Pb).** Sat., 21 Sept., 8 a.m.–5 p.m. US$130. Limit: 30. CEU: 0.8. **Instructor:** Richard Hurst, California Lutheran University.

516. **Ground-Penetrating Radar—Principles, Practice, and Processing.** Sat., 21 Sept., 8 a.m.–5 p.m. US$80. Limit: 24. CEU: 0.8. **Instructors:** Greg Johnston, Sensors & Software Inc.; Troy De Souza, Sensors & Software Inc. **Cosponsor:** *Sensors & Software Inc.*

517. **Interpretation of Natural Gases.** Sat., 21 Sept., 8 a.m.–5 p.m. US$250. Limit: 40. CEU: 0.8. **Instructor:** Alexei Milkov, Colorado School of Mines.

518. **Successfully Planning and Executing Your Limnogeology/Paleolimnology Project.** Sat., 21 Sept., 8 a.m.–5 p.m. US$30 students, US$50 professionals. Limit: 40. CEU: 0.8. **Instructors:** Amy Myrbo, University of Minnesota; Anders Noren, University of Minnesota; Kathleen Benison, West Virginia University; Lisa Park Boush, University of Connecticut; Michael Eliot Smith, Northern Arizona University; David Finkelstein, Hobart and William Smith Colleges; Simon Goring, University of Wisconsin Madison. **Cosponsors:** *GSA Limnogeology Division; GSA Continental Scientific Drilling Division; EarthRates RCN.*

519. **Preparing Undergraduates: Data-Rich Introductory Teaching Modules and Connecting Content to Geoscience Careers.** Sat., 21 Sept., 8 a.m.–5 p.m. US$20. Limit: 40. CEU: 0.8. **Instructors:** Beth Pratt-Sitaula, UNAVCO; Becca Walker, Mt. San Antonio College; Aisha Morris, National Science Foundation; Donna Charlevoix, UNAVCO. **Cosponsors:** *GEodesy Tools for Societal Issues (GETSI) project; Geo-Launchpad; GAGE Facility; UNAVCO; National Association of Geoscience Teachers.* Participating undergraduate instructors are eligible for a stipend after course completion—$220 for Phoenix-area residents; $520 for those from elsewhere. In addition to registering with GSA, APPLY for the stipend now at **https://serc.carleton.edu/getsi/workshops/gsa19/application.html.**

520. **Geostatistical Modeling of Geochemical Data.** Sat., 21 Sept., 8 a.m.–5 p.m. US$126. Limit: 40. CEU: 0.8. **Instructor:** Abani Samal, GeoGlobal LLC. **Cosponsor:** *American Institute of Professional Geologists.*

521. **Geological Mapping.** Sat., 21 Sept., 8 a.m.–5 p.m. US$114. Limit: 40. CEU: 0.8. **Instructor:** Harvey Thorleifson, Minnesota Geological Survey. **Cosponsor:** *Association of American State Geologists.*

522. **Using the StraboSpot Data System for Structural Geology.** Sat., 21 Sept., 8 a.m.–5 p.m. US$35. Limit: 40. CEU: 0.8. **Instructors:** Andreas Möller, University of Kansas; Emily Bunse, Illinois State Geologic Survey; Doug Walker, University of Kansas. **Cosponsors:** *GSA Geoinformatics Division; GSA Structural Geology and Tectonics Division.*

523. **Planetary Geologic Mapping for Students.** Sat., 21 Sept., 8 a.m.–5 p.m. US$114. Limit: 25. CEU: 0.8. **Instructors:** Jeannette Wolak, Tennessee Tech University; Kelsey Crane, University of Georgia. **Cosponsors:** *GSA Planetary Geology Division; U.S. Geological Survey Astrogeology Science Center.*

524. **Inclusive and Effective College Science Classrooms: Engaging Students, Designing Lessons, and Integrating Diversity into Curriculum.** Sat., 21 Sept., 8:30 a.m.–4:30 p.m. US$45. Limit: 50. CEU: 0.7. **Instructors:** Kimberly Tanner, San

Francisco State University; Jeff Schinske, Foothill College; Heather Macdonald, College of William & Mary. **Cosponsors:** *National Association of Geoscience Teachers (NAGT); Geo2YC Division of NAGT; GSA Geoscience Education Division; SAGE 2YC.*

525. **Student and Young Professionals Career Workshop.** Sat., 21 Sept., 9 a.m.–5 p.m. US$20. Limit: 100. CEU: 0.7. **Instructors:** Dawn Garcia, Celeritas Consulere; Bill Greenslade, Matrix New World Engineering. **Cosponsors:** *American Institute of Professional Geologists Arizona Section; Stantec Inc.*

526. **Teaching Quantitative Structural Geology.** Sat., 21 Sept., 9 a.m.–5 p.m. US$20 (a GSA bookstore voucher for US$20 will be given upon completion of the course). Limit: 30. CEU: 0.7. **Instructors:** David Pollard, Stanford University; Stephen Martel, University of Hawaii.

527. **Introduction to Planetary Image Analysis with ArcGIS.** Sat., 21 Sept., 9 a.m.–5 p.m. US$20 (a GSA bookstore voucher for US$20 will be given upon completion of the course). Limit: 30. CEU: 0.7. **Instructors:** Zoe Learner Ponterio, Cornell University Spacecraft Planetary Imaging Facility; David Nelson, Arizona State University Ronald Greeley Center for Planetary Studies. **Cosponsors:** *Cornell University Spacecraft Planetary Imaging Facility; Arizona State University Ronald Greeley Center for Planetary Studies.*

528. **Making Geoscience Animations and Videos and Assessing Them in the Classroom.** Sat., 21 Sept., 9 a.m.–5 p.m. US$155. Limit: 30. CEU: 0.5. **Instructors:** Robert Stern, University of Texas at Dallas; Jeffrey Ryan, University of South Florida; Ning Wang, University of Texas at Dallas; Siloa Willis, University of Texas at Dallas.

529. **Scientific Writing Skills for Geologists Whose Native Language is Not English.** Sat., 21 Sept., 8 a.m.–noon. US$107. Limit: 40. CEU: 0.4. **Instructor:** Patricia Bobeck, Geotechnical Translations.

530. **Thinking Scientifically in a Changing World.** Sat., 21 Sept., 1–5 p.m. US$40. Limit: 30. CEU: 0.4. **Instructor:** Doug Lombardi, University of Maryland. **Cosponsor:** *National Science Foundation.*

531. **Petroleum Systems Fundamentals.** Sat., 21 Sept., 1–5 p.m. US$25. Limit: 40. CEU: 0.4. **Instructors:** Keith Mahon, Chesapeake Energy; Zach Miller, Anadarko Petroleum. **Cosponsors:** *Chesapeake Energy; Anadarko Petroleum.*

Ticketed Events

The following events require tickets purchased in advance; please purchase your ticket when you register for GSA 2019. If you are *not* attending the GSA Annual Meeting & Exposition but would like to purchase a ticket to one of these events, please contact the GSA Meetings Department at meetings@geosociety.org.

Paleontological Society (PS) Business Meeting & Awards Reception Buffet
Sun., 22 Sept., 6:30–10:30 p.m. Professionals: US$TBD; students: US$TBD.

Student & Early Career Professionals Networking Reception
Sun., 22 Sept., 7–9:30 p.m. US$10 (increases to US$15 after 19 Aug.).

Association for Women Geoscientists (AWG) Awards & Networking Breakfast
Mon., 23 Sept., 6:30–8:30 a.m. Professionals: US$42; students: US$15*.

Geoscience Information Society (GSIS) Awards Luncheon
Mon., 23 Sept., noon–1:30 p.m. US$54.

