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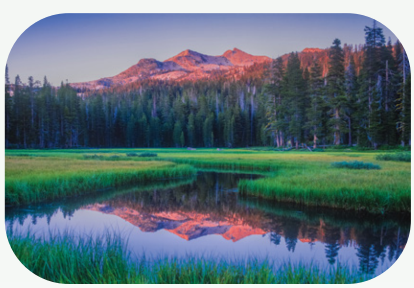

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A view of the stratigraphic section at Punta di Malata, southern Sicily, Italy, which is a reference section for the Zanclean Stage (early Pliocene). Such sections studied for their sequence- and cyclo-stratigraphies provide a framework for the history of sea-level changes of the past. See related article on pages 4–11.

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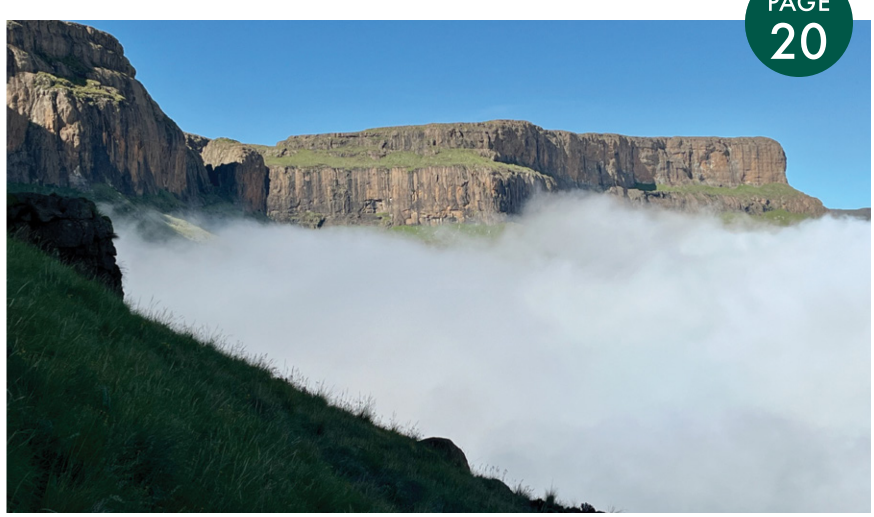

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Retraversing the Highs and Lows of Cenozoic Sea Levels

Bilal U. Haq*,[1] and James G. Ogg[2]

ABSTRACT

We present a sequence-stratigraphically based reappraisal of sea-level variations for the Paleogene, Neogene, and early Quaternary Periods (66.0–1.5 Ma) that is biochronostratigraphically controlled and then fine-tuned through oxygen-isotopic ($\delta^{18}O$) calibrations, with a higher-frequency, mostly isotopically calibrated curve for the last 1.5 m.y. of the Quaternary Period. Depositional sequences that form the basis of sea-level curves are largely third-order cycles (~0.5–2.5 m.y. in duration) for the Paleogene–Neogene interval and fourth- and fifth-order cycles (~400–100 k.y.) for the Quaternary. The availability of better-resolved, astronomically tuned Cenozoic chronostratigraphy and new sequence-stratigraphic studies in the past three decades makes this update timely. In this major revision, the ages of the depositional surfaces (i.e., sequence boundaries and maximum flooding surfaces, which form the basis of the sea-level curves) have been calibrated to marine benthic foraminiferal oxygen-isotopic data, thereby improving their chronologic precision. The amplitudes of sea-level highs and lows have been reevaluated based on global averaging of stratigraphic estimates, aided by isotopic data, where we also discuss the many inherent issues that reduce the efficacy of both methodologies. The global-mean data suggest that the shorter-term highs and lows are extremely variable during the Cenozoic Era, ranging from ~150 to a few tens of meters of change. Refined ages of the sequence boundaries and the resultant durations of third-order sequences imply their strong linkage to the long-period modulations of the obliquity and eccentricity cycles and, thus, to climatic variations.

INTRODUCTION

Knowledge of sea-level (SL) variations through time is integral to the study of basin-wide geodynamics and for deciphering past climatic, oceanographic, and environmental conditions, and through the latter, the understanding of the potential drivers of biotic macro-evolutionary trends controlled directly or indirectly by SL change (e.g., Cloetingh and Haq, 2015; Boulila at al., 2023). Such knowledge of past SL variations has been garnered through local, regional, and global stratigraphic and paleogeographic reconstructions and through isotopic analyses. Any measure of SL change deciphered from stratigraphic data at any location is local or regional by definition (i.e., eurybatic), caused partially or wholly by local factors such as seafloor subsidence, isostatic rebound, or changes in the rate of sediment input, even when there is a strong global signal in the background. Thus, no singular location represents the broader history of SL variations that can be considered a global standard. Instead, paleoceanographers use widely distributed stratigraphic records from multiple, noncontiguous sections that show similarities in trends, and in timing of SL falls, to provide a quasi-quantitative trajectory of the underlying global (eustatic) signal. Nevertheless, while we are able to reconstruct temporal variations displaying eustatic trends, the amplitude of highs and lows will remain variable from one location to the other due to variable local factors. That is one reason why the shorter-term variations (third order: ~0.5–2.5 m.y.; fourth or fifth order: averaging 400–100 k.y.) are often tied to a longer-term envelope (representing second-order trends) that is deciphered independently from a different set of data and measures that have global causality (see discussion in Haq, 2014).

Our previous study of global mean SL curves for the Cenozoic interval was published several decades ago (Haq et al., 1987, 1988), where a key feature was the incorporation of data from the accessible stratotypes/neostratotypes of the European Stages, allowing more accurate placement of the sequence boundaries against the extant "standard" biochronostratigraphic time scales. Several updates of Cenozoic eustasy have since been published, along with revisions of the numerical time scales, and independent proxies have been deployed (such as the combined use of $\delta^{18}O$ of seawater and Mg/Ca ratios in benthic foraminifera), which have greatly advanced our knowledge of the uncertainties, the timing, and the nature of eustatic variations (e.g., Hardenbol et al., 1998; Miller et al., 1998, 2020; DeConto and Pollard, 2003; Haq and Al-Qahtani, 2005; Kominz et al., 2008, 2016; Cramer et al., 2009; Raymo et al., 2018, among others).

The eustatic histories of the three Mesozoic Periods have recently been reappraised (Cretaceous: Haq, 2014; Jurassic: Haq, 2018a; and Triassic: Haq, 2018b), incorporating wider stratigraphic data and linking updated time scales. Here we present a revision for the Cenozoic, which also incorporates

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widely distributed sequence-stratigraphic and isotopic data, calibrated to the most recent version of the Cenozoic time scales (Gradstein et al., 2020), as well as the astronomically tuned, smoothed oxygen-isotopic data of Westerhold et al. (2020).

CURRENT STATUS OF THE CENOZOIC TIME SCALE

Many of the recent refinements to the Cenozoic biochronological time scale have come from high-resolution cyclostratigraphic analyses (using X-ray fluorescence scanning or other proxies) that tie relatively continuous sections to Milankovitch orbital cycles (or their long-period modulations), where both the magnetic-polarity reversal scale and the biostratigraphic zonal schemes have been astronomically tuned. Additional refinements come from the use of oxygen-isotopic calibrations where prominent positive or negative excursions provide more precise and globally valid stratigraphic constraints that are useful for both refining the biochronologic time scale and in fine-tuning the timing of sequence boundaries. For individual updates of the Paleogene, Neogene, and Quaternary, more detailed discussions, and cross correlations among various fossil groups, see Speijer et al. (2020), Raffi et al. (2020), and Gibbard and Head (2020), respectively.

FINE-TUNING OF TIMING OF CYCLE BOUNDARIES

In a sedimentary edifice, our ability to detect depositional sequences that form the basis of the short-term SL curves (third- and higher-order cycles) depends on the local rate of sediment accumulation, which affects our resolving capability. On continental margins (and interior basins) where seismic profiling is the major investigative tool and sedimentation rates are moderate or low, the resolving capability is generally limited to the third-order cycles. However, as we move closer to higher-sedimentation-rate areas (e.g., deltaic regions), the expanded sections allow us to discriminate higher-frequency (fourth- and higher-order) cycles as well. This is also true of the outcrop sections on land, where higher-frequency cycles can be studied with greater facility and more detail.

A marine sequence boundary (SB), the end of a depositional cycle, is traditionally positioned at the inflection point of the falling limb and not when it is at its lowest. The rationale for doing so is that because such a boundary represents an erosional episode that accompanies the withdrawing sea, the place to draw the limit of the cycle within the missing section ought to be where the rate of change was maximum (i.e., the inflection point). Past this point in time, at least a part of the depositional system may already begin to backfill with reworked sediments (e.g., in incised valleys on the distal shelf).

SBs of the third-order cycles are normally dated through their biostratigraphic associations—for example, in the Cenozoic they are commonly based on planktonic foraminiferal and nannofossil zones. However, SBs can often fall within long-ranging biozones that can range from >0.2 m.y. to as much as 3.0 m.y. in duration. This can imply high uncertainty as to the precise age of the boundary. Such uncertainties can be reduced by the use of overlapping zonal schemes of multiple fossil groups, which requires several specialists working together on the same sample sets (see, e.g., Haq et al., 1988, where multiple fossil groups were used to narrow the age picks of the SBs). In practice, however, this is not always possible, and the position of the SBs within long-ranging biozones is simply placed at the mid-point of the zonal range for consistency.

