NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

MEETING ANNOUNCEMENT

DATE: **Wednesday, November 20, 2019**

LOCATION: **Orinda Masonic Center, 9 Altarinda Rd., Orinda**
(see map on back page)

TIME: **Social Hour: 6:30 – 7 pm; Program: 7 pm**

SPEAKER: ***Dr. David P. Schwartz, Earthquake Geologist Emeritus, USGS***

TOPIC: ***"Earthquakes of the East Bay"***

If you live in the East Bay you can run but you can't hide. The San Francisco Bay Area occupies the boundary zone between the Pacific and North American plates, which slide past each other in this region at ~40 mm/yr. This plate boundary slip is currently distributed on the major faults including the San Andreas and San Gregorio west of the bay, and the Hayward-Rodgers Creek, northern Calaveras, Greenville, Mt. Diablo, and Concord-Green Valley faults in the East Bay. The East Bay faults accommodate about 50 percent of the total plate motion across a 45-50 km-wide zone.

Historically, the 1868 Hayward earthquake remains the largest East Bay earthquake with an estimated magnitude of M~6.8. To the east of the East Bay Hills, the largest historical events are: the 1861 M~6(?) Calaveras earthquake south of San Ramon that may be associated with surface rupture; the 1954 M5.5 Concord fault earthquake; the 1980 M5.8 Greenville fault event, which is associated with small coseismic surface slip and afterslip (afterslip also occurred on the conjugate Las Positas fault); and the 1986 M5.7 Mt. Lewis sequence, which may be part of a broad zone of N-S shear between the Calaveras and Greenville faults. With the exception of consistent microseismicity along the East Bay's creeping faults, seismicity is broadly distributed with magnitudes on the small side (commonly M1-3) and with typical shallow crustal depths of ≤10±2 km; however, a 25-km-long NW-trending zone of diffuse seismicity east of Mt. Diablo is characterized by small events occurring at depths of 14-19 km, reflecting a thicker crust associated with Mt. Diablo folding. Additionally, the San Ramon Valley is unique in the Bay Area as the home to earthquake swarms, with seven occurring since 1970. These swarms may be a response to stresses in a complex structural zone between the NW-striking right lateral Calaveras and west-verging compressional structures of Mt. Diablo—and associated with the eastward stepping of plate boundary slip from the Calaveras to the Concord-Green Valley fault. Some small amount of Calaveras slip may also extend north and drive earthquake occurrence along the West Napa fault zone.

(continued on Page 12)

NCGS 2019 – 2020 Calendar

January 29 **7:00 pm**

Program not yet set

February 26 and later dates through June **7:00 pm**

Programs not yet set

THE 75th ANNIVERSARY VOLUME OF THE NORTHERN CALIFORNIA GEOLOGICAL SOCIETY:

THE REGIONAL GEOLOGICAL SETTING OF MOUNT DIABLO

The following table summarizes the contributions to the Volume scheduled to be published by the Geological Society of America in December 2020.

The editors are Ray Sullivan, Doris Sloan, Jeff Unruh and David Schwartz.

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NCGS 75th Anniversary

It's been 75 years since the NCGS began as an outgrowth of a genial gathering, over brews, of geologists from a variety of mostly petroleum exploration companies, in Rio Vista in 1944. Please join us in 2019 as we celebrate this landmark anniversary, and come to as many of our events as you can! We are progressing toward completion of the release ***The Regional Geologic Setting of Mount Diablo*** in a special publication of the GSA. On November 16 and in early 2020, we plan to run additional **field trips** reprising the excellent trip of Nov. 2, and will keep you posted. Other ways to participate and/or re-connect with your fellow members are to attend any or all of our **upcoming meetings** for which we have some of our anniversary volume authors slated to speak, and to assist at any of our **outreach opportunities**, where you can meet and encourage the next generation of geologists and their parents!

NCGS Field Trip

"A Fresh Look at the Geology of Mount Diablo's Summit and Southwest Flank"

Saturday, November 16, 2019 starting at 9:30 am

Leaders: Dr. Will Schweller and Dr. Don Medwedeff

This half-day field trip will give participants an updated understanding of the geology of Mount Diablo, focusing on the Franciscan Complex that forms the upper half of the mountain and the Cretaceous and Tertiary sedimentary formations that form the southwest flank of the mountain, plus the structural and tectonic processes that created this mountain.

The trip will begin near the top of the mountain, at the large parking area just below the summit, and proceed downhill to end at Rock City, just uphill from the ranger station at the park's south entrance. Please see details in the form emailed recently by Crystal Replogle, and mail in your reservation. Don't dally! However, the good news is that Will and Don will likely run a third trip!

NCGS Outreach Opportunity: Bay Area Science Festival

There are no announcements for NCGS outreach this month, but keep an eye on this space, and for emails that may come from Crystal Replogle, our recording secretary. The outreach group had a successful day interfacing with students at the recent science fair at California State East Bay.

AAPG Teacher of the Year Award

Earth Science / Natural Resources Teachers wanted to apply for this award, which amounts to $6,000!

Check out the Requirements and Guidelines at foundation.aapg.org .

Questions? Contact Paul Henshaw at drphenshaw@comcast.net

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.

UC Berkeley Earth & Planetary Science Weekly Seminar Series

Interesting seminars are presented at 141 McCone Hall on Thursdays (usually) at 3:45 pm for most of the academic year, from late August through early May. On November 14, Jessica Creveling of Oregon State University will speak on ***Assessing uncertainty in early Cambrian fossil first appearances.*** For a list of seminars, go to http://eps.berkeley.edu/events/seminars.