National Association of Geoscience Teachers (NAGT), GSA Geoscience Education Division, and the Council for Undergraduate Research (CUR) Joint Awards Luncheon
Tues., 24 Sept., 11:30 a.m.–1 p.m. US$54.

GSA Hydrogeology Division Luncheon, Awards & Business Meeting
Tues., 24 Sept., 11:30 a.m.–2:30 p.m. US$54.

GSA History and Philosophy of Geology Division Luncheon & Awards Ceremony
Tues., 24 Sept., noon–1:30 p.m. Professionals: US$54; students: US$25*.

Mineralogical Society of America (MSA) Awards Luncheon
Tues., 24 Sept., 12:15–2:30 p.m. US$54.

MGPV–MSA–GS Joint Reception
Tues., 24 Sept., 5:45–7:30 p.m. Professionals: US$10; students: US$5.

GSA Environmental & Engineering Geology Division Awards Reception
Tues., 24 Sept., 6:30–9:30 p.m. Professionals: US$45; students: US$20.

GSA Planetary Geology Division Annual Banquet & G.K. Gilbert Awardee Celebration
Tues., 24 Sept., 7–10 p.m. Professionals: US$60; students: US$40*.

*There is a limited number of student tickets available at this price. Once they are gone only professional price tickets will be available.

Notice of GSA Council Meetings

GSA 2019 Annual Meeting & Exposition
Phoenix, Arizona, USA

Day 1: Saturday, 21 Sept.
Day 2: Wednesday, 25 Sept.

Council Meetings will be held from 8 a.m.–noon in the GSA Headquarters Hotel—Sheraton Grand Phoenix*, 340 N 3rd Street, Phoenix, Arizona 85004, USA.

All GSA members are invited to attend the open portions of these meetings.

**Meeting room is to be announced. Updates will be posted on GSA website.*

Event Space & Event Listing Requests

Please let us know about your non-technical events via our online event space & event listing database—connect via **community.geosociety.org/gsa2019/connect/events.** Space is reserved on a first-come, first-served basis. Event space & event listing submissions should be used for meeting rooms to hold events (i.e., business meetings, luncheons, receptions, etc.). We will continue to take requests through 29 August on a space available basis and the event can be included on the mobile app.

Guest Program

Penrose Guest Hospitality Suite

Hours: Sun.–Wed., 22–25 Sept., 8 a.m.–5:30 p.m.

We warmly welcome all members of the GSA community to Phoenix! As part of that welcome, we offer registered guests and Penrose Circle Invitees a comfortable hospitality suite for rest and relaxation while technical sessions are happening. As a registered guest, you are welcome to attend your companion's technical session(s), and you will have admittance to the Exhibit Hall. Activities in the suite include complimentary refreshments, entertaining and complimentary seminars, and local experts ready to answer your questions about the area. Local tours and activities will also be offered for an additional fee. We hope you take advantage of the tours to learn about the area from one of the knowledgeable guides.

Seminars

Southwest Wildlife Exhibit

Sun., 22 Sept., 10–11 a.m.

Enjoy an up-close-and-personal look at the creatures that call the Southwest desert home. A sample of our native Sonoran reptiles, birds, and/or mammals will be available, along with their handler, for a brief presentation on life in the Arizona wild.

Edible Gardening

Mon., 23 Sept., 10–11 a.m.

Often confined to the backyard, edible gardens are about to make their front-yard debut. A certified garden expert will introduce the concept of incorporating traditional landscape plants with edible plants to create a visually appealing and functional garden. Selecting the right plants and incorporating design into your garden will provide food season after season by using eco-friendly solutions to create an environment for them to flourish. The resulting productive crop of seasonal herbs and vegetables can become a part of your family's health and well-being as you learn where and how your food is produced.

Desert Hacks & Facts

Tues., 24 Sept., 10–11 a.m.

Learn a potpourri of skills, techniques, tricks, and facts that make a walk in the desert enjoyable, interesting, and survivable. Want to enjoy that hike in the desert a bit more? Want answers to questions such as: "How do I find my direction when my GPS and cell phone don't work?" "Can I really start a campfire with a soda can?" "How do I know what type of animal track I am looking at?" "What is a glochid?" "How does a saguaro thrive?" "Where can I find pierogi?" This 60-minute stomp through unusual desert trivia will prepare you to fake being a desert denizen and impress your family and friends.

Twin-spotted Spiny Lizard (*Sceloporus magister*). Photo by Kaldari, Public Domain, via Wikimedia Commons.

Local Tours

The following tours are open to all registered meeting attendees and guests.

Photo © Visit Phoenix/Jill Richards.

Heard Museum

Sun., 22 Sept., 9:30 a.m.–1 p.m. US$59; 20-person minimum.

We're off to the Heard Museum, which reigns as the leading exhibitor of the heritage and history and arts and crafts of the Native American people. You'll trace the development of the culture of the Southwestern Indians through the many art displays, including Kachina carvings, silver-smithing, rug weavings, pottery, and basketry, to name a few. Look in on a Southwestern Indian craftsman as they create an original work of art, and browse through the gift shop, offering one of the finest selections of original Indian crafts available in the Valley. We'll also include a tour of the surrounding neighborhood to familiarize you with the downtown convention center area.

Desert Botanical Garden

Mon., 23 Sept., 8 a.m.–noon. US$64; 20-person minimum.

Most of the world's 20,000 varieties of cacti and desert plants are displayed in this 145-acre living museum, along with succulents, trees, wildflowers, and shrubs from arid regions of Asia, Africa, Australia, and the Americas. Temporary art exhibits rotate throughout the year, and guests will enjoy the creations of both national and local artists with colorful and monumental exhibitions, which can be found throughout the garden. Our guide will be available during the self-guided tour to answer any questions. You won't want to miss "Plants and People of the Sonoran Desert," a three-acre trail through a saguaro cactus forest, a mesquite thicket, a desert stream environment, and an upland chaparral habitat that explores the many uses of desert plants for food, construction, tools, basket making, and more. As we travel through the city to the gardens, our guide will showcase various points of interest along the route.

Taliesin, Frank Lloyd Wright's School of Architecture, and Carefree

Tues., 24 Sept., 8 a.m.–noon. US$81; 20-person minimum.

Follow us to the foothills of Frank Lloyd Wright's Taliesin West, the architectural school and foundation of the legendary master. You'll look in on his architects of tomorrow and their blueprints for the future and view a slide show highlighting the past works created by Wright. During this 90-minute tour, you'll visit the Wrights' private living quarters, the gracious Taliesin West "garden room," the drafting studio, music pavilion, the cabaret cinema, and more while you enjoy a walking tour around the terraces and walkways with an experienced guide who will explain the history and importance of the architecture. From there, we'll head on to Carefree, a resort community north of the city, nestled in the Foothills, offering a rugged Western, yet upscale, vibe. We'll stop at some of the boutique shops and galleries and include plenty of sightseeing along the way.

Taliesin West, Scottsdale. Photo by Jwagg0309 via Wikimedia Commons.

Hello Phoenix, Hello Scottsdale

Wed., 25 Sept., 9 a.m.–12:30 p.m. US$42; 20-person minimum.

Join us for an introduction and overview to the 5th largest city in America, Phoenix, Arizona. Our experienced guide will keep you entertained and informed during our tour around the historic, financial, and entertainment districts surrounding the convention center and beyond. From past to present, you'll learn about our vibrant city, including a drive past the capitol building, the sports arena, and several historic Phoenix landmarks. We'll also travel to the Old Town/5th Ave. area of Scottsdale, where you'll have time to explore the unique Southwestern shops, boutiques, and galleries that make Scottsdale "The West's Most Western Town."

The Geological Society of America®

GEOCAREERS

If you are entering the job market or are supporting someone who is and want more information about career pathways in the geosciences, plan to attend one or more of the GeoCareers events below.

