DEEP CARBON OBSERVATORY

The Deep Carbon Cycle

Discoveries of the Deep Carbon Observatory

Craig Schiffries
Geophysical Laboratory
Carnegie Institution for Science
16 January 2019

Credit: Katie Pratt

Why Deep Carbon?

- Carbon is the element of life
- Carbon-based fuels supply most of our energy
- The carbon cycle plays a fundamental role in controlling Earth's climate and habitability
- The vast majority of previous research has focused on small fraction of Earth's carbon in the oceans, atmosphere, & shallow crustal environments
- In contrast, DCO focuses on the vast majority (>90%) of Earth's carbon in the planet's deep interior and the entire carbon cycle

Mission

The Deep Carbon Observatory is a ten-year research program to discover the quantities, movements, forms, and origins of Earth's deep carbon.

Quantities How much carbon is stored in Earth? Where is it stored?

Movements How does it move between and within reservoirs?

Forms What are the forms of carbon at depth, both organic and inorganic?

Origins What can deep carbon tell us about origins of life, Earth, and the Solar System?


Credit: Tobias Fischer

DEEP CARBON OBSERVATORY

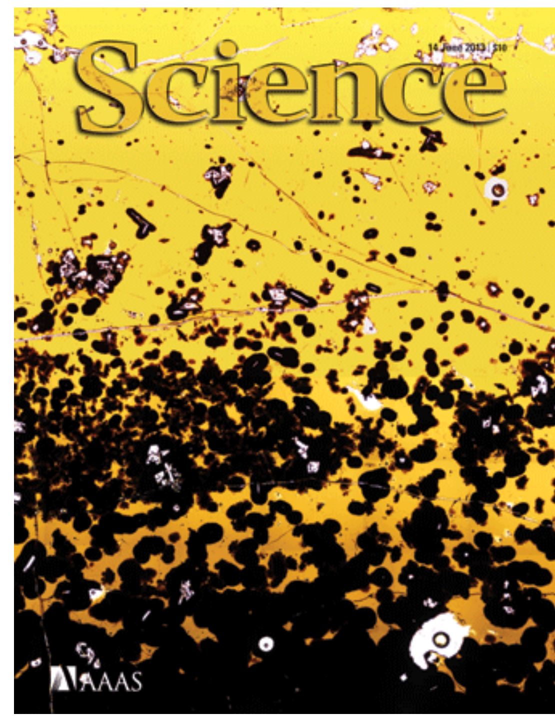
Deep Carbon Observatory Overview

- A 10-year project launched in September 2009
- Foster international collaboration. Engage over 1100 researchers, including more than 500 early career scientists, from approximately 50 countries
- Interdisciplinary scientific approach bridges multiple fields including geology, chemistry, biology, and physics
- More than 80 field sites in 30 countries, involving more than 250 scientists from numerous disciplines
- A pledge of $50 million from the Alfred P. Sloan Foundation has been leveraged with more than $500 million in support from other organizations worldwide
- DCO Task Force 2020 is planning for the future of deep carbon science

DEEP CARBON OBSERVATORY

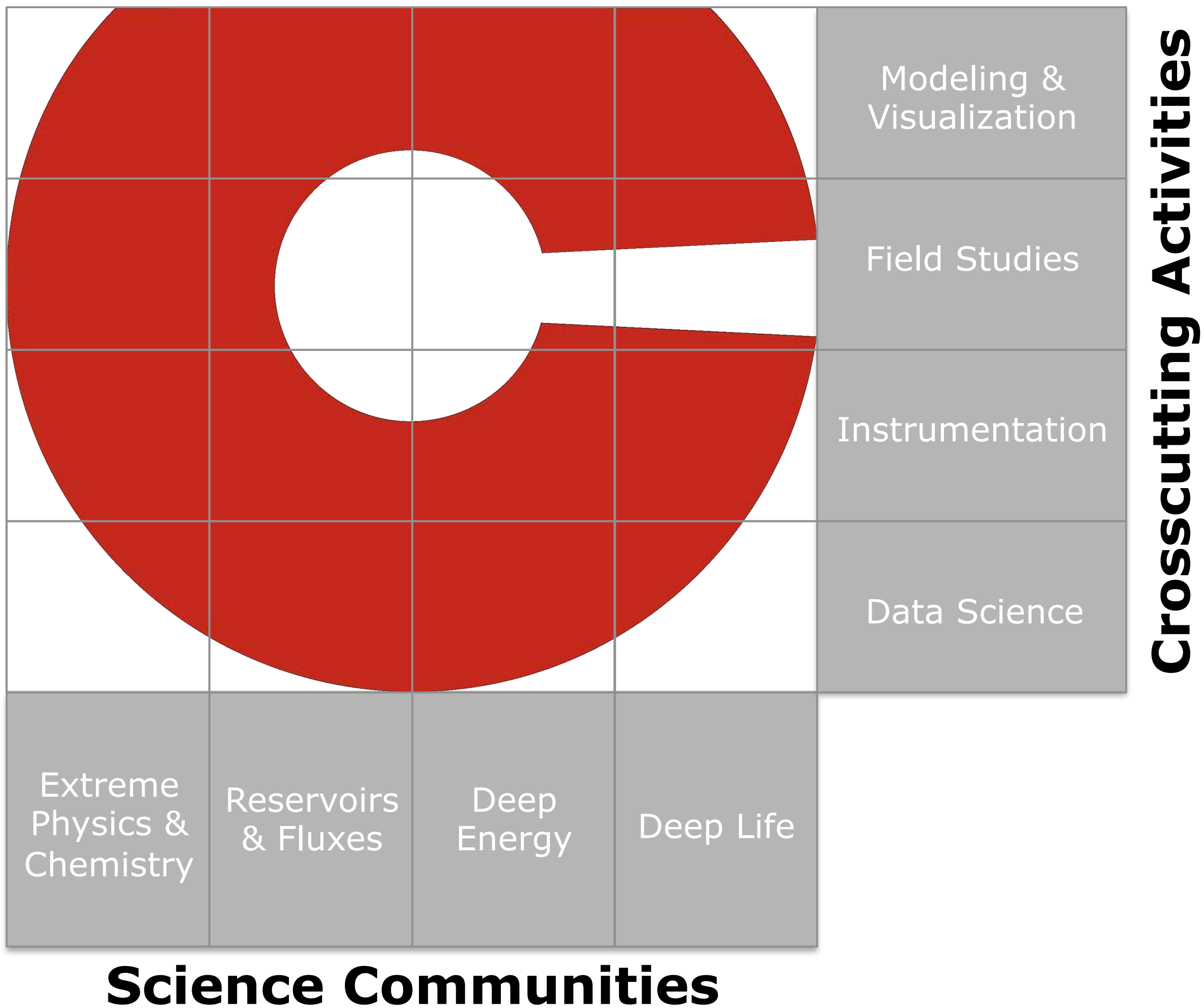
DCO Publications

- DCO scientists have published more than 1400 peer reviewed publications, including 109 papers in *Nature, Science,* and *PNAS*, documenting novel results of broad interest beyond traditional scientific disciplines.
- View the Bibliography of Contributions to DCO through the DCO Publication Browser (https://info.deepcarbon.net/vivo/publications)



DEEP CARBON OBSERVATORY

Science Communities and Crosscutting Activities



DEEP CARBON OBSERVATORY

DCO Groups and Teams

Leadership

- Executive Committee
- Four Scientific Steering Committees
- Secretariat

Science Communities

- Extreme Physics and Chemistry
- Deep Energy
- Deep Life
- Reservoirs and Fluxes

Cross-Community Groups and Teams

- Synthesis Group 2019
- Task Force 2020
- Engagement Team
- Data Science Team
- Modeling & Visualization Forum

DEEP CARBON OBSERVATORY

Community Building

- Community Building, Partnerships, and Leverage
  - ✓ Community building is an explicit goal
  - ✓ DCO meetings and workshops
  - ✓ DCO website, social media, and mass media
  - ✓ Partners, sponsors, and leverage

DEEP CARBON OBSERVATORY

✓ Community building

Deep Volatiles Summit - China

13-15 March 2018 • Shanghai, China

- Co-sponsored by DCO and the Chinese Academy of Engineering
- Included presentations from representatives of each Science Community as well as local deep carbon researchers
- Expanded the DCO science network in China
- Organized by HPSTAR Director Dave Ho-Kwang Mao

DEEP CARBON OBSERVATORY

Deep Carbon Cycle Symposium - India

- Held in Hyderabad, India on 7 December 2017 following the 54th Indian Geophysical Union Annual Convention
- Co-sponsored by India's Council of Scientific and Industrial Research–National Geophysical Research Institute, the Indian Geophysical Union, and DCO
- Included presentations from representatives of each Science Community as well as local deep carbon researchers
- Expanded the DCO science network in India

DEEP CARBON OBSERVATORY

- ✓ Meetings and Events
- ✓ Synthesis

Third DCO International Science Meeting - UK

- Held at the University of St Andrews, Scotland in March 2017
- Brought together more than 150 DCO members from all science communities and cross-community initiatives
- Meeting program included approximately 40 oral presentations, 90 poster presentations, and five workshops
- Emphasized and promoted early career scientists throughout meeting

DEEP CARBON OBSERVATORY

- ✓ Community building
- ✓ Instrumentation
- ✓ Field studies

DCO Symposium - Japan

- Activities in conjunction with 2016 Goldschmidt meeting in Yokohama, Japan
- DCO Executive Committee meeting and field trip to D/V *Chikyu*
- Open symposium on deep carbon science attended by more than 100 Japanese colleagues and Goldschmidt attendees
- DCO Symposium in Yokohama organized by:
  - Eiji Ohtani (Tohoku University)
  - Fumio Inagaki (JAMSTEC)
  - Kagi Hiroyuki (University of Tokyo)
  - Yuji Sano (University of Tokyo)


Credit: Katie Pratt

DEEP CARBON OBSERVATORY

- ✓ Integration & synthesis
- ✓ Field studies
- ✓ Instrumentation

DCO Executive Committee Meeting - Italy

- Accademia Nazionale dei Lincei, Rome; 8-9 October 2015
- More than 50 scientists from over 25 Italian institutions participated
- Increase collaboration with Italian scientific community
- Field visits to explore diffuse degassing of CO_2; 6-7 October 2015

DEEP CARBON OBSERVATORY

- ✓ Integration & synthesis
- ✓ Field studies

DCO Executive Committee Meeting - Oman

- 27-29 January 2015, meetings in Muscat, Oman
- 25-26 January 2015, field visits to Samail Ophiolite, which is the focus of the Oman Drilling Project, sponsored by the International Continental Drilling Program, DCO, and other organizations

DEEP CARBON OBSERVATORY

DCO Early Career Scientist Workshops

DEEP CARBON OBSERVATORY

- ✓ Community building
- ✓ Synthesis

Deep Carbon Science Gordon Research Conference

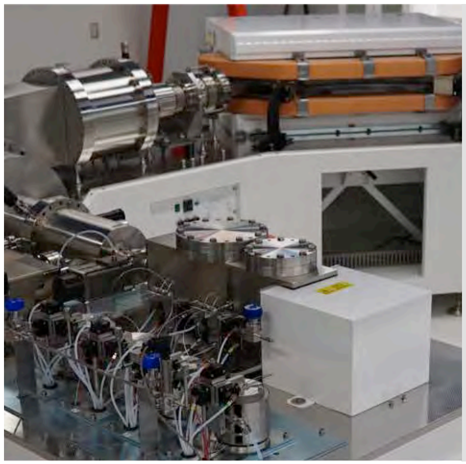
- DCO organized the first Gordon Research Conference (GRC) on Deep Carbon Science from 17-22 June, 2018
- All interested deep carbon researchers are encouraged to apply for the second GRC on Deep Carbon Science in 2020

GRC Gordon Research Conferences frontiers of science

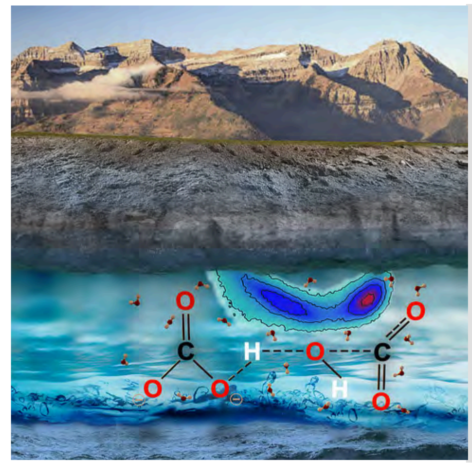
Bryant University 1863

DEEP CARBON OBSERVATORY

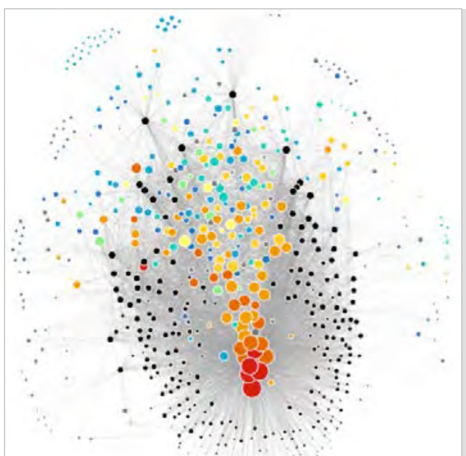
Crosscutting Activities



INSTRUMENTATION



MODELING AND VISUALIZATION



DATA SCIENCE

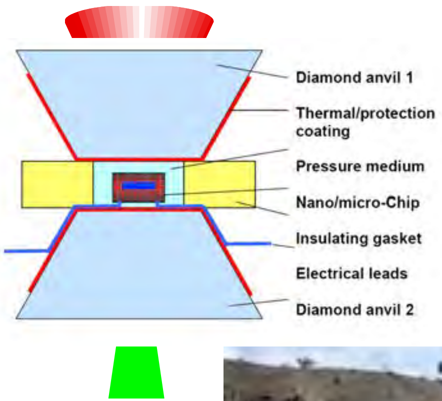
FIELD STUDIES

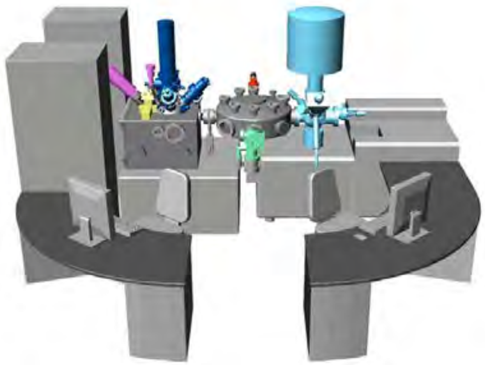
Instrumentation

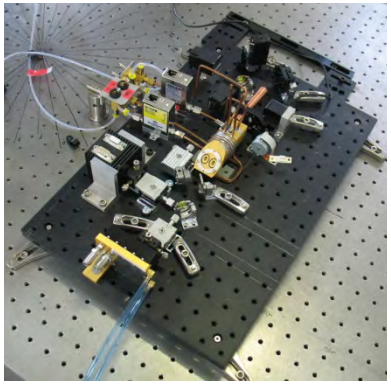
- Instrumentation
  - ✓ New instrumentation is needed to achieve each set of decadal goals
  - ✓ Hypothesis-driven instrumentation development projects
  - ✓ High risk, high reward
  - ✓ The DCO front-loaded its decadal program with investments in instrument development due to long lead times
  - ✓ Partnerships between academic institutions and private sector
  - ✓ Commercialization of new instruments by existing companies and startups

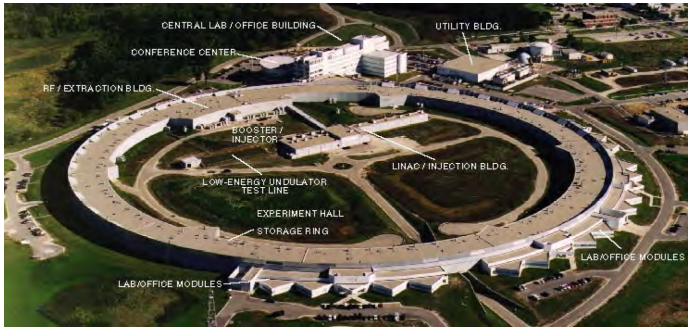
Next generation instrumentation is needed to achieve DCO goals

DEEP CARBON OBSERVATORY



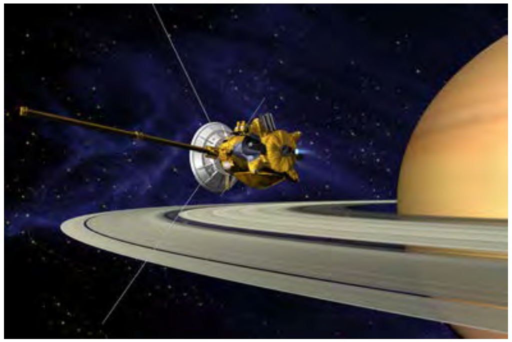


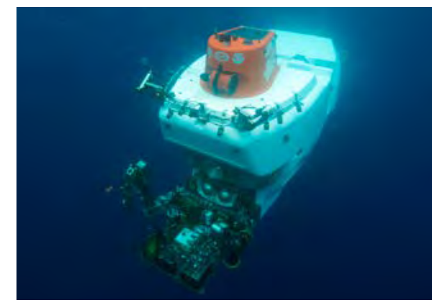




DEEP CARBON OBSERVATORY

DCO Field Studies: Deep Earth to Outer Space





Oman Drilling Project

- Successfully completed Phase 1 and Phase 2 drilling in Oman and core logging aboard Drilling Vessel *Chikyu* in Japan
- Special session on results from Oman Drilling Project at 2019 AGU Fall Meeting

oman drilling project

Credit: Oman Drilling Project


Credit: Oman Drilling Project

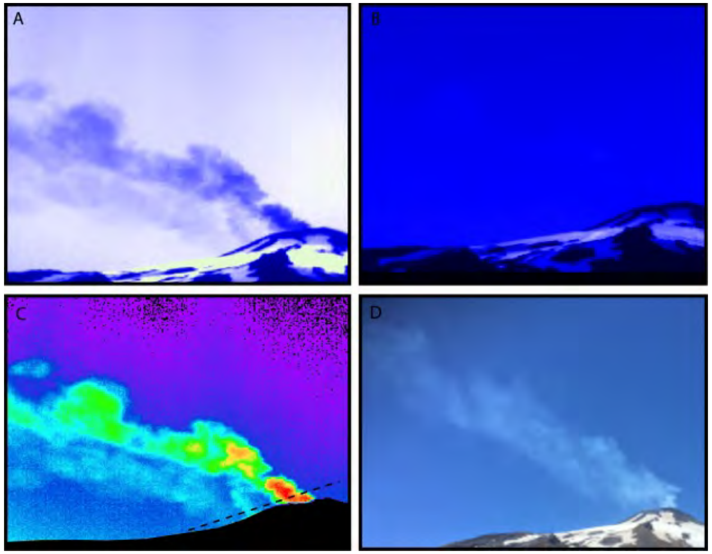

Credit: Oman Drilling Project

DEEP CARBON OBSERVATORY

✓ Field Studies
✓ Early Career Scientists

Trail by Fire Expedition – South America

- Conducted fieldwork in 2015/2016 and 2017 along the Nazca subduction zone using a Land Rover outfitted to become the world's first mobile volcano observatory
- Resulted in initial suite of four papers by in *Earth and Planetary Science Letters*, *Bulletin of Volcanology*, and *Journal of Volcanology and Geothermal Research*
- Team leader Yves Moussallam received a DCO Emerging Leader Award for this work




