NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

MEETING ANNOUNCEMENT

DATE: **Wednesday, October 26, 2022**

LOCATION: **Orinda Masonic Hall - and - Online using Zoom**

Note: Zoom meeting attendees should see Page 2 for "Zoom Meeting Instructions"

TIME: **7 pm to 8:30 pm (Social half-hour at 6:30 pm)**

SPEAKER: ***Jonathan Payne, Doerr School of Sustainability, Stanford University***

TOPIC: ***"Connecting end-Permian paleontological and geochemical records using physiology and Earth system models"***

Abstract:

The end-Permian mass extinction eliminated nearly 80% of marine animal genera, making it the most severe biodiversity crisis in the half-billion-year history of animal life. Over the past several decades, advances in geochemistry, especially isotope geochemistry, have provided better constraint on the environmental circumstances of this catastrophe and exhaustive sampling efforts have better documented the pattern and timing of diversity loss. Determining exactly how environmental changes caused extinction, however, has remained a challenge. In this talk, I will present the geochemical and paleontological data that have painted an increasingly clear picture of end-Permian environmental and biological change. I will then discuss how data from physiological experiments can be combined with Earth system models to test mechanistic models for the extinction event. The success of this approach suggests that it may also be useful in forecasting future extinctions and that past events can be used the calibrate the relationship between environmental change and biodiversity loss.

Biography:

I received my B.A. in Geosciences from Williams College in 1997. After graduation, I spent two years working as a high school math and science teacher. I then returned to graduate school, earning my Ph.D. in Earth and Planetary Sciences from Harvard University in the spring of 2005. Following a post-doctoral fellowship at Penn State, I joined the faculty at Stanford University in the fall of 2005. My research addresses the relationship between environmental change and biological evolution in the fossil record, with a focus on mass extinction events and long-term trends in the ecological structure of marine ecosystems. I teach courses for undergraduates in historical geology and invertebrate paleobiology, and

(Continued on last page)

Website: www.ncgeolsoc.org

NCGS 2022 – 2023 Calendar

November 16, 2022 7:00 pm
Dr. Marty Grove, Stanford University
Use of detrital zircons in determining sediment provenance

January 25, 2023 7:00 pm
Dr. Erik Sperling, Stanford University
Paleo-oceanography using mud-rock chemistry

February 22, 2023 7:00 pm
Mathieu LaPotre, Stanford University
Eolian dunes and landscapes on Mars – 10 years into the mission of Curiosity Rover

March 29, 2023 7:00 pm
Dr. Don Lowe, Stanford University
Early Precambrian environments

April 26, 2023 7:00 pm
Speaker and program to be announced

May 31, 2023 – Dinner Meeting – 6:00 pm
Speaker and program to be announced

June 28, 2023 7:00 pm
Speaker and program to be announced

Zoom Meeting Instructions – ADVANCE REGISTRATION REQUIRED

Now that Contra Costa County Health Department has cleared us to meet in person, we are holding hybrid monthly meetings – in person and via ZOOM. The Zoom option is available for those not wishing to come to the in-person meeting at our Orinda Masonic Hall meeting place. Jim O'Brient, our Program Manager, will host the Zoom meeting.

Members only can reserve a slot. Register by Sunday, October 23, 2022. Zoom **invitations will be emailed** on Monday, October 24, **by 7 PM.** The invitations will come via a calendar invite that you simply accept (YES) in order to place this on your calendar. Jim's default calendar is Google. He will also copy the link to you in email, but if that is used, a password may be required as well (that will be included in the invitation). DO NOT FORWARD THIS LINK TO ANYONE ELSE.

The meeting will use a "waiting room" for security purposes. The host will open the meeting about 6:45 PM. You will be admitted by host after matching names to the registration list. To save the host work, please try to join the meeting no later than 6:50 PM as it will take longer to gain admittance after the meeting starts. You will need to turn on your own video and audio once you have entered the meeting. Once the meeting starts, the host will mute everyone and ask that your video be turned off to minimize bandwidth constraints for a big group except when requested by the host for specific meeting roles.

Pix from Great Trips

Ray Sullivan forward this photo of the 2006 NCGS field trip to observe the San Andreas fault in the Olema Valley in Marin County (here: the Earthquake Trail). If anyone else has photographs of past NCGS trips or other events, we would like to share more of them via the newsletter. Sorry, but we can't recall who led this trip! If you know, please let the newsletter editor know!

An Update on the NCGS Social Hour!

The inaugural NCGS Social Hour, held on Saturday Oct. 1 at a Lafayette brewpub, featured fine weather and good beverages. Attendees included the President, three past presidents, two officers, and several other members, including our newest. The relaxed schedule and comfortable, if tight, seating encouraged multiple vibrant discussions of hobbies, personal histories, geology, the profession, and opportunities for NCGS activities. We all enjoyed the opportunity to engage more than the restricted time that our monthly meetings allow.

Members interested in initiating and "hosting" a no-host Social Hour at your favorite establishment are encouraged to contact Noelle Schoellkopf a few weeks in advance to avoid schedule conflicts and to ensure time to advertise in the Newsletter and via announcement at the prior monthly meeting. We suggest that the "host" review the venue and recruit a couple of other members to provide a quorum.

View the September Presentation

We held another excellent meeting in September – both live and via Zoom – and we hope that all who wanted to see it were able to, without significant interruption or other issues. If you missed it or would just like to see it again, please use the following link and password:

https://us02web.zoom.us/rec/share/xjGTChpOhLCubJzWRoKUbktULEgYpnpMVY61MmXETbKNFNIklMHiXN7byeMYxvg.KWmvbzNShTEJvF0_.

Passcode: ^^Cn#+0U

(**Note**: We suggest that you type in the password, rather than cutting and pasting it in.)