NCGS members are invited our next **Board of Directors meeting,** in January at the APTIM office at 4005 Port Chicago Highway. Board meetings will now be generally held at 9 am on a Saturday in January, May, and September, and are open to all NCGS members. Please contact Tom MacKinnon if you'd like to attend, at tom.mackinnon@comcast.net.

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. The next lecture will be given Thursday, ***November 21st*** at 7 pm by ***Sean Vitousek***, USGS, on ***Sea-Level Rise, Extreme Water Levels, and Coastal Erosion... How bad could it possibly be?*** at Rambo Auditorium, 345 Middlefield Road, Menlo Park. For more information on the lectures, and for a map of the location, go to: https://online.wr.usgs.gov/calendar/.

Welcome back from summer break! And that means it's time to renew your membership!

We realize that it's still summer – especially in California – but September is when our program year begins. Please see page 13 for a blank registration form, and mail it in as indicated, or drop it off with Barbara Matz at the check-in desk at the next meeting.

Call for Abstracts: Pacific Section AAPG/SEPM/SEG Convention

2020 Vision: Producing Our Future

April 4-8, 2020

Join us in Oxnard, California, just an hour north of Los Angeles, at the Embassy Suites Beach Resort, an oceanfront hotel and excellent convention venue. We are currently seeking abstracts for a high quality technical program that covers the broad interests of our members and the geoscience community. Convention information and instructions for abstracts at http://psaapgconvention.org/2020. Technical presentations will be scheduled for Monday and Tuesday, April 6-7.

Abstract Deadline is Friday, January 10, 2020.

Help Requested at Math Science Nucleus

Joyce Blueford at MS Nucleus says that they are redoing their rock and mineral hall. They have 2 display cases that she wants to place the mineral specimens by their chemical families. They have many specimens (not always the best), but are looking for someone who might want to put a display together. Minerals are easy because everyone likes to look at pretty shapes....

They do have a rock display that the kids use in their scavenger hunt, but most of the rock education is done in field trips. However, they are always interested in making rocks tell a story.... they like to change displays, but would welcome any help.

Mark Petrofsky and Paul Henshaw are coordinating this with Joyce, and they suggest that this could be an ongoing project with periodic changes to the display, annually or biannually. Joyce also wants to make the geology portion of the museum more interactive. We could also go beyond the display cases to maps and materials on local geology and display books about local geology. NCGS has provided the California geologic maps, large and 8x10, for MSNucleus use with teachers and students. A continuing and expanding long term relationship would be great.

Did an extraterrestrial impact trigger the extinction of ice-age animals?

Archaeologist finds evidence in South Carolina to support controversial theory

ScienceDaily, October 25, 2019
Source: University of South Carolina

Wooly mammoth (stock image).
Credit: © dottedyeti / Adobe Stock

A controversial theory that suggests an extraterrestrial body crashing to Earth almost 13,000 years ago caused the extinction of many large animals and a probable population decline in early humans is gaining traction from research sites around the world.

The Younger Dryas Impact Hypothesis, controversial from the time it was presented in 2007, proposes that an asteroid or comet hit the Earth about 12,800 years ago causing a period of extreme cooling that contributed to extinctions of more than 35 species of megafauna including giant sloths, sabre-tooth cats, mastodons and mammoths. It also coincides with a serious decline in early human populations such as the Clovis culture and is believed to have caused massive wildfires that could have blocked sunlight, causing an "impact winter" near the end of the Pleistocene Epoch.

In a new study published this week in Scientific Reports, a publication of Nature, UofSC archaeologist Christopher Moore and 16 colleagues present further evidence of a cosmic impact based on research done at White Pond near Elgin, South Carolina. The study builds on similar findings of platinum spikes -- an element associated with cosmic objects like asteroids or comets -- in North America, Europe, western Asia and recently in Chile and South Africa.

"We continue to find evidence and expand geographically. There have been numerous papers that have come out in the past couple of years with similar data from other sites that almost universally support the notion that there was an extraterrestrial impact or comet airburst that caused the Younger Dryas climate event," Moore says.

Moore also was lead author on a previous paper documenting sites in North America where platinum spikes have been found and a co-author on several other papers that document elevated levels of platinum in archaeological sites, including Pilauco, Chile -- the first discovery of evidence in the Southern Hemisphere.

"First, we thought it was a North American event, and then there was evidence in Europe and elsewhere that it was a Northern Hemisphere event. And now with the research in Chile and South Africa, it looks like it was probably a global event," he says.

In addition, a team of researchers found unusually high concentrations of platinum and iridium in outwash sediments from a recently discovered crater in Greenland that could have been the impact point. Although the crater hasn't been precisely dated yet, Moore says the possibility is good that it could be the "smoking gun" that scientists have been looking for to confirm a cosmic event. Additionally, data from South America and elsewhere suggests the event may have actually included multiple impacts and airbursts over the entire globe.

While the brief return to ice-age conditions during the Younger Dryas period has been well-documented, the reasons for it and the decline of human populations and animals have remained unclear. The impact hypothesis was proposed as a possible trigger for these abrupt climate changes that lasted about 1,400 years.

The Younger Dryas event gets its name from a wildflower, Dryas octopetala, which can tolerate cold conditions and suddenly became common in parts of Europe 12,800 years ago. The Younger Dryas Impact Hypothesis became controversial, Moore says, because the all-encompassing theory that a cosmic impact triggered cascading events leading to extinctions was viewed as improbable by some scientists.

"It was bold in the sense that it was trying to answer a lot of really tough questions that people have been grappling with for a long time in a single blow," he says, adding that some researchers continue to be critical.