Trail by Fire

Aerial Observations of Volcanic Emissions

- This DCO expedition is using innovative unmanned aerial system technologies (or drones) to collect volcanic gas measurements at Manam and Rabaul Volcanoes in Papua New Guinea
- These strongly degassing volcanoes are largely uncharacterized because their plumes are challenging to access using ground-based techniques


Credit: Emma Liu

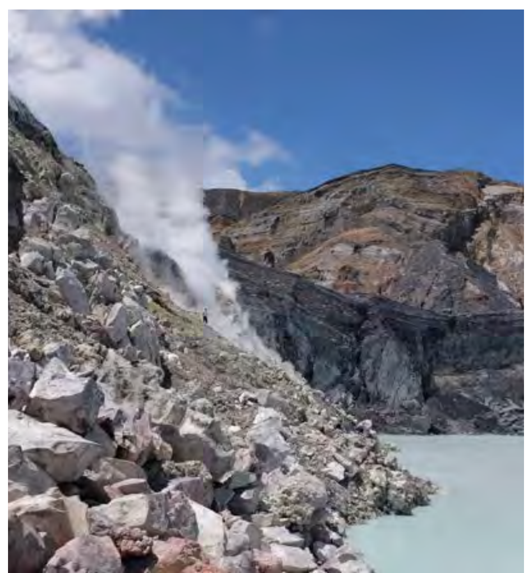

Credit: Emma Liu

DEEP CARBON OBSERVATORY

- ✓ Field Studies
- ✓ Early Career Scientists

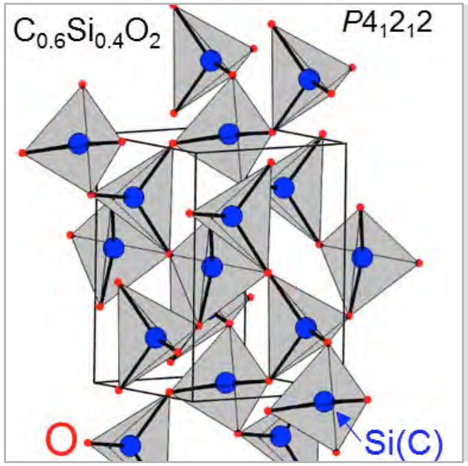
Biology Meets Subduction

- In February 2017, 25 researchers from six countries met in San José, Costa Rica, for a 12-day sampling expedition across the Costa Rica volcanic arc
- Team included members of all four Science Communities
- Explored Costa Rican volcanic sites through the lenses of biology, chemistry, physics, and geology



DEEP CARBON OBSERVATORY

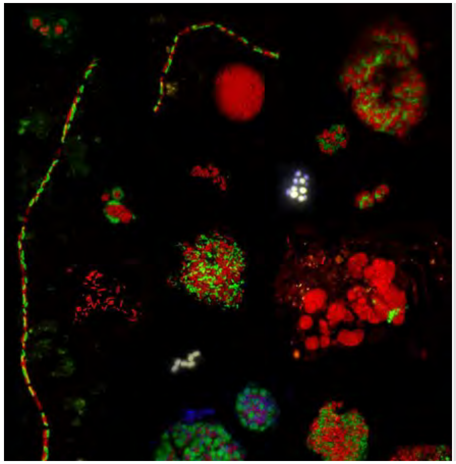
Science Communities



EXTREME PHYSICS AND CHEMISTRY

RESERVOIRS AND FLUXES

DEEP ENERGY



DEEP LIFE

Diamonds & Mantle Geodynamics of Carbon

Large gem diamonds from metallic liquid in Earth's deep mantle

Smith EM, Shirey SB, Nestola F, Bullock ES, Wang J, Richardson SH, Wang W

SCIENCE
16 December 2016

Cover: Standing at 7-centimeners tall, this 404.2-carat rough diamond was recovered from the Lulo mine, Angloa, in February 2016. Evidence from the interior of such large gem diamonds suggests that these diamonds grow from an iron-nickel metallic liquid in Earth's deep convecting mantle. The presence of metal in regions of the deep mantle has broad implications for Earth's evolution.

✓ Reservoirs and Fluxes

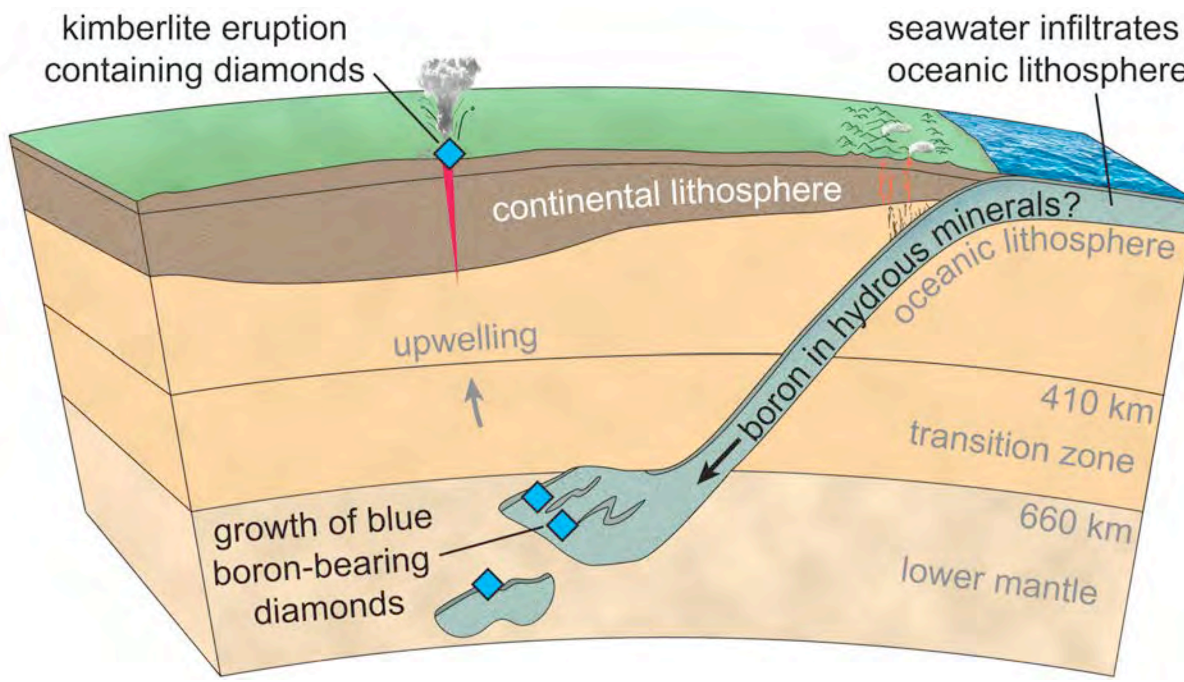
DEEP CARBON OBSERVATORY

Diamonds & Mantle Geodynamics of Carbon

Blue boron-bearing diamonds from Earth's lower mantle

Smith EM, Shirey SB, Richardson SH, Nestola F, Bullock ES, Wang J, Wang W

NATURE
August 2018



Credit: Evan M. Smith/GIA

Diamonds & Mantle Geodynamics of Carbon

Highly saline fluids from a subducting slab as the source for fluid-rich diamonds

Yaakov Weiss, John McNeill, D. Graham Pearson, Geoff M. Nowell, and Chris J. Ottley

nature

20 AUGUST 2015 **NATURE**

DEEP CARBON OBSERVATORY

✓ Reservoirs and Fluxes

Diamonds & Mantle Geodynamics of Carbon

Hydrous mantle transition zone indicated by ringwoodite included within diamond

Graham Pearson, Frank Brenker, Fabrizio Nestola, John McNeill, Lutz Nasdala, Mark Hutchison, Sergei Matveev, Kathy Mather, Geert Silversmit, Sylvia Schmitz, Bart Vekemans, Laszlo Vincze

nature

MARCH 2014 VOL 507 **NATURE**

DEEP CARBON OBSERVATORY

✓ Reservoirs and Fluxes

Diamonds & Mantle Geodynamics of Carbon

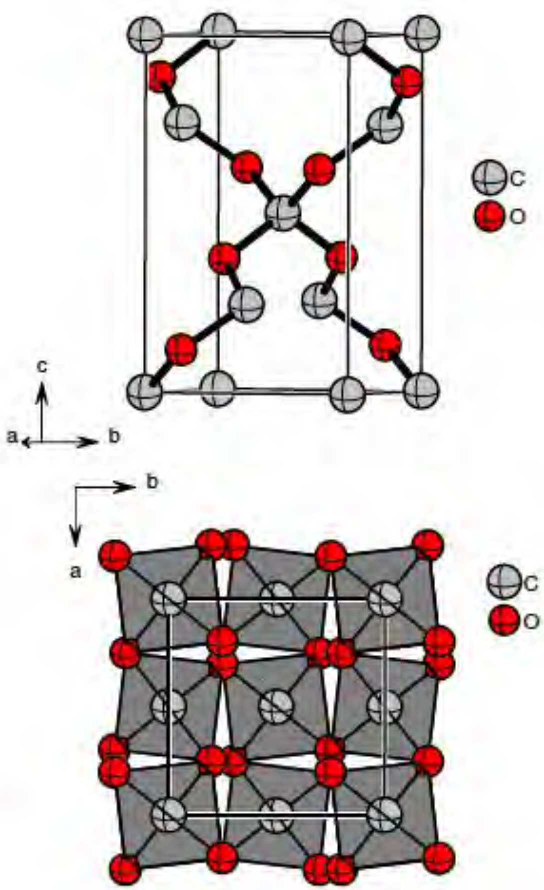
$CaSiO_3$ perovskite in diamond indicates the recycling of oceanic crust into the lower mantle

Nestola F, Korolev N, Kopylova M, Rotiroti N, Pearson DG, Pamato MG, Alvaro M, Peruzzo L, Gurney JJ, Moore AE, Davidson J

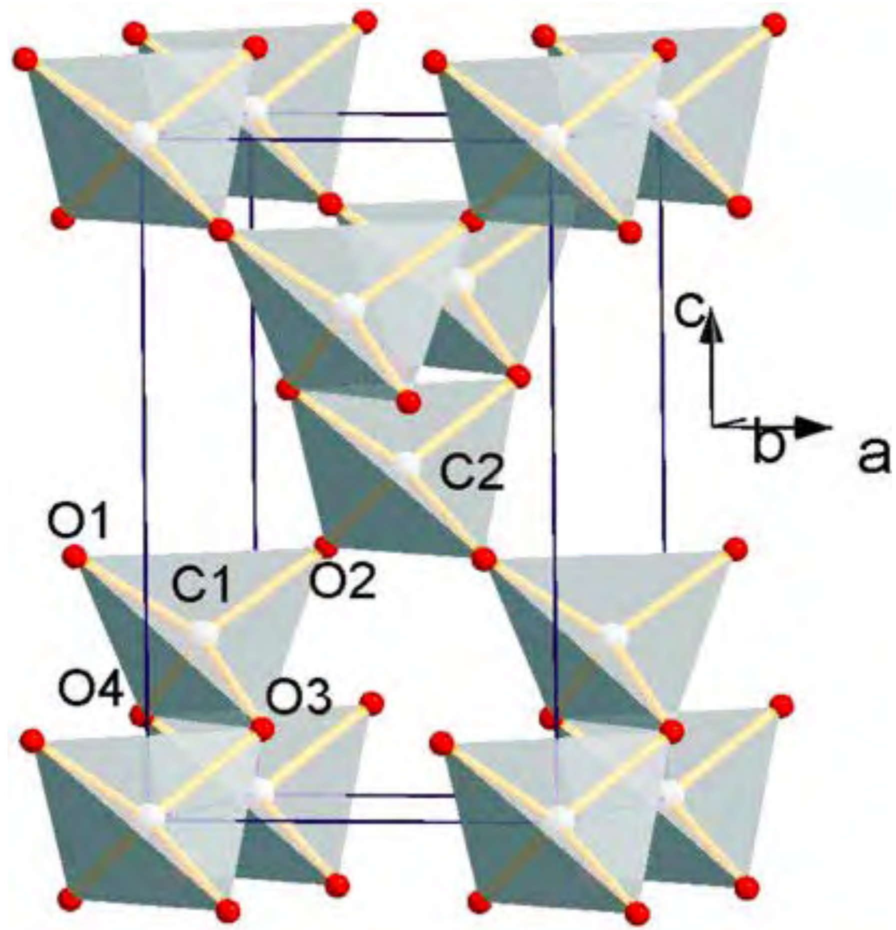
NATURE
March 2018

Researchers discovered a pocket of Ca-Pv in a diamond that formed 780 kilometers deep inside Earth. The analysis also revealed that the carbon in the surrounding diamond originally came from ocean crust, suggesting that surface carbon travels incredibly deep into the mantle to be recycled.

Structure of Crystalline Polymeric CO_2-V



Santoro et al, PNAS, 2012

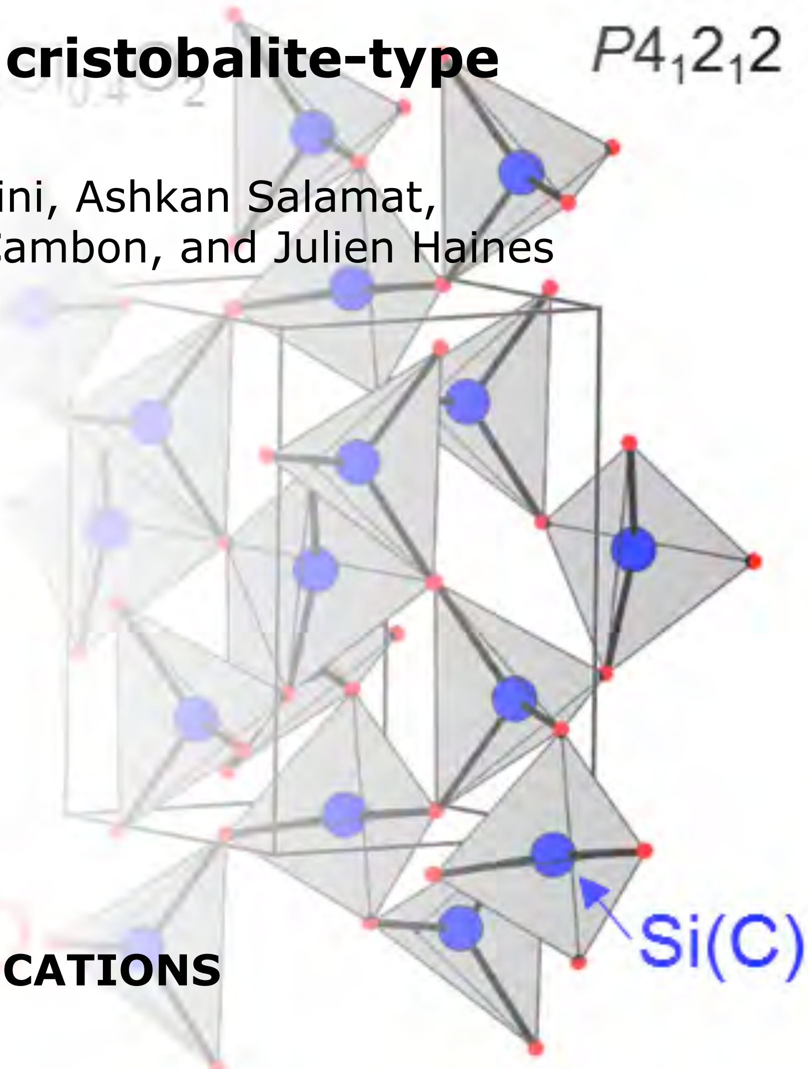


Datchi et al, PRL, 2012

Crystalline Polymeric CO_2 Solid Solutions

Carbon enters silica forming a cristobalite-type CO_2-SiO_2 solid solutions

Mario Santoro, Federico Gorelli, Roberto Bini, Ashkan Salamat, Gaston Garbarino, Claire Levelut, Olivier Cambon, and Julien Haines



nature COMMUNICATIONS

APRIL 2014 VOL 5 **NATURE COMMUNICATIONS**

DEEP CARBON OBSERVATORY

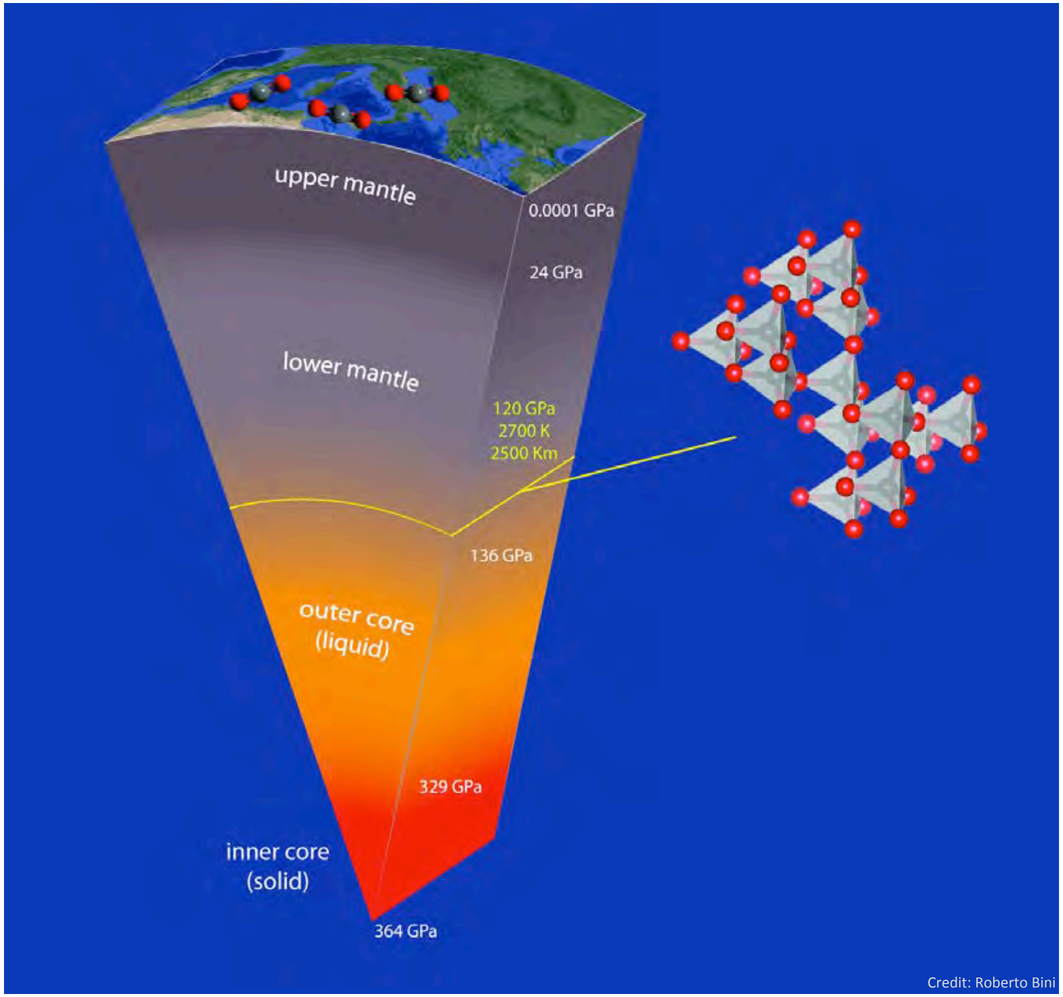
✓ Extreme Physics and Chemistry

Polymeric CO_2 at Deep Mantle Conditions

Crystalline polymeric carbon dioxide stable at megabar pressures

Dziubek KF, Ende M, Scelta D, Bini R, Mezouar M, Garbarino G, Miletich R

NATURE COMMUNICATIONS
August 2018



Researchers showed that under the P/T conditions close to the core-mantle boundary, carbon dioxide can exist as a covalently bonded, extended crystalline form called phase V. These findings contradict similar experiments where carbon dioxide split into diamond and oxygen under deep mantle conditions.