- Pre-Meeting Webinars (Aug./Sept.)
- Career Workshop (Sun.)
- Company Lightning Talks (Sun.)
- GeoCareers Panel Luncheon (Sun.)
- Résumé Bank & Interviews (Sun.–Wed.)
- Company Connection (Sun.–Wed.)

Visit the GeoCareers Center

Phoenix Convention Center, Sun.–Tues., 9 a.m.–5 p.m., Wed., 9 a.m.–noon

- Career Information
- Career Presentations
- Drop-in Mentoring
- Early Career Professionals Coffee
- Geology Club Meet Up
- Networking Reception
- Post or View Jobs
- Résumé Review Clinic
- Women in Geology Program

community.geosociety.org/gsa2019/connect/student-ecp/geocareers

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Mentoring Opportunities

GSA has a tradition of offering a variety of mentoring opportunities at the meeting, whether you are a student, early career professional, professional, or retiree. Please consider being a mentor at the annual meeting. Complete an application at **https://goo.gl/forms/WVsFCPStWh9hByev1.** Questions? Contact Jennifer Nocerino, jnocerino@geosociety.org.

Drop-in Mentor: This one-on-one mentoring activity takes place in the GeoCareers Center and offers up to 30 minutes for students to ask questions and seek advice from a mentor. At least 24 mentors are needed.

Networking Reception Mentor: This reception brings together students, early career professionals, and mentors. Mentors answer questions, offer advice about careers plans, and comment on job opportunities within their fields. At least 40 mentors are needed.

On To the Future Mentor: On To the Future (OTF) mentors are paired with a student who is a part of the OTF program, which supports students from diverse groups who are attending their first Annual Meeting. Mentors will meet with their mentee each day of the meeting, introduce the mentee to five contacts, and share their professional experiences in the geosciences. Matching will be completed using an online platform. Learn more at **https://bit.ly/2r1EwZ1.** At least 100 mentors are needed.

Résumé Mentor: Résumé mentors are matched with a student on-site to review the student's résumé. Consultations take place for 30 minutes in the GeoCareers Center in a one-on-one format. At least 28 mentors are needed.

Women in Geology Mentor: Female mentors from a variety of sectors answer career questions during the Women in Geology Reception. At least 30 mentors are needed.

On To the Future

GSA has supported more than 570 students from diverse backgrounds to attend their first Annual Meeting through the On To the Future (OTF) program. Mentorships are instrumental in helping shape careers of the next generation of geoscientists. Six years into the program, here is a sampling of where some OTF students are working now:

AECOM
Apache Corporation
Bureau of Land Management
Chesapeake Energy
Colorado Parks and Wildlife
Comprehensive Nuclear-Test-Ban Treaty Organization
Florissant Fossil Beds National Monument
Halliburton
Horizon Well Loggins LLC
James Madison University
NASA Langley Research Center
Navajo Nation
Nebraska Department of Environment Quality
New Jersey Department of Environmental Protection
Paleontological Research Institute and Museum of Earth
Radar Solutions International Inc.
Roux Associates
San Diego Natural History Museum
TerraFirm Construction
Texas Commission on Environmental Quality
U.S. Army Corps of Engineers

Learn more about this program and how you can help mentor a student at **www.geosociety.org/otf.**

Celebrate Diversity at the Diversity and On To the Future (OTF) Alumni Reception

Tuesday, 24 Sept.

Everyone is welcome at this celebration of diversity sponsored by the GSA Diversity in the Geosciences Committee. Socialize and share ideas at this informal gathering for those interested in broadening diversity in the geosciences. OTF awardees, the recipient of the OTF research grant, and minority scholarship recipients will be recognized, with a special presentation by the Bromery Award winner.

"My high school class visited this meeting for the first time and we loved it! It really opened our views to the world of geology and geosciences."
—Feedback from GSA 2018 Indy

Visit Phoenix

Let Us Surprise You

With so much to do in Phoenix you'll need more than a few days.

Family Fun

Head downtown for imaginative learning and exploration in Phoenix's top family-friendly museums and attractions:

- The four floors of interactive exhibits at the **Arizona Science Center** are engaging for all ages. Once you've walked through a giant stomach and engineered your own airplane, you can kick back for a planetarium show or big-screen IMAX theater adventure.
- Little ones up to age 10 can crawl, build, and pedal their way through exhibits at the **Children's Museum of Phoenix,** designed to stimulate the senses and launch the imagination.
- Older children can discover the culture of Southwest American Indian communities at the **Heard Museum** through hands-on learning and interactive exhibits.
- Start a visit to the **Phoenix Art Museum** by picking up a scavenger hunt for kids to guide their exploration of the museum's collections.
- The one-of-a-kind **Musical Instrument Museum** invites visitors of all ages to explore a global collection of more than 6,600 assembled from around 200 of the world's countries and territories—and try their hand at playing a few. Have a Taylor Swift fan in the family? They'll love her exhibit in the artist gallery.
- Go wild for more than 1,400 local and exotic animals at the **Phoenix Zoo,** including up-close encounters with giraffes, stingrays, and camels.

Children's Museum. Photo © Visit Phoenix.

Sports Fans

- Catch a Major League Baseball game. The **Arizona Diamondbacks** will be taking on the St. Louis Cardinals on 23 & 24 September at 6:40 p.m.
- Tee off where the pros play at **TPC Scottsdale's Stadium Course,** or if you forget your clubs, take a tour of **PING's** world headquarters.

South Mountain. Photo © Visit Phoenix.

Travel Like a Local

- Hit all the local favorites and hidden treasures by starting downtown at **Roosevelt Row Arts District.** There you'll be able to get some amazing photos of vibrant murals splashed along the sides of businesses and down the alleys and side-streets. You can also stop in numerous galleries, boutiques, and beloved eateries.
- Take to nature and hit the trails that locals tend to favor, including Dobbins Lookout, the highest point of **South Mountain Park and Preserve.** Plenty of trails explore **Papago Park's** iconic red buttes, and for an easy hike with a big scenic payoff, you'll want to visit Hole-in-the-Rock.

Exhibit Hall

SUNDAY
Exhibits open 2–7 p.m.
Exhibits Opening Reception begins at 5:30 p.m.

MONDAY–TUESDAY
Exhibits open 10 a.m.–6:30 p.m.
Collaborations and Conversations Poster Reception: 4:30–6:30 p.m.

WEDNESDAY
Exhibits open 10 a.m.–2 p.m.
Collaborations and Conversations Poster Reception: 4:30–6:30 p.m.

Feedback from GSA 2018 Indy Exhibitors

"During annual meetings, it's great to meet new people, visit with our GSA member-authors, and catch up with friends. GSA members are the best!" —*Mountain Press*

"GSA brings together key players from a variety of scientific backgrounds and always provides us the opportunity to catch the latest discoveries within the geoscience industries." —*Beta Analytic*

"One of the things I really appreciate, and something that sets the GSA apart from other conferences, is that booth personnel can attend talks and poster sessions. This allows us to see and hear first-hand how our technology is being used in geologic research and speak directly with GPR users." —*Sensors & Software*

"Proto's participation with GSA affords a unique opportunity to discuss with the scientifically diverse GSA membership ways that we might make our product more versatile when presented with new scientific questions that can't be answered with typical XRD setups." —*Proto Manufacturing*

—Come visit these and other fine GSA exhibitors while you're at GSA 2019 Phoenix!

CAMPUS CONNECTION
Bringing Students and Schools Together

Open in the Exhibit Hall Sunday, 2–7 p.m., Monday–Tuesday, 10 a.m.–6:30 p.m., and Wednesday, 10 a.m.–2 p.m.
GSA's Campus Connection provides an excellent opportunity for students to meet face to face with representatives from top geoscience schools. This four-day event saves students time and travel expenses, giving the schools a chance to meet with some of the best student geoscientists in the world in a relaxed, informal setting.