The conventional view has been that the failure of glacial ice dams allowed a massive release of freshwater into the north Atlantic, affecting oceanic circulation and causing the Earth to plunge into a cold climate. The Younger Dryas hypothesis simply claims that the cosmic impact was the trigger for the meltwater pulse into the oceans.

In research at White Pond in South Carolina, Moore and his colleagues used a core barrel to extract sediment samples from underneath the pond. The samples, dated to the beginning of the Younger Dryas with radiocarbon, contain a large platinum anomaly, consistent with findings from other sites, Moore says. A large soot anomaly also was found in cores from the site, indicating regional large-scale wildfires in the same time interval.

In addition, fungal spores associated with the dung of large herbivores were found to decrease at the beginning of the Younger Dryas period, suggesting a decline in ice-age megafauna beginning at the time of the impact.

"We speculate that the impact contributed to the extinction, but it wasn't the only cause. Over hunting by humans almost certainly contributed, too, as did climate change," Moore says. "Some of these animals survived after the event, in some cases for centuries. But from the spore data at White Pond and elsewhere, it looks like some of them went extinct at the beginning of the Younger Dryas, probably as a result of the environmental disruption caused by impact-related wildfires and climate change."

Additional evidence found at other sites in support of an extraterrestrial impact includes the discovery of meltglass, microscopic spherical particles and nanodiamonds, indicating enough heat and pressure was present to fuse materials on the Earth's surface. Another indicator is the presence of iridium, an element associated with cosmic objects, that scientists also found in the rock layers dated 65 million years ago from an impact that caused dinosaur extinction.

While no one knows for certain why the Clovis people and iconic ice-age beasts disappeared, research by Moore and others is providing important clues as evidence builds in support of the Younger Dryas Impact Hypothesis.

"Those are big debates that have been going on for a long time," Moore says. "These kinds of things in science sometimes take a really long time to gain widespread acceptance. That was true for the dinosaur extinction when the idea was proposed that an impact had killed them. It was the same thing with plate tectonics. But now those ideas are completely established science."

Journal Reference: Christopher R. Moore, Mark J. Brooks, Albert C. Goodyear, Terry A. Ferguson, Angelina G. Perrotti, Siddhartha Mitra, Ashlyn M. Listecki, Bailey C. King, David J. Mallinson, Chad S. Lane, Joshua D. Kapp, Allen West, David L. Carlson, Wendy S. Wolbach, Theodore R. Them, M. Scott Harris, Sean Pyne-O'Donnell. Sediment Cores from White Pond, South Carolina, contain a Platinum Anomaly, Pyrogenic Carbon Peak, and Coprophilous Spore Decline at 12.8 ka. *Scientific Reports*, 2019; 9 (1) DOI: 10.1038/s41598-019-51552-8.

Massive fangs and a death crush: How a 370 million year old tetrapod hunted and killed

ScienceDaily, October 24, 2019
Source:University of Lincoln

The habits of a needle-toothed tetrapod which lived more than 370 million years ago have filled in a piece of the evolutionary puzzle thanks to new research.

An international team of palaeontologists pieced together the fossilised skeletons of a new species of tetrapod called Parmastega aelidae and found it had a skull which resembled a crocodile -- a unique feature among the earliest tetrapods -- with eyes situated well above the top of its head, suggesting it was capable of "keeping an eye" on unsuspecting prey while swimming close to the surface of a tropical lagoon.

The unusual combination of anatomical features has cast new light on how one of most distant ancestors hunted and its life-style. Researchers believe it would have used its slender needle-like teeth and elastic jaw to snatch prey before crushing it to death with massive fangs protruding from its palate.

The team also found that part of its shoulder girdle consisted of cartilage, and its vertebral column and paired limbs could also be made of cartilage, indicating it probably spent most or all its time in water. The concentration of the fossil remains also suggests that it may have lived in large groups

Tetrapods are represented today by amphibians, reptiles, birds and mammals, and Parmastega predates the former earliest records of complete or almost complete tetrapod skeletons by nearly 12 million years.

The new study was led by the Ural Branch of the Russian Academy of Science, in partnership with the Universities of Lincoln and Cambridge in the UK, the University of Latvia, and the University of Uppsala in Sweden. It was funded by the National Geographic Society, the Latvian Council of Science, and the Knut and Alice Wallenberg Foundation.

Professor Per Ahlberg from the University of Uppsala in Sweden, explained that a clue to the lifestyle of Parmastega was provided by its sensory canals, used to detect vibrations in the water, which Parmastega inherited from its fish ancestors.

"These canals are well developed on the lower jaw, the snout and the sides of the face, but they die out on top of the head behind the eyes," he said. "This probably means that it spent a lot of time hanging around at the surface of the water, with the top of the head just awash and the eyes protruding into the air.

"We believe there may have been large arthropods such as millipedes or 'sea scorpions' to catch at the water's edge. The slender, elastic lower jaw certainly looks well-suited to scooping prey off the ground, its needle-like teeth contrasting with the robust fangs of the upper jaw that would have been driven into the prey by the body weight of Parmastega.

"These fossils give us the earliest detailed glimpse of a tetrapod: an aquatic, surface-skimming predator, just over a metre in length, living in a lagoon on a tropical coastal plain."

Dr Marcello Ruta from Lincoln's School of Life Sciences added: "The evolution of tetrapods is one of the most important events in the history of backboned animals, and ultimately led to the appearance of our own species. Early in their history, tetrapods evolved many changes in their feeding strategies, movement abilities, and sensory perception, but many of these are still shrouded in mystery.

"Like all fossil organisms, Parmastega occupies a special and unique place in the tree of life. Our study welcomes a new, very early member of that tree which shows considerable anatomical, functional and ecological experimentation.