The age assignments for the maximum flooding surfaces (MFSs) have even greater uncertainties associated with them. Conceptually, the timing of when a surface representing maximum flooding of the shelf or an interior basin is reached is a function of the rate of SL rise competing with the rate of sediment supply to determine when the transgressive trend will switch to a largely regressive one. A high-sediment input can overwhelm a transgressing sea and can force a regression earlier than in a low-sediment supply region. Thus, the timing of the change from marine (retrograding to aggrading) facies to predominantly nonmarine (prograding) facies will vary from one location to the other (even along the same margin), making the age of the MFS time-variable. Again, in the absence of independent refining criteria, MFSs are often dated simply at the mid-point of the sequence cycle.

This is where oxygen-isotopic ($\delta^{18}O$) data can aid us in refining the age assignments of SBs and MFSs. Because the oxygen-isotopic trends represent a largely global signal, isotopically aided refinements can bring us closer to globally useable age picks for these events. Researchers have known since the 1970s that bottom-water temperatures have varied by >10 °C through the Cenozoic and that the oxygen-isotopic record of calcitic benthic foraminiferal tests incorporates two dominant ambient signals: the $\delta^{18}O$ composition of seawater and the bottom-water temperature. During those intervals when glaciation is extant, the $\delta^{18}O_{sw}$ also contains a strong continental ice-volume component due to preferred sequestration of the lighter isotope of oxygen (^{16}O) in ice sheets on land in the higher latitudes (where the cold-bottom water originates), and thus a signal of the waxing and waning of continental ice cover (see, Pearson, 2012, for a review).

Substantial accumulation of ice on Antarctica is deemed to have begun in the late middle Eocene, although some ephemeral ice is suspected as far back as late Cretaceous (Miller at al., 2008; Haq, 2014). Paleoceanographers, however, now concur that the Paleocene to Early Eocene Earth was an almost ice-free interval, while the oceanic bottom-water temperatures were at their peak—modeled as 10–14 °C in the Early Eocene, compared to present-day 2–3 °C (Valdes et al., 2021). Things began to change during the middle Eocene. Dawber and Tripati (2011) argue for at least three major glacial-deglacial pulses as far back as the Lutetian and Bartonian, based on benthic oxygen-isotopic data from the Shatsky Rise. This means that the oxygen-isotopic trends can be utilized to refine the ages of both SBs and MFSs for much of the Cenozoic. Even prior to mid-Eocene, isotopic data that reflect major climatic shifts can aid us in refining the timing of key depositional surfaces.

In this update of the Cenozoic eustasy, we have used the synthesis of Westerhold et al. (2020) for such chronological refinements of depositional boundaries that represent SL highs and lows. Our use of the Westerhold et al. $\delta^{18}O$-stack is predicated on the fact that in this synthesis much of the existing and new Cenozoic isotopic data were incorporated to produce a composite that is highly resolved, astronomically tweaked, and statistically polished to provide internally consistent comparisons. These authors convincingly argue for latitudinally specific climate processes driven by astronomical forcing and ice-sheet dynamics. We have used the relatively prominent trends in enrichment of $\delta^{18}O$ versus its depletion as partial indicators of waxing versus waning of ice sheets since the Lutetian. The beginning of the cooling trends, when they occur close to the biostratigraphically dated SBs, help us refine the ages of the SBs, while the warming trends aid in ascertaining the ages of MFSs. In the background of this isotopically refined sequence chronology for the pre-Quaternary interval, however, there still persists the mostly third-order sequence-stratigraphic framework and its relationship to the "standard" Cenozoic stratigraphy, the basic units being the European Stages (see Supplemental Material[1] for more detailed discussion). The framework of the higher-frequency Quaternary depositional cycles is, however, mostly based on isotopic data and would be largely applicable in high-sediment-input areas where shorter-duration depositional cycles can be resolved.

APPROXIMATING THE AMPLITUDE OF SEA-LEVEL VARIATIONS

Stratigraphic Measures

The sense of the amplitude of SL rises and falls on a continental margin or inland basin can be gauged stratigraphically from the overall architecture of sedimentary edifice, the bio- and lithofacies of the sediments that represent changes in depth habitats, the surfaces of erosion and reworking, and thus, the movements of the shoreline landward or basinward. In practice, however, postdepositional changes to the sediments complicate these inferences and may require corrections for local factors such as loading, compaction, and subsidence effects. Complications may also occur due to such factors as intraplate deformation on a regional stress-province scale (e.g., Cloetingh et al., 1985) and far-field dynamic topographic changes whose impact can often go undetected in local studies, leading to under- or overestimation of subsidence and erroneous conclusions (e.g., Müller et al., 2008). Dynamic topography (DT) is the surface expression of the relatively slow (multiple m.y.) mantle flow that originates from the upper thermal boundary of mantle convection (Müller et al., 2018; Davies et al., 2023). The inherited measure of DT on the surface topography is what is left over once the shorter-term local effects of isostatic rebound due to loading/unloading of ice, water, sediment, and crust have been corrected for local effects. If the DT effects go undetected, stratigraphic measures of SL change are likely to be off the mark. The New Jersey margin estimates of SL changes along the East Coast of the United States are a good example of the low estimates of SL change made on this margin before DT influences were known (Miller et al., 1998). Once this margin had been modeled for the long-wavelength dynamic topographic effects, it implicated the previously unsuspected additional subsidence that revised the amplitude estimates upward considerably (Moucha et al., 2008; Müller et al., 2008; Spasojević et al., 2008; Rowley et al., 2013). More recently, the New Jersey researchers have modeled their own earlier back-stripped results for dynamic topographic effects and also found an undetected ~40 m of subsidence over the past 55 m.y. on this margin (Schmelz et al., 2021). These studies convincingly explain the reasons for the discrepancies between the low New Jersey initial estimates and the higher global mean estimates of Haq et al. (1988; also see discussion in Haq, 2014). Rowley et al. (2013) also introduced a cautionary note about the uncertainties inherent in the parameters used in dynamic topographic modeling and the resultant estimates, as well as the difficulties in teasing out guesstimates for the size of Antarctic ice sheets from local data such as the New Jersey margin (e.g., Miller et al., 2008).

Isotopic Measures

While the oxygen-isotopic trends can aid us in better definition of the ages of the SBs within long-ranging biozones, their utility as accurate ice-volume (and thus SL amplitude) determinants have several serious issues that reduce their efficacy. When Earth transitions to icehouse conditions, the predominant signal of bottom-water temperature variations contained in the benthic $\delta^{18}O_{sw}$ record switches to a combination of bottom temperature and ice volume of the accumulated ice sheets. Thus, the argument goes that if we can tease out the temperature component from this record (through an independent proxy, such as Mg/Ca ratios), the residual will then represent a measure of ice volume that can be converted to a global measure of ~0.08–0.11‰ of residual $\delta^{18}O$ value representing ~10 m of SL height (e.g., Adkins et al., 2002; Elderfield et al., 2012). Nonetheless, this conversion recipe does not work well in deep time (>1 Ma), as the benthic oxygen-isotopic record is fraught with inherent as well as external uncertainties that become progressively more challenging farther back in time. Some of these complications include intra-specimen variability of up to 2‰ within the same species (which would be otherwise interpreted as ~200 m of SL change); diagenetic alterations through postdepositional dissolution; precipitation of calcite cements from pore waters (including micro-recrystallization in carbonate tests); and exposure of samples to oxygen during storage. These factors alter the original oxygen-isotopic values in both planktonic and benthic foraminiferal tests (see Pearson, 2012, for details).

The use of Mg/Ca ratios has its own limitations. Cramer at al. (2009) caution that determining paleotemperatures from Mg/Ca values depends on the assumptions we make about the parameters we use for such conversions, and that these are open to variable interpretations (see also Dawber and Tripati, 2011). These authors contend that the uncertainty related to varying pH and ocean's crustal recycling effects on $\delta^{18}O_{sw}$ allows for widely differing results. In addition, Mg/Ca

[1]Supplemental Material. Supplemental Text S1. Further discussion of topics in main paper, rationale for refining ages of depositional surfaces, and additional documentation sources. Figure S1. Composite Cenozoic depositional sequences and eustatic sea-level variations. Please visit https://doi.org/10.1130/GSAT.S.25587480 to access the supplemental material, and contact editing@geosociety.org with any questions.

composition of seawater has itself varied considerably (up to 60%) over the span of the Cenozoic (Horita et al., 2002). Also, Mg/Ca ratios do not always express the prevailing benthic paleotemperatures if the sites are below the calcite compensation depth, an anomaly ascribed to the saturation-state effect on benthic foraminifera at deep-water sites (Lear et al., 2008). Such uncertainties can be significant sources of error in teasing out an accurate temperature component from the overall $\delta^{18}O_{sw}$ signal.