"The wide scope of poster sessions made for delightful geological saturation. Phoenix next!"
—Feedback from GSA 2018 Indy

Bust of Hugh Miller in the Hall of Heroes, National Wallace Monument, Stirling, Scotland.

Hugh Miller (1802–1856): Scottish Geologist, Popular Writer, and National Hero

Kevin Ray Evans, *Dept. of Geography, Geology, and Planning, Missouri State University, Springfield, Missouri 65897, USA; kevinevans@missouristate.edu*

INTRODUCTION

It may not surprise you that one of eighteen busts in the Hall of Heroes at the National Wallace Monument in Stirling, Scotland, is the likeness of a famous geologist, except it is not James Hutton, Roderick Murchison, nor Charles Lyell—it is a bust of Hugh Miller. As an American traveling through Scotland, I discovered the profound reverence bestowed on the memory of Hugh Miller, a man who brought colorful observations, as well as interpretations, from his geologic explorations to the common man in newspaper serials and books. He was among the first popular and prolific science writers to promote the nascent field of geology. He gave it credibility and soothed tensions that developed between “anti-geology” biblical literalists and scientists. He wrote, “Let me qualify myself to stand as an interpreter between nature and the public; while I strive to narrate as pleasingly and describe as vividly as I can, let truth, not fiction be my walk ...” (Miller, 1840, p. 438).

EARLY LIFE

Hugh Miller was born on the Old Red Sandstone of the Black Isle in Cromarty, Scotland. The thatch-roofed, long, low, two-story house of his birth and early childhood stands on Church Street. It currently houses the Hugh Miller Museum, designated a National Trust for Scotland. Miller was five years old when his father, a ship captain, was lost at sea (Miller, 1840). He and his young sisters were raised under austere conditions by his widowed mother, her unmarried sister, and his uncles Sandy and James. His education was not without troubles, involving obstinacy in the face of authority and altercations with fellow students. Yet, equipped with a keen intellect, young Hugh was an avid reader and precocious with a willful, wild, and good-natured mischievousness. His uncle Sandy guided his studies and instructed him in reasoning and the nuances of the natural world around him, so that even as a child he began to collect rocks and fossils and developed a habit of making careful, thorough observations. These were the roots of a common man, not a gentleman scientist.

His mother remarried, and in 1820 at age 18, Miller apprenticed as a stonemason with his stepfather’s brother. It was in the rocks of the Black Isle quarries, and between Cromarty and the Sutors, twin buttresses that guard the south entrance to Cromarty Firth, that Miller visited caves and collected fossil fish and eurypterids from the Devonian Old Red Sandstone and ammonites from Jurassic exposures near Eathie. He wrote (Miller, 1840, p. 163), “Who, after even a few hours in such a school, could avoid becoming a geologist?” Miller worked among stonemason crews building houses at Conon Bridge and Gairloch in Wester Ross. In 1824–1826, he traveled to Niddrie Woods, near Edinburgh, as a journeyman. Tragically, he was afflicted with the “stonecutter’s malady,” silicosis, and weakened lungs would plague him throughout his life. He recuperated from acute symptoms at Cromarty and Inverness, threw off an earlier skepticism of faith, and continued studies of geology. To make ends meet, he engraved headstones, wrote articles and poetry for local newspapers, and produced a volume of Scottish folklore (Miller, 1835). From humble beginnings, he never lacked ambition. He ventured into bookkeeping for a bank to offer the station in society that he felt his fiancé and her family could accept. In 1837, he married Lydia Mackenzie Falconer. With the loss of an infant, and unhappy in his career, Hugh and Lydia moved to Edinburgh to start anew.

THE WITNESS AND GEOLOGIC WRITINGS

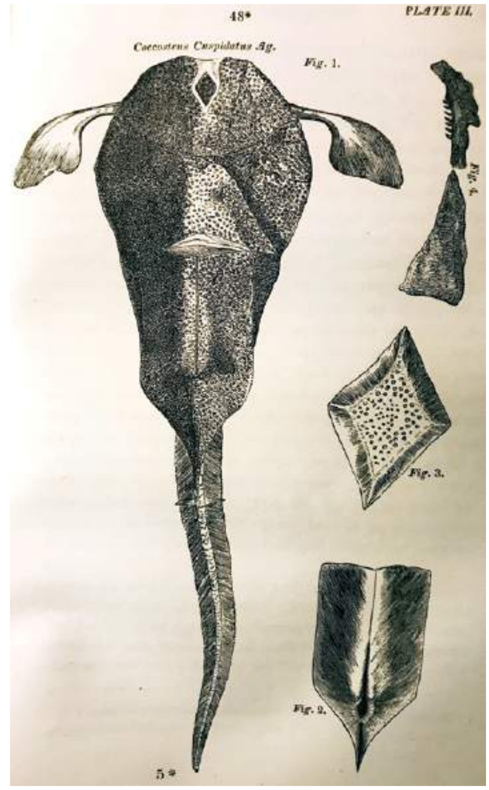
In 1840, Hugh Miller became chief editor and writer for *The Witness*, a newspaper that promoted separatist sectarian views, and it also provided an outlet for narratives of his adventures. As a well-read, self-taught geologist, his explorations of the Scottish Highlands and islands were subjects of a series of articles that became books, like *The Old Red Sandstone or, New Walks in an Old Field* (Miller, 1841) and several others (Miller, 1849, 1857a, 1857b). Miller became a celebrity.

Portrait of Hugh Miller by Robert Adamson and David Octavius Hill, ca. 1843–1847, National Galleries of Scotland (https://www.nationalgalleries.org/art-and-artists/67146/hugh-miller-1802-1856-geologist-and-author-c>).

Miller corresponded with famous contemporaries Louis Agassiz and Roderick Murchison, sharing fossil fish collections with the former. Agassiz and others named genera and species in his honor. He was a friend of geologist Dr. John Grant Malcolmson of the Geological Society of London and amateur fossil collectors Robert Dick, a baker from Thurso, and Patrick Duff, town clerk of Elgin. Miller's acumen is encapsulated in a sculptured inscription at the Hugh Miller Museum, "Learn to make a right use of your eyes." As an example, he noted in *The Cruise of the Betsey* (Miller, 1857b, p. 431),

> I observed scattered over the beach, in the neighborhood of the lead mine, considerable quantities of the hard chalk of England; and, judging there could be no deposits of the hard chalk in this neighborhood, I addressed myself on my way back, to a kelp-burner engaged in wrapping up his fire for the night with a thick covering of weed, to ascertain how it had come there. "Ah, master," he replied, "That chalk is all that remains of a fine large English vessel, that was knocked to pieces here a few years ago. She was ballasted with the chalk; and as it is a light sort of stone, the surf has washed it ashore from that low reef in the middle of the tideway where she struck and broke up."

Like many of his contemporaries, Hugh Miller was a man of faith, but one who did not struggle in reconciling evidence from the natural world with the notions and culture of Christian-centric Victorian Britain. He considered fossils in a pre-Darwinian view as manifestations of earlier creations, and he accepted the idea of deep time, but not without biblical-literalist detractors. Miller was a man of conscience. He supported the rights of common folk and was a central character in the Disruption of 1843, a historic rift in the Church of Scotland that saw founding of the Free Church. Many of his compatriots viewed this movement as a step toward ecclesiastical democratization.