✓ Extreme Physics and Chemistry

DEEP CARBON OBSERVATORY

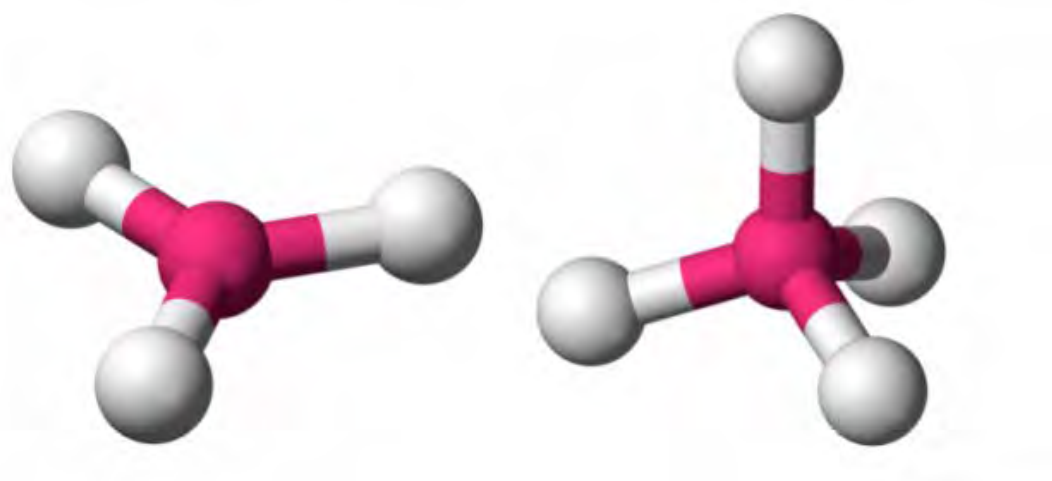
Carbonates in the Deep Mantle

Raman spectroscopy and x-ray diffraction of *sp*^{3} $CaCO_3$ at lower mantle pressures

Lobanov SS, Dong X, Martirosyan NS, Samtsevich AI, Stevanovic V, Gavryushkin PN, Litasov KD, Greenberg E, Prakapenka VB, Oganov AR, Goncharov AF

PHYSICAL REVIEW B
September 2017

Lobanov and colleagues experimentally demonstrated that calcium carbonate forms a more compact, tetrahedrally-coordinated structure at lower mantle pressure and temperature conditions.



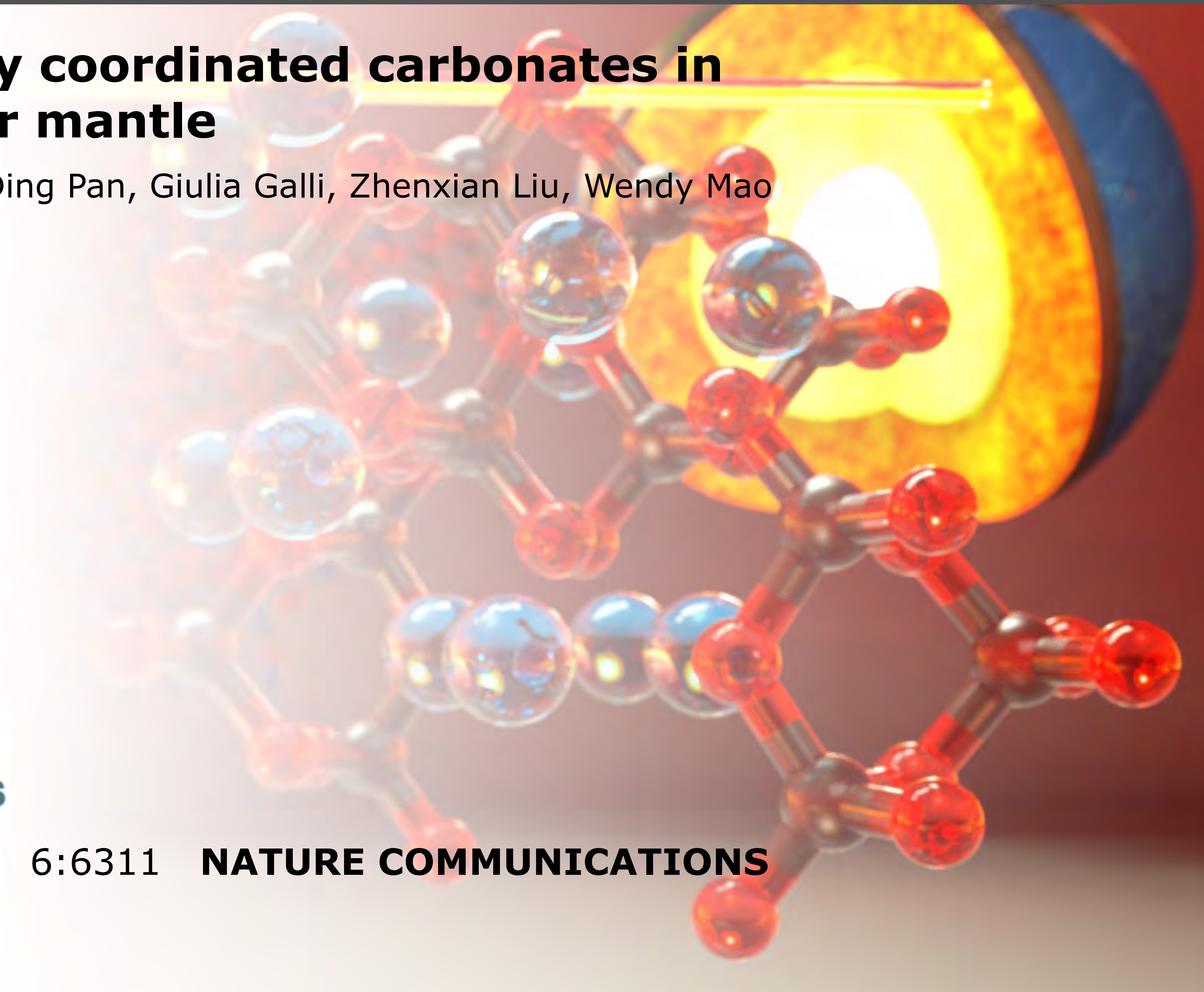
✓ Extreme Physics and Chemistry

DEEP CARBON OBSERVATORY

Carbonates in the Deep Mantle

Tetrahedrally coordinated carbonates in Earth's lower mantle

Eglantine Boulard, Ding Pan, Giulia Galli, Zhenxian Liu, Wendy Mao



nature COMMUNICATIONS

18 February 2015 6:6311 **NATURE COMMUNICATIONS**

DEEP CARBON OBSERVATORY

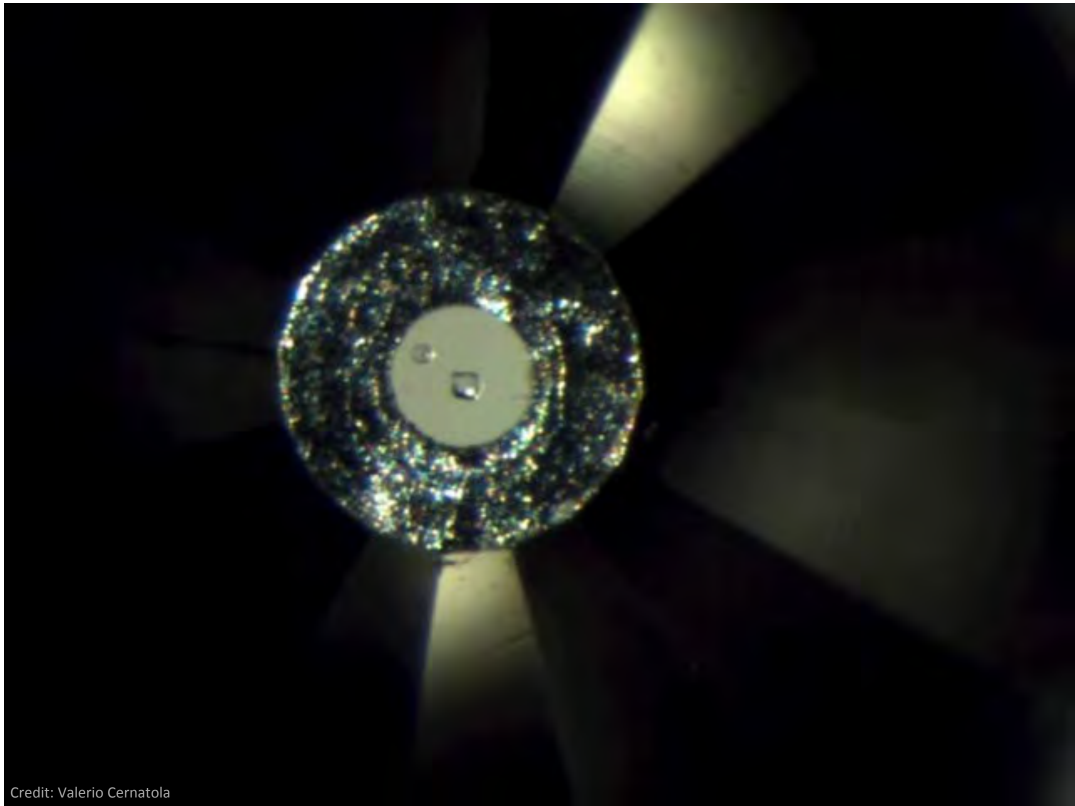
Carbonates in the Deep Mantle

Stability of iron-bearing carbonates in the deep Earth's interior

Cerantola V, Bykova E, Kupenko I, Merlini M, Ismailova L, McCammon C, Bykov M, Chumakov AI, Petitgirard S, Kantor I, Svitlyk V, Jacobs J, Hanfland M, Mezouar M, Prescher C, Rüffer R, Prakapenka V, Dubrovinsky L

NATURE COMMUNICATIONS
July 2017

Under the high pressure and temperature conditions present in the deep mantle, carbonate molecules can reorganize so that the carbon carries an extra oxygen atom, forming a tetrahedral shape. The researchers detected two new compounds created at these extreme conditions, with one "tetracarbonate" having the potential to survive travel deep into the lower mantle, where it may play a role in diamond formation.



Credit: Valerio Cernatola

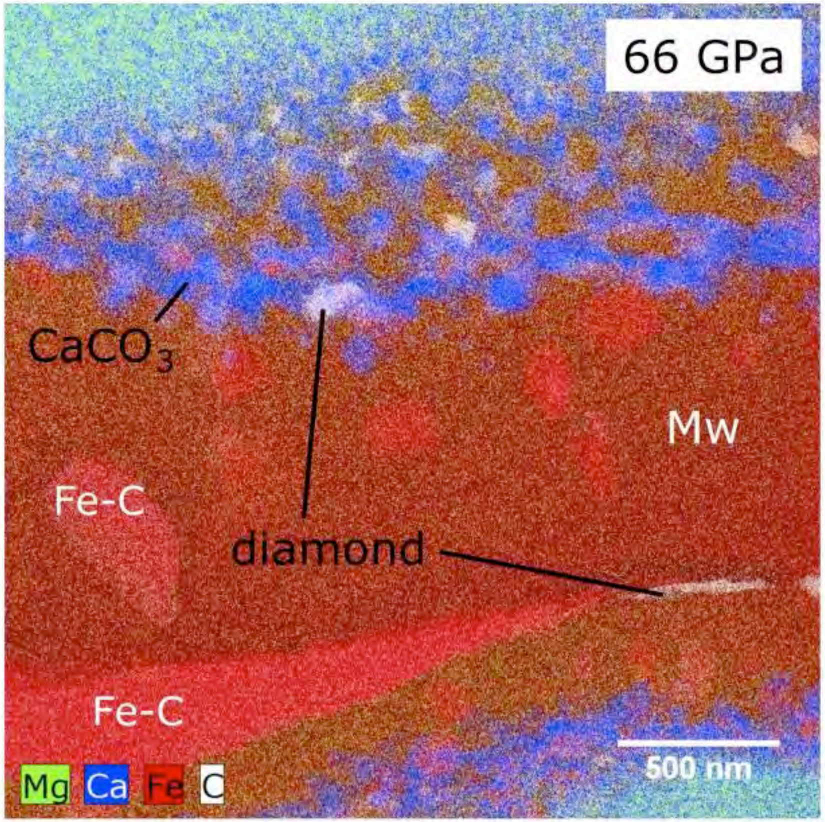
Carbonates in the Deep Mantle

Carbonate stability in the reduced lower mantle

Dorfman SM, Badro J, Nabiei F, Prakapenka VB, Cantoni M, Gillet P

EARTH AND PLANETARY SCIENCE LETTERS
May 2018

Researchers find that carbonates may reach the deep lower mantle in the form of high-pressure marble rich in calcium carbonate.



✓ Extreme Physics and Chemistry

DEEP CARBON OBSERVATORY

Deep Earth Water Model

Dielectric properties of water under extreme conditions and transport of carbonates in the deep Earth

Ding Pan, Leanardo Spanu, Bandon Harrison,
Dimitri A. Sverjensky, and Giulia Galli

Deep water gives up another secret

Commentary on "Dielectric properties of water under extreme conditions and transport of carbonates in the deep Earth" (Pan et al, PNAS, 2013)

Craig E. Manning

PNAS

MARCH 2013 VOL 110 **PNAS**

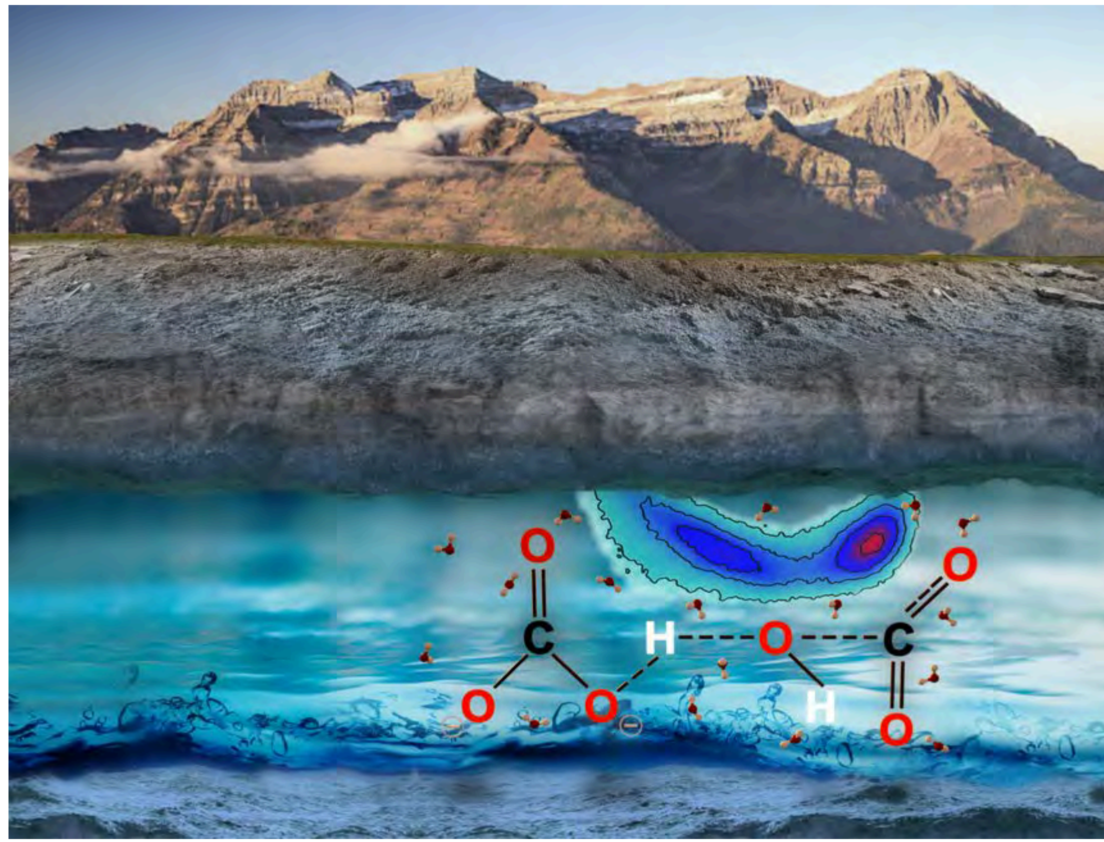
DEEP CARBON OBSERVATORY

- ✓ Extreme Physics & Chemistry
- ✓ Modeling & visualization
- ✓ Early career scientists

New Understanding of Carbon in Deep Water

The fate of carbon dioxide in water-rich fluids under extreme conditions

Pan D, Galli G



> "Our study shows the importance of of accounting for the changes of water properties at the atomistic scale, under extreme conditions. Only by doing so, one can understand chemical reactions in aqueous media at high pressure and temperature."
>
> – Giulia Galli

SCIENCE ADVANCES
12 October 2016

DEEP CARBON OBSERVATORY

- ✓ Extreme Physics & Chemistry
- ✓ Modeling & visualization
- ✓ Early career scientists

New Understanding of Deep Water

Implications for Volatile and Metal Cycles from the pH of Subduction Zone Fluids

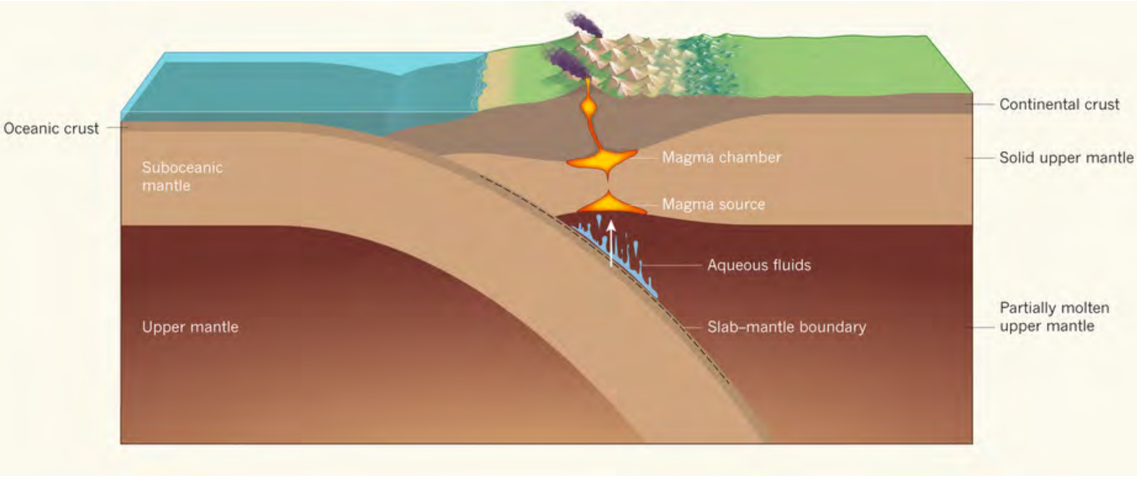
Galvez ME, Connolly JA, Manning CE

Nature News and Views article:
Geochemistry: Ions surprise in Earth's deep fluids

Dolejš D (16 November 2016)

"This transforms our view of global geochemical transport."