"These new findings demonstrate that the sequence of evolutionary changes that occurred during the transition from fish-like creatures to tetrapods were much less linear than previously thought. This helps us to amend or challenge previous evolutionary scenarios and give new insights into the life and environments of our most distant forerunners. Findings like those of Parmastega can help us grasp the complex patterns and processes that have shaped life's diversity for hundreds of millions of years."

Journal Reference: Pavel A. Beznosov, Jennifer A. Clack, Ervīns Lukševičs, Marcello Ruta & Per Erik Ahlberg. Morphology of the earliest reconstructable tetrapod Parmastega aelidae. *Nature,* 2019 DOI: 10.1038/s41586-019-1636-y.

3-D models of Cascadia megathrust events match coastal changes from 1700 earthquake

ScienceDaily, October 29, 2019
Source: Seismological Society of America

By combining models of magnitude 9 to 9.2 earthquakes on the Cascadia Subduction Zone with geological evidence of past coastal changes, researchers have a better idea of what kind of megathrust seismic activity was behind the 1700 Cascadia earthquake.

The analysis by Erin Wirth and Arthur Frankel of the U.S. Geological Survey indicates that a rupture extending to just offshore for most of the Pacific Northwest could cause the pattern of coastal subsidence seen in geologic evidence from the 1700 earthquake, with an estimated magnitude between 8.7 and 9.2.

An earthquake rupture that also contains smaller patches of high stress drop, strong motion-generating "subevents" matches the along-fault variations in coastal subsidence seen from southern Oregon to British Columbia from the 1700 earthquake, the researchers conclude in their study published in the Bulletin of the Seismological Society of America.

The seismic hazard associated with Cascadia megathrust earthquakes depends on how far landward the rupture extends, along with differences in slip along the fault. For this reason, the new study could help improve seismic hazard estimates for the region, including estimates of ground shaking intensity in Portland, Oregon, Seattle, Washington and Vancouver, British Columbia.

For instance, the 2014 National Seismic Hazard Maps assigned different "weights" to earthquake scenarios that rupture to different extents of the down-dipping plate in the region's subduction zone, as a way to express their potential contribution to overall megathrust earthquake hazard. An earthquake where the rupture extends deep and partially inland is weighted at 30%, a shallow rupture that is entirely offshore is weighted at 20%, and a mid-depth rupture that extends approximately to the coastline is weighted at 50%.

"We looked at various magnitude 9 rupture scenarios for Cascadia, to see how the coastal land level changes under those scenarios," said Wirth, " and you can't match the paleoseismic estimates for how the land level changed along the Pacific Northwest coast during the 1700 Cascadia earthquake" with rupture scenarios at the shallowest and deepest points.

"This may mean that these scenarios deserve less weight in assessing the overall seismic hazard for Cascadia," Wirth noted.

The researchers used data from other megathrust earthquakes around the world, such as the 2010 magnitude 8.8 Maule, Chile and the 2011 magnitude 9.0 in Tohoku, Japan earthquakes to inform their models. One of the features found in these and other megathrust events around the world are distinct patches of strong motion-generating "subevents" that take place in the deeper portions of the megathrust fault.

Wirth and Frankel show that variations in coastal subsidence caused by the 1700 earthquake may be due to the locations of these subevents. But improving the accuracy of paleoseismic estimates for how the land level changed during previous Cascadia earthquakes is critical to ascertain this, said Wirth.

It's unclear what causes these subevents, other than that these areas of the fault must generate high stress that can be released in the form of strong ground shaking. This might indicate that the subevents have a physical cause like the structure or composition of the rocks along the fault that makes them mechanically strong, or changes in friction or fluid pore pressure related to their depth.

In the Tohoku and Maule earthquakes, Wirth noted, "the frequency of ground shaking that is most damaging to buildings and infrastructure seemed to be radiated from these discrete patches on the fault."

More research to understand what and where these subevents are, and whether they change over time, could improve seismic hazard estimates in Cascadia, she said. "If we could constrain the location of these subevents ahead of time, then you could anticipate where your strongest ground shaking might be."

In 2002, the USGS estimated that there was a 10% to 14% chance of another magnitude 9.0 Cascadia earthquake occurring in the next 50 years.

Journal Reference: Erin A. Wirth, Arthur D. Frankel. Impact of Down-Dip Rupture Limit and High-Stress Drop Subevents on Coseismic Land-Level Change during Cascadia Megathrust Earthquakes. *Bulletin of the Seismological Society of America*, 2019; DOI: 10.1785/0120190043.

Imperfect diamonds paved road to historic Deep Earth discoveries

Materials trapped inside diamonds offer clues to life's origin; suggest oceans' worth of water hidden in Deep Earth

ScienceDaily, October 24, 2019
Source: Deep Carbon Observatory

A Decade of Discovery

Hundreds of scientists from around the world met in Washington DC Oct. 24 to 26 to share and celebrate results of the wide-ranging, decade-long Deep Carbon Observatory -- one of the largest global research collaborations in Earth sciences ever undertaken.

With its Secretariat at the Carnegie Institution for Science in Washington DC, and $50 million in core support from the Alfred P. Sloan Foundation, multiplied many times by additional investment worldwide, a multidisciplinary group of 1,200 researchers from 55 nations worked for 10 years in four interconnected scientific "communities" to explore Earth's fundamental workings, including:

How carbon moves between Earth's interior, surface and atmosphere

Where Earth's deep carbon came from, how much exists and in what forms

How life began, and the limits -- such as temperature and pressure -- to Earth's deep microbial life

They met the challenge of investigating Earth's interior in several ways, producing 1,400 peer-reviewed papers while pursuing 268 projects that involved, for example:

Studying diamonds, volcanoes, and core samples obtained by drilling on land and at sea

Conducting lab experiments to mimic the extreme temperatures and pressures of Earth's interior, and through theoretical modeling of carbon's evolution and movements over deep time, and

Developing new high-tech instruments

DCO scientists conducted field measurements in remote and inhospitable regions of the world: ocean floors, on top of active volcanoes, and in the deserts of the Middle East.