Coccosteus cuspidatus **collected from the Old Red Sandstone by Miller, described and illustrated by Louis Agassiz, and published in Miller (1841).**

SUICIDE

The legacy of Hugh Miller is bittersweet. Despite his accomplishments and influence on geology and the church, around midnight on the eve of 24 December 1856, at Shrub Mount his home in Portobello, he committed suicide with a gunshot to his chest. In the suicide note, he expressed emotionally an unbearable burning pain in his head with a mysterious reference, "I must have walked." He asked forgiveness and bade farewell to his family. In recollections of his last days, to his family, he spoke of his increasing cognitive dysfunction; to a close friend, he described hallucinations. Despite published accounts of a posthumous medical examination, we only can speculate on the full circumstances surrounding his death. He wrote of dark times in his earlier stonemason years; others mentioned his obsession with thwarting theft from his collections at Shrub Mount (Swiderski, 1983; Campbell and Holder, 2005). Hugh Miller was buried in Grange Cemetery in Edinburgh, but in Cromarty Cemetery, a statue of Hugh Miller stands atop a 15-m column erected in commemoration of his life and work. He was a favorite son of his community, a common man, and a hero of Scotland.

In honoring great geoscientists, we mustn't ignore the difficult parts. While his writings expressed the depth of his passions and compassion, Hugh Miller had human frailties.

A lesson may be learned in acknowledging that even brilliant, self-made individuals are susceptible to mental illness and suicide. In 2017, ~47,000 people committed suicide in the United States (*USA Today*, 2018; American Foundation for Suicide Prevention, https://afsp.org/about-suicide/suicide-statistics/). It is the 10th leading cause of death, and the third leading cause of death among young people in the U.S. The rate of suicide, 14 in 100,000, is rising. Suicide has touched many of our lives and families; it is preventable. If you or someone you know is at risk of suicide, you can find help at the National Suicide Prevention Lifeline (https://suicidepreventionlifeline.org) or call +1-800-273-8255, available 24 hours every day.

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USA Today Editorial Board, 2018, Suicide kills 47,000 men, women and children a year. Society shrugs: USA Today, 28 Nov. 2018, https://www.usatoday.com/story/opinion/2018/11/28/suicide-kills-45-000-annually-society-shrugs-editorials-debates/1661312002/ (last accessed 28 Nov. 2018).

A More Informative Way to Name Plutonic Rocks—Comment by Frost et al.

B. Ronald Frost, Carol D. Frost, *Dept. of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071, USA;* **J. Lawford Anderson,** *Dept. of Earth and Environment, Boston University, Boston, Massachusetts 02215, USA;* **Calvin G. Barnes,** *Dept. of Geosciences, Texas Tech University, Lubbock, Texas 79409, USA; and* **Marjorie Wilson,** *School of Earth & Environment, Leeds University, Leeds LS2 9JT, UK*

In a recent paper, Glazner et al. (*GSA Today*, Feb. 2019) proposed a major change in the terminology of plutonic rocks, whereby a simplified rock name is prefixed with the mode. In this classification, a granite might be named *20,20,50 granite*. Glazner et al. (2019) proposed this classification system for three reasons. First, they maintain that rock terminology is too complex; they note that at least 157 igneous rock names exist. The second is that the boundaries in the International Union of Geological Sciences (IUGS) classification are arbitrary and hence are confusing when applied to plutonic rock units that show a range in composition. Third, the IUGS system of classification is qualitative, and the quantitative data from which the classification is derived are discarded once the name is determined. To solve these problems Glazner et al. (2019) propose that the petrologic community discard the IUGS classification system and substitute a system with a limited number of rock names that are prefixed by the modal abundance of major phases (such as quartz, alkali feldspar, and plagioclase [QAP] in felsic rocks). They maintain that this is a simpler classification and that it lends itself to a more quantitative classification scheme.

We take exception to Glazner et al.'s (2019) proposal and instead recommend that geologists continue to use the IUGS classification system for naming plutonic rocks. Their first justification, that there are too many obscure terms in igneous petrology, was a problem recognized by the IUGS commission (Streckeisen, 1976; Le Maitre et al., 2002). Hence, the IUGS rock names replaced a plethora of obscure terms. The IUGS classification scheme involves only 55 names for common plutonic igneous rocks. Of these, rocks with ≥10% quartz (the most common group) are described by only 23 names, many of which share the same root name. These names need not be memorized because they are present in the various IUGS diagrams for rock names, a diagram that is easily pasted into field notebooks.

The argument of Glazner et al. (2019) that rock names are determined by "arbitrary" boundaries is not compelling. These boundaries are not arbitrary: The IUGS commission spent many years developing a system that conformed, as much as possible, with existing classification systems. Furthermore, the rock terms have meaning in the sense that geologists know what to expect of a rock described as tonalite instead of granite. Glazner et al. (2019) support their arguments with the observation that two of the plutons in the Sierra Nevada batholith, the Cathedral Peak Granodiorite and the El Capitan Granite, contain rocks that look the same (their Fig. 1). Thus they conclude that the names "granodiorite" and "granite" are in error. However, the error is not in the names of the individual rocks, it is in the assumption that the Cathedral Peak Granodiorite contains only granodiorite whereas the El Capitan Granite contains only granite. Plutons are rarely homogeneous over distances greater than a few tens of meters: they contain rocks with a range of compositions. Whereas each rock named by the IUGS classification is valid, the assumption that the pluton name (i.e., Cathedral Peak Granodiorite) classifies all rocks within the pluton as granodiorite, as implied by Glazner et al. (2019), is simply false.

Glazner et al. (2019)'s third point is that appending numbers that reflect modal abundances to a simple name will result in a more precise description of the rock. This suggestion indicates a confusion of precision and accuracy. Modes are difficult to determine in the field where, as Glazner et al. (2019) observe, the distinction between alkali feldspar and plagioclase can be subtle. Field estimation of modes is unlikely to be better than ±10%. With this precision, a rock classified as a *25,25,40 granite* would occupy a large field in the QAP diagram (Fig. 1). For this reason, Streckeisen (1976) suggested a preliminary classification in which granitic rocks may be named with the termination "*-oid*," as in *granitoid*. Point-counting a minimum of 1000 points on stained slabs or thin sections produces a more accurate determination of quartz, plagioclase, and alkali feldspar abundances that are used to identify the appropriate IUGS rock name. However, as Glazner et al. (2019) observe, only 5% of the analyses archived in the NAVDAT database have associated modal data. This means that their quantitative classification system, in addition to being of limited value in the field, is not likely to be widely applied.

A further problem with modal classification is that even when mineral proportions are accurately determined there remains an inherent, irreducible uncertainty. First, the abundance of feldspars in a granitoid is dependent on the cooling history of the rock. A rock that cooled relatively swiftly and contains sodium-bearing orthoclase will have a different ratio of alkali feldspar to plagioclase than one that cooled slowly and contains sodium-poor microcline and plagioclase with sodic rims. Furthermore, crystallization of any muscovite or biotite in a rock will deplete the orthoclase component from the feldspar matrix. Similarly, hornblende crystallization will deplete a

GSA Today, v. 29, https://doi.org/10.1130/GSATG405C.1.