Missing NCGS Field Trip Guidebooks

Do you have any of the guidebooks on the list?

NCGS is working to track down older missing field trip guidebooks so we can post them on our website for free download. We already have over 70 historic guidebooks available in PDF format at http://www.ncgeolsoc.org/.

The guidebooks we still need were listed in the September 2022 newsletter. If you have a copy of any of those guidebooks, please contact Greg Bartow at gbartow @ gmail.com or 925-818-8525.

AAPG Delegate Opportunity

NCGS is entitled to have one member who is an AAPG member to serve as delegate to the House of Delegates, AAPG's legislative body. Don Lewis has been a delegate for many years but would be happy to pass the torch to someone who might be interested in AAPG's governance. The term is three years and the duties are few. There are one or a few Zoom meetings per year, but they are not burdensome. For more information, please contact Don at donlewis2 @ comcast.net.

Interesting Local-themed Geo-Website

Steven Edwards, Ph.D. and **Director Emeritus** of the Regional Parks Botanic Garden in Berkeley, has developed a website centered on California geology and plants. Steve has gathered some beautiful photographs of, among other things, wildflowers and petrographic thin sections – he secured some expert help from John Wakabayashi and Howard Day in interpreting thin sections. There are also essays on botany and conservation, poetry, and lithic replicas, landscapes, and animals.

You can find the site at http://californiageology.net, or it can be googled at californiawildflowers.net (which leads to the same site).

NCGS Outreach Opportunities

Watch this space and watch for any emailed messages from the secretary.

UC Berkeley Earth & Planetary Science Weekly Seminar Series

UC Berkeley's seminar series has returned for the academic year. Among a couple other talks currently listed, on Thursday, October 27, 2022, Cynthia Gerlein of the UCB Civil and Environmental Engineering program will speak on the topic ***The CYGNSS small-sat mission: a new window into the hydrology of wetlands and its consequence for methane emissions modeling***, at 3:45 pm at 141 McCone Hall. Send an email to eps_frontoffice@berkeley.edu to join the department's email list. For updated listings of upcoming seminars, go to http://eps.berkeley.edu/events/seminars.

USGS Evening Public Lecture Series

The USGS evening public lecture series events are free and are intended for a general public audience that may not be familiar with the science being discussed. Pre-Covid, talks were held at USGS; the talks are now online. There are talks scheduled through next April (except for December). On October 27 at 6:00 PM, Manuela Huso, USGS Forest and Rangeland Ecosystem Science Center will speak on "***Blowing in the Wind: Science to Help Understand and Help Reduce Wildlife Impacts from Wind Energy.***" Check the website to join the live stream, at: www.usgs.gov/pls/. To be added to the email notification list for future USGS Public Lecture Series events, please email: wmcesic@usgs.gov.

It's Membership Renewal Time!

Please see page 13 for a blank registration form, fill it out with your check and send to our Treasurer, Don Medwedeff. **Note**: Please do not pay for more than 3 years in advance, as it introduces bookkeeping issues.

AAPG Distinguished Lecture: Submarine-channel Evolution from Seismic Stratigraphy and Numerical Models: Patterns and Predictions Revisited

Jacob Covault of The University of Texas at Austin's Quantitative Clastics Laboratory will present this year's distinguished lecture, on how three-dimensional (3D) seismic-reflection surveys provide one of the most important data types for understanding subsurface depositional systems. Quantitative analysis is commonly restricted to geophysical interpretation of elastic properties of rocks in the subsurface. Wide availability of 3D seismic-reflection data and integration provide opportunities for quantitative analysis of subsurface stratigraphic sequences. Here, we integrate traditional seismic-stratigraphic interpretation with quantitative geomorphologic analysis and numerical modeling to explore new insights into submarine-channel evolution. 1) We show that submarine-channel patterns in a range of basin settings qualitatively resemble meandering rivers. 2) We mapped submarine-channel centerlines to reconstruct system migration at a level of detail similar to that of geomorphologic studies of rivers. Our results show that submarine channels migrate like freely meandering rivers unless confined by salt structures or other obstructions. 3) This result is confirmed by a simple numerical model of meandering, called meanderpy. 4) A potential consequence of submarine-channel meandering is a progressive increase in sinuosity, which decreases the channel thalweg slope through time. We evaluate the dynamic connectivity of these process-based 3D stratigraphic models using the MATLAB Reservoir Simulation Toolbox. The process-based models yield distinctively different flow behavior compared to a model that does not account for systematic submarine-channel meandering.

Time: Oct 27, 2022 01:00 PM in Central Time (US and Canada)

To register, go to: https://aapg.zoom.us/webinar/register/WN_cZAeKJ_9RuSztFRuWCB7Aw.

WE HAVE A FACEBOOK GROUP! FIND US ON FACEBOOK @NCGEOLSOC AND TWITTER @NORCALGEOSOC

Check out our updated NCGS Website at http://ncgeolsoc.org/. We have posted many older field trip guidebooks for free downloading, and we describe the process for purchasing newer guidebooks. The website includes a list of upcoming meetings, information on our scholarship program, a list of useful web links, and list of NCGS officers.

NCGS Board Meetings

Board meetings (online for now) are open to all NCGS members. If you'd like to attend, please contact president Noelle Schoellkopf at NoellePrince @ sbcglobal.net. Board meetings generally are on Saturday mornings in Jan., Apr./May, and Aug./Sep. Upcoming meeting: **Saturday, January 7 (9 am)**, location to be determined.

Dinosaur-killing asteroid triggered global tsunami that scoured seafloor thousands of miles from impact site

ScienceDaily, October 4, 2022
Source: University of Michigan

The miles-wide asteroid that struck Earth 66 million years ago wiped out nearly all the dinosaurs and roughly three-quarters of the planet's plant and animal species.