- David Dolejš



NATURE
17 November 2016

DEEP CARBON OBSERVATORY

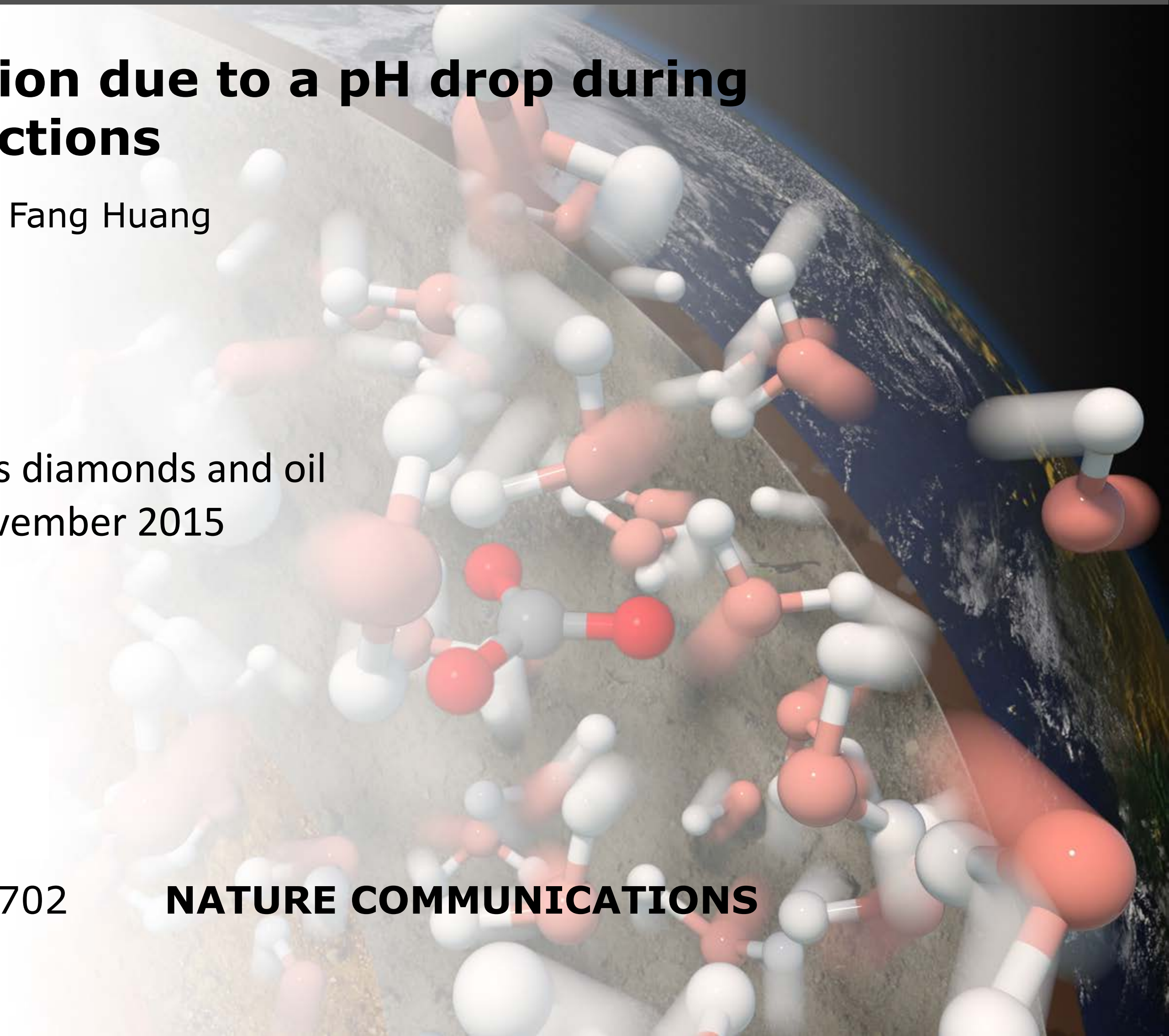
- ✓ Extreme Physics and Chemistry
- ✓ Modeling & visualization

Deep Earth Water Model

Diamond formation due to a pH drop during fluid-rock interactions

Dimitri A. Sverjensky and Fang Huang

News article:
How buried water makes diamonds and oil
Eric Hand, *Science*, 6 November 2015



nature COMMUNICATIONS

3 November 2015 6:8702 **NATURE COMMUNICATIONS**

DEEP CARBON OBSERVATORY

- ✓ Extreme Physics and Chemistry
- ✓ Deep Energy
- ✓ Modeling & visualization

Deep Earth Water Model: Abiotic Hydrocarbons

Important role for organic carbon in subduction-zone fluids in the deep carbon cycle

Dimitri Sverjensky, Vincenzo Stagno, Fang Huang

Subduction goes organic

Commentary on "Important role for organic carbon in subduction-zone fluids in the deep carbon cycle"

Jay Ague

Press Release

"It is a very exciting possibility that these deep fluids might transport building blocks for life into the shallow Earth," said Sverjensky. "This may be a key to the origin of life itself."

nature geoscience

DECEMBER 2014 **NATURE GEOSCIENCE**

DEEP CARBON OBSERVATORY

✓ Deep Energy
✓ Modeling & visualization

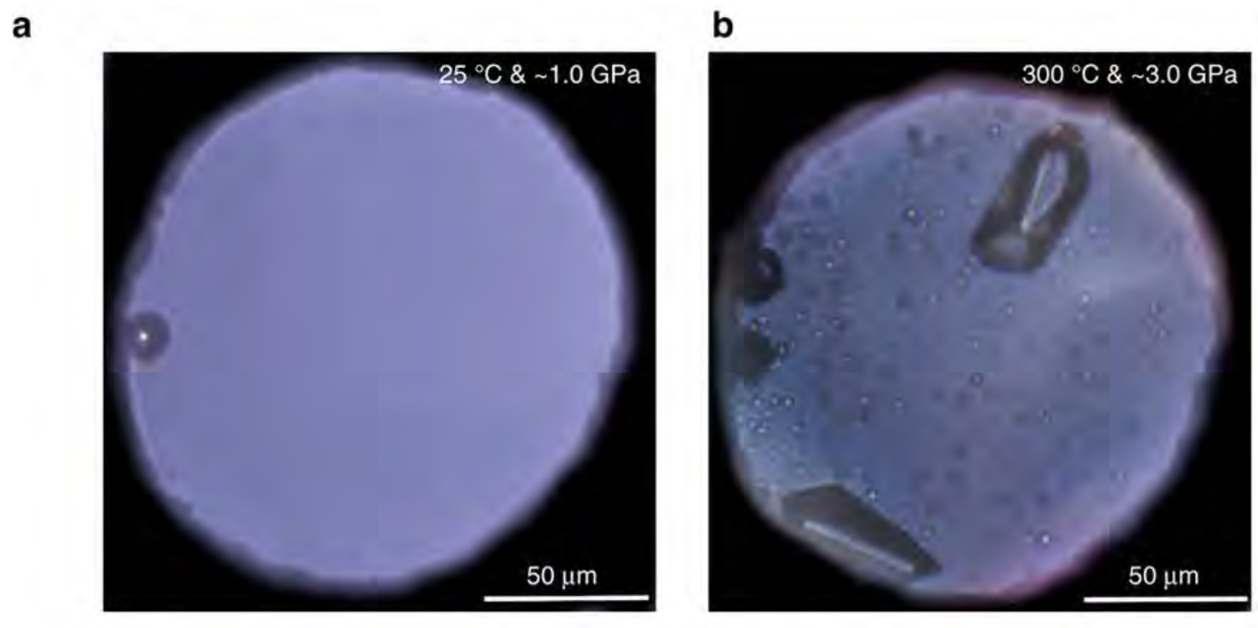
Deep Hydrocarbons

Immiscible hydrocarbon fluids in the deep carbon cycle

Huang F, Daniel I, Cardon H, Montagnac G, Sverjensky DA

NATURE COMMUNICATIONS
June 2017

A new study finds that acetate dissolved in water can transform into the hydrocarbon isobutane at the high temperatures and pressures of subduction zones. Isobutane does not mix well with water, and instead forms an oily liquid that might migrate independently in the subduction zone environment. The discovery represents a novel source of deep hydrocarbons and a new way for carbon to move through the subsurface.



DEEP CARBON OBSERVATORY

✓ Deep Energy

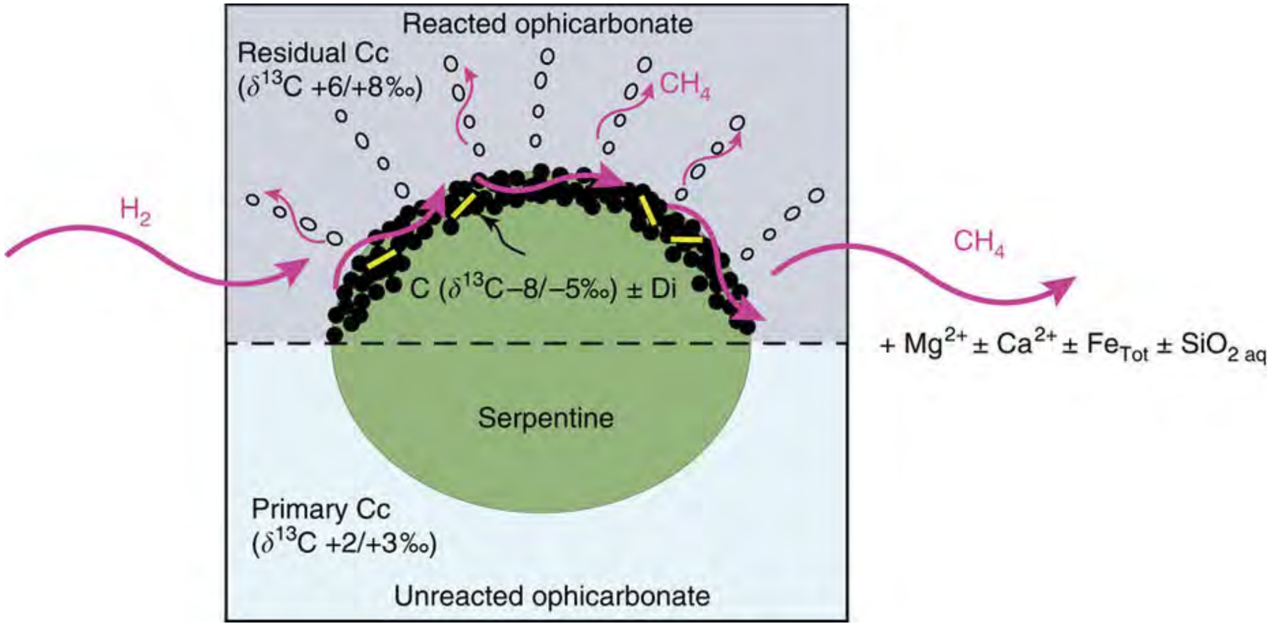
Methane Formation

Massive production of abiotic methane during subduction evidenced in metamorphosed ophicarbonates from the Italian Alps

Vitale Brovarone A, Martinez I, Elmaleh A, Compagnoni R, Chaduteau C, Ferraris C, Esteve I

NATURE COMMUNICATIONS
February 2017

Vitale Brovarone and colleagues studied rock samples from the Lanzo Massif in the Western Alps. Their analysis shows that deep serpentinization reactions can generate methane at rates that are comparable to shallow serpentinization environments.



DEEP CARBON OBSERVATORY

✓ Deep Energy
✓ Extreme Physics and Chemistry

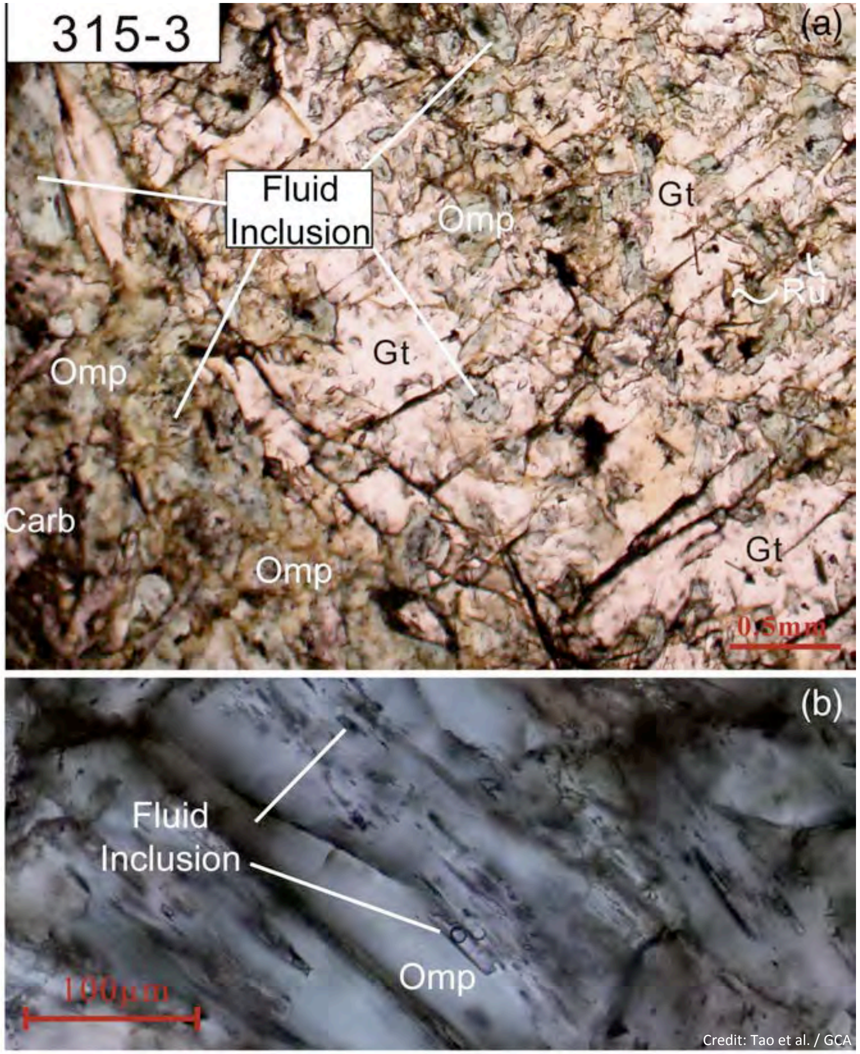
Abiotic Hydrocarbons at Subduction Zones

Formation of abiotic hydrocarbon from reduction of carbonate in subduction zones: Constraints from petrological observation and experimental simulation

Tao R, Zhang L, Tian M, Zhu J, Liu X, Liu J, Höfer HE, Stagno V, Fei Y

GEOCHIMICA ET COSMOCHIMICA ACTA
August 2018

Lab experiments and observations of high-pressure minerals from a subduction zone suggest that carbonates and water react to form light hydrocarbons during subduction.



Credit: Tao et al. / GCA

DEEP CARBON OBSERVATORY

- ✓ Instrumentation
- ✓ Deep Life
- ✓ Deep Energy

Instrumentation: Methane Clumped Isotopes

DCO is simultaneously pursuing two radically different approaches for measuring clumped isotopes in methane and other gases:

- **Mass spectrometry**
  - Caltech/Thermo Fisher
  - UCLA/Carnegie/Nu Instruments
- **Absorption spectroscopy**
  - MIT/Aerodyne Research

Data from these instruments are enabling DCO to achieve a major decadal goal regarding methane formation temperatures, sources, and provenance.

Caltech, MIT, UCLA (clockwise from top left)

DEEP CARBON OBSERVATORY

$^{13}CH_3D$ clumped isotope thermometry

$$^{13}CH_3D + {}^{12}CH_4 \leftrightarrow {}^{13}CH_4 + {}^{12}CH_3D, \quad K(T)$$

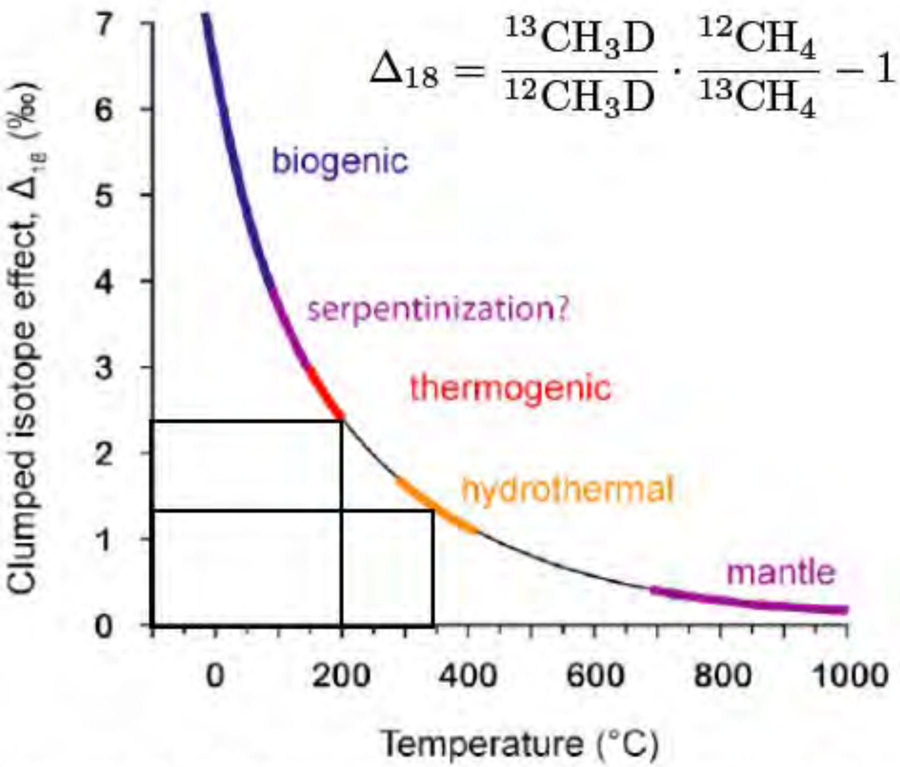


Figure 2: Methane clumped isotope thermometry scale.