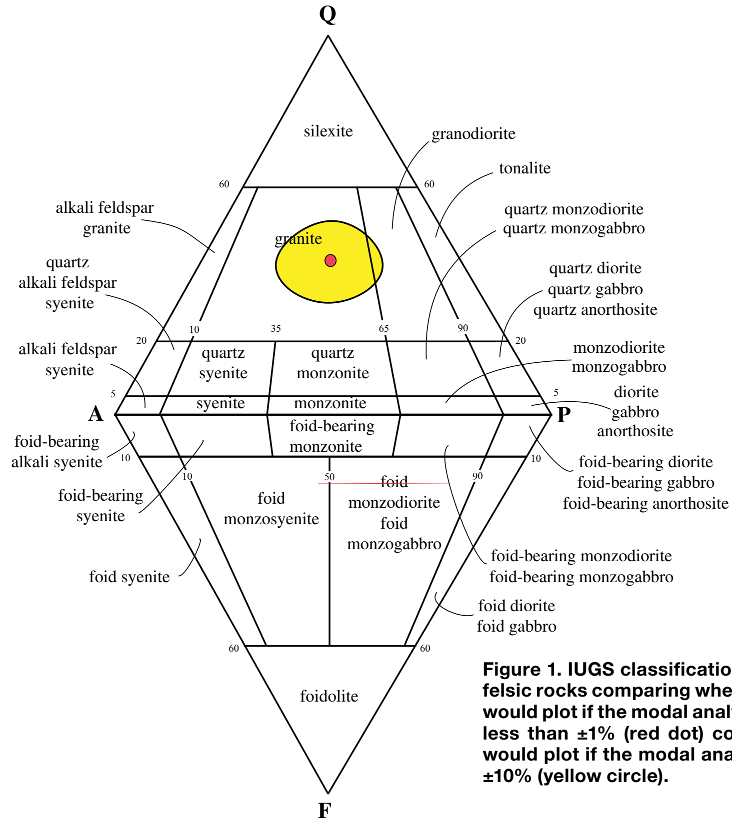

Figure 1. IUGS classification for quartz-bearing felsic rocks comparing where a *25,25,40 granite* would plot if the modal analyses were precise to less than ±1% (red dot) compared to where it would plot if the modal analysis was precise to ±10% (yellow circle).

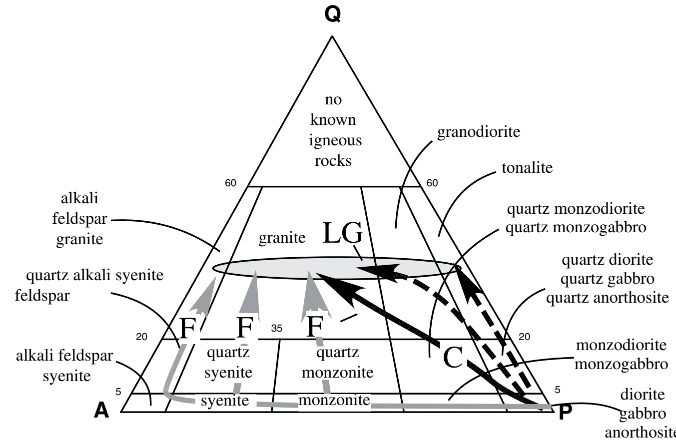

Figure 2. IUGS classification for quartz-bearing felsic rocks showing the differentiation paths followed by various granitic plutons Dashed lines—granitoids of Cordilleran batholiths; C—Caledonian batholiths; F—ferroan granites; LG—peraluminous leucogranites; Q—quartz; A—alkali feldspar; P—plagioclase. From Frost and Frost (2014).

plagioclase component. Any statistical application of a modal classification system would involve these uncertainties.

The IUGS classification bins samples into a relatively small number of rock names to give geologists a general sense of the rock composition. As Streckeisen (1976) puts it, "The system is merely of descriptive character, as it serves to order the rocks that occur in nature according to their mineral content." Moreover, the system allows for modification of the IUGS rock name to make it more informative: a biotite hornblende granodiorite has more hornblende than biotite. A geologist knows that magnetite granite contains Fe_3O_4 as the main mafic component of the rock. The prefixes leuco- and mela- may be used to indicate the abundance of mafic minerals in the rock. In addition, the assemblage of IUGS rock names determined from a particular intrusion provides information about magma evolution, which in turn can help identify tectonic setting. For example, a suite of plutonic rocks containing quartz diorite, tonalite, and granodiorite is typical of continental arc batholiths, whereas a suite consisting of monzonite, syenite, quartz syenite, and granite is typical of ferroan granitoids from extensional environments (Fig. 2).

We conclude that it is a mistake to modify the IUGS classification system to make it into a quantitative naming system. The IUGS classification system was developed over nearly 20 years and involved 456 petrologists from 52 countries (Le Maitre et al., 2002). The idea that it should be overturned by a single paper is inadvisable. Glazner et al.'s (2019) proposal to use modes in a quantitative way eliminates rock names that are meaningful and well-established in the geological literature and is burdened by the inherent imprecision of modal analyses. Whole rock chemical analyses are more accurate and reproducible than modes; consequently, as far as quantitative databases are concerned, geochemical databases, coupled with a complete IUGS rock name, provide a better way to quantify rock variability than modes. Together, the IUGS rock names and the corresponding geochemical analyses provide insights into the most important, and frankly most exciting, questions in petrology, including how igneous melts form, how the magmas evolve, and how their compositions reflect the tectonic environments where these processes take place. Let's leave the well-established IUGS classification system in place rather than to try to fix something that is not broken.

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A More Informative Way to Name Plutonic Rocks—Comment by Hogan

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Glazner et al. (*GSA Today*, Feb. 2019) propose major modifications to the International Union of Geological Sciences (IUGS) classification of igneous rocks (see Streckeisen, 1976; Le Maitre, 2002) to correct what they see as major shortcomings, including: (1) consanguineous, mappable, igneous rock bodies can exhibit modal variation requiring multiple rock names to describe; (2) these names rarely convey information regarding rock-forming processes or tectonic settings; and (3) their discussion imparts the perception that their "*quantitative*" approach corrects these problems. In addition, they portend the "*qualitative*" nature of the IUGS system inhibits the use of artificial intelligence (AI) for data mining and analysis of igneous rocks. I present several points for consideration and recommend against adopting Glazner et al.'s (2019) suggestions.

The strength(s) of the IUGS system are as follows: (A) It is a *quantitative* classification scheme based upon modal abundances of minerals in the rock sample, which can be measured, with associated uncertainties, following well-known procedures (see Chayes, 1956). Quantitative modal analysis is accomplished at many scales: thin-sections (Willis et al., 2017), hand-samples (Elliott, 1999), and map-scale or pluton/batholith-scale using multiple hand samples (see Figure 7 *in* Hogan and Sinha, 1989). (B) Procedures for classifying rocks using this data are self-consistent and easily followed. A root name (e.g., granodiorite) is assigned using normalized modal abundances of major minerals (e.g., quartz, alkali feldspar, plagioclase). (C) The IUGS classification scheme *does* include the abundance and identity of minor and accessory minerals in naming the rock. Modifiers reflect the modal abundance of mafic minerals ("color index" "M") of the rock (e.g., leucocratic granodiorite). Trends in M are readily discernible using the IUGS scheme (Figure 13 *in* Streckeisen, 1976; Figure 8 *in* Wones, 1980). (D) The identity of minor and accessory minerals is included in the name according to their modal abundance, with greater abundance closer to the root name (e.g., leucocratic, titanite, hornblende, biotite, granodiorite). (E) Preliminary rock names, based upon "rough" estimation (i.e., using charts as a visual aid) of modal abundance (e.g., a leucocratic, biotite, hornblende *granitoid*) are used until the alkali feldspar/plagioclase ratio is constrained (Figure 6 *in* Streckeisen, 1976). (F) The IUGS procedure is quantitative, readily reproducible, easily followed, and understood by geoscientists worldwide.

The IUGS classification scheme is compatible with mapping heterogeneous igneous rocks. Sedimentary strata commonly consist of multiple rock types, interbedded at several scales, with sharp or gradational contacts, and are mapped as a "formation" without abandoning well-established sedimentary nomenclature. Heterogeneous intrusive igneous rocks, composed of multiple rock types with gradational contacts, can be mapped as lithodemes or as suites (e.g., Tuolumne Intrusive Suite; see Easton et al., 2016) without abandoning well-established IUGS nomenclature for igneous rocks. The description of the physical characteristics of the rock types, nature of the contacts, comprising mappable lithodemes or suites, along with the IUGS names, are included in its formal description.