It also triggered a monstrous tsunami with mile-high waves that scoured the ocean floor thousands of miles from the impact site on Mexico's Yucatan Peninsula, according to a new University of Michigan-led study.

The study, scheduled for online publication Oct. 4 in the journal AGU Advances, presents the first global simulation of the Chicxulub impact tsunami to be published in a peer-reviewed scientific journal. In addition, U-M researchers reviewed the geological record at more than 100 sites worldwide and found evidence that supports their models' predictions about the tsunami's path and power.

"This tsunami was strong enough to disturb and erode sediments in ocean basins halfway around the globe, leaving either a gap in the sedimentary records or a jumble of older sediments," said lead author Molly Range, who conducted the modeling study for a master's thesis under U-M physical oceanographer and study co-author Brian Arbic and U-M paleoceanographer and study co-author Ted Moore.

The review of the geological record focused on "boundary sections," marine sediments deposited just before or just after the asteroid impact and the subsequent K-Pg mass extinction, which closed the Cretaceous Period.

"The distribution of the erosion and hiatuses that we observed in the uppermost Cretaceous marine sediments are consistent with our model results, which gives us more confidence in the model predictions," said Range, who started the project as an undergraduate in Arbic's lab in the Department of Earth and Environmental Sciences.

The study authors calculated that the initial energy in the impact tsunami was up to 30,000 times larger than the energy in the December 2004 Indian Ocean earthquake tsunami, which killed more than 230,000 people and is one of the largest tsunamis in the modern record.

The team's simulations show that the impact tsunami radiated mainly to the east and northeast into the North Atlantic Ocean, and to the southwest through the Central American Seaway (which used to separate North America and South America) into the South Pacific Ocean. In those basins and in some adjacent areas, underwater current speeds likely exceeded 20 centimeters per second (0.4

mph), a velocity that is strong enough to erode fine-grained sediments on the seafloor.

In contrast, the South Atlantic, the North Pacific, the Indian Ocean and the region that is today the Mediterranean were largely shielded from the strongest effects of the tsunami, according to the team's simulation. In those places, the modeled current speeds were likely less than the 20 cm/sec threshold.

For the review of the geological record, U-M's Moore analyzed published records of 165 marine boundary sections and was able to obtain usable information from 120 of them. Most of the sediments came from cores collected during scientific ocean-drilling projects.

The North Atlantic and South Pacific had the fewest sites with complete, uninterrupted K-Pg boundary sediments. In contrast, the largest number of complete K-Pg boundary sections were found in the South Atlantic, the North Pacific, the Indian Ocean and the Mediterranean.

"We found corroboration in the geological record for the predicted areas of maximal impact in the open ocean," said Arbic, professor of earth and environmental sciences who oversaw the project. "The geological evidence definitely strengthens the paper."

Of special significance, according to the authors, are outcrops of the K-Pg boundary on the eastern shores of New Zealand's north and south islands, which are more than 12,000 kilometers (7,500 miles) from the Yucatan impact site.

The heavily disturbed and incomplete New Zealand sediments, called olistostromal deposits, were originally thought to be the result of local tectonic activity. But given the age of the deposits and their location directly in the modeled pathway of the Chicxulub impact tsunami, the U-M-led research team suspects a different origin. "We feel these deposits are recording the effects of the impact tsunami, and this is perhaps the most telling confirmation of the global significance of this event," Range said.

The modeling portion of the study used a two-stage strategy. First, a large computer program called a hydrocode simulated the chaotic first 10 minutes of the event, which included the impact, crater formation and initiation of the tsunami. That work was conducted by co-author Brandon Johnson of Purdue University.

Based on the findings of previous studies, the researchers modeled an asteroid that was 14 kilometers (8.7 miles) in diameter, moving at 12 kilometers per second (27,000 mph). It struck granitic crust overlain by thick sediments and shallow ocean waters, blasting a roughly 100-kilometer-wide (62-mile-wide) crater and ejecting dense clouds of soot and dust into the atmosphere.

Two and a half minutes after the asteroid struck, a curtain of ejected material pushed a wall of water outward from the impact site, briefly forming a 4.5-kilometer-high (2.8-mile-high) wave that subsided as the ejecta fell back to Earth.

Ten minutes after the projectile hit the Yucatan, and 220 kilometers (137 miles) from the point of impact, a 1.5-kilometer-high (0.93-mile-high) tsunami wave -- ring-shaped and outward-propagating -- began sweeping across the ocean in all directions, according to the U-M simulation.

At the 10-minute mark, the results of Johnson's iSALE hydrocode simulations were entered into two tsunami-propagation models, MOM6 and MOST, to track the giant waves across the ocean. MOM6 has been used to model tsunamis in the deep ocean, and NOAA uses the MOST model operationally for tsunami forecasts at its Tsunami Warning Centers.

"The big result here is that two global models with differing formulations gave almost identical results, and the geologic data on complete and incomplete sections are consistent with those results," said Moore, professor emeritus of earth and environmental sciences. "The models and the verification data match nicely."

According to the team's simulation:

One hour after impact, the tsunami had spread outside the Gulf of Mexico and into the North Atlantic.

Four hours after impact, the waves had passed through the Central American Seaway and into the Pacific. Twenty-four hours after impact, the waves had crossed most of the Pacific from the east and most of the Atlantic from the west and entered the Indian Ocean from both sides.

By 48 hours after impact, significant tsunami waves had reached most of the world's coastlines. For the current study, the researchers did not attempt to estimate the extent of coastal flooding caused by the tsunami.

However, their models indicate that open-ocean wave heights in the Gulf of Mexico would have exceeded 100 meters (328 feet), with wave heights of more than 10meters (32.8 feet) as the tsunami approached North Atlantic coastal regions and parts of South America's Pacific coast.