As discussed before by Haq (2014), an additional, perhaps invasive but little realized, source of error is the issue of the progressive depletion of developing ice sheets with respect to ^{18}O (as more ^{16}O isotope is preferentially sequestered in the ice sheet) with increasing elevation and decreasing temperature. This implies that in the early growth phases the mean $\delta^{18}O$ values of ice sheets are higher than later on, and when ice sheets wane without melting completely, the next growth phase (or phases) will make the mean values challenging to unravel. In fact, the data seem to suggest that complete meltings of land-based ice sheets during interglacials were relatively uncommon. These issues indicate that the use of benthic oxygen-isotopic data alone to decipher supposedly accurate quantitative estimates of SL amplitudes of the deep past is not always reliable (see further discussion in the Supplemental Material).

Amplitude Depiction on the Revised Cenozoic Cycle Charts

Because neither direct stratigraphic gauging nor those deciphered from benthic oxygen-isotopic plus Mg/Ca data alone can provide us with an accurate meter of amplitudes of global SL changes, we conclude that it is more meaningful to combine the two methodologies, where possible, to get a sense of the magnitude of variations within each cycle, which will always remain a guesstimate. Oxygen-isotopic data have one advantage over the stratigraphic data—while stratigraphic estimates are mostly eurybatic, the prominent isotopic trends that are replicated in different basins can be interpreted as being global. Thus, we have adopted the approach to use the latter, though not precise, as it provides us with a sense of the relative magnitude of eustatic variations that can constrain those averaged from widely distributed stratigraphic deciphers. We have employed the same quasi-quantitative scheme that we used for the Paleozoic (Haq and Schutter, 2008) and later for the revisions of the Mesozoic Period (Haq, 2014, 2018a, 2018b), to represent the amplitude variations. We classify the amplitude (amount of SL fall from the previous highstand) along a relative scale of ranges rather than as singular values: Minor (<25 m), Medium (25–75 m), and Major (>75 m; see Supplemental Material for more details).

In the summary results shown here, the Cenozoic eustatic framework is presented in two cycle charts (Figs. 1 and 2). A total of 64 SBs have been identified in the Cenozoic. Of these, 55 are interpreted to be of third-order duration (~0.5–2.5 m.y.). In the Paleogene, 34 widely occurring SBs (all third order, except one) have been recorded (Fig. 1), and in the Neogene, 17 SBs are listed (Fig. 2), also all third order, except one. Twelve SBs listed in the Quaternary (Fig. 2) are mostly isotopically calibrated higher-frequency cycles (~400–100 k.y.) that are likely to be identified stratigraphically more readily only in areas of high sedimentation input.

CONCLUSIONS

The Cenozoic eustatic framework presented here reconciles more recent sequence-stratigraphic documentation and ties the SL curves to the latest versions of the biochronologic time scale. We have discussed our rationale for refining the ages of the third order as well as higher-frequency sequence boundaries and MFSs through $\delta^{18}O$ calibrations. We have also discussed our reasons for not professing purely quantitative estimates of the amplitude of SL changes, as both the stratigraphic and isotopic estimates incorporate numerous critical sources of uncertainty in calculating these values. In a best-case scenario, benthic $\delta^{18}O_{sw}$ aided by Mg/Ca ratios could yield such desirable quantitative measures, at least since the onset of major ice sheets on land. Nevertheless, in practice the realty is different; studies that have relied on isotopic data alone to produce amplitude estimates, where there are many uncertainties, are no more accurate than those relying on stratigraphic data alone, where local factors can bias our calculations. In the current revision, for the pre-Quaternary, we continue to rely of the global averaging approach, aided by isotopic data where possible, to get an improved sense of the global mean from several noncontiguous locations. We have to face the fact that meaningful precision with respect to amplitude is not attainable with the methodologies available and we can only guesstimate the eustatic ups and downs using multiple criteria.

Finally, because most Cenozoic fine-tuned, third-order sequence durations fall within the range of long-period modulations of the obliquity (1.2 m.y.) and eccentricity (2.4 m.y.), it is reasonable to affirm that third-order depositional cycles have a close link to major climatic variations, with deviations caused by the tectonic overprint (see further discussion in the Supplemental Material).

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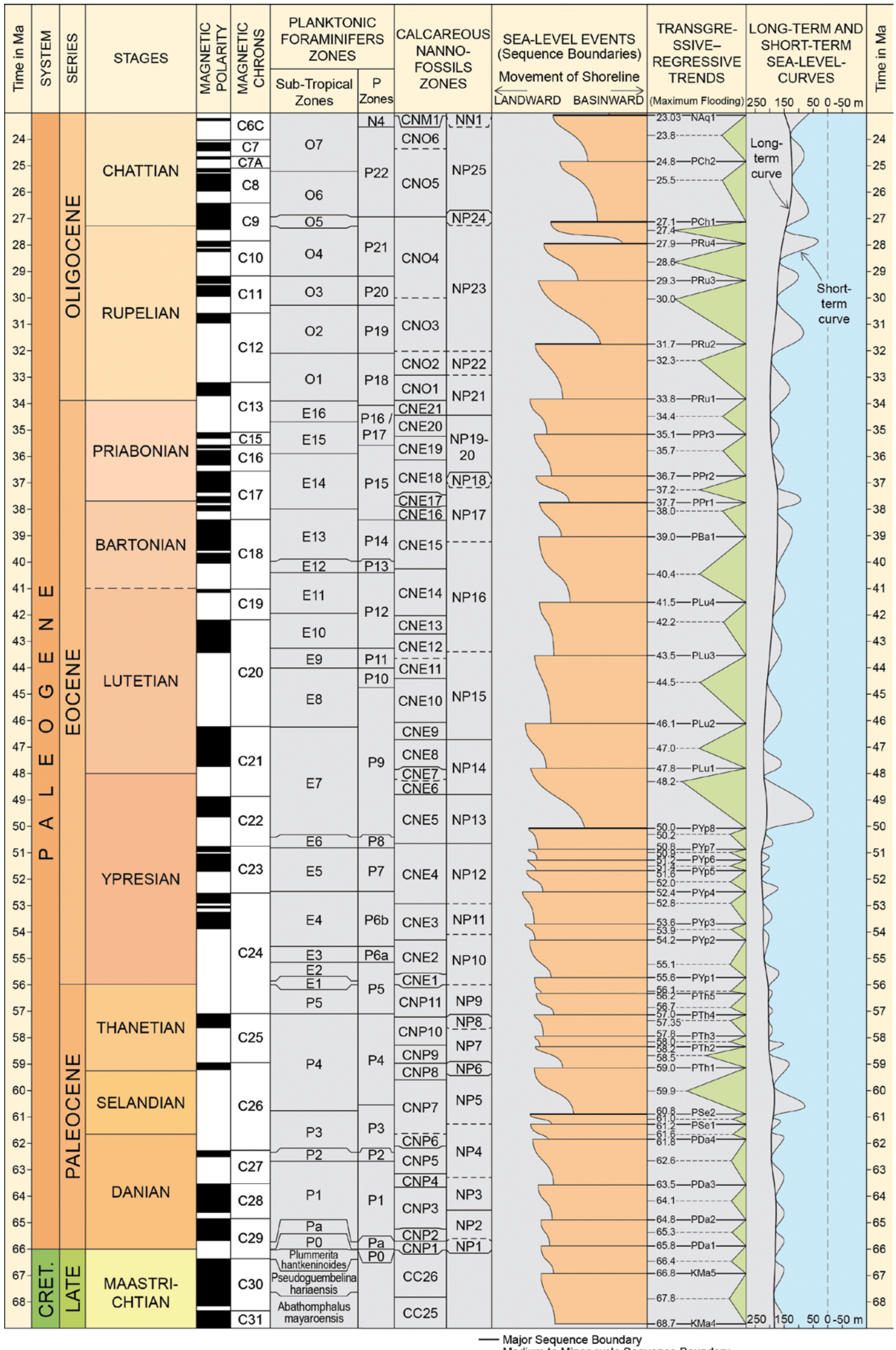

Figure 1. Paleogene depositional sequences and eustatic sea-level variations. Numerical time scale, magnetostratigraphy, and biostratigraphic zones after various authors (in Gradstein et al., 2020). Sequence boundaries are labeled with unique alphanumeric designations (third column from right), where first letter "P" is for Paleogene, followed by two first letters of the Stage name and a number to identify the oldest to youngest events in that Stage. Also listed in this column are the ages of the sequence boundaries and maximum flooding surfaces that have been calibrated to $\delta^{18}O$ data (after Westerhold et al., 2020).