Lost City Hydrothermal Field

Potentially abiogenic CH_4

1 to 2 mmol/kg CH_4

$\delta^{13}C_{CH4}$ = -9.5 to -13.6 ‰

DEEP CARBON OBSERVATORY

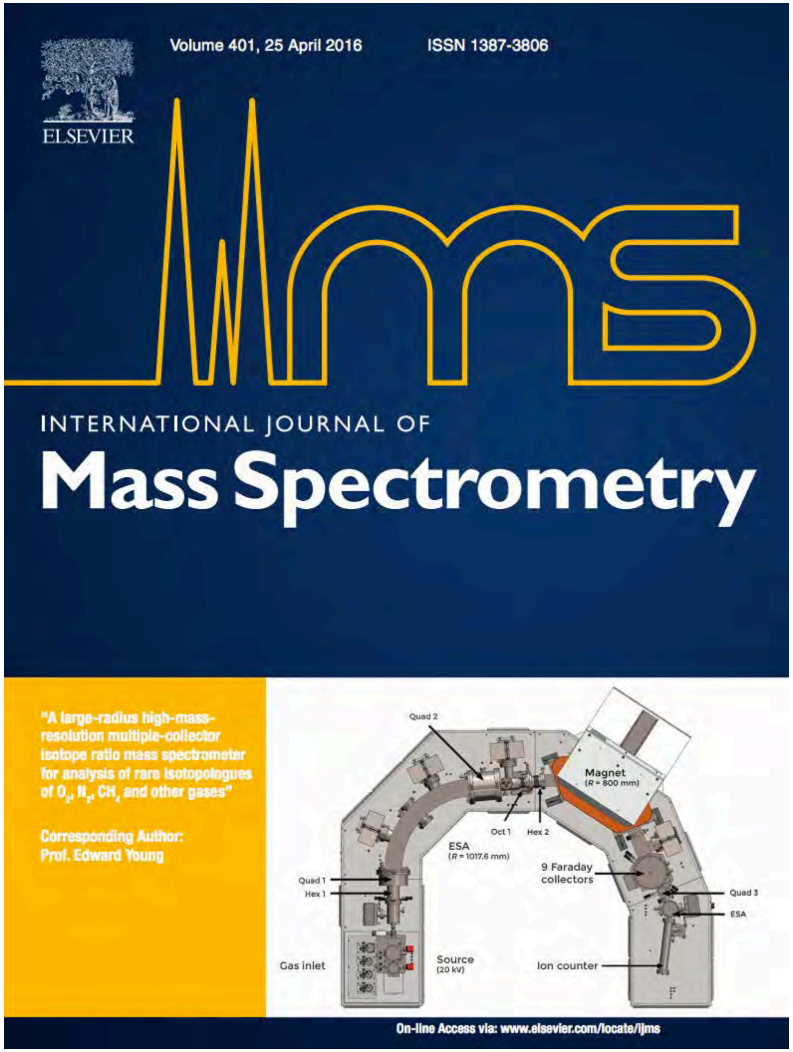
- ✓ Instrumentation
- ✓ Deep Energy
- ✓ Deep Life

Panorama Mass Spectrometer

A large-radius high-mass-resolution multiple-collector isotope ratio mass spectrometer for analysis of rare isotopologues of O_2, N_2, CH_4, and other gases

Young ED, Rumble D, Freedman P, Mills M

The Panorama is the first large-radius gas-source multiple-collector isotope ratio mass spectrometer. It has the potential to facilitate a new type of isotope chemistry based on isotopic bond-ordering.



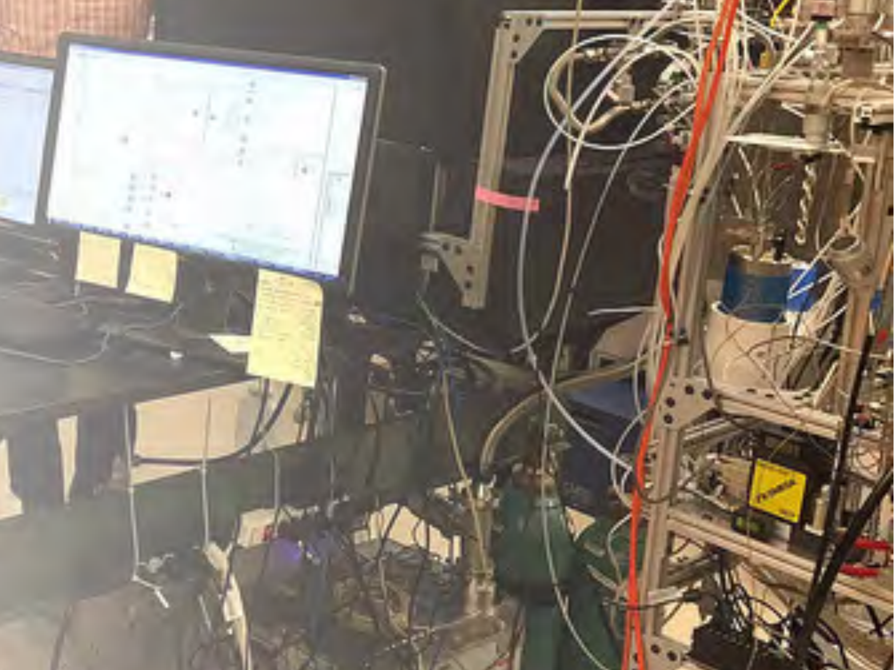
INTERNATIONAL JOURNAL OF MASS SPECTROMETRY
25 April 2016

DEEP CARBON OBSERVATORY

Methane Clumped Isotopes

Nonequilibrium clumped isotope signals in microbial methane.

David T. Wang, Danielle S. Gruen, Barbara Sherwood Lollar, Kai-Uwe Hinrichs, Lucy C. Stewart, James F. Holden, Alexander N. Hristov, John W. Pohlman, Penny L. Morrill, Martin Könneke, Kyle B. Delwiche, Eoghan P. Reeves, Chelsea N. Sutcliffe, Daniel J. Ritter, Jeffrey Seewald, Jennifer C. McIntosh, Harold F. Hemond, Michael D. Kubo, Dawn Cardace, Tori M. Hoehler, Shuhei Ono

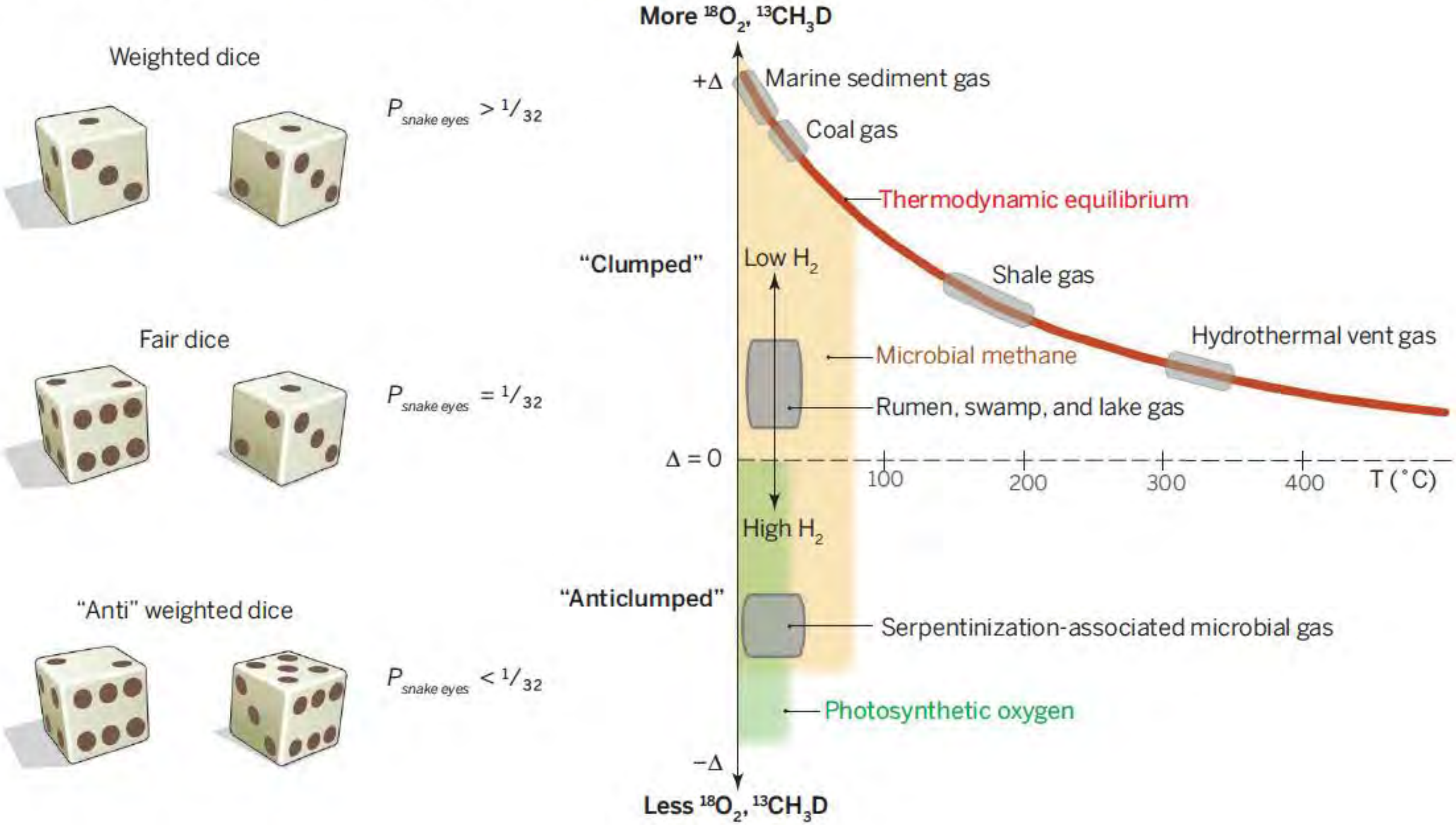


Science
AAAS

24 April 2015 348:428-431 **SCIENCE**

DEEP CARBON OBSERVATORY

Isotope clumping and anticlumping in oxygen and methane



24 April 2015 348:394-395 **SCIENCE**

DEEP CARBON OBSERVATORY

✓ Deep Energy
✓ Deep Life

Origins of Hydrothermal Vent Methane

Clumped isotopologue constraints on the origin of methane at seafloor hot springs

Wang DT, Reeves EP, McDermott JM, Seewald JS, Ono S

GEOCHIMICA ET COSMOCHIMICA ACTA
February 2018

DCO researchers find striking similarities between methane from very diverse vents associated with relatively high amounts of methane, pointing to a common source in the crust.

DEEP CARBON OBSERVATORY

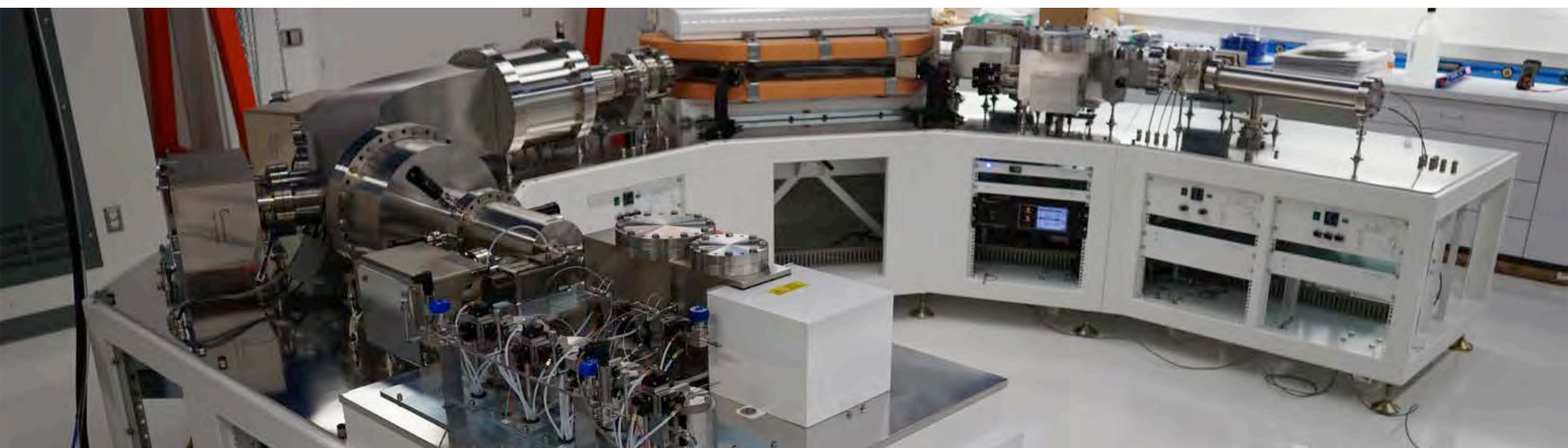
✓ Instrumentation
✓ Deep Energy

Methane Clumped Isotopes

The relative abundances of resolved $^{12}CH_2D_2$ and $^{13}CH_3D$ and mechanisms controlling isotopic bond ordering in abiotic and biotic methane gases

Young ED, Kohl IE, Sherwood Lollar B, Etiope G, Rumble III D, Li S, Haghnegahdar MA, Schauble EA, McCain KA, Foustoukos DI, Sutclife C, Warr O, Ballentine CJ, Onstott TC, Hosgormez H, Neubeck A, Marques JM, Pérez-Rodríguez I, Rowe AR, LaRowe DE, Magnabosco C, Yeung LY, Asha JL, Bryndzia LT

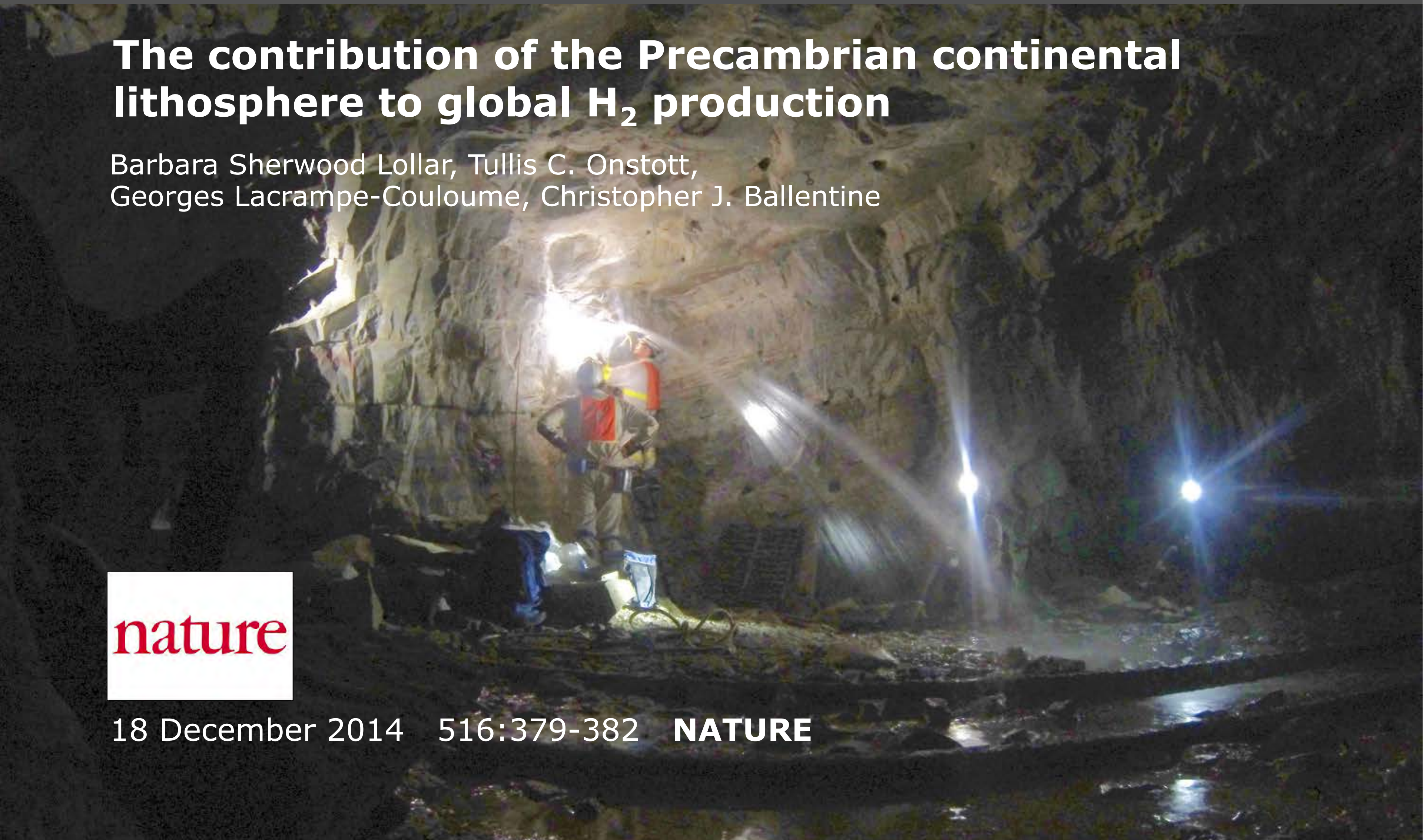
GEOCHIMICA ET COSMOCHIMICA ACTA
April 2017



DEEP CARBON OBSERVATORY

- ✓ Deep Energy
- ✓ Field studies

Global H_2 Production



The contribution of the Precambrian continental lithosphere to global H_2 production