As the tsunami neared those shorelines and encountered shallow bottom waters, wave heights would have increased dramatically through a process called shoaling. Current speeds would have exceeded the 20 centimeters per second threshold for most coastal areas worldwide.

"Depending on the geometries of the coast and the advancing waves, most coastal regions would be inundated and eroded to some extent," according to the study authors. "Any historically documented tsunamis pale in comparison with such global impact."

Video: https://youtu.be/hy6wfjqFBE0

A follow-up study is planned to model the extent of coastal inundation worldwide, Arbic said. That study will be led by Vasily Titov of the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Lab, who is a co-author of the AGU Advances paper.

Funding was provided by the National Science Foundation and the University of Michigan Associate Professor Support Fund, which is supported by the Margaret and Herman Sokol Faculty Awards. The MOM6 simulations were carried out on the Flux supercomputer provided by the University of Michigan Advanced Research Computing Technical Services.

Journal Reference: Molly M. Range, Brian K. Arbic, Brandon C. Johnson, Theodore C. Moore, Vasily Titov, Alistair J. Adcroft, Joseph K. Ansong, Christopher J. Hollis, Jeroen Ritsema, Christopher R. Scotese, He Wang. The Chicxulub Impact Produced a Powerful Global Tsunami. AGU Advances, 2022; 3 (5) DOI: 10.1029/2021AV000627.

[Editor's note: We thank Don Medwedeff for assembling this excellent article about the regional geology of a part of south-central Africa]

Geology of the Zambezi Basin and Adjacent Southern Africa

Donald A. Medwedeff, Ph.D.

In July of 2022 I went on a Southern Africa safari to experience the wildlife and landscape of the Zambezi River basin in Botswana, Zimbabwe, and Zambia. Although the wildlife was the focus of the trip, the group did get a brief lecture on the Geology of Victoria Falls (Fig. 1) that related its formation to the breakup of Gondwana, the East African Rift, and included hominid artifacts amongst the dating methods. I found this both surprising and a bit hard to follow without maps or figures. However, I was inspired to review the available literature and generate this summary to better appreciate the geology myself and as a guide to others that might have interest.

Physical Geography of Southern Africa

The geologic history of Southern Africa is reflected in the modern topography, which in turn influences the present-day sedimentation and erosion patterns. Figure 2 shows the topography using color to indicate elevation and shaded relief to indicate topographic roughness. The first order feature is a one-kilometer-high plateau centered in Botswana and surrounded to the west, south, and east by highlands with steep ocean facing slopes and gentle landward slopes. The land also slopes up to the north towards the rainforests of Angola and the Democratic Republic of the Congo forming the Kalahari Basin. Thus, though the plateau is in a dry climate zone, it receives large amounts of run off and sediment from rainfall far to the north.

Figure 1. Aerial view looking east of Victoria Falls and canyons of the Zambezi River exposing early Jurassic flood basalt of the Karoo Super Group. The Zambezi River separates Zambia on the far bank from Zimbabwe on the near bank. Photo by the author, July 2022.

This pattern is complicated on the northeast by linear valleys formed by extension across the East Africa Rift System. This system emanates from the Afar triangle in northeast Ethiopia and extends southward to southern Zambia where it connects to an east-west trending

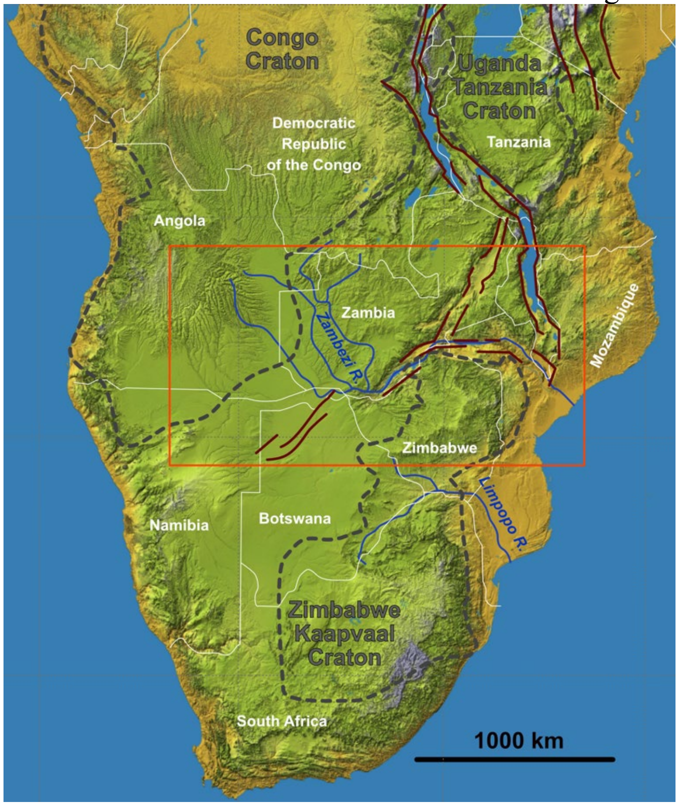

Figure 2. Shaded topographic map of Southern Africa. National borders shown in white. Approximate boundaries of Pre-Cambrian cratons shown in dark grey. Tertiary faults of the East African Rift System shown in dark red. The orange rectangle shows the location of Figure 7. Topographic base derived from the Space Shuttle Radar Topographic Mission (Nasa-JPL, 2000).

depression that controls the path of the Zambezi River. The Zambezi River is the primary drainage system for water moving across the plateau.