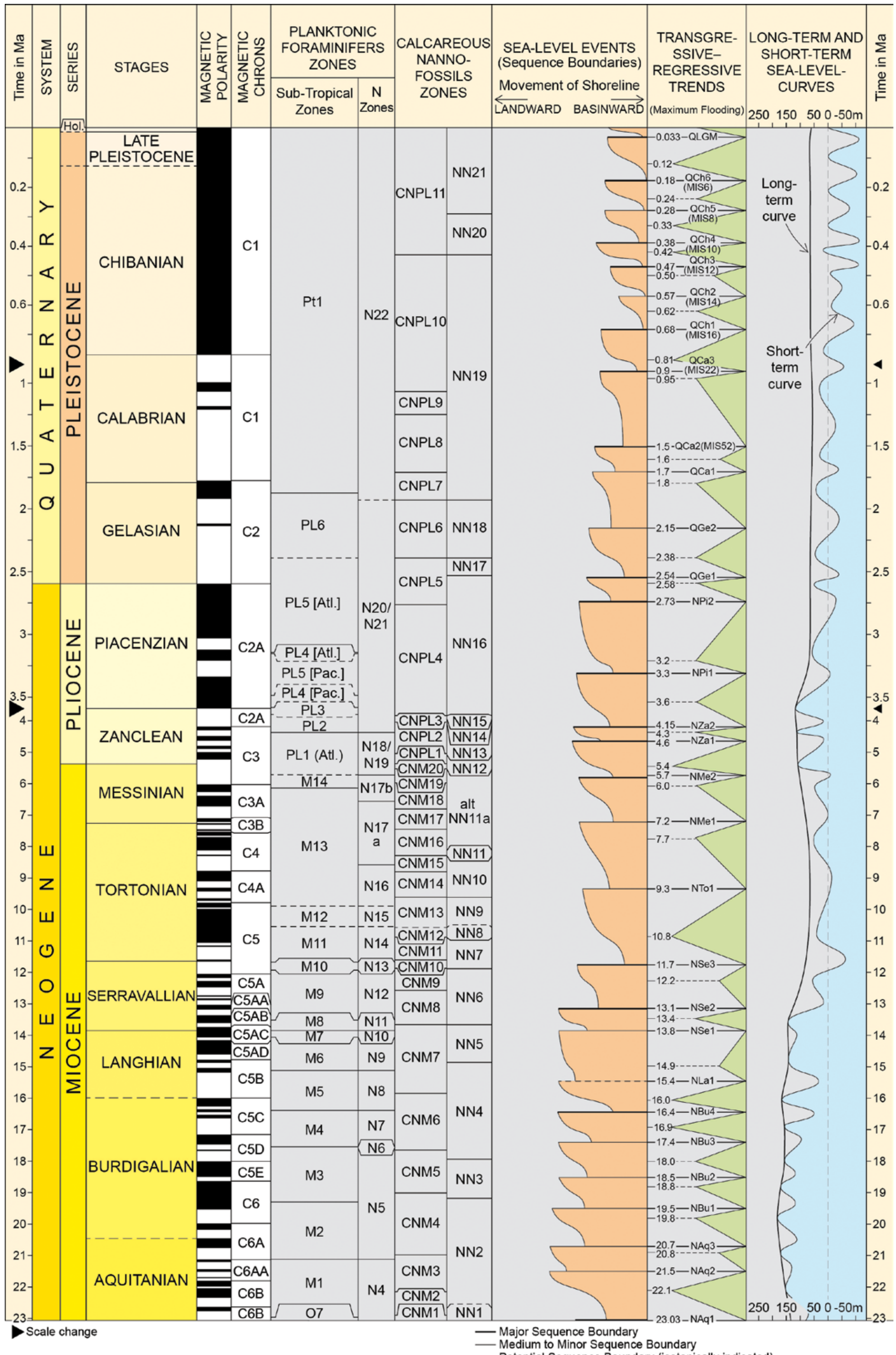

Figure 2. Neogene and Quaternary depositional sequences and eustatic sea-level variations. Numerical time scale, magnetostratigraphy, and biostratigraphic zones after various authors (in Gradstein et al., 2020). Sequence boundaries are labeled with unique alphanumeric designations (third column from right), where first letter "N" and "Q" stand for Neogene and Quaternary, respectively, followed by two first letters of the Stage name and a number to identify the oldest to youngest events in that Stage. Also listed in this column, the ages of sequence boundaries (SB) and maximum flooding surfaces that have been fine-tuned by calibrations with oxygen-isotopic data. For the Quaternary sequences 1.5 Ma and younger, Marine Isotope Stage numbers (e.g., MIS22) in which the SB occurs are also added. The youngest SB that was caused by the withdrawal of the sea during the Last Glacial Maximum is designated as QLGM. [Note: the scale changes at 3.6 and 1.8 Ma in the numerical time scale columns.]

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THE GEOLOGICAL SOCIETY OF AMERICA®
CONNECTS 2024
22–25 September
Anaheim, California, USA

LETTER FROM THE MAYOR OF ANAHEIM

Geological Society of America members,

On behalf of Anaheim, we look forward to you joining us for GSA Connects 2024 at the Anaheim Convention Center.

Our city is proud to host geoscientists from across our nation and the world to share research, enhance collaboration, and advance learning and understanding.

The conference's topics of water importance in a changing climate and living with geology in flux resonate here in Anaheim and across Southern California.

While you are here, I invite you to enjoy our theme parks, restaurants, shops, attractions, arts, and entertainment.

And know that you will leave Anaheim better than you found it. Visitors to our city help fund parks, libraries, community centers, and other services for our residents.

As you visit, know that you will be helping to improve the lives of those who call Anaheim home. On behalf of our city, thank you.

I wish you all an engaging and enriching conference and extend appreciation for your great work on behalf of all of us.

Photo by Derek Humphrey via Flickr. https://creativecommons.org/licenses/by/2.0/

Ashleigh Aitken,
Mayor of Anaheim

Register Now to Secure Your Spot

This year GSA is offering three tiers of registration rates: Early, Regular, and Late. Save big by taking advantage of early registration rates! All rates are in US$.

Category	Member Status	EARLY PRICE (through 31 July)	REGULAR PRICE (1 August–4 September)	LATE PRICE (after 5 September)
Professional	Member	$625	$665	$755
Professional	Non-Member	$850	$890	$980
Senior Professional	Member	$350	$365	$460
Lifetime	Member	$580	$605	$725
Affiliate	Member	$625	$665	$755
Early Career Professional	Member	$385	$400	$485
Student	Member	$185	$200	$275
Student	Non-Member	$260	$275	$400
K–12 Teacher	Member	$85	$85	$95
K–12 Teacher	Non-Member	$150	$150	$200
Guest/Companion	Guest/Companion	$120	$120	$130

Cancelation Policy: A $50 processing fee will be charged for cancelation of a registration if received in writing prior to 11:59 p.m. MDT on 8 August. No refunds will be given after the cancelation deadline of 8 August for any registration type or events.

MEMBER BENEFIT: Reduced registration fees for GSA meetings. Join GSA today at **www.geosociety.org/members**

*Looking to register to attend only one day of the meeting? Use the following promo codes at check out to receive 35% off full-meeting prices.
Sunday – OneDaySun
Monday – OneDayMon
Tuesday – OneDayTues
Wednesday – OneDayWed

**The guest or companion registration fee is for non-geologists accompanying a professional, early career, or student meeting registrant. This fee does not include access to technical sessions. Any guest wishing to see a specific presentation should go to the on-site registration desk to request a special pass.

***GSA offers a 50% discount on annual meeting registration fees for individuals who are both residing in and are citizens of low and low-middle income countries as classified by the World Bank. The 50% discount does not apply to the K–12 Teacher, Guest or Companion, or Field Trip/Short Course Only registration categories.

Visit Anaheim

Anaheim offers an abundance of recreational and scientific opportunities. Visit Disneyland Resort and Downtown Disney District, enjoy the culinary delights of the Anaheim Packing District and Little Saigon, and explore Southern California's geological wonders, from coastal landscapes to hiking trails and iconic sites like the La Brea Tar Pits and Mt. Wilson Observatory.
www.visitanaheim.org

Photo courtesy of Visit Anaheim.

GeoCareers: Your Guide to Career Success

Envision your future career in the geosciences and learn how to make it a reality by attending these events.

GEOCAREERS DAY
Sun., 22 Sept.
Career insights from industry and government representatives.
- Résumé and USAJobs Workshop
- Company Connection
- Mentor Roundtables
- Career Panel

GEOCAREERS CORNER
Sun.–Tues., 22–24 Sept.
Learn valuable information that will help you guide your career to the next level.
- Career Presentations
- Résumé Review Clinic
- Drop-in Mentoring
- Early Career Professional Coffee
- Geology Club Meet-Up
- Networking Reception
- Women in Geology Program
- Post or View Jobs

Visit website for event details, dates, and times.

Make Your Hotel Reservation Now

Stay at one of the hotels in GSA's block steps away from the convention center (ACC). Book your hotel reservation through GSA Housing Bureau/Orchid.Events by 28 August to guarantee you receive GSA's special meeting rates. Please visit https://bit.ly/4bsRy4u for more information.

Hotels	Rate*	Distance to ACC	Parking Per Day
Anaheim Marriott (HQ Hotel)	$249	200 ft	Self: $34; Valet: $44
Hilton Anaheim	$244	200 ft	Self: $24; Valet: $39
Best Western Plus Stovall's Inn	$219	½ mile	Self: $20
Homewood Suites by Hilton Anaheim	$269	¼ mile	Self: $28
Hyatt Place at Anaheim Resort/Convention Center	$269	¼ mile	Self: $28
Residence Inn at Anaheim Resort/Convention Center	$259	Adjacent	Self: $28

*Rates are in U.S. dollars and do not include the current applicable tax of 15% per room, per night.