Where instrumentation and models were lacking, DCO scientists developed new tools and models to meet the challenge. Throughout these studies, DCO invested in the next generation of deep carbon researchers, students and early career scientists, who will carry on the tradition of exploration and discovery for decades to come.

Hydrogen and oxygen, trapped inside diamonds from a layer 410 to 660 kilometers below Earth's surface, reveal the subterranean existence of oceans' worth of H_2O -- far more in mass than all the water in every ocean in the surface world.

This massive amount of water may have been brought to Deep Earth from the surface by the movement of the great continental and oceanic plates which, as they separate and move, collide with one another and overlap. This subduction of slabs also buries carbon from the surface back into the depths, a process fundamental to Earth's natural carbon balance, and therefore to life.

Knowledge of Deep Earth's water content is critical to understanding the diversity and melting behaviors of materials at the planet's different depths, the creation and flows of hydrocarbons (e.g. petroleum and natural gas) and other materials, as well as the planet's deep subterranean electrical conductivity.

By dating the pristine fragments of material trapped inside super-deep diamond "inclusions," DCO researchers could put an approximate time stamp on the start of plate tectonics -- "one of the planet's greatest innovations," in the words of DCO Executive Director Robert Hazen of the Carnegie Institution for Science. It started roughly 3 billion years ago, when the Earth was 1.5 billion years old.

While as many as 90% of analyzed diamonds were composed of carbon scientists expected in the mantle, some "relatively young" diamonds (up to a few hundred million years old) appear to include carbon from once-living sources; in other words, they are made of carbon returned to Deep Earth from the surface world.

Diamonds also revealed unambiguous evidence that some hydrocarbons form hundreds of miles down, well beyond the realm of living cells: abiotic energy.

Unravelling the mystery of deep abiotic methane and other energy sources helps explain how deep life in the form of microbes and bacteria is nourished, and fuels the proposition that life first originated and evolved far below (rather than migrating down from) the surface world.

Diamonds also enabled DCO scientists to simulate the extreme conditions of Earth's interior.

DCO's Extreme Physics and Chemistry community scientists used diamond anvil cells -- a tool that can squeeze a sample tremendously between the tips of two diamonds, coupled with lasers that heat the compressed crystals -- to simulate deep Earth's almost unimaginable extreme temperatures and pressures.

Using a variety of advanced techniques, they analyzed the compressed samples, identified 100 new carbon-bearing crystal structures and documented their intriguing properties and behaviors.

DCO's discoveries and research are important and applicable in many ways, including the development of new materials and potential carbon capture and storage strategies.

Key discoveries during the 10-year Deep Carbon Observatory program

In addition to insights from its diamond research above, the program's top discoveries include:

The deep biosphere is one of Earth's largest ecosystems

Life in the deep subsurface totals 15,000 to 23,000 megatons (million metric tons) of carbon, about 250 to 400 times greater than the carbon mass of all humans.

The immense Deep Earth biosphere occupies a space nearly twice as large as all the world's oceans.

DCO scientists explored how microbes draw sustenance from "abiotic" methane and other energy sources -- fuel that wasn't derived from biotic life above.

If microbes can eek out a living using chemical energy from rocks in Earth's deep subsurface, that may hold true on other planetary bodies.

This knowledge about the types of environments that can sustain life, particularly those where energy is limited, can guide the search for life on other planets. In the outer solar system, for example, energy from the sun is scarce, as it is in Earth's subsurface environment.

DCO researchers also found the deepest, lowest-density, and longest-lived subseafloor microbial ecosystem ever recorded and changed our understanding of the limits of life at extremes of pressure, temperature, and depth.

Rocks and fluids in Earth's crust provide clues to the origins of life on this planet, and where to look for life on others

DCO scientists found amino acids and complex organic molecules in rocks on the seafloor. These molecules, the building blocks of life, were formed by abiotic synthesis and had never before been observed in the geologic record.

They also found pockets of ancient salty fluids rich in hydrogen, methane, and helium many kilometers deep, providing evidence of early, protected environments capable of harboring life.

Abiotic methane forms in the crust and mantle of Earth

When water meets the ubiquitous mineral olivine under pressure, the rock reacts with oxygen atoms from the H_2O and transforms into another mineral, serpentine -- characterized by a scaly, green-brown, snakeskin-like appearance.

This process of "serpentinization" leads to the formation of "abiotic" methane in many different environments on Earth. DCO scientists developed and used sophisticated analytical equipment to differentiate between biotic (derived from ancient plants and animals) and abiotic formation of methane.

DCO field and laboratory studies of rocks from the upper mantle document a new high-pressure serpentinization process that produces abiotic methane and other forms of hydrocarbons.

The formation of methane and hydrocarbons through these geologic, abiotic processes provides fuel and sustenance for microbial life.

Atmospheric CO_2 has been relatively stable over the eons but huge, occasional catastrophic carbon disturbances have taken place

DCO scientists have reconstructed Earth's deep carbon cycle over eons to the present day. This new, more complete picture of the planetary ingassing and outgassing of carbon shows a remarkably stable system over hundreds of millions of years, with a few notable episodic exceptions.

Continental breakup and associated volcanic activity are the dominant causes of natural planetary outgassing. DCO scientists added to this picture by investigating rare episodes of massive volcanic eruptions and asteroid impacts to learn how Earth and its climate responds to such catastrophic carbon disturbances.