The motivation for classification schemes is an important and fundamental subject for all students investigating a topic of interest. Classification schemes can be largely objective, based upon measurable and reproducible facts, and internally consistent rules. Alternatively, classification schemes can be interpretive and based upon inferred parameters. Each type of classification scheme serves an important scientific purpose. Glazner et al. (2019) suggest transforming the objective IUGS classification scheme into an interpretive classification scheme where well-established taxonomy are repurposed to convey a vision of how igneous rocks form. The example they use is "granodiorite" and propose this term to become synonymous with a subduction zone setting. Unfortunately, such classification schemes tend to be transient, as leucocratic biotite-muscovite granite is not universally accepted as an S-type granite, nor are gradational lit-par-lit contacts considered proof of granitization. In contrast, by keeping observations (modal data) separate from interpretation (e.g., zone refining) the integrity of names determined by correct application of the IUGS classification scheme (e.g., hornblende-biotite granodiorite) will continue to hold factual meaning worldwide, well into the future, despite any interpretation of the tectonic setting or the processes by which a rock formed (see Streckeisen, 1976, p. 4, section "Principles of Classification").

Scientific classification schemes are challenged by imposing order on the continuum that is the natural world. This is evident in every science discipline including biology despite the oversimplification of "doggish cats" and "cattish dogs" manufactured by Glazner et al. (2019). For example, lichens are living organisms that are neither a fungi nor a cyanobacterium but a blend (DePriest, 2004). Their form bears no resemblance to either organism(s) from either Kingdom that make up the lichen. Many life forms are continuums and present

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taxonomical challenges, which will be understood, not by text-mining alone, but by publishing accurate, precise, and reproducible biological findings (Gough, 2017). The contributors to the IUGS classification scheme, recognizing that many rock suites are continuums, devoted considerable thought in choosing the boundaries, knowing that this property of rocks does not invalidate the general usefulness of the proposed classification scheme (see Streckeisen, 1976). The petrological community needs to increase the opportunity to explore petrological trends in the variation of mineral assemblages that define igneous rock suites using AI and continue to debate possible origins for these trends. To do so, I recommend petrologists continuing to use the IUGS classification scheme and focusing their energy on seeking publication of accurate and reproducible modal analysis data in consistent formats (i.e., similar to geochemical data) suitable for data mining.

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A More Informative Way to Name Plutonic Rocks—Reply

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> I learned very early the difference between knowing the name of something and knowing something. —Richard Feynman

We appreciate that our paper has generated comments and thank their authors for giving us the opportunity to clarify some of the points that we made.

We assume that anyone who uses the International Union of Geological Sciences (IUGS) classification to name a rock has estimated modal data, whether by eye in the field, by point counting, by electron-beam methods, etc. The main point of our paper was simply that these data should be part of the name rather than discarded or left in a field notebook. Our system permits the use of the IUGS name if one wishes. However, adding modal data to the name permits current terminology to be simplified, and it permits name boundaries to be fuzzy without loss of precision. In our view, fuzzy name boundaries have at least two advantages: the names better depict the nature of modal variation, and they eliminate the use of multiple rock names to refer to suites of closely similar rocks.

As an example, calling a rock a 30,30,30 granite tells you rather directly what is in the rock. In contrast, calling a rock "granite" is vague; the IUGS name "granite" can only be quantified as two inequalities plus an equation, in four unknowns:

$$0.2 < \frac{q}{q+a+p} < 0.6 \quad (1)$$

$$0.1 < \frac{p}{a+p} < 0.65 \quad (2)$$

$$q+a+p+m=100 \quad (3)$$

where the variables are modal abundances of quartz (q), alkali feldspar (a), plagioclase (p), and the sum of everything else (m).

The IUGS term "granite" applies to any composition within the shaded pyramid (Fig. 1) defined by the inequalities and equation above. We know by experience that real granites lie somewhere near the base of this volume, but the IUGS name, even with a modifier such as "leucocratic," gives little help. In contrast, Figure 1 shows 500 variations of a 30,30,30 granite wherein normally distributed numbers with a mean of five were added to the modal abundances. Even with such variation in the estimates, the composition of the rock is narrowed down far better than with the bare IUGS name.

Hogan (2019) states that the IUGS classification is quantitative. It is, at the same level that knowing a postal code narrows down where someone lives—not very precisely. Similarly, he contends that color index is given quantitatively by words such as "leucocratic," which again are quite imprecise; this is akin to noting the time by saying that it is night. We contend that if the color index is observed (as it must be to apply an IUGS name), then it should be reported and not discarded.

We disagree with Hogan (2019) that rock classification is no different from biologic classification. A biologist keying out dogs and cats will find a split after Order Carnivora with dogs at the end of one branch, cats at another, bears at another, and so on; there are no doggish cats or cattish bears—they are discrete species owing to discrete genomes, which is why the Linnaean system has served biologists so well. Not so with igneous rocks; even the volcanic and plutonic realms grade into one another. Thus, any system with sharp boundaries, no matter how well-intentioned, will split continua of rock compositions.

The IUGS system almost seems to have been designed to carve up cogenetic calc-alkaline suites into as many boxes as

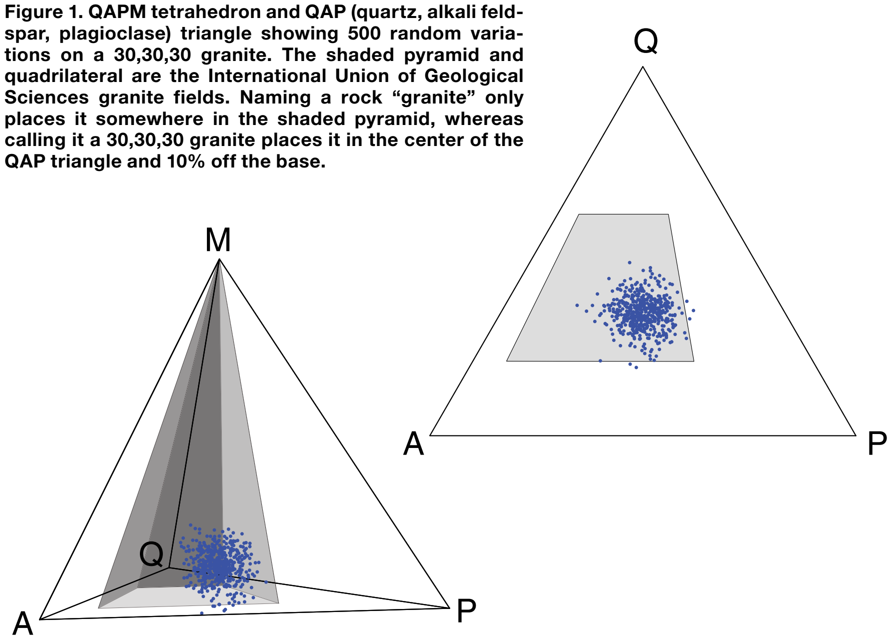

Figure 1. QAPM tetrahedron and QAP (quartz, alkali feldspar, plagioclase) triangle showing 500 random variations on a 30,30,30 granite. The shaded pyramid and quadrilateral are the International Union of Geological Sciences granite fields. Naming a rock "granite" only places it somewhere in the shaded pyramid, whereas calling it a 30,30,30 granite places it in the center of the QAP triangle and 10% off the base.