PLEASE NOTE: The official GSA housing bureau is Orchid.Events. To receive the GSA group rate at each hotel, reservations must be made through Orchid and not directly with the hotels. GSA and Orchid will NOT contact attendees directly to solicit new reservations. If you are contacted by a vendor who claims to represent GSA, please notify the GSA Meetings Department at meetings@geosociety.org. Please do not make hotel arrangements or share any personal information through any means other than a trusted, reliable source.

Sponsorship Opportunities

Don't miss the opportunity to reach a broad cross section of geoscientists.

5 BENEFITS OF SPONSORING

1. Support budding and established geoscientists in their academic and professional journeys.
2. Boost your company's visibility and recognition within the international geoscience community.
3. Enhance the overall conference experience for all attendees.
4. Gain exposure on an international stage and tap into a network of global professionals.
5. Leverage unique branding opportunities tailored to your organization's needs.

"Our partnership with the Geological Society of America has been part of our overall engagement plan to build more informal connections with the scientific community. It has been a resounding success."

—Jonathan Knapp, Bruker

For more information on sponsorship opportunities, visit **https://bit.ly/3QCSZp2.**

Exhibit at GSA Connects 2024

Reach a target audience of geoscientists who are eager to learn about your products and services.

EXHIBITOR MOVE IN & MOVE OUT

Move In: Sat., 21 Sept., 8 a.m.–5 p.m.
Sun., 22 Sept., 8 a.m.–3 p.m.
Move Out: Wed., 25 Sept., 2–8 p.m.

RESOURCE & INNOVATION CENTER (EXHIBIT HALL) HOURS

Sun., 22 Sept., 5–7 p.m.
Opening Reception begins at 5 p.m.

Mon., 23 Sept., 10 a.m.–6:30 p.m.
Afternoon Reception: 4:30–6:30 p.m.

Tues., 24 Sept., 10 a.m.– 6:30 p.m.
Afternoon Reception: 4:30–6:30 p.m.

Wed., 25 Sept., 10 a.m.–2 p.m.

TO RESERVE, CONTACT:

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For booth pricing go to **https://bit.ly/4bhbZBW**.

Ignite Your Curiosity with Noontime Lectures

Grab your lunch and listen to engaging talks on hot geoscience topics.

Assessing Landscape Response to Modern Climate Change: How Much Do We Know?

Amy E. East, Jonathan A. Warrick, Amy E. Gibbs, and Patrick L. Barnard, U.S. Geological Survey Pacific Coastal and Marine Science Center, Santa Cruz, California

Dongfeng Li, National University of Singapore and Peking University, Beijing, China

Joel B. Sankey, U.S. Geological Survey Southwest Biological Science Center, Flagstaff, Arizona

Margaret H. Redsteer, University of Washington Bothell, Bothell, Washington

Jeffrey A. Coe, U.S. Geological Survey Landslide Hazards Program, Golden, Colorado

Today, climate change is affecting virtually all terrestrial and nearshore settings. This presentation will discuss the challenges of identifying and measuring climate-driven physical landscape responses to modern warming and its associated hydrologic shifts. These challenges include short and incomplete data records, land use and seismicity masking climatic effects, biases in data availability and resolution, and signal attenuation in sedimentary systems. Despite such challenges, the scientific community has important opportunities to learn from historical and paleo data, select especially sensitive study sites, and ensure that null results are reported to better characterize the extent and nuances of climate-change effects. Determining with greater confidence whether landscape changes are attributable to climate change (as opposed to land use, tectonic effects, or natural variability) will also lead to better predictive capabilities. Evaluating and quantifying climate-driven sedimentary and geomorphic changes will enable societies to better manage the effects on human health and safety, infrastructure, water–food–energy security, economies, and ecosystems that follow from climate-driven physical landscape change.

Be a Mentor, Share Your Experience

Become a mentor and help students navigate the meeting, introduce them to contacts, discuss career paths, and offer advice. Graduate students, early career geoscientists, professionals, and retirees are welcome to serve as mentors.

DROP-IN MENTOR
This one-on-one mentoring activity takes place in the GeoCareers Corner. Students have 30 minutes to ask questions and seek advice from a mentor. Approximately 28 mentors are needed.

NETWORKING RECEPTION MENTOR
The Networking Reception is a gathering of students, early career professionals, and mentors. Mentors answer questions, offer advice about career plans, and comment on job opportunities within their fields. Approximately 40 mentors are needed.

RÉSUMÉ OR CV MENTOR
Résumé mentors are matched with a student on-site to review the student's résumé or curriculum vitae (CV). Consultations take place for 30 minutes in the GeoCareers Corner in a one-on-one setting. Approximately 28 mentors are needed.

WOMEN IN GEOLOGY MENTOR
Mentors from a variety of sectors answer career questions and offer advice during the Women in Geology Reception. Approximately 30 mentors are needed.

"THE STUDENTS' QUESTIONS WERE THOUGHT-PROVOKING AND THEY MADE ME REALIZE WHAT A SATISFYING JOB I'VE GOT. I'D LIKE TO DO THIS AGAIN!"

Complete the mentor interest form at **https://bit.ly/BeaMentorGSA.**

Share Your Science with a Global Audience

Abstracts are vital to creating a robust technical program for Connects 2024. Submit your abstract to a topical or discipline session to get your research in front of an engaged audience of geoscience students and professionals.

Abstract submissions relating to the meeting themes ***Life Along an Active Margin*** *and* ***Water in Our Changing World*** *are encouraged.*

Submit Your Abstracts: **https://bit.ly/3VDhuWt**

FAQ

Submission guide: **https://bit.ly/3VFv37K**

NUMBER OF ABSTRACTS

- You can submit up to two abstracts if:
  - One is for a poster presentation.
  - Both cover different content.
- Invited submissions to Pardee Keynote or topical sessions don't count against your limit!

FEES

- GSA Members: Professionals $60, Students $25
- Non-Members: Professionals $80, Students $50

POSTER PRESENTERS

- GSA provides one free horizontal 8' w x 4' h display board and Velcro to hang your poster.

ORAL PRESENTERS

- Presentation length: 12 minutes + 3 minutes for Q&A.
- Check in at the Speaker Ready Room 24 hours before you present.
- Tech session rooms include a PC with Windows 10/MS Office 2021.
- Use a 16:9 screen ratio for presentations.

Recordings of topical sessions, keynote symposia, and more will be available online after the meeting.

Abstracts deadline: 18 June

KNOW BEFORE YOU GO

When you submit an abstract to GSA, it's more than just sharing your research; it's a promise to present your findings with integrity and respect. All our authors and presenters agree to:

- **Commit to Present:** Submitting your abstract means you're planning to be there, ready to share and discuss your work.
- **Maintain Integrity in Research:** Stay true to your abstract's content and conclusions as reviewed, ensuring high quality and honesty throughout.
- **Recognize All Efforts:** Celebrate collaboration! Ensure any co-authors are acknowledged, have contributed significantly, are informed of, and consent to their inclusion.
- **Ensure Quality:** Craft a presentation that reflects your dedication to excellence in research.

At GSA, we're passionate about fostering diversity among our event speakers and panelists, ensuring a rich, inclusive experience for everyone.

GSA Connects 2024 is an in-person event.
We can't wait to see you in Anaheim, California, USA!


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Early registration deadline: 31 July
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Standard registration deadline: 4 Sept.
Registration after 4 Sept. will cost an additional US$30.

Short Course information:

Did you know? You are welcome to take short courses without registering for the meeting.

ONLINE COURSES

501. **Engineering Geological Investigations for Pumped Storage Hydro Projects.** Fri., 13 Sept., 8 a.m.–noon PDT. US$40. Limit: 40. CEU: 0.4. **Instructors:** Imran Sayeed, Aquagreen Engineering Management Ltd.; Sabiha Imran, Manav Rachna International Institute of Research and Studies.

502. **Finding and Telling Your Science Story with Data Visualization in Tableau.** Fri., 13 Sept., 8 a.m.–noon PDT. US$40. Limit: 40. CEU: 0.4. **Instructors:** Lisa Stright, Colorado State University; Dana Stright, Skye Analytics.

FRIDAY COURSES (IN-PERSON)

503. **Forensic Geochemistry: Integrating Lead and Strontium Isotopes into Environmental Investigations of Contaminant Releases into Soil and Groundwater Systems.** Fri., 20 Sept., 8 a.m.–5 p.m. PDT. US$95. Limit: 40. CEU: 0.8. **Instructor:** Richard Hurst.

504. **Methods and Geological Applications in Geo-Thermo-Petrochronology I.** Fri., 20 Sept., 8 a.m.–5 p.m. PDT. US$30. Limit: 40. CEU: 0.8. **Instructors:** Mauricio Ibanez-Mejia, University of Arizona; George Gehrels, University of Arizona; Michelle Foley, University of Arizona; Clay Campbell, University of Arizona; Martin Senger, University of Arizona. ***Part II of this course takes place on Saturday (510).***

FRIDAY–SATURDAY COURSES (IN-PERSON)

505. **Innovations in 3-D Geology.** Fri.–Sat., 20–21 Sept., 8 a.m.–5 p.m. PDT both days. US$70. Limit: 40. CEU: 1.6. **Instructors:** Richard Berg, Illinois State Geological Survey; Harvey Thorleifson, University of Minnesota; Kelsey MacCormack, Alberta Geological Survey. Course Endorser: Association of American State Geologists.