Barbara Sherwood Lollar, Tullis C. Onstott,
Georges Lacrampe-Couloume, Christopher J. Ballentine

nature

18 December 2014 516:379-382 **NATURE**

DEEP CARBON OBSERVATORY

✓ Deep Energy
✓ Field studies

World’s Oldest Water

Deep fracture fluids isolated in the crust since the Precambrian era

G. Holland, B. Sherwood Lollar, L. Li, G. Lacrampe-Couloume, G.F. Slater & C.J. Ballentine

nature

16 MAY 2013 VOL 497 **NATURE**

DEEP CARBON OBSERVATORY

Carbon dioxide released from subduction zones by fluid-mediated reactions

Jay Ague and Stefan Nicolescu

nature geoscience

MAY 2014 **NATURE GEOSCIENCE**

DEEP CARBON OBSERVATORY

Graphite Formation by Carbonate Reduction During Subduction

Matthieu Galvez, Olivier Beyssac, Isabelle Martinez, Karin Benzerara, Carine Chaduteau, Benjamin Malvoisin, Jaques Malavieille

nature geoscience

JUNE 2013 **NATURE GEOSCIENCE**

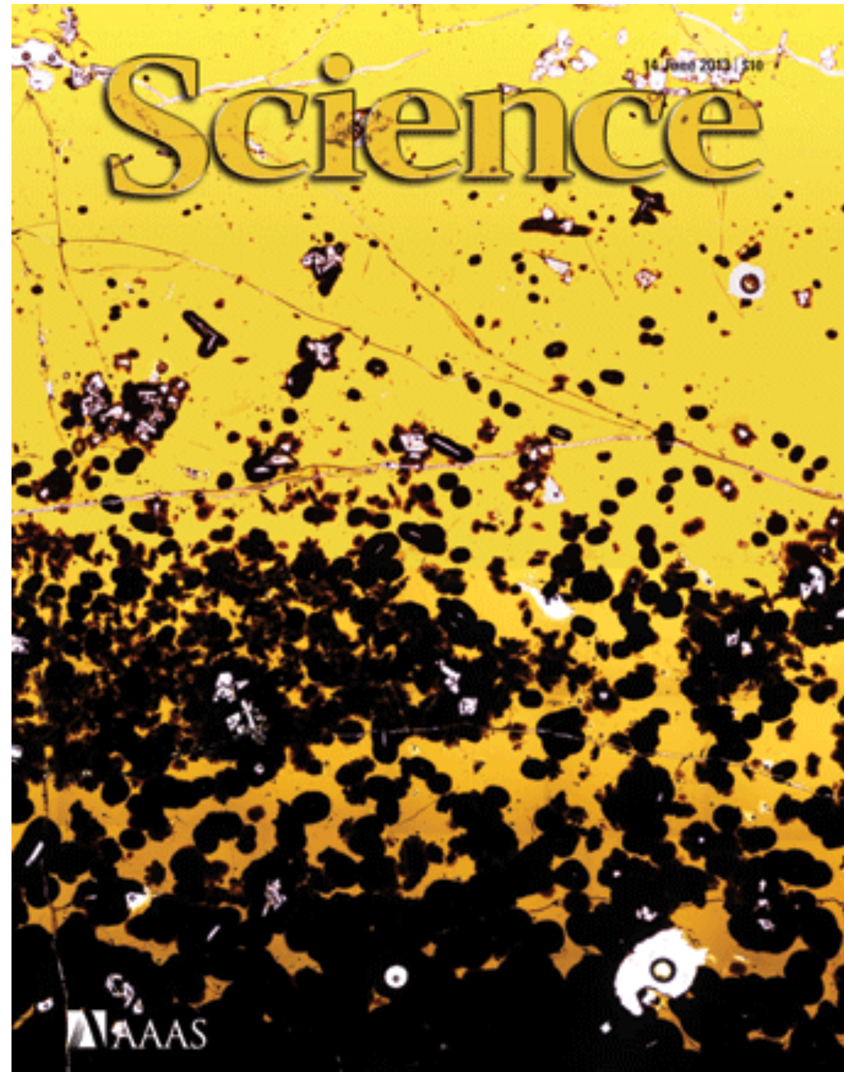
DEEP CARBON OBSERVATORY

✓ Reservoirs and Fluxes

Mantle Redox State Linked to Deep Carbon Cycle

Redox Heterogeneity in Mid-Ocean Ridge Basalts as a Function of Mantle Source

Elizabeth Cottrell,
Katherine A. Kelley



Science AAAS

14 JUNE 2013 **SCIENCE**

DEEP CARBON OBSERVATORY

- ✓ Publications
- ✓ Reservoirs and Fluxes

Detecting CO_2 from Space

Spaceborne detection of localized carbon dioxide sources

Schwander FM, Gunson MR, Miller CE, Carn SA, Eldering A, Krings T, Verhulst KR, Schimel DS, Nguyen HM, Crisp D, O'Dell CW, Osterman GB, Iraci LT, Podolske JR

SCIENCE
October 2017

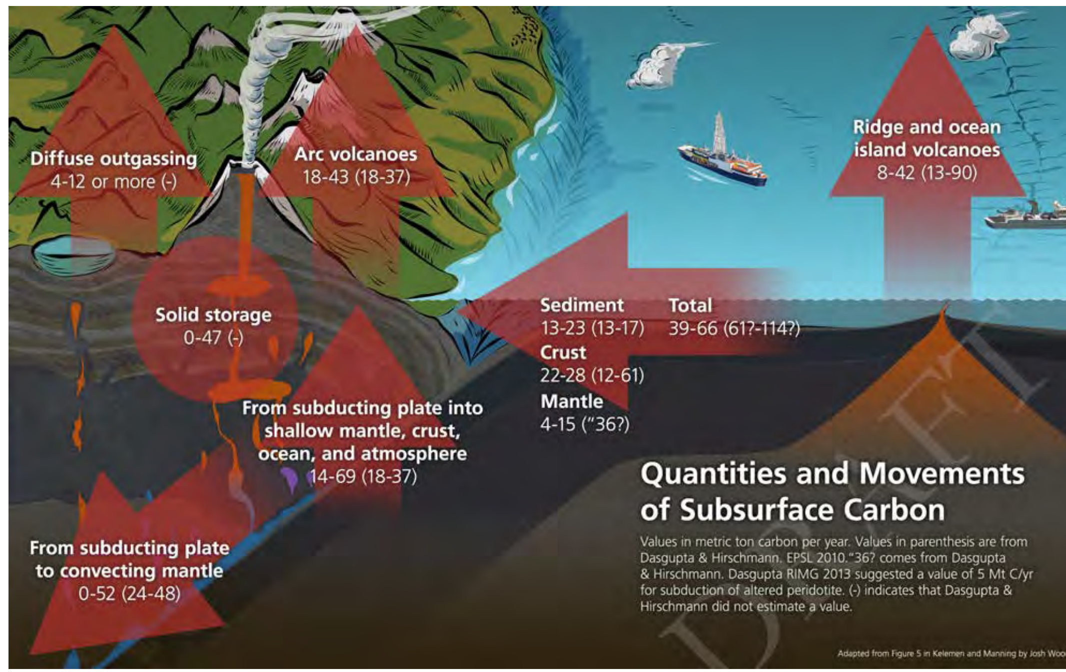
This landmark paper reports the first detection of passive degassing of volcanic CO_2 from space.

DEEP CARBON OBSERVATORY

Deep Carbon Cycle

Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up

Peter B. Kelemen and Craig E. Manning



PNAS

June 2015 Early Edition **PNAS**

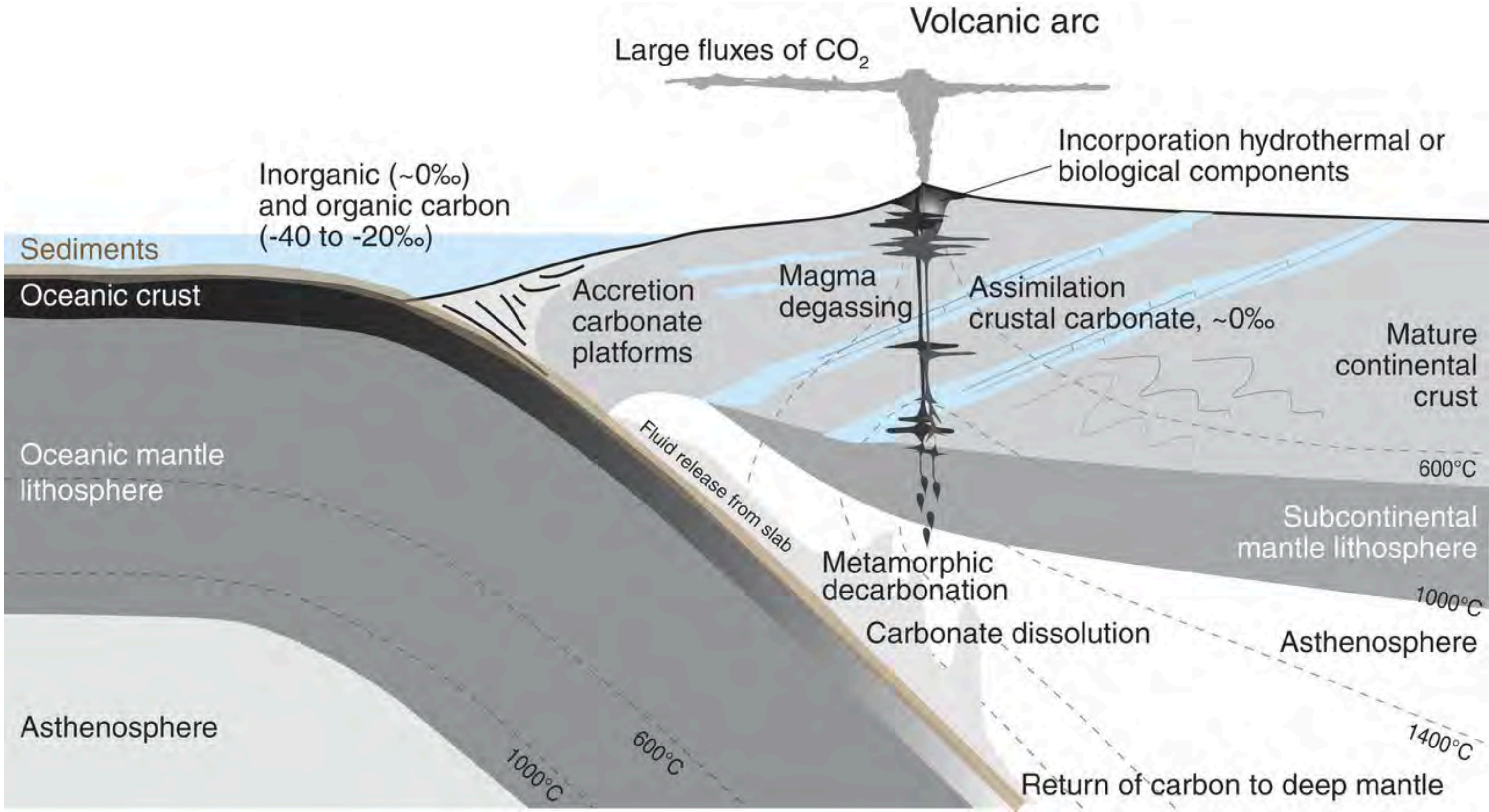
DEEP CARBON OBSERVATORY

Deep Carbon Cycle

Remobilization of crustal carbon may dominate volcanic arc emissions

Mason E, Edmonds M, Turchyn AV

SCIENCE
July 2017



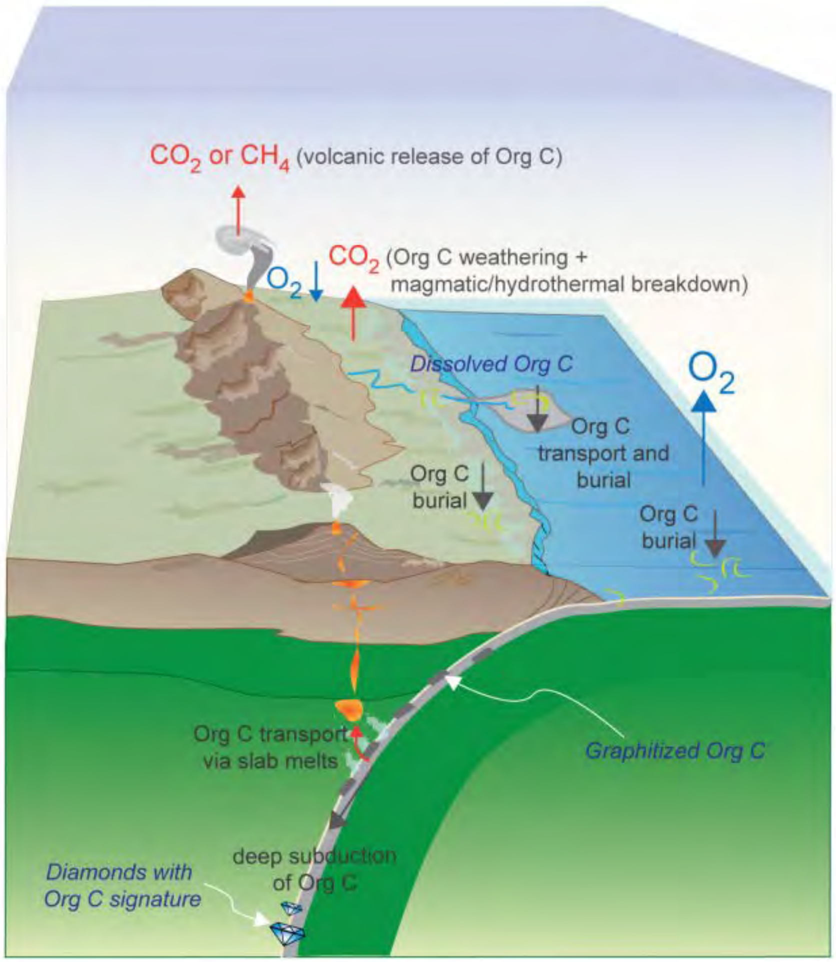
✓ Reservoirs and Fluxes
✓ Extreme Physics and Chemistry

Deep Carbon Cycle

Rise of Earth's atmospheric oxygen controlled by efficient subduction of organic carbon

Duncan M, Dasgupta R

NATURE GEOSCIENCE
April 2017



Duncan and Dasgupta propose that subduction was a key process in the efficient, long-term storage of reduced carbon. Using high-temperature and high-pressure experiments combined with thermodynamic models, they looked back in time to model how carbon burial would impact atmospheric oxygen levels.

DEEP CARBON OBSERVATORY

Life in the Hydrated Suboceanic Mantle

Bénédicte Ménez, Valerio Pasini
& Daniele Brunelli

nature geoscience

FEB 2012 **NATURE GEOSCIENCE**

DEEP CARBON OBSERVATORY

✓ Deep Life
✓ Deep Energy

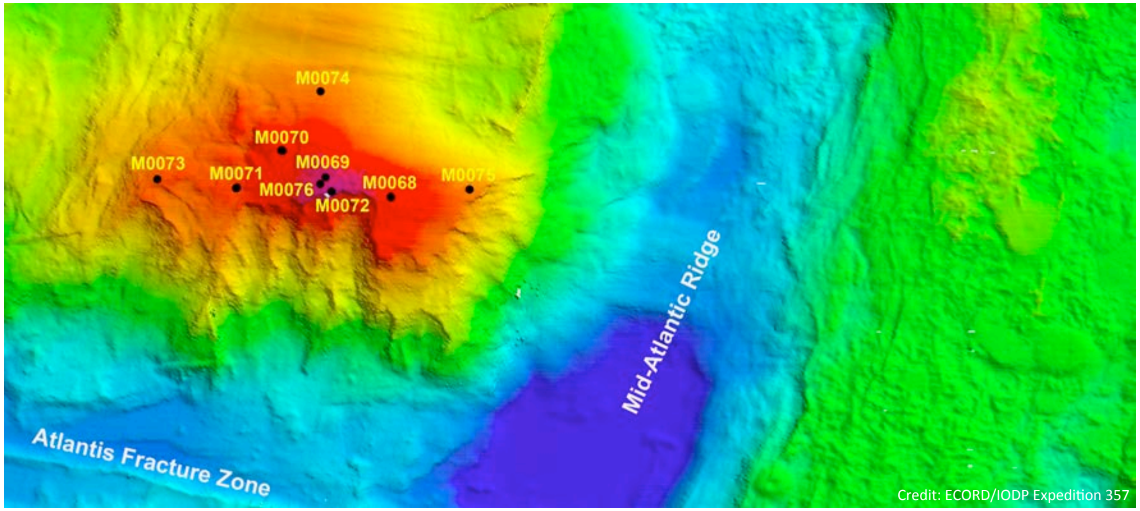
Subsurface Life in the Atlantis Massif

Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif (IODP Expedition 357)

Früh-Green GL, Orcutt BN, Rouméjon S, Lilley MD, Morono Y, Cotterill C, Green S, Escartin J, John BE, McCaig AM, Cannat M, Ménez B, Schwarzenbach EM, Williams MJ, Morgan S, Lang SQ, Schrenk MO, Brazelton WJ, Akizawa N, Boschi C, Dunkel KG, Quéméneur M, Whattam SA, Mayhew L, Harris M, Bayrakci G, Behrmann JH, Herrero-Bervera E, Hesse K, Liu HQ, Sandaruwan Ratnayake A, Twing K, Weis D, Zhao R, Bilenker L

LITHOS
September 2018


Credit: Dave Smith and BGS/ECORD/IODP Expedition 357



Credit: ECORD/IODP Expedition 357

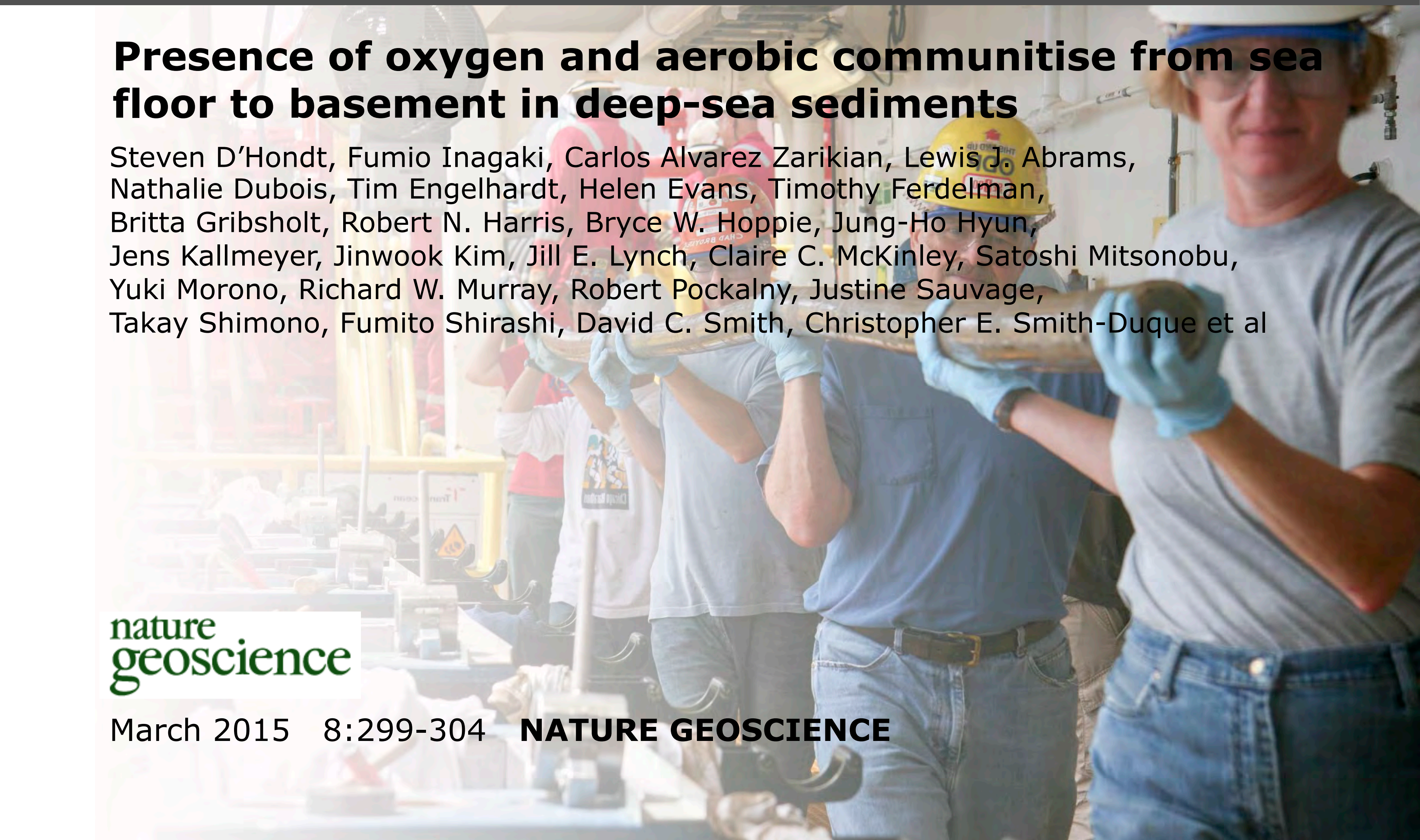
DEEP CARBON OBSERVATORY

- ✓ Deep Life
- ✓ Field studies

IODP Expedition 329: South Pacific Gyre

Presence of oxygen and aerobic communitise from sea floor to basement in deep-sea sediments