Pre-Mesozoic Foundation

Southern Africa has an unusually long geologic history going back to the first half of earth's existence or more than 2.5 billion years. Rocks of this age are termed Archean and because they underly the younger rocks are referred to as "basement". As is commonly the case, in Southern Africa these rocks are deeply-eroded igneous and metamorphic rocks (Figs. 3 and 4). They represent sediments deposited early in Earth history which were then buried and modified by high temperatures and intruded by younger magma. Similar rocks occur across most of Southern Africa, but differences allow them to be grouped into three distinct regions called cratons (Congo, Zimbabwe/Kaapvaal, and Uganda/Tanzania; Fig. 2). Although these cratons were not directly evident on my journey, they are important as their boundaries seem to control the geometry of East African Rift System and by extension the modern drainage.

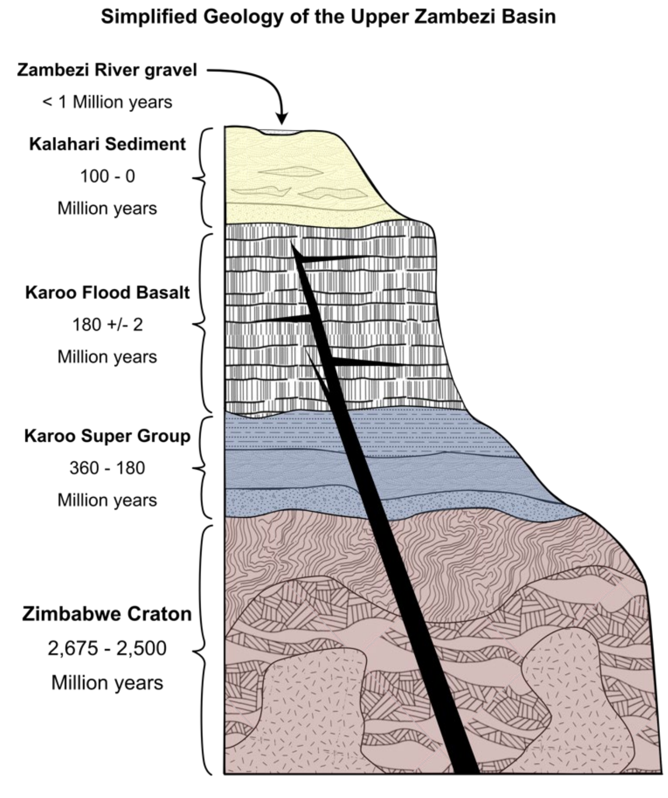

Figure 3. Simplified geologic column of the Upper Zambezi River Basin illustrating the lithology and ages of the four major units: 1. Plutonic and metamorphic rocks of the Zimbabwe Craton, 2. Clastic sedimentary rocks of the Karoo Super Group, 3. Massive flood basalts that form the top of the Karoo Group, and 4. Kalahari Basin sediments comprising braided stream, lake, and dune sediments, and soils derived from them. Colors per the geologic map in Figure 4.

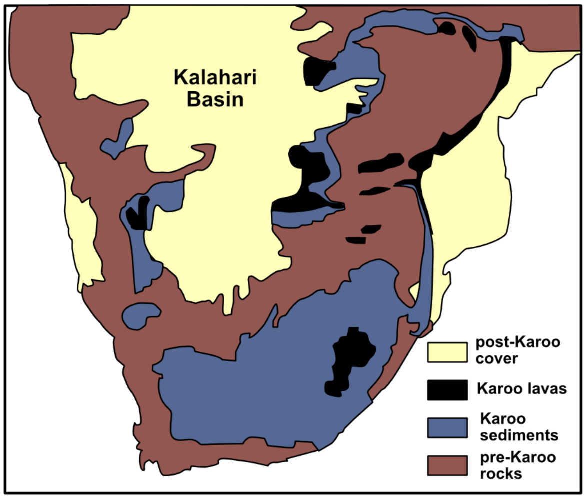

Figure 4. Distribution of Pre-Karoo, Karoo, and Kalahari basin rocks in Southern Africa (after Duncan et al., 1997).

After an extended period of erosion, sedimentary rocks of the Karoo Super Group were deposited across the area during the late Paleozoic and early Mesozoic eras (from 360 to 180 million years [Ma]). These rocks represent shallow seas and continental lowlands (Key et al., 1998). Though it was widely deposited the Karoo Super Group has limited exposure due to erosion and burial beneath younger strata (Figs. 3 and 4).

Gondwana Breakup and Plateau Formation

Deposition of the marine Karoo sediments was ended by widespread uplift above a buoyant plume of anomalously hot material in the mantle. The mantle plume extends from about 100 km depth to about 2,900 km depth and is an integral part of mantle convection driven by plate tectonics. The areal and vertical extent of the mantle plume is responsible for the large extent and longevity of the high plateau in Southern Africa which has endured to the present. In addition to the uplift, the hot mantle plume also melted portions of the lower crust resulting in extrusion of massive flood basalts from 184 - 174 Ma (Figs. 3 and 4; Duncan et al., 1997, de Wit, 2007). These basalts covered portions of South America, Antarctica, Australia, and India which were then joined with Africa as the Gondwana mega-continent (Fig. 5). Crustal uplift generated by the plume seems to have initiated rifting of Gondwana at about 180 Ma and resulted in the modern continent forms by about 100 Ma (Fig 6). Enhanced uplift associated with rifts around the edges of Southern Africa caused the remnant high plateau to be internally drained - forming the Kalahari Basin (Fig 5). The combination of dry climate and resistant basalt at the surface resulted in very slow erosion and limited deposition for the past 180 Ma.