506. **Modeling Magmatic and Mantle Processes along Active Plate Margins with alphaMELTS.** Fri., 20 Sept., 1–5 p.m. PDT and Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95. Limit: 40. CEU: 1.2. **Instructors:** Paula Antoshechkina, California Institute of Technology; Paul Asimow, California Institute of Technology; Matthew Gleeson, University of California, Berkeley; Penny Wieser, University of California, Berkeley. **Course Endorser:** *National Science Foundation.*

SATURDAY COURSES (IN-PERSON)

507. **How to Design a Good Survey: Developing and Validating Instruments for Geoscience Educators and Researchers: Human Subject Research Insights for Using Surveys and Interviews.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$90. Limit: 50. CEU: 0.8. **Instructors:** Pierre Lu, University of Texas Rio Grande Valley; Leilani Arthurs, University of Colorado, Boulder.

508. **Introduction to Drones (sUAS) in the Geosciences.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95.

INDUSTRY TRACKS

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

Economic Geology | Energy | Engineering | Hydrogeology and Environmental Geology

Limit: 40. CEU: 0.8. **Instructor:** Gregory Baker, Colorado Mesa University. **Course Endorsers:** *GSA Hydrogeology Division; GSA Geoarchaeology Division; GSA Quaternary Geology and Geomorphology Division.*

509. **Unraveling the Thermal Signature of Mountain Building.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95. Limit: 40. CEU: 0.8. **Instructors:** Kevin Furlong, Pennsylvania State University; Matthew Herman, California State University, Bakersfield; Kirsty McKenzie, University of North Carolina at Chapel Hill. **Course Endorsers:** *GSA Geochronology Division; GSA Geophysics and Geodynamics Division; GSA Quaternary Geology and Geomorphology Division; GSA Structural Geology and Tectonics Division.*

510. **Methods and Geological Applications in Geo-Thermo-Petrochronology II.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$30. Limit: 40. CEU: 0.8. **Instructors:** Mauricio Ibanez-Mejia, University of Arizona; Kendra Murray, Idaho State University; Allen Schaen, University of Arizona. ***Part I of this short course takes place on Friday (504).***

511. **Talking Science: A Communicating Science Workshop.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$15. Limit: 40. CEU: 0.8. **Instructors:** Steven Jaret, Kingsborough Community College; William Holt, Stony Brook University. **Course Endorser:** *Planetary Geology.*

512. **Geological Models—and Why They Are Indispensable.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95. Limit: 15. CEU: 0.8. **Instructor:** Tom Martlev Pallesen, I-GIS, Denmark.

513. **Introduction to ArcGIS Pro for Planetary Geology.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$40. Limit: 40. CEU: 0.8. **Instructor:** Zoe Learner Ponterio, Cornell University. **Course Endorser:** *Planetary Data Training Workshops.*

514. **Quantitative Analysis, Visualization, and Modeling of Detrital Geochronology Data.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95 professionals; US$50 students. Limit: 40. CEU: 0.8. **Instructors:** Joel Saylor, University of British Columbia; Kurt Sundell, Idaho State University; Glenn Sharman, University of Arkansas; Gabriel Bertolini, University of British Columbia.

515. **Geochemical Modeling through the Water-Organic-Rock-Microbe Portal.** Sat., 21 Sept., 8 a.m.–5 p.m. PDT. US$95. Limit: 15. CEU: 0.8. **Instructors:** Everett Shock, Arizona State University; Grayson Boyer, Arizona State University.

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

516. **Decoding the Past: Deep Learning for Macro-evolutionary Analysis.** Sat., 21 Sept., 9 a.m.–5 p.m. PDT. US$95. Limit: 40. CEU: 0.7. **Instructors:** Rebecca Cooper, University of Fribourg; Fernando Blanco, University of Gothenburg; Juan Cantalapiedra, Museo Nacional de Ciencias Naturales (CSIC); Torsten Hauffe, University of Fribourg; Kateryn Pino, Universidad de Concepción; Daniele Silvestro, University of Fribourg.

517. **Introduction to High-Resolution Topography and OpenTopography.** Sat., 21 Sept., 9 a.m.–5 p.m. PDT. US$50. Limit: 40. CEU: 0.7. **Instructors:** Christopher Crosby, Earthscope Consortium; Ramon Arrowsmith, Arizona State University. **Course Endorser:** *OpenTopography.*

518. **OneStratigraphy Database and Its Applications in Stratigraphy and Paleobiology.** Sat., 21 Sept., 9 a.m.–5 p.m. PDT. US$25. Limit: 40. CEU: 0.7. **Instructors:** Junxuan Fan, Nanjing University; Jiao Yang, Nanjing University; Zhengbo Lu, Nanjing University; Tianyi Chu, Nanjing University. ***Those who complete the course will receive two free GSA ebooks of their choice ($25 value).***

519. **Designing Field Safety Resources within an Intersectional Framework Lens.** Sat., 21 Sept., 9 a.m.–5 p.m. PDT. US$90. Limit: 40. CEU: 0.7. **Instructor:** Blair Schneider, University of Kansas. **Course Endorser:** *ADVANCEGeo Partnership.*

520. **Food-Energy-Water-Nexus–Based Education: Promising Practices and New Directions for Geoscience Education and Education Research.** Sat., 21 Sept., 8 a.m.–noon PDT. US$20. Limit: 40. CEU: 0.4. **Instructors:** Hannah Scherer, Virginia TechAg, Leadership, & Community Education; Bradlee Wahid Cotton, Auburn University; Jerry Burgess, Johns Hopkins University; Katherine McCarville, University of Iowa. **Course Endorsers:** *GSA Geoscience Education Division; National Association of Geoscience Teachers (NAGT); NAGT Geoscience Education Research Division.* ***Those who complete the course will receive two free GSA ebooks of their choice ($20 value).***

521. **Tectonochronology: New Methods, Theories, and Some Cases.** Sat., 21 Sept., 8 a.m.–noon PDT. US$25. Limit: 40. CEU: 0.4. **Instructor:** Yu Wang, China University of Geosciences, Beijing.

522. **Preparing Your Students for the Jobs They Want.** Sat., 21 Sept., 1–5 p.m. PDT. US$95. Limit: 40. CEU: 0.4. **Instructors:** Anne Egger, Central Washington University; Karen Viskupic, Boise State University. **Course Endorser:** *National Association of Geoscience Teachers (NAGT).*

523. **Quality Management Systems and Their Application in Geoscience Laboratories.** Sat., 21 Sept., 1–5 p.m. PDT. US$55. Limit: 40. CEU: 0.4. **Instructor:** Michele Wolf, U.S. Geological Survey.

Figure 1. Basalt cliffs of the Drakensberg Escarpment rise above the typical summer mist. Photo credit: Lon Abbott and Terri Cook.

The Drakensberg Mountains: Southern Africa's Barrier of Spears

Lon Abbott[1,*] and Terri Cook[2]

When the Zulu and the Sotho, two Bantu-speaking peoples, migrated into southern Africa from the north around 500 C.E. (Ehret, 1998), they marveled at the precipitous, 1,500-m-high escarpment that marks the southern and eastern edges of the highlands along today's Lesotho–South African border (Fig. 1). Both groups drew on their martial traditions when naming this seemingly impenetrable feature, calling it the "barrier of spears'" in their respective languages. To the Dutch-speaking Boer who encountered the escarpment over a millennium later, it resembled a dragon's back, hence the name Drakensberg in Afrikaans. All these immigrant groups both mixed and clashed with the local, click language–speaking San people, the traditional inhabitants, who have left a 3,000-year legacy of evocative paintings in the natural rock shelters formed by overhangs in the range's Clarens Sandstone (Fig. 2; Witelson et al., 2021).

The Drakensberg Escarpment's magnificent scenery continues to fuel popular imagination today. South Africans are fond of claiming that the Drakensberg were the inspiration for J.R.R. Tolkien's Misty Mountains, which feature in *The Hobbit* and the *Lord of the Rings* trilogy. Although the comparison is apt, the author, who was born in Bloemfontein, South Africa, emigrated at the age of three and said he had few memories of the continent. The Drakensberg did, however, inspire a

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twenty-first-century cultural icon: Wakanda, the mythical country featured in director Ryan Coogler's 2018 Academy Award–nominated film *Black Panther*, which he based on the geography and history of Lesotho (Jones, 2018).

HOW DO GREAT ESCARPMENTS EVOLVE? THE DRAKENSBERG AS A TESTING GROUND

The Drakensberg constitute the most dramatic section of the much longer Great Escarpment, whose ramparts form a ring paralleling southern Africa's coastline and separate the inland Karoo/Kalahari plateau from the coastal lowlands (Fig. 3). Such inland plateaus flanked by escarpments are common features of the passive continental margins surrounding the Atlantic, Indian, and other ocean basins that formed during breakup of the supercontinent Pangaea. These features are called elevated passive continental margins (EPCM), and most geologists consider them an enduring legacy of continental rifting (e.g., Blenkinsop and Moore, 2013).