Steven D'Hondt, Fumio Inagaki, Carlos Alvarez Zarikian, Lewis J. Abrams, Nathalie Dubois, Tim Engelhardt, Helen Evans, Timothy Ferdelman, Britta Gribsholt, Robert N. Harris, Bryce W. Hoppie, Jung-Ho Hyun, Jens Kallmeyer, Jinwook Kim, Jill E. Lynch, Claire C. McKinley, Satoshi Mitsonobu, Yuki Morono, Richard W. Murray, Robert Pockalny, Justine Sauvage, Takay Shimono, Fumito Shirashi, David C. Smith, Christopher E. Smith-Duque et al



nature geoscience

March 2015 8:299-304 **NATURE GEOSCIENCE**

DEEP CARBON OBSERVATORY

- ✓ Deep Life
- ✓ Field studies
- ✓ Instrumentation

IOPD Expedition 337: Deep Coalbed Biosphere

Exploring deep microbial life in coal-bearing sediment down to ~2.5km below the seafloor

Inagaki F, Hinrichs K-U, Kubo Y, Bowles MW, Heuer VB, Hong W-L, Hoshino T, Ijiri A, Imachi H, Ito M, Kaneko M, Lever MA, Lin Y-S, Methé BA, Morita S, Morono Y, Tanikawa W, Bihan M, Bowden SA, Elvert M, Glombitza C, Gross D, Harrington GJ, Hori T, Li K, Limmer D, Liu C-H, Murayama M, Ohkouchi N, Ono S, Park Y-S, Phillips SC, Prieto-Mollar X, Purkey M, Riedinger N, Sanada Y, Sauvage J, Snyder G, Susila-wati R, Takano Y, Tasumi E, Terada T, Tomaru H, Trembath-Reichert E, Wang DT, Yamada Y

Science AAAS

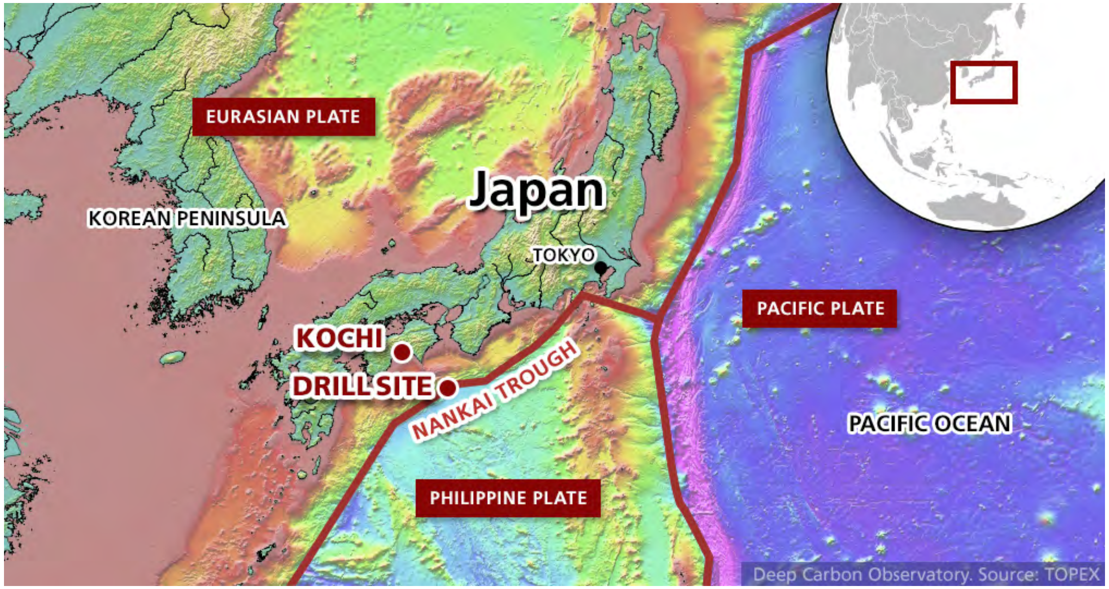
24 July 2015 349:420-424 **SCIENCE**

- Deep Life
- Field studies

DEEP CARBON OBSERVATORY

IODP Expedition 370: T-Limits of Life

- IODP Expedition 370 seeks to answer key questions about Earth's habitable zone and the deep biosphere
- Expedition elements:
  - 31 researchers from 8 nations, including several DCO colleagues
  - World's largest, most stable scientific research ship
  - Helicopters to speed fresh samples from ship to shore
  - Super-clean lab on shore to prevent sample contamination



DEEP CARBON OBSERVATORY

- ✓ Deep Life
- ✓ Deep Energy

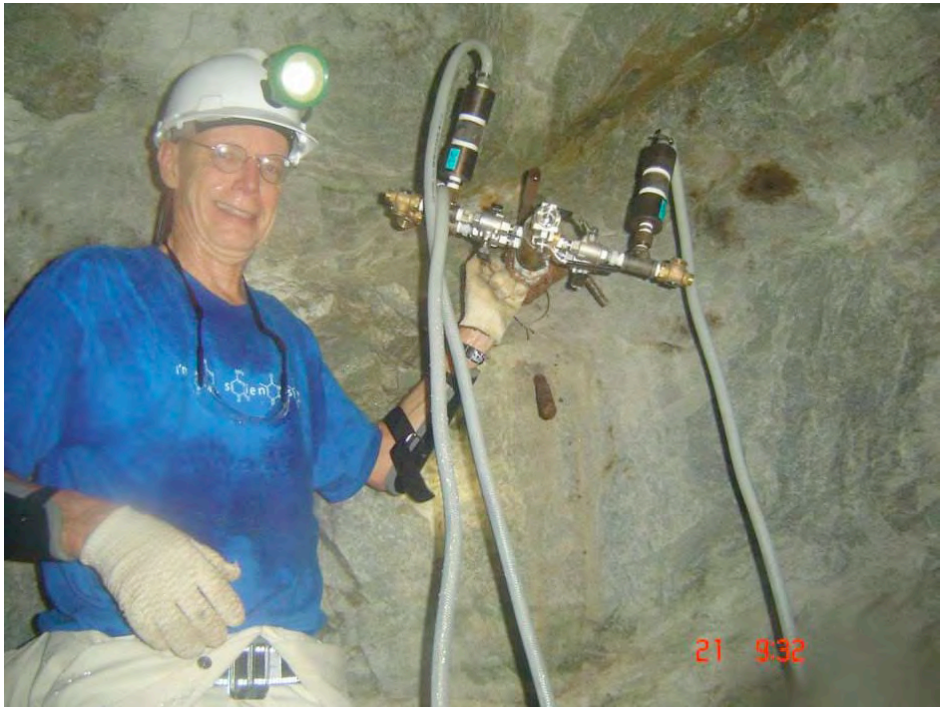
Microbes in Deep African Mines

Dissolved organic matter compositions in 0.6–3.4 km deep fracture waters, Kaapvaal Craton, South Africa

Kieft TL, Walters CC, Higgins MB, Mennito AS, Clewett CFM, Heuer V, Pullin MJ, Hendrickson S, van Heerdene E, Sherwood Lollar B, Lau MCY, Onstott TC

ORGANIC GEOCHEMISTRY
April 2018

Researchers sampled from mine boreholes reaching just over 3.4 kilometers deep and characterized the dissolved organic matter within. The results paint a picture of isolated microbial communities eking out a living using dissolved hydrogen gas (H_2) and inorganic carbon released by the rocks, with little or no input of organic carbon from the surface.



DEEP CARBON OBSERVATORY

✓ Deep Life

New Estimate of Subsurface Life

The biomass and biodiversity of the continental subsurface

Magnabosco C, Lin L-H, Dong H, Bomberg M, Ghiorse W, Stan-Lotter H, Pedersen K, Kieft TL, van Heerden E, Onstott TC

NATURE GEOSCIENCE
September 2018


Credit: Gaetan Borgonie

DEEP CARBON OBSERVATORY

✓ Deep Energy

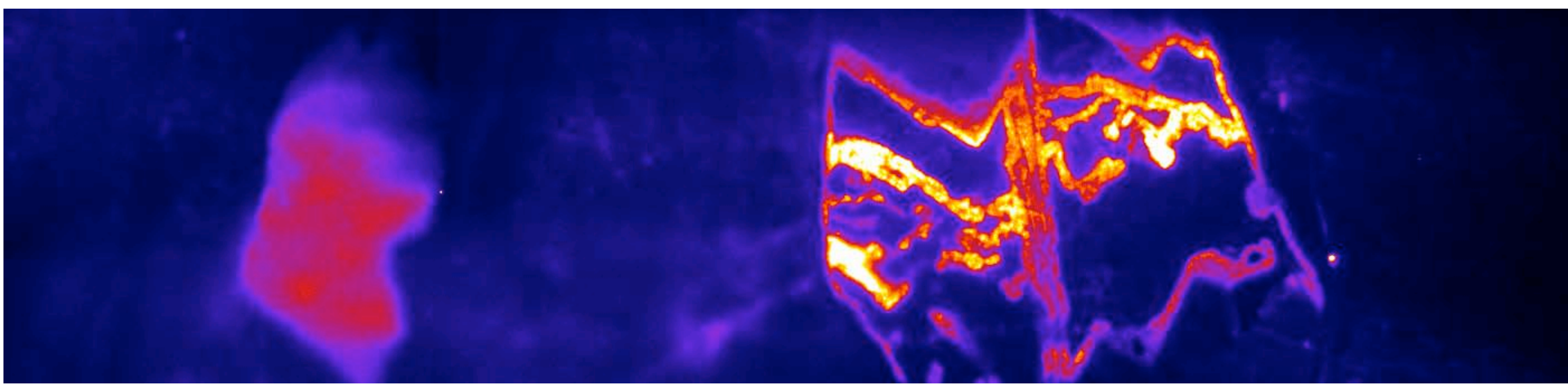
Abiotic Synthesis of Amino Acids

Abiotic synthesis of amino acids in the recesses of the oceanic lithosphere

Ménez B, Pisapia C, Andreani M, Jamme F, Vanbellingen QP, Brunelle A, Richard L, Dumas P, Réfrégiers M

NATURE
November 2018

A new study finds that when certain rocks below the seafloor interact with seawater and undergo serpentinization, they can create amino acids. These serpentinizing rocks were common in early Earth's crust, and may have provided the chemical precursors for the origin of life.



DEEP CARBON OBSERVATORY

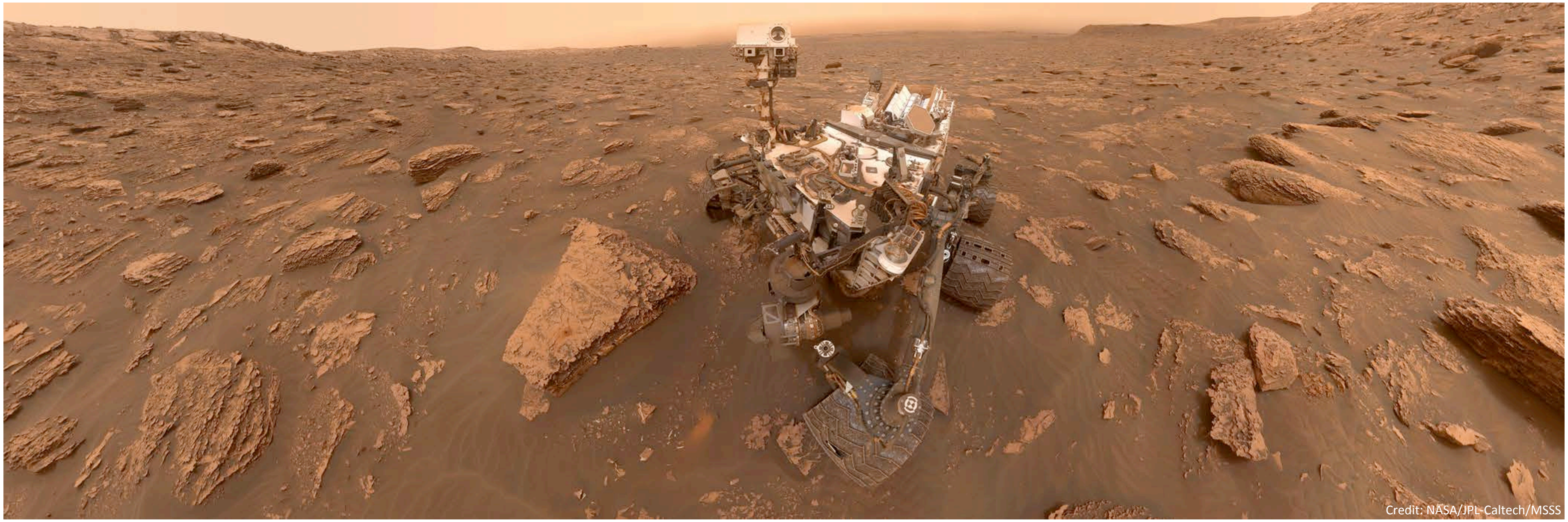
- ✓ Reservoirs and Fluxes
- ✓ Deep Energy
- ✓ Deep Life

Martian Organic Molecules

Organic synthesis on Mars by electrochemical reduction of CO2

Steele A, Benning LG, Wirth R, Siljeström S, Fries MD, Hauri E, Conrad PG, Rogers K, Eigenbrode J, Schreiber A, Needham A, Wang JH, McCubbin FM, Kilcoyne D, Rodriguez-Blanco JD

SCIENCE ADVANCES
October 2018



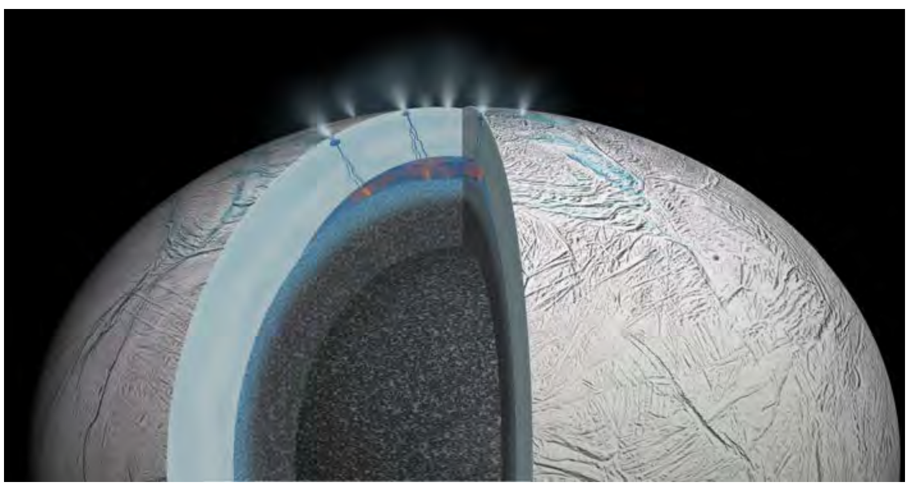
DEEP CARBON OBSERVATORY

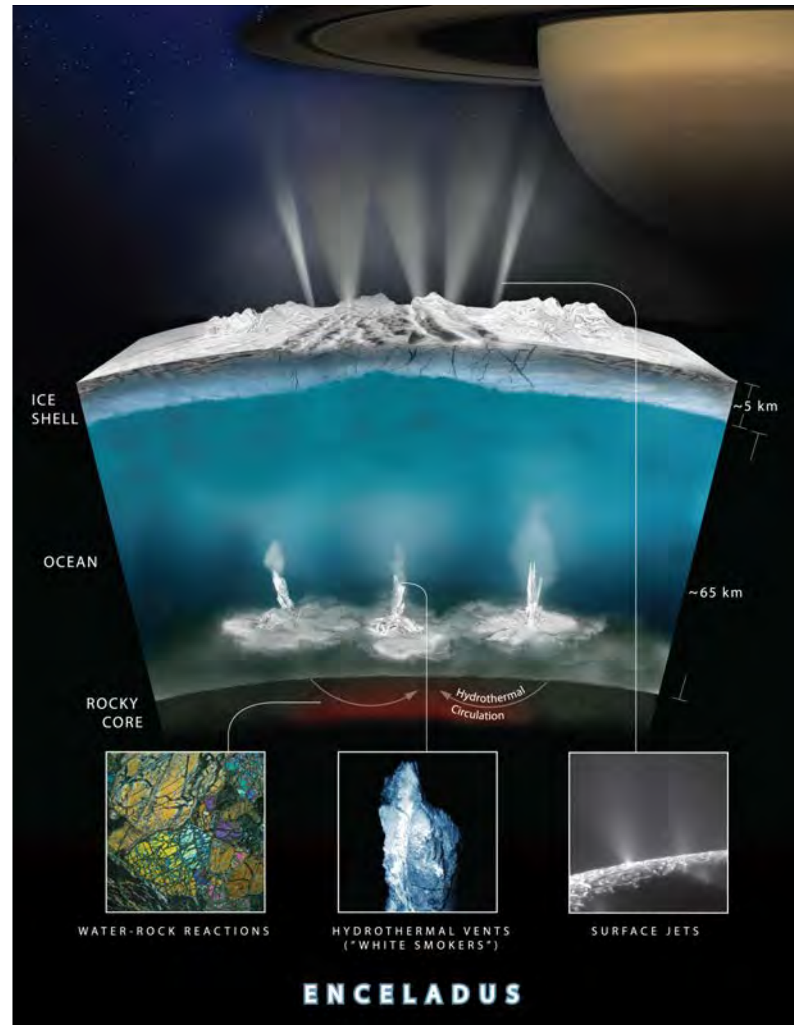
✓ Deep Energy

"Food for microbes abundant on Enceladus"

Cassini finds molecular hydrogen in the Enceladus plume: Evidence for hydrothermal processes

Waite JH, Glein CR, Perryman RS, Teolis BD, Magee BA, Miller G, Grimes J, Perry ME, Miller KE, Bouquet A, Lunine JI, Brockwell T, Bolton SJ