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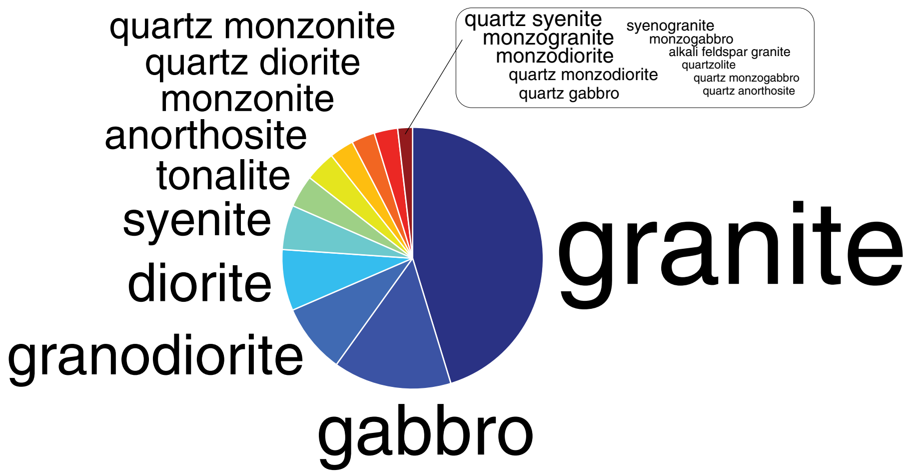

Figure 2. Relative frequency of occurrence of International Union of Geological Sciences quartz-bearing plutonic rock names in the *Geological Society of America Bulletin*, 1890–present. Relative areas of letters are proportional to frequency. "Granite" dominates, and the top 10 make up over 98% of the names, with the remaining 14 comprising only 1.8%.

possible. As noted by Frost et al. (2019), such systems produce arrays that radiate from near the P apex and, as we noted in Figure 3 of our original paper, one Yosemite unit crosses the four-way junction where the granodiorite, tonalite, quartz monzodiorite/quartz monzogabbro and quartz diorite/quartz gabbro/quartz anorthosite fields come together. Only confusion can come of this, as four separate field estimates of modes of a rock from near this junction could be 20,10,50; 20,5,55; 15,10,60; and 15,5,60. In our system these are all granodiorites (or tonalites, as the name is secondary), but these would end up with four different IUGS names: granodiorite, tonalite, quartz monzodiorite, and quartz diorite. One could use the full IUGS names, but as long as the numbers are there the names are not important, the similarities among the four estimates are clear, and the estimated color index is derivable.

The contention that one need not know what the IUGS names mean because they can be looked up strikes us as similar to saying that one need not memorize vocabulary to be fluent in a language because one can always just look up all the words. It is self-evident that the use of words that must be decoded interferes with communication.

Many IUGS names are rarely used. Figure 2 shows the frequency of occurrence of the rock names in the quartz-present part of the IUGS diamond in the *Geological Society of America Bulletin*, 1890–2018. As we noted in our paper, rock names generally follow Zipf's Law, in which the frequency of a word or set of words is inversely proportional to its frequency rank. The IUGS names follow this for the first 10 and then drop off precipitously. Many names have been used only a few times, and then only to define a field on an IUGS diagram, a usage that scarcely justifies their continued presence on classification diagrams.

Nothing in our method asks that a rock name be tied to its origin.

Frost et al. (2019) state that the lack of modal data in databases such as EarthChem means that "... their quantitative classification system, in addition to being of limited value in the field, is not likely to be widely applied." This misses the point. Perhaps our field methods differ, but we attempt to estimate modes in the field so that we can correlate, map, and understand the units more effectively. Most field petrologists do so, but the lack of such data in databases means that such data are effectively discarded. Our proposal aims to fix that.

ACKNOWLEDGMENTS

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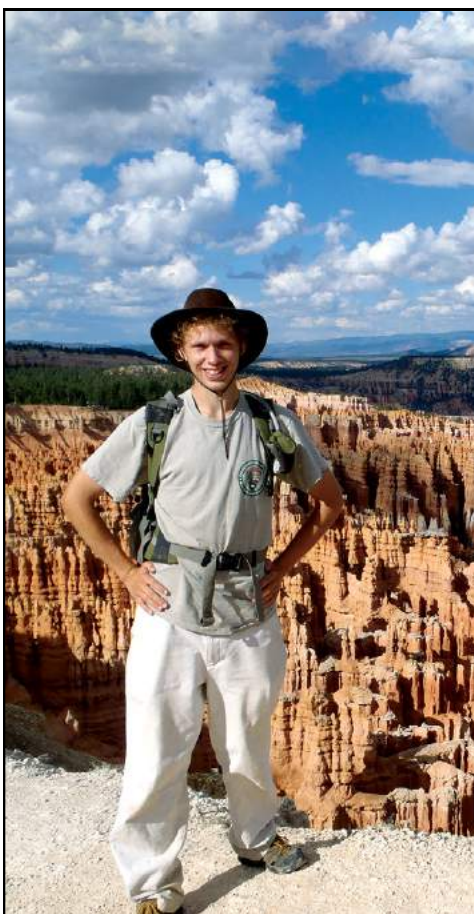

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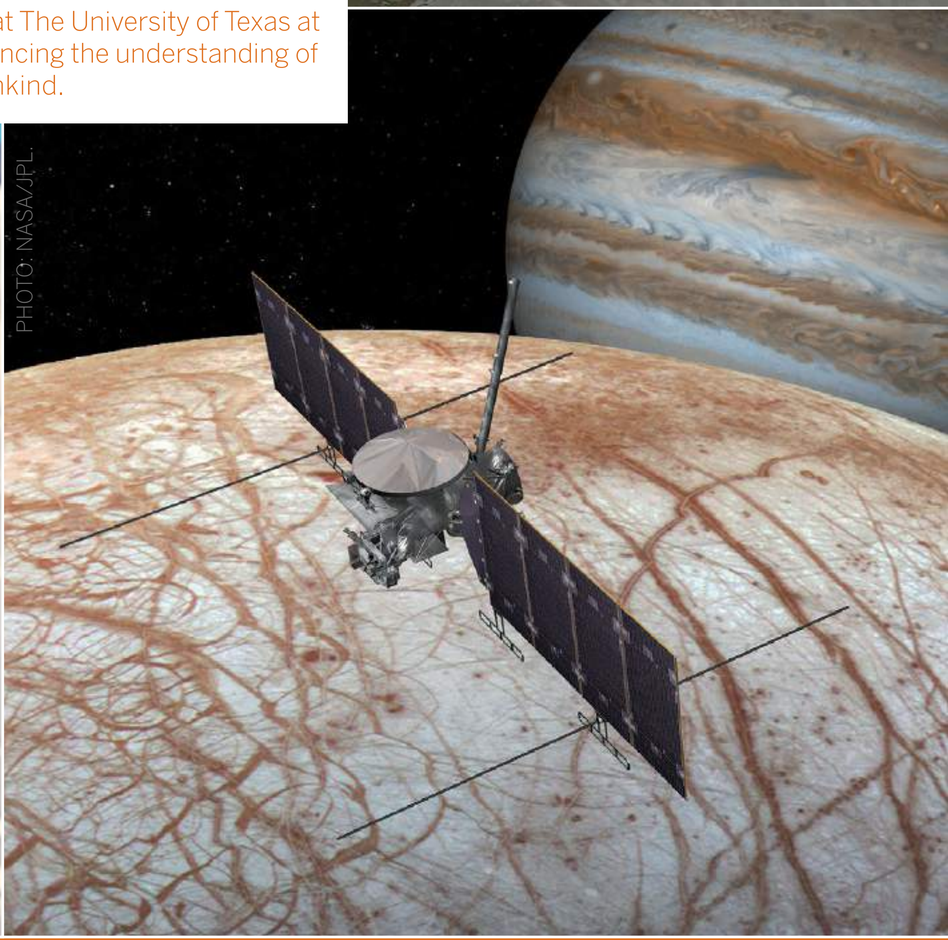

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