Ever since the classic work of Lester King (1947), the Drakensberg Escarpment has played a prominent role in scientists' attempts to decipher how EPCMs evolve. The Drakensberg Escarpment currently lies 200 km from the coast, and it isn't associated with major faults. But King, an early supporter of continental drift, concluded that the escarpment originated along Mesozoic coastal faults when Gondwana split apart. He argued that the escarpment retreated landward, a process called backwearing. That was a departure from William Morris Davis's (1909) then-preeminent downwearing model, which emphasized vertical erosion. Despite their disagreement on mechanism, both Davis and King believed that today's landscapes were produced by multiple cycles of uplift and subsequent erosion. The end result of each cycle was a nearly flat plain, which Davis called a peneplain and King called a pediplain. The number of low-relief surfaces preserved in a landscape equals the number of cycles of uplift that landscape has experienced.

Subsequent researchers have built on King's (1953) ideas, producing the "classical" cyclic model of southern African landscape development. It calls for three cycles, including major uplift at 2.5 Ma and retreat of the Drakensberg Escarpment at an average rate >1 km/m.y. since the Mesozoic (Partridge and Maud, 1987).

Work in the Drakensberg using cosmogenic radionuclide dating (CRN) and low-temperature thermochronology has been central to a comparatively recent reassessment of the classical model and the tenet that EPCM escarpments retreat inland from the coast. Using CRN dating, Fleming et al. (1999) measured the current escarpment retreat rate at a mere 50–95 m/m.y., an order of magnitude slower than the classical model predicts. Two low-temperature thermochronology studies bolstered the case that the Drakensberg Escarpment did not originate on the coast (Brown et al., 2002; Flowers and Schoene, 2010), and a numerical model (van der Beek et al., 2002) indicated that fluvial erosion quickly erases the rift-generated coastal escarpment. Downwearing then produces a new escarpment (the modern one) along the post-breakup drainage divide.

These results placed downwearing, minus Davis's or King's erosion cycles, back at the forefront of scientific thinking about EPCM evolution. But not everyone agrees that the Drakensberg Escarpment is the result of downwearing (Blenkinsop and Moore, 2006; Roberts and White, 2010). How and when EPCM escarpments form remains an open question; given that the Drakensberg is the type example of this landform, it's a good bet that it will figure prominently in future research striving for an answer.

ROCKS OF THE DRAKENSBERG: THE KAROO SUPERGROUP

All rocks exposed in the Drakensberg belong to the Karoo Supergroup, a world-class sequence of sedimentary and volcanic rocks that accumulated in the Karoo Basin, which formed in the Carboniferous in response to flexural loading by the Cape Fold Belt Mountains

THE RANGE'S GEOLOGIC AND GEOMORPHOLOGIC ATTRIBUTES MAKE IT A TESTING GROUND IN THE CONTINUING QUEST TO ANSWER FIRST-ORDER SCIENTIFIC QUESTIONS.

Figure 2. Gudu Falls tumbles over a cliff in the Clarens Sandstone, the uppermost formation in the Stormberg Group. Photo credit: Lon Abbott and Terri Cook.

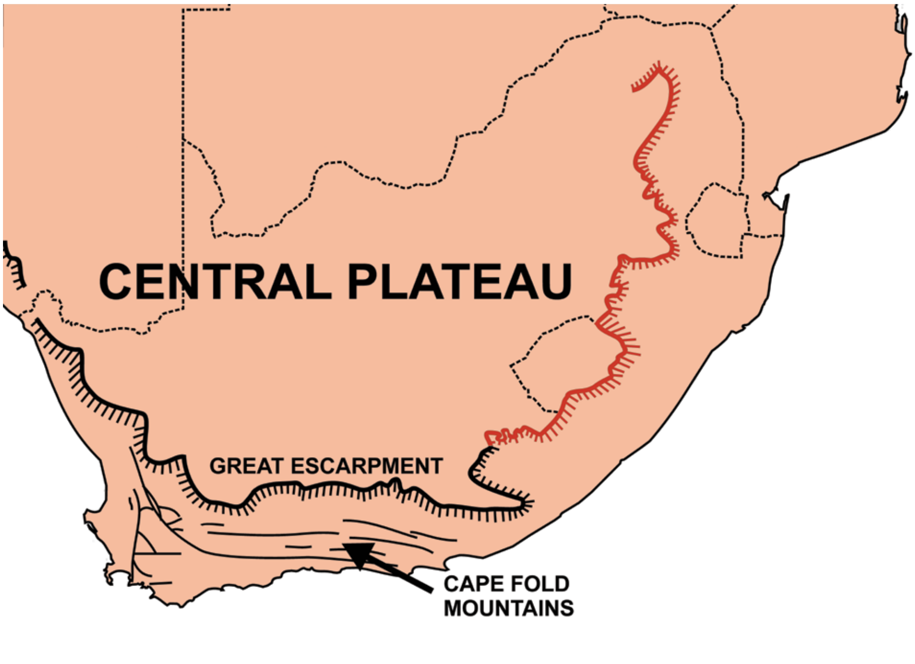

Figure 3. Map of southern Africa showing the high Central Plateau (Karoo/Kalahari Plateau) flanked by the Great Escarpment, shown by the hatched line. The red hatched line delineates the Drakensberg portion of the escarpment. The country of Lesotho is outlined by the dashed black line and the segment of the red hatched line it touches. That is the High Drakensberg. Credit: Oggmus via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:The_Escarpment_and_the_Drakensberg.jpg).

(Catuneanu et al., 2005). The Supergroup consists of a >6-km-thick stack of fossiliferous sedimentary rocks that accumulated between ~300–183 Ma and that preserve excellent records of both the Permian–Triassic and Triassic–Jurassic mass extinction events, two of the "Big Five" extinctions. These are overlain by 1.6 km of Jurassic basalt that erupted from the Karoo Large Igneous Province (LIP); LIPs are Earth's biggest volcanic centers. The Karoo Basin stretches across most of South Africa, and only the two stratigraphically highest of the Supergroup's five groups, the Stormberg and Drakensberg groups, are exposed in the high Drakensberg Mountains.

The 1.5-km-thick Stormberg Group, which is exposed on the lower flanks of the Drakensberg, consists of Triassic to Early Jurassic fluvial and aeolian sediments deposited in an increasingly arid climate. Deposition of the Elliot Formation spanned the Triassic–Jurassic boundary, and it contains an abundant and diverse vertebrate fossil record. That makes it a global standard for study of Mesozoic vertebrate evolution and the Triassic–Jurassic mass extinction event (Bordy et al., 2020). This formation is overlain by the cliff-forming, aeolian Clarens Sandstone (Fig. 2). Erosion of the Clarens produces abundant overhangs, beneath which the San left thousands of evocative paintings, typically in locations where the rock face is irregular. That technique causes the figures to appear as if they are either emerging from the rock or receding into the background. Archaeologists conclude that the San used the rock face as a "veil" that obscures other spiritual worlds from our own; the paintings depict a shaman's out-of-body experiences while visiting other worlds during their spiritual work (Lewis-Williams and Dowson, 1990).

THAT TECHNIQUE CAUSES THE FIGURES TO APPEAR AS IF THEY ARE EITHER EMERGING FROM THE ROCK OR RECEDING INTO THE BACKGROUND.

Clarens deposition ended with the onset of rapid and massive basaltic volcanism in the Karoo LIP (Fig. 1; Catuneanu et al., 2005). Although most of the Clarens Formation was deposited in a sand dune–dominated desert, just before the eruptions began the area became moist enough to support a diverse biota, including gymnosperm trees. Some of the earliest lava flows spilled into streams and lakes, producing pillow basalts. The lava flows carried logs with them, as evidenced by the petrified wood that is preserved among the pillow lavas (Bordy et al., 2021).

DO FLOOD BASALTS TRIGGER MASS EXTINCTIONS?

Multiple researchers have noted the striking age correlation between the emplacement of LIPs, various indicators of environmental perturbations such as carbon isotope excursions and oceanic anoxic events, and mass extinctions. This temporal correlation has led to the hypothesis that injection of massive quantities of CO_2 and SO_2 into Earth's atmosphere during LIP eruptions produces massive environmental change that in turn triggers mass extinction (e.g., Courtillot and Renne, 2003). The Karoo LIP is an excellent example of that correlation (e.g., Pálfy and Smith, 2000; Moulin et al., 2011; Sell et al., 2014).

The Drakensberg flood basalts are big, covering 3 million km^2, but they are merely the biggest surviving remnant of what was once a much larger basalt plain. The 183 Ma basalt over which Victoria Falls plunges along the Zimbabwe–Zambia border is another remnant, and the contemporaneous dolerite dikes and sills that are abundant throughout southern Africa record a vast area where these lavas were once continuous but subsequently eroded (Marsh et al., 1997). The Karoo LIP erupted immediately before Gondwana broke up, and it also covered portions of Antarctica and Australia in what is called the Ferrar LIP. Together, the estimated volume of the Karoo-Ferrar LIP is a massive 2.5 million km^3. The ascending magmas not only carried large quantities of volcanically derived CO_2 and SO_2 but also oxidized the abundant carbon- and sulfur-rich Karoo Supergroup rocks, generating yet more of these temperature-altering gases (Svensen et al., 2007). Moulin et al. (2011) estimated that Karoo LIP eruption liberated >60,000 gigatons of CO_2, enough to affect global climate.