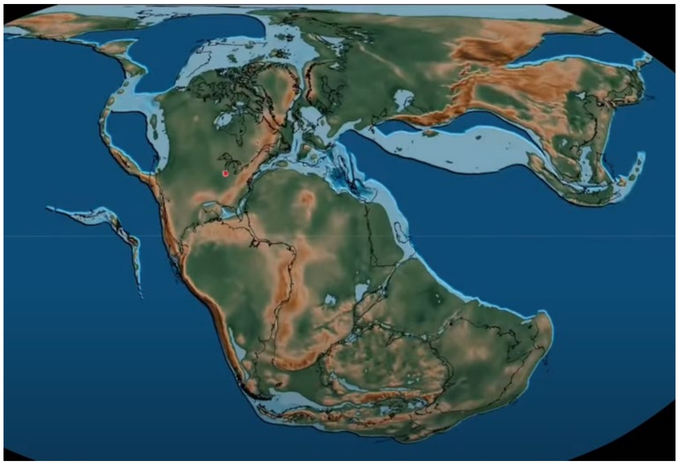

Figure 5. Jurassic paleogeography, 200 million years ago (Scotese and van der Pluijm, 2020). Note formation of the internally drained basin in Southern Africa.

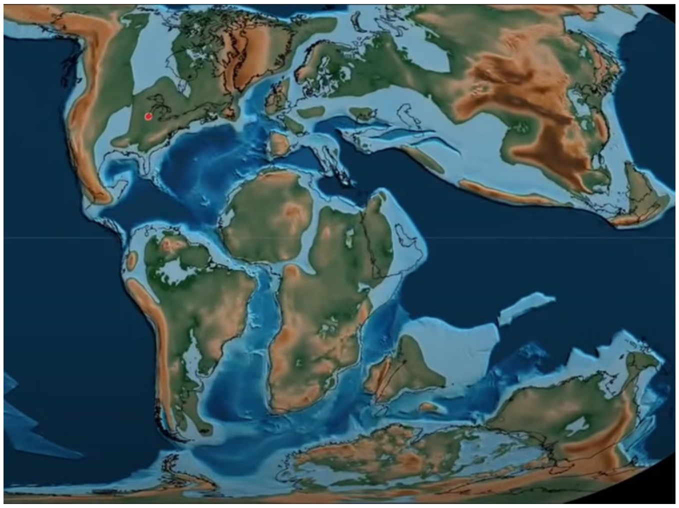

Figure 6. Cretaceous paleogeography, 100 million years ago (Scotese and van der Pluijm, 2020). Note preservation of the internally drained basin in Southern Africa.

Kalahari Plateau Sedimentation

Sediments deposited in the internally drained basin form the Kalahari Sedimentary Basin. The southern Kalahari basin is still internally drained so that the Cubango and Okavango Rivers terminate in the Okavango delta generating large ephemeral lakes and swamps (Figure 7). Though separated by an arch only 10 m high, the northern Kalahari Basin now drains into the Upper Zambezi River and its tributaries and thence over the Victoria Falls and through the Batoka Gorge before flowing to the rift valleys of the Lower Zambezi and thence to the Indian Ocean (Figure 7).

Kalahari Basin sediments range in age from 100 Ma to the present and are up to 500 m thick. However, most of the basin is much younger and much thinner. In the Chobe River area (Fig. 7) of northeast Botswana, the sediments are about 30 m thick (Fig. 8) and primarily Late Tertiary (Moore, 2013).

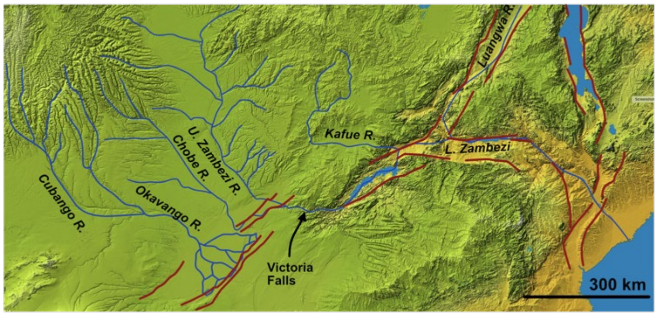

Figure 7. Shaded topographic map of a portion of the Zambezi River basin and adjoining areas. The river drains the northern portion of the Kalahari basin over Victoria Falls, and into the incipient southwest part of the East Africa Rift System (shown in red). See text for further discussion. Topographic base derived from the Space Shuttle Radar Topographic Mission (Nasa-JPL, 2000).

Figure 8. Profile of Kalahari Basin sediments exposed along a bluff on the shore of the Chobe River, Botswana. The total height of the exposure is about 30 m.

A light-colored resistant unit is exposed at the lowest exposures along the Chobe River west of Kasane, Botswana (Figs. 9 and 10). This unit is likely the Pipe Sandstone described by Moore (2013). This rock is unusually well cemented given its maximum burial of a few 10's of meters. Formation of the siliceious cement has been attributed long exposure in the vadose zone (the variably saturated zone between the ground surface and the permanent water table of the groundwater) and to repeated filling and draining of large lakes in the Kalahari Basin. These wet and dry periods were in turn caused by variation in climate during the Tertiary and Quaternary (Linol, et al., 2015).

Above the Pipe Sandstone is 10–20 m of angular clasts embedded in a matrix of quartz and carbonate (Fig. 9). The quartz was carried to the basin both by wind in dry periods and by rivers in wet periods (Linol, et al., 2015). The angular blocks formed by calcite cementation in the vadose zone. Acidic groundwater percolating though the sands dissolved the carbonate grains and re-precipitated the material as cement around quartz grains below the

Figure 9. Exposure near the base of the Kalahari section exposed along the shore of the Chobe River, Botswana. Light-colored, well-cemented rocks likely represent silicified sandstone formed in lakes at times of high water (inferred from Moore, 2013). Darker, more angular rocks exposed as “float” on the hillside likely represent cemented soil, known as “carstone” or “calcrete”, formed during repeated wet and dry cycles.