Plate tectonics modeling using DCO's new GPlates platform made it possible to reconstruct the Earth's carbon cycle through geologic time.

Much of the carbon outgassed from Deep Earth seeps from fractures and faults unassociated with eruptions

Volcanoes and volcanic regions outgas carbon dioxide (CO_2) into the ocean / atmosphere system at a rate of 280-360 megatons per year. This includes both emissions during volcanic eruptions and degassing of CO_2 out of diffuse fractures and faults in volcanic regions worldwide and the mid-ocean ridge system. Human activities, such as burning fossil fuels, are responsible for about 100 times more CO_2 emissions than all volcanic and tectonic region sources combined.

The changing ratio of CO_2 to SO_2 emitted by volcanoes may help forecast eruptions

The volume of outgassed CO_2 relative to SO_2 increases for some volcanoes days to weeks before an eruption, raising the possibility of improved forecasting and mitigating danger to humans.

DCO researchers measured volcanic outputs around the globe. Italy's Mount Etna, for example, one of Earth's most active volcanoes, typically spewed 5 to 8 times more CO_2 than usual about two weeks before a large eruption.

Fluids move and transform carbon deep within Earth

Experiments and new theoretical work led to a revolutionary new DCO model of water in deep Earth and the discovery that diamonds can easily form through water-rock interactions involving organic and inorganic carbon.

This model predicted the changing chemistry of water found in fluid inclusions in diamonds and yields new insights into the amounts of carbon and nitrogen available for return to Earth's atmosphere over deep time.

DCO scientists also discovered that the solubility of carbon-bearing minerals, including carbonates, graphite, and diamond, is much higher than previously thought in water-rock systems in the mantle.

31 new carbon-bearing minerals found in four years

After cataloguing known carbon-bearing minerals at Earth's surface, their composition and where they are found, DCO researchers discovered statistical relationships between mineral localities and the frequency of their occurrence. With that model they predicted 145 yet-to-be-discovered species and in 2015 challenged citizen scientists to help find them.

Of the 31 new-to-science minerals turned up during the Carbon Mineral Challenge, two had been predicted, including triazolite, discovered in Chile and thought to have derived in part from cormorant guano. Photo below.

Meanwhile, scientists led by DCO Executive Director Robert Hazen, established an entirely new mineral classification system.

Through experiment and observation, DCO scientists discovered new forms of carbon deep in Earth's mantle, shedding new light on the carbon "storage capacity" of the deep mantle, and on the role of subduction in recycling surface carbon back to Earth's interior.

Studies also cast new light on the record of major changes in our planet's history such as the rise of oxygen and the waxing and waning of supercontinents.

Two-thirds of Earth's carbon may be in the iron-rich core

DCO research suggests that two-thirds or more of Earth's carbon may be sequestered in the core as a form of iron carbide. This "hidden carbon" brings the total carbon content of Earth closer to what is observed in the Sun and helps us to understand the origin of Earth's carbon from celestial material.

What makes Earth's surface move? Could the surface drive mantle movement?

ScienceDaily, October 30, 2019
Source: French National Centre for Scientific Research - CNRS

Do tectonic plates move because of motion in the Earth's mantle, or is the mantle driven by the movement of the plates? Or could it be that this question is ill-posed? This is the point of view adopted by scientists at the École Normale Supérieure -- PSL, the CNRS and the University of Rome 3, who regard the plates and the mantle as belonging to a single system. According to their simulations, published in Science Advances on October 30, 2019, it is mainly the surface that drives the mantle, although the dynamic balance between the two changes over supercontinent cycles.

Which forces drive tectonic plates? This has remained an open question ever since the advent of plate tectonic theory 50 years ago. Do the cold edges of plates slowly sinking into the Earth's mantle at subduction zones cause the motion observed at the Earth's surface? Or alternatively, does the mantle, with its convection currents, drive the plates? For geologists, this is rather like the problem of the chicken and the egg: the mantle apparently causes the plates to move, while they in turn drive the mantle...

To shed light on the forces at work, scientists from the Geology Laboratory of the École Normale Supérieure (CNRS/ENS -- PSL), the Institute of Earth Sciences (CNRS/Universities Grenoble Alpes and Savoie Mont Blanc/IRD/Ifsttar) and the University of Rome 3 treated the solid Earth as a single indivisible system and carried out the most comprehensive modelling to date of the evolution of a fictional planet very similar to the Earth. The scientists first had to find the appropriate parameters, and then spend some nine months solving a set of equations with a supercomputer, reconstructing the evolution of the planet over a period of 1.5 billion years.

Using this model, the team showed that two thirds of the Earth's surface moves faster than the underlying mantle, in other words it is the surface that drags the interior, while the roles are reversed for the remaining third. This balance of forces changes over geological time, especially for the continents. The latter are mainly dragged by deep motion within the mantle during the construction phases of a supercontinent, as in the ongoing collision between India and Asia: in such cases, the motion observed at the surface can provide information about the dynamics of the deep mantle. Conversely, when a supercontinent breaks up, the motion is mainly driven by that of the plates as they sink down into the mantle.

The computation contains a wealth of data that remains largely unexploited. The data obtained could help us to understand how mid-ocean ridges form and disappear, how subduction is triggered, or what determines the location of the plumes that cause vast volcanic outpourings.

Journal Reference: Nicolas Coltice, Laurent Husson, Claudio Faccenna, Maëlis Arnould. What drives tectonic plates? *Science Advances*, 2019; 5 (10): eaax4295 DOI: 10.1126/sciadv.aax4295.