But directly ascribing environmental changes to outgassing from the Karoo or any LIP is tricky and requires ultra-precise dating of both the LIP and the environmental changes. For the Karoo LIP, the combination of stratigraphic observations and magnetostratigraphy with high-precision Ar/Ar and U/Pb dating has enabled geoscientists to approach the necessary resolution (Moulin et al., 2011; Sell et al., 2014; Antoine et al., 2022). Evidence indicates that the Karoo LIP experienced multiple eruptive phases, with the vast majority of the volcanic pile erupted in as little as 250,000 years at ~183 Ma. The first pulse seems to correspond with global cooling and marine regression at the Pliensbachian–Toarcian stage boundary, while the main eruptive event coincides with global warming and oceanic anoxia in the early Toarcian. Sharp carbon isotope excursions testify to the profound ecological disruptions that accompanied both pulses and correspond to the two phases of a second-order mass extinction event (Pálfy and Smith, 2000; Moulin et al., 2011). The ever-higher precision age constraints on the Karoo LIP and contemporaneous environmental effects have made it a prominent test case for the idea that LIP eruptions have triggered most of the planet's profound environmental and biotic crises.

AN OUTSTANDING EXAMPLE OF AFRICA'S GEOHERITAGE

The Drakensberg possess grand scenery that has nurtured the spiritual life of its inhabitants for millennia and continues to inspire the popular imagination. The range's geologic and geomorphologic attributes make it a testing ground in the continuing quest to answer first-order scientific questions. These characteristics are the very essence of the concept of geoheritage, which the Geological Society of America (GSA) defines as "sites or areas of geologic features with significant scientific, educational, cultural, and/or aesthetic value" (National Academies of Sciences, Engineering, and Medicine, 2021; GSA, 2022).

Protection of landscapes that possess such international geological significance is the goal of UNESCO Global Geoparks, as is ensuring that their protection goes hand in hand with sustainable development that benefits the geopark's inhabitants (UNESCO, 2023). Yet despite Africa's rich geoheritage, only two of the 177 UNESCO Global Geoparks are on the continent, in Morocco and Tanzania. In December 2022, UNESCO conducted a capacity-building workshop on African geoheritage in Kenya. It focused on devising ways to connect Africa's rich geological and cultural heritage to mechanisms that promote regional sustainable development (UNESCO, 2023). We hope this workshop catalyzes the establishment of more UNESCO Global Geoparks in Africa, and we think that portions of the Drakensberg are worth considering as additions to that illustrious list.

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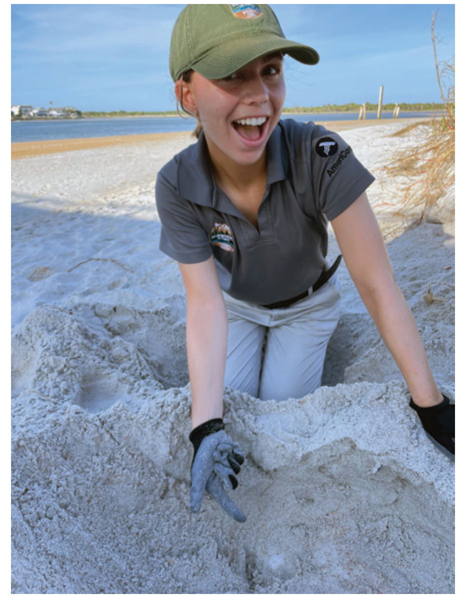

Molly Niekamp next to a sea turtle nest egg cavity during a nest site evaluation at Fort Matanzas National Monument, Florida (NPS photo).

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The award is a travel grant for a student (undergraduate or graduate) presenting a paper or poster at GSA Connects. The grant is competitive and will be awarded based on evaluation of the scientific merit of the research topic and the clarity of an expanded abstract for the paper or poster prepared by a student for presentation in the Division's technical session at the meeting. **community.geosociety.org/geoarchdivision/awards/student/hay**

GEOLOGY AND SOCIETY DIVISION

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HISTORY AND PHILOSOPHY OF GEOLOGY DIVISION

HISTORY AND PHILOSOPHY OF GEOLOGY STUDENT AWARD

Nominations due **15 June**

Submit nominations to the Division secretary/treasurer: Christopher Hill, chill2@boisestate.edu

The History and Philosophy of Geology Division provides a student award in the amount of US$1,000 for a paper to be given at GSA Connects. Awards may also be given for second place. Oral presentations are preferred. Faculty advisors may be listed as second author, but not as the lead author of the paper. The proposed paper may be (1) a paper in the history or philosophy of geology; (2) a literature review of ideas for a technical work or thesis/dissertation; or (3) some imaginative aspect of the history or philosophy of geology we have not thought of before. Students should submit an abstract of their proposed talk and a 1,500–2,000-word prospectus for consideration. Currently enrolled undergraduates and graduate students are eligible, as are students who received their degrees at the end of the fall or spring term immediately preceding GSA Connects. The award is open to all students regardless of discipline, provided the proposed paper is related to the history or philosophy of a geological idea/person. The award is made possible by a bequest from the estate of Mary C. Rabbitt. Monies for the award are administered by the GSA Foundation. **community.geosociety.org/histphildiv/awards/student**

PLANETARY GEOLOGY DIVISION

EUGENE M. SHOEMAKER IMPACT CRATERING AWARD

Nominations due **15 August**

Submit nominations here: https://www.lpi.usra.edu/Awards/shoemaker/

The Eugene M. Shoemaker Impact Cratering Award is for undergraduate or graduate students, of any nationality, working in any country, in the disciplines of geology, geophysics, geochemistry, astronomy, or biology. The award, which will include US$2500, is to be applied to the study of impact craters, either on Earth or on the other solid bodies in the solar system. Areas of study may include but shall not necessarily be limited to impact cratering processes; the bodies (asteroidal or cometary) that make the impacts; or the geological, chemical, or biological results of impact cratering. **community.geosociety.org/pgd/awards/shoemaker**

SOILS AND SOIL PROCESSES DIVISION

STUDENT RESEARCH AWARDS
Nominations due **1 June**

Submit nominations to the Division awards committee chair: Steven Driese, Steven_Driese@baylor.edu

The Soils and Soil Processes Division of GSA is pleased to announce the availability of three student awards: two for graduate research (US$1,000) and one for undergraduate research (US$500). The proposed research must emphasize soil or paleosol research for it to be considered for an award. Awards will be announced by 15 June 2024. Funds may be used for field or laboratory research. Applicants are encouraged to become members of the Division, but it is not a requirement for proposal consideration.

Proposal materials should include the following, in a single file (PDF or Word only):

1. Student's full legal name, affiliation, contact information, current degree program, and expected graduation date.
2. Proposal narrative (1–2 pages): this will include the purpose and significance of the proposal research and the methods employed to complete the research.
3. Itemized budget. Please include information on all additional sources of funding for the project, including previous and pending sources of funding.
4. Project supervisor's name and contact information. Your supervisor may be contacted for a recommendation if your proposal is considered for funding.

POLICY

Geosciences Congressional Visits Day 2024

Looking for a way to engage with policy makers and share the importance of the geosciences? **Geoscience Congressional Visits Day (GEO-CVD)** will take place in **Washington, D.C.,** on **11–12 September 2024.** GEO-CVD is an annual event sponsored by the Geological Society of America in conjunction with other earth science societies to increase the visibility of and support for the geosciences in Congress.

GEO-CVD participants will take part in a workshop that will offer a foundational introduction to science policy through a series of brief seminars and panels; networking opportunities; and resources for participants to develop messaging and materials for successful congressional visits. Participants in GEO-CVD have an opportunity to meet with members of Congress and staff from key congressional offices and committees.

If you are interested in attending, visit **https://bit.ly/4ddIjqE.**
Deadline: 2 August 2024

Get tips on how to organize and prepare for an office visit: **https://tinyurl.com/ycpuwpp4.**

Contribute to the Conversation

Join **GSA's Geology and Society Division** to be part of a group that brings together multiple fields of geoscience to address important societal issues. Head to the updated Community site to share new research related to science policy, ask questions about upcoming science legislation, and contribute to meaningful discussions at the intersection of geology and society. We'd love to hear from you! To join, go to:


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GEOLOGY THROUGH THE LENS

Mirror Lake's Tranquil Reflections

Eagle Cap (in image center) is part of the composite Wallowa batholith in the Wallowa Mountains and Wallowa terrane of Northeast Oregon, USA. Ages and compositions of its four units (140.2 to 125.6 Ma) correlate with the amalgamation of the Wallowa and Olds Ferry terranes at 140 Ma and collision of the combined terranes with North America at 128 Ma (Schwartz et al., 2011).

Photo credit: Ellen Morris Bishop is a geologist, photographer, and writer whose life's work has been making science more enjoyable and understandable to non-scientists. Learn more at www.ellenmorrisbishop.com.

Schwartz, J.J., Snoke, A.W., Cordey, F., Johnson, K., Frost, C.D., Barnes, C.G., LaMaskin, T.A., and Wooden, J.L., 2011, Late Jurassic magmatism, metamorphism, and deformation in the Blue Mountains Province, northeast Oregon: GSA Bulletin, v. 123, no. 9–10, https://doi.org/10.1130/B30327.1.

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