Figure 10. Resistant, silicified sandstone forming a rough pavement along the shore of the Chobe River, Botswana. Lions for scale. Photo by the author, July 2022.

water table. As the water table moved up and down the cements redissolved resulting in the chaotic blocks observed when exposed (Fig. 9).

Covering the variably cemented sediment are several meters of completely uncemented sands deposited by wind (Fig. 11). These are known locally as the Kalahari Sands and likely derive from the dry pans of the Kalahari drainage basin during dry periods such as the present time.

Geologic Processes and Zambezi River History

Figure 11. Wind-blown “Kalahari sands”, stabilized by vegetation, cover much of the land above the bluff along Chobe River, Botswana. Photo by the author, July 2022.

The Zambezi River is one of the great rivers of Africa. At 2,574 km, it is the 4th longest, its 1.3 million square km drainage area is the 5th largest, and its average flow of 4,134 m^3/s is the 7th largest in Africa (Wikipedia, 2022). Despite its great size flow, the Zambezi drainage has varied dramatically over the last 100 Ma or so. Prior to the late Cretaceous (about 100 Ma), the upper reaches of the modern Zambezi drained from Angola, across the Kalahari basin, and down what is now the Limpopo River (Fig. 2; Haddon and McCarthy, 2005). In the late Cretaceous or early Tertiary (about 65 Ma), crustal faulting and westward tilting reduced the grade of the river and it deposited gravel, sand, and clay in large lakes. From then until the late Tertiary the river terminated in the Kalahari Basin as the Okavango does today (Fig. 7; Haddon and McCarthy, 2005), sustaining a Lake Paleo-Makgadikgadi at over 60,000 km2 (Haddon and McCarthy, 2005). Finally, in the late Tertiary, westward propagation of the East African Rift System, headward erosion of the Middle Zambezi River, and possible catastrophic flooding by overtopping of Lake Paleo-Makgadikgadi diverted the Zambezi River into is its modern channel (Fig. 7; Haddon and McCarthy, 2005).

The large-scale changes in the river discussed above are only evident through regional mapping and integration of

Figure 12. Victoria Falls viewed to the North from the Zimbabwe side of the Zambezi River (see Fig. 14 for location). Outcropping basalt in the foreground is weathered smooth indicating it was previously part of the river bed. Photo by the author, July 2022.

diverse data. More detailed changes in the river bed are directly evident at Victoria Falls.

Figure 12 shows the falls viewed from the south on the Zimbabwean side of the river. The basalt rocks in the foreground, which are 100 m above the gorge below, exhibit smooth surfaces and rounded edges typical of the abrasion by sand and gravel in a large flowing river. This indicates the Zambezi River formerly flowed across this terrace. Another rock on the same terrace provides even stronger evidence of this in the form of circular depressions or "potholes" (Fig. 13).

Figure 13. Smoothly weathered basalt outcrop, about 1 m across, in the vicinity of the photo in Figure 12 (see Fig. 14 for location). Note circular kettle pots formed by trapped cobbles when the outcrop was in the bed of the Zambezi River. Photo by the author, July 2022.

Potholes form by the grinding action of pebbles or cobbles that are trapped and swirled by eddies in strong currents. This evidence indicates that prior to the excavation of the gorge at the base of the present Victoria Falls, the river continued to the next gorge to the south labeled V.F.-B in Figure 14. There are at least five gorges successively farther south, indicating that the northward migration of the falls is a continuing process.

The former falls have azimuths that vary between 75□ and 105□ east of north and spacing between them averages about 500 m (Fig. 14). Subtle differences in height of identifiable lava flows (Fig. 15) suggest that positions of the falls are controlled by faults which formed fractured zones that are more susceptible to erosion. Faults of a similar age are known from the Chobe River area and the Okavango Delta to the west (Haddon and McCarthy, 2005) and the middle Zambezi River to the east. The faults expressed at Victoria Falls and along the Batoka Gorge to the south are thus consistent with the westward propagation of the East African Rift System as discussed above.

The northward migration of the falls is linked to the progressive incision of the Batoka Gorge. The timing of the latter has been documented by dating the age of river gravels in the gorge. These gravels are too coarse to have been carried and deposited by tributary streams and thus document the former position of the Zambezi River (Moore, 2013). The position of the various age gravels within the gorge are illustrated in Figure 16. The gravels range in age from Early Pleistocene (about 2.5 Ma) to Quaternary (about 20,000 years). All the gravels are found along abandoned river sections of the river bed. Generally, the older gravels are found both higher and north (upstream) of the younger gravels. This suggests that the river has cut progressively down as the falls retreated to the north during the last 3 million years (Fig. 16).