Southern California earthquakes increased stress on major fault line

ScienceDaily, October 30, 2019
Source: University of Iowa

A University of Iowa-led study has found that a series of Southern California earthquakes last summer increased stress on the Garlock Fault, a major earthquake fault line that has been dormant for at least a century.

The researchers used satellite imagery and seismic instruments to map the effects of the Ridgecrest earthquakes, a sequence that began with a magnitude 6.4 foreshock in the Mojave Desert on July 4 before a magnitude 7.1 earthquake that struck the next day. In all, there were more than 100,000 aftershocks stemming from the twin earthquakes.

The analysis by Bill Barnhart, a geodesist at Iowa, and researchers at the U.S. Geological Survey showed the Ridgecrest earthquakes and aftershocks caused "aseismic creep" along a 12- to 16-mile section of the Garlock Fault, which runs east to west for 185 miles from the San Andreas Fault to Death Valley, and perpendicular to the Ridgecrest earthquake region.

"The aseismic creep tells us the Garlock Fault is sensitive to stress changes, and that stresses increased across only a limited area of the fault," says Barnhart, assistant professor in the UI Department of Earth and Environmental Sciences and corresponding author on the study, published in the journal Geophysical Research Letters.

"So, if -- and that's a big if -- this area were to slip in a future earthquake, we are showing where that might happen," he adds.

The Ridgecrest earthquakes and aftershocks led to ruptures on the surface and below ground right up to the Garlock Fault. Other than the one stressed section on the Garlock Fault identified by the research team, the remaining 165 or so miles of the fault actually shows decreased stress from the Ridgecrest seismic activity.

"This is good news," Barnhart says.

Aseismic creep is slip on a fault that does not produce the shaking or seismic waves associated with earthquakes. Creep on the Garlock Fault following the Ridgecrest earthquakes was shallow, occurring from the surface to around 300 feet below ground.

The Garlock Fault has not produced large earthquakes since instrument-keeping began -- at least a century -- but is considered a potential seismic risk to Southern California. "The Garlock Fault has been quiet for a long time," Barnhart says. "But there's geologic evidence that there have been large earthquakes on it. It's a major fault line."

Barnhart's team says the stressed section could be capable of producing an earthquake between a magnitude 6.7 to a magnitude 7.0 if it ruptured." It would be an earthquake of the magnitude of the Ridgecrest sequence," Barnhart says. "That means it would be big. You'd feel some swaying in Los Angeles, but it wouldn't be a magnitude 7.8 that could be more damaging."

Aseismic creep triggered on faults by nearby earthquakes in Southern California are relatively common, and do not necessarily lead to earthquakes, Barnhart says.

Another analysis of the Ridgecrest earthquakes, published this month in the journal Science, reached the same general conclusions about the effects of the Ridgecrest temblors. Barnhart's study, though, identifies a longer stretch of the Garlock Fault that has slipped, and gives a physical explanation for why the slip happened.

The USGS and the Southern California Earthquake Center funded the research.

Journal Reference: William D. Barnhart, Gavin P. Hayes, Ryan D. Gold. The July 2019 Ridgecrest, California Earthquake Sequence: Kinematics of Slip and Stressing in Cross-Fault Ruptures. *Geophysical Research Letters*, 2019; DOI: 10.1029/2019GL084741.

Geoscientists hope to make induced earthquakes predictable

ScienceDaily, November 7, 2019
Source: University of Oklahoma

University of Oklahoma Mewbourne College of Earth and Energy assistant professor Xiaowei Chen and a group of geoscientists from Arizona State University and the University of California, Berkeley, have created a model to forecast induced earthquake activity from the disposal of wastewater after oil and gas production.

"In this region of the country, for every barrel of oil produced from the ground, usually between eight and nine barrels of water are also extracted from many wells," said Chen.

The large amount of water leads to a problem for oil producers -- what to do with it?

Also called brine, this wastewater contains salt, minerals and trace amounts of oil, making it unusable for consumption or agricultural purposes and cost-prohibitive to treat. It is disposed of by injecting it back into the earth, deep into porous rock formations.

Wastewater injection can cause earthquakes, explained Chen, and while most of the recent earthquakes in Oklahoma have been small, several have been in excess of 3.0 on the Richter scale.

Chen and a team of researchers, led by Guang Zhai and Manoochehr Shirzaei from ASU, and Michael Manga from UC Berkeley, set out to find a way to make induced earthquakes in Oklahoma predictable and small.

Their method, explained Chen, was to "create a model that correlates injected wastewater volume with stress changes on nearby faults and the number of earthquakes in that area."

Finding the Formula

Forecasting the amount of seismic activity from wastewater injection is difficult because it involves accounting for numerous variables:

> How easily brine can move through the rock in a given region
>
> Where and how much brine is injected
>
> The regional stress on those faults
>
> The presence of existing geological faults
>
> The team tackled each issue.

Chen and her fellow researchers studied subsurface hydrology parameters -- how fast fluid moves within porous rocks and how quickly introduced fluid changes the stress in the subsurface basement. This is important because the subsurface basement is the location of Oklahoma's induced earthquakes.

While the ASU team used satellite data to determine subsurface hydrology parameters, Chen focused on space and time distributions of earthquakes, and determined hydrology parameters by looking at how fast earthquakes move away from injection zones. By comparing both sets of data, researchers further increased the accuracy of their model.

As it turns out, the Arbuckle Group, a sedimentary layer that sits on top of the subsurface basement deep within the earth, is especially permeable, allowing brine, and therefor earthquakes, to easily spread.

"When we inject brine into the Arbuckle Group at a depth of 1-3 kilometers, it can transport through the porous rocks, modifying stresses and causing earthquakes on basement faults," said Chen.