SCIENCE
14 April 2017

DEEP CARBON OBSERVATORY

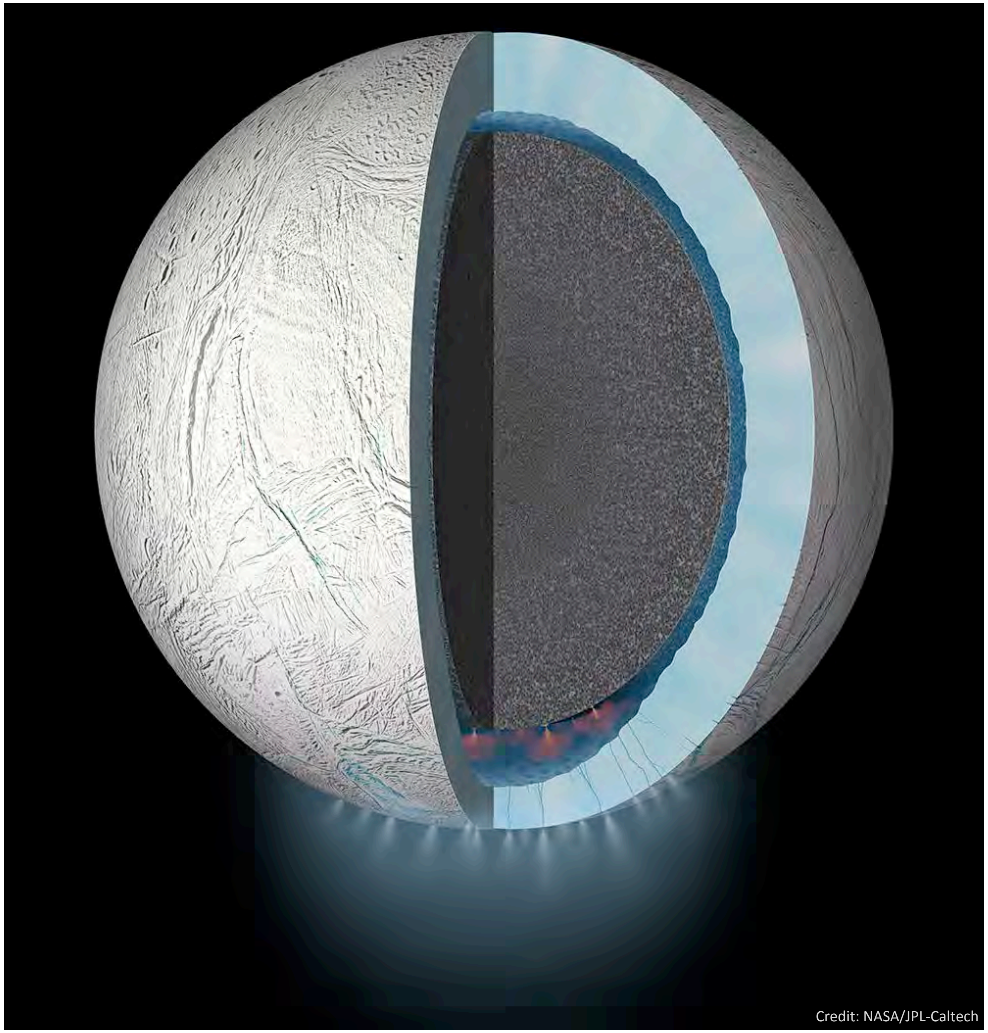
✓ Deep Energy

Enceladus Harbors Complex Carbon Compounds

Macromolecular organic compounds from the depths of Enceladus

Postberg F, Khawaja N, Abel B, Choblet G, Glein CR, Gudipati MS, Henderson BL, Hsu HW, Kempf S, Klenner F, Moragas-Klostermeyer G, Magee B, Nölle L, Perry M, Reviol R, Schmidt J, Srama R, Stolz F, Tobie G, Trieloff M, Waite JH

NATURE
June 2018


Credit: NASA/JPL-Caltech

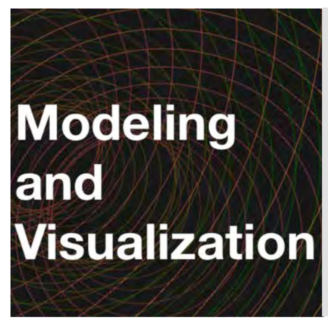
DEEP CARBON OBSERVATORY

Synthesis Activities

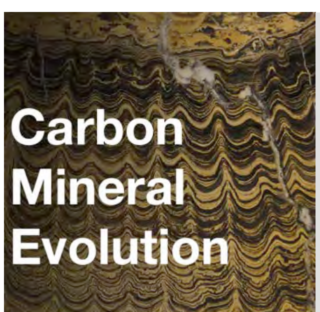
12-day field expedition Costa Rica's volcanic arc followed by integrated sample analysis and modeling

Integration of existing thermodynamic models of magmas (MELTS) and fluids (DEW)

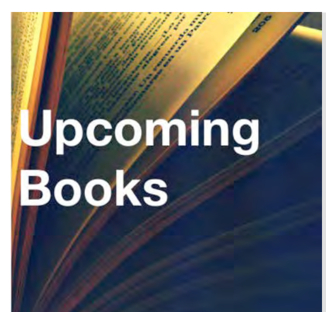
Uniting deep carbon scientists to debate and arrive at a consensus regarding the most important carbon-related reactions on Earth



Development of new computational tools needed to probe and visualize carbon transport in Earth



Using big data to document the diversity and distribution of more than 500 carbon minerals in Earth's crust and upper mantle



Three upcoming books explore deep carbon for a variety of audiences

DEEP CARBON OBSERVATORY

Upcoming DCO Books

- A general-audience book that explores carbon in four ‘movements’ – earth, air, fire, and water – by DCO Executive Director Robert Hazen
- In 2018, the manuscript was completed and submitted to the publisher
- Release date: Spring 2019

- An edited, open-access volume that will define the present knowledge about the quantities, movements, forms, and origins of carbon in Earth
- In 2018, all chapters were submitted and reviewed
- Release date: Fall 2019

- A scholarly history of deep carbon science from the 1600s to the present by historian Simon Mitton
- In 2018, eight chapters were completed
- Release date: Fall 2019

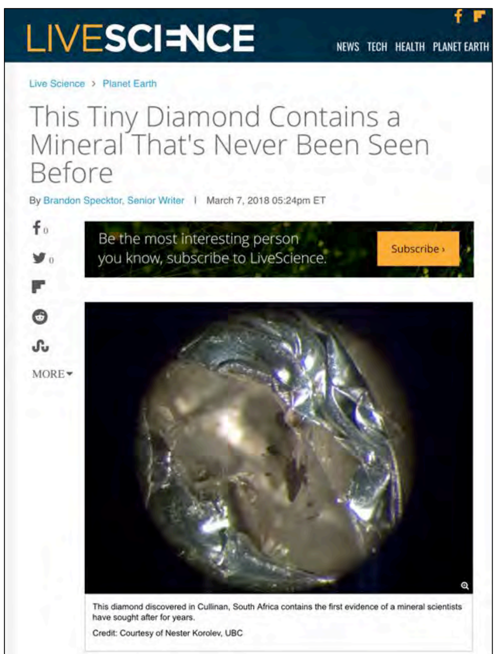
DEEP CARBON OBSERVATORY

✓ Engagement
✓ Reservoirs and Fluxes

Media Coverage

March 2018

- DCO’s first big headlines in 2018 announced the discovery of a natural sample of Earth’s fourth-most abundant mineral, calcium silicate perovskite
- Found as an inclusion in a “superdeep” diamond, from more than 380 kilometers deep


LIVESCIENCE NEWS TECH HEALTH PLANET EARTH

Live Science › Planet Earth

This Tiny Diamond Contains a Mineral That's Never Been Seen Before

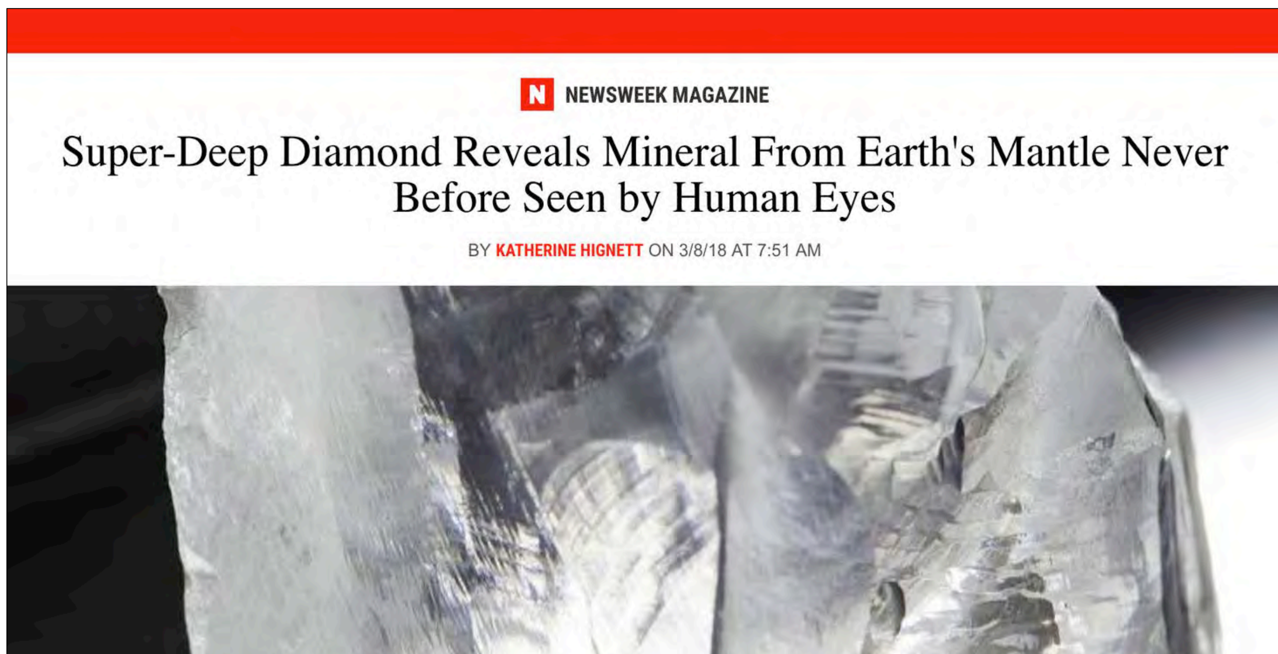
By Brandon Specktor, Senior Writer | March 7, 2018 05:24pm ET

Be the most interesting person you know, subscribe to LiveScience. Subscribe ›

MORE

This diamond discovered in Cullinan, South Africa contains the first evidence of a mineral scientists have sought after for years.

Credit: Courtesy of Nester Korolev, UBC


NEWSWEEK MAGAZINE

Super-Deep Diamond Reveals Mineral From Earth's Mantle Never Before Seen by Human Eyes

BY KATHERINE HIGNETT ON 3/8/18 AT 7:51 AM

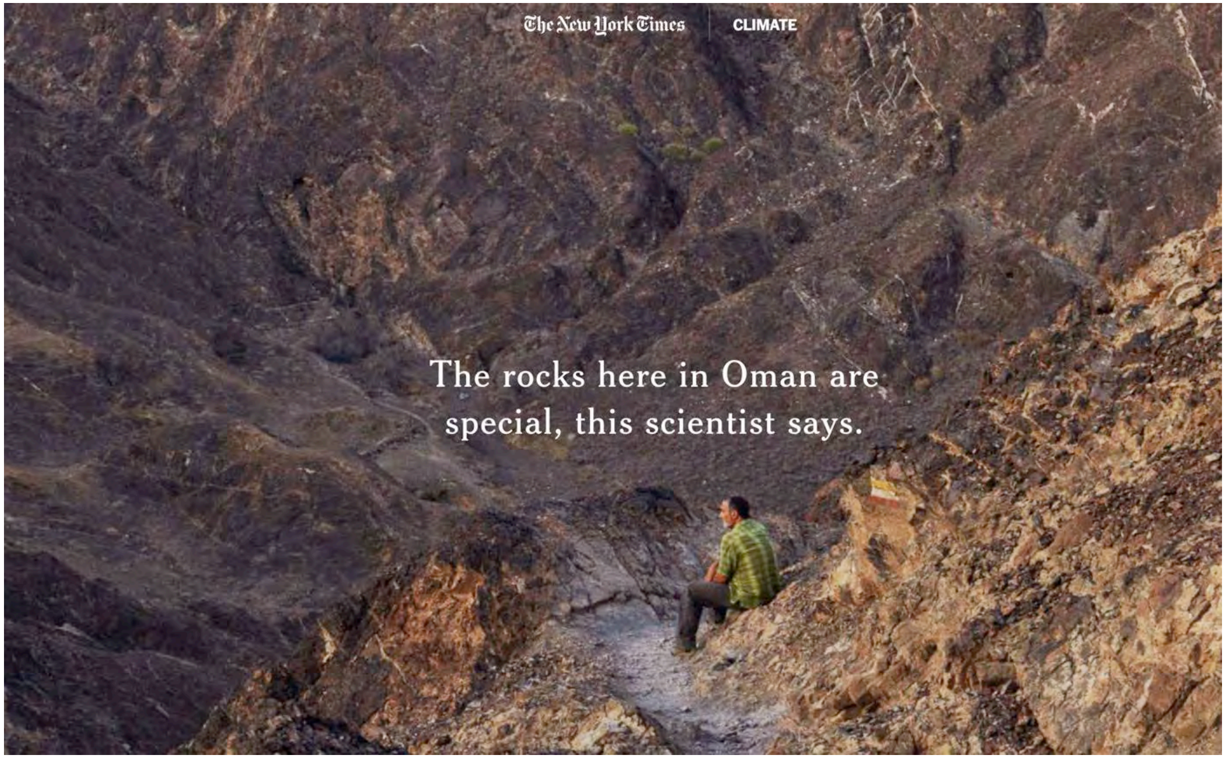
DEEP CARBON OBSERVATORY

✓ Engagement
✓ Field Studies

Media Coverage

April 2018

- The New York Times featured DCO scientist Peter Kelemen and the Oman Drilling Project
- A NYT photographer captured spectacular images of the Samail Ophiolite



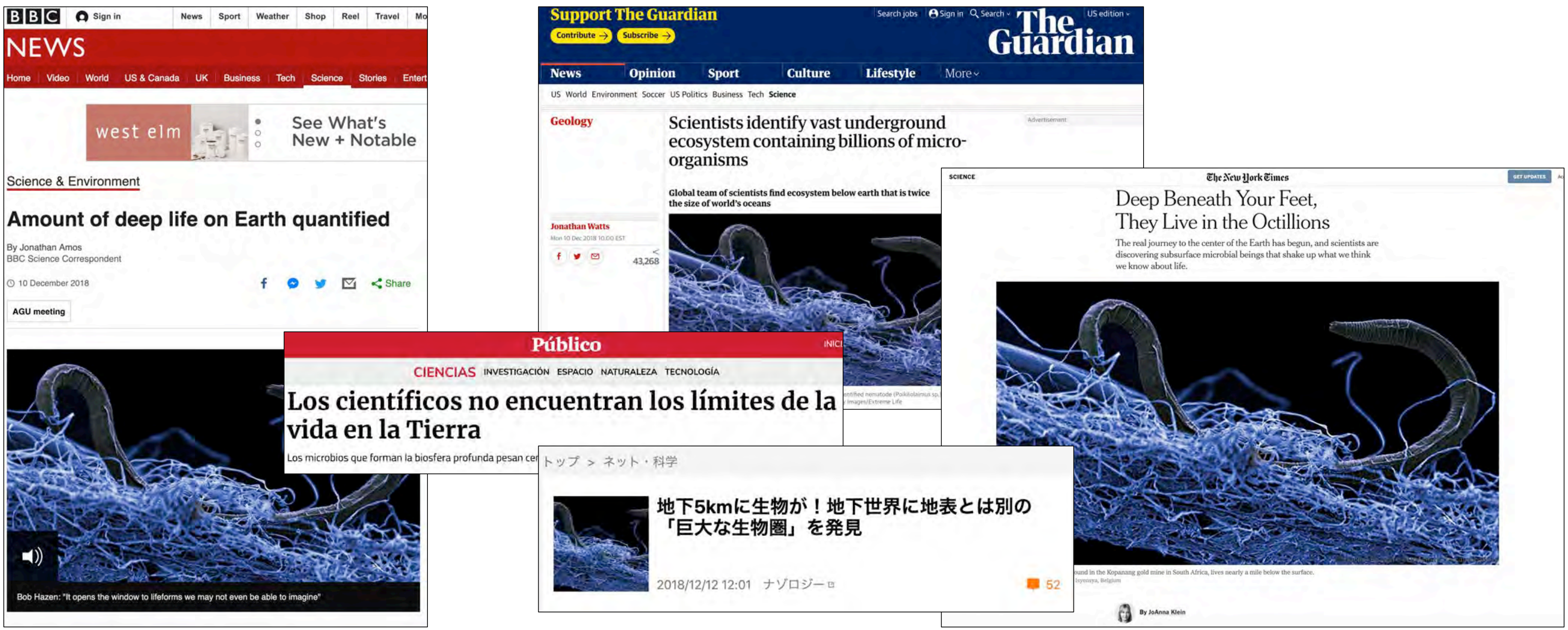
DEEP CARBON OBSERVATORY

- ✓ Engagement
- ✓ Deep Life
- ✓ Deep Energy

Media Coverage

December 2018

- DCO news release: "Life in Deep Earth Totals 15 to 23 Billion Tonnes of Carbon—Hundreds of Times More than Humans"
- Covered in 1100+ stories in 84 countries and 30 languages



DEEP CARBON OBSERVATORY

✓ Engagement

Selected 2018 Media Outlets

The New York Times
Forbes
nature
france inter
BBC NEWS
CNN
theguardian
Smithsonian Magazine
The Atlantic
THE TIMES
The Washington Post
DW Deutsche Welle
SCIENTIFIC AMERICAN
GIZMODO
Newsweek
EFE
Los Angeles Times
Science AAAS
XIN HUA 新华社 XINHUA NEWS AGENCY
NATIONAL GEOGRAPHIC
livescience
Daily Mail
NewScientist
POPULAR MECHANICS

DEEP CARBON OBSERVATORY

Organizations Supporting DCO Science

Deep carbon science advances through the collective efforts of many organizations including:

ALFRED P. SLOAN FOUNDATION 1934

NERC SCIENCE OF THE ENVIRONMENT

MINISTRY OF EDUCATION AND SCIENCE OF THE RUSSIAN FEDERATION

erc European Research Council

NSERC CRSNG

NSF

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

NASA

CARNEGIE SCIENCE

JAMSTEC 国立研究開発法人 海洋研究開発機構 Japan Agency for Marine-Earth Science and Technology

icdp

IODP INTERNATIONAL OCEAN DISCOVERY PROGRAM

CHINESE ACADEMY OF SCIENCES

DFG Deutsche Forschungsgemeinschaft

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

Supplemental Slides