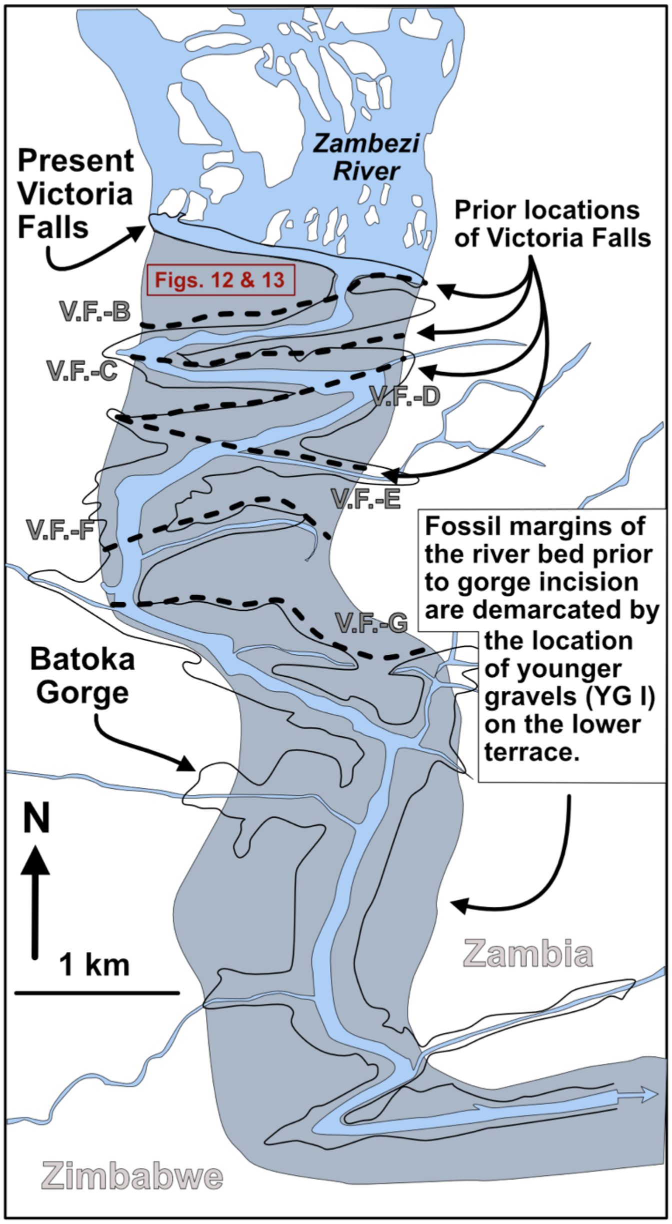

Figure 14. Map of the Zambezi River adjacent to Victoria Falls illustrating the present width of the river in light blue and the width of the river prior to incision of the Batoka Gorge in grey. The falls has progressively stepped northward as the gorge was incised. Six prior locations of the falls (V.F.-G to V.F.-B) are shown in dashed lines. Adapted from Moore, 2013.

Notably, the age of the various river gravel deposits has been dated by the occurrence of human and hominid artifacts that have been ascribed to the Early, Middle, and Late Stone Ages (Moore, 2013).

Figure 15. Batoka basalt flows viewed from the lower catwalk of the Victoria Falls Bridge. The white lines highlight the visual offset, of about 2m, of the pre-incision erosion surface. Though not calibrated, the viewpoint is very close to the far erosion surface minimizing perspective distortion at this level. Photo by the author, July 2022.

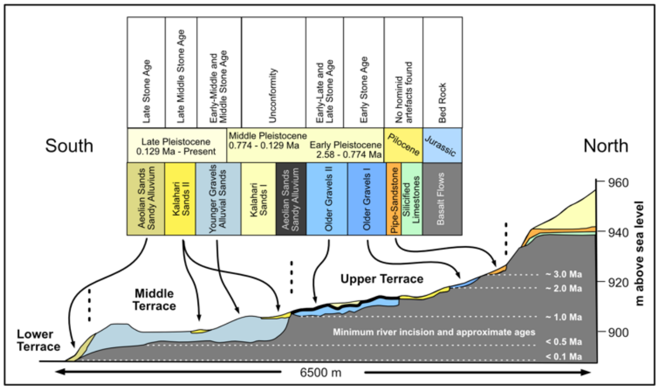

Figure 16. Schematic profile of the Zambezi River below Victoria Falls. Note North is on the right. After Moore, 2013.

Concluding Remarks

The Zambezi River Basin and adjacent region of Southern Africa has limited outcrop mostly of flat lying layers and sediment. This apparent simplicity belies the long and complex history that formed the landscape and its foundation. Unusually, this history includes humans and our hominid ancestors. Though surprising, it is in hindsight to be expected in an area where humanity has such deep roots.

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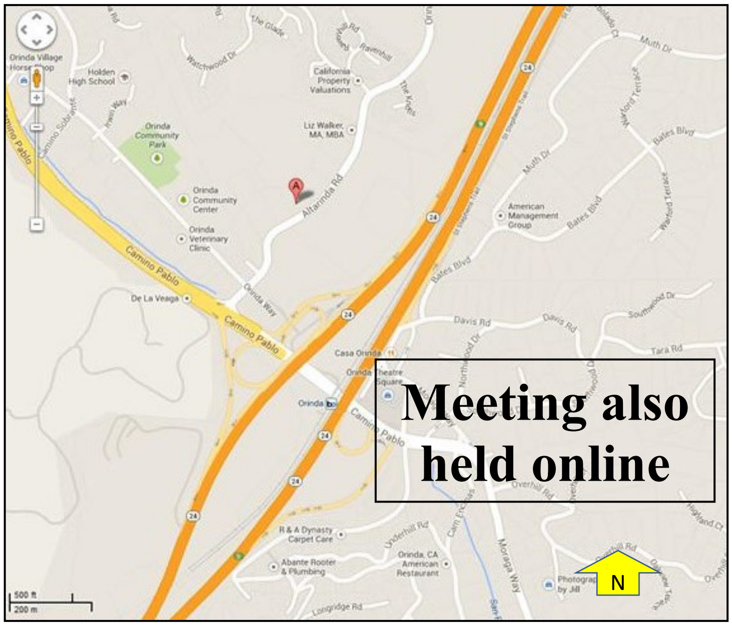

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(Continued from Page 1)

courses for graduate students in carbonate sedimentology, geobiology, and paleobiology. I served as the Chair of Geological Sciences at Stanford from 2015-2019 and have served as a Senior Associate Dean for Faculty Affairs since 2020, first in the School of Earth, Energy & Environmental Sciences and, since September 1, 2022, in the Doerr School of Sustainability.

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