Next, researchers can plug in the amount of fluid into the model. By adding the volume of fluid injected in a particular area into their model, they can determine the stress it will place on that region as it spreads.

With the brine variables accounted for, researchers then added information about pre-existing faults into regional calculations. The more researchers know about a particular area, the more accurate the data will be.

"If we are going to operate in an area where we don't have any prior seismicity, it will be a little challenging to forecast accurately," said Chen. "But by operating in a new area and taking real-time parameters, operators and researchers should be able to forecast future behavior."

Results

Chen hopes that by following the results of the models she helped create, oil operators in the state can create new protocols for how much wastewater to inject and where.

This could help prevent large induced earthquakes in Oklahoma. Chen does not believe forthcoming protocols will end induced seismicity altogether, but rather will help cap earthquake size and rate with restricted injection control. This method can forecast future induced seismicity.

Chen foresees a protocol similar to tornado watches -- a window of time where Oklahomans are warned they may feel minor tremors in a region of the state.

According to Chen, this is an area where the close working ties between geoscientists and petroleum engineers will need to be even stronger. So far, her research has garnered interest from both geoscientists and petroleum engineers in industry and academia.

Journal Reference: Guang Zhai, Manoochehr Shirzaei, Michael Manga, Xiaowei Chen. Pore-pressure diffusion, enhanced by poroelastic stresses, controls induced seismicity in Oklahoma. Proceedings of the National Academy of Sciences, 2019; 116 (33): 16228 DOI: 10.1073/pnas.1819225116.

Summary of Dr. David Schwartz's talk on Earthquakes of the East Bay

(continued from Page 1)

None of the major active East Bay faults has historically produced what's considered to be its maximum earthquake, and the concept of what that magnitude is has changed over time. The 1999/2002 Bay Area Probability Working Group and the 2007 Uniform California Earthquake Rupture Forecast (UCERF 2) identified distinct segments or sections of faults—sometimes single, sometimes multiple —based on changes in fault zone properties such as slip rate, geometry (bends and steps), and timing of past earthquake ruptures. The area of these segments, with lengths varying from about 40-150 km, was used to calculate magnitudes that generally ranged from the high M6s to low-mid M7s. The most recent source characterization, UCERF 3 in 2013, relaxed the concept of fault segmentation and through a new, and controversial to many, rupture-making model allows faults to link up. As examples, the northern Calaveras can fail with ruptures extending from the south end of the San Jacinto or San Andreas faults to the north end of the West Napa fault zone; similarly, the southern Hayward can fail with ruptures extending from the San Jacinto and southern San Andreas to the north end of the Maacama fault. While these long ruptures are infrequent in the model they are considered plausible. The UCERF 3 model raises many questions about future earthquake size and probability. The talk will discuss earthquake behavior past and present with regard to the magnitude and probability of future earthquakes in the East Bay.

Biography:

David Schwartz is a leading earthquake geologist. He received his BA and MA from Queens College, City University of New York, and his Ph.D. from the State University of New York, Binghamton. After 33 years at the US Geological Survey he retired from his full-time position in October 2017

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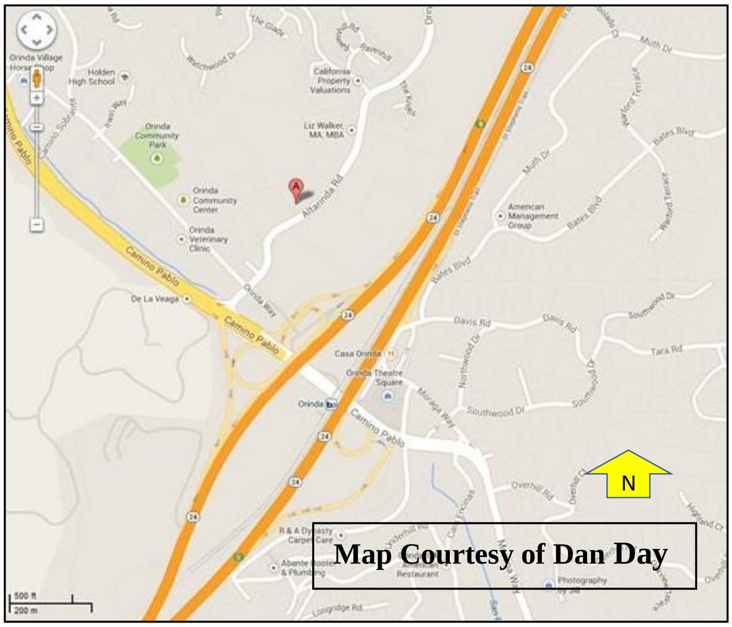

Map Courtesy of Dan Day

(continued from Page 12)

but remains an active voice in Bay Area earthquake hazard circles as an Emeritus Scientist with the Survey. He is credited with having pushed forward the fields of earthquake geology and paleoseismology (the study of prehistorical seismic events). One of his major contributions is the characteristic earthquake recurrence model, which has become a cornerstone of many seismic hazard analyses. He headed the San Francisco Bay Area Earthquake Hazards Project, co-chaired the Working Group on California Earthquake Probabilities that issued the first major Bay Area 30-year earthquake forecast, and was as a member of the Science Review Panels for the 2008 and 2013 Uniform California Earthquake Rupture Forecasts and the most recent (2014) earthquake probability estimate for the Bay Area. In addition, he twice served as the Northern California Regional Coordinator for the USGS National Earthquake Hazard Program. He has traveled extensively outside the U.S. studying faults that have produced large, historical earthquakes including Mongolia, Tierra del Fuego, northern Peru, Italy, Guatemala, and central Alaska. His current research remains focused on active faults and seismic hazards in the Bay Area, Alaska, and the Intermountain West.

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