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Views & Comments

The Deep Carbon Observatory: A Ten-Year Quest to Study Carbon in Earth

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1. Overview

The Deep Carbon Observatory (DCO) is a ten-year research program to investigate the quantities, movements, forms, and origins of carbon in Earth. More than 90% of Earth's carbon may reside in the planet's deep interior, and DCO's overarching mission is to understand Earth's *entire* carbon cycle—beyond the atmosphere, oceans, and shallow crustal environments, which have drawn most previous research attention—to include the deep carbon cycle [1,2]. A decade of focused research has led to major discoveries by DCO scientists on the physical, chemical, and biological roles of carbon in Earth.

To pursue its multidisciplinary mission, DCO connects more than 1200 scientists worldwide, broadly grouping them into four Science Communities: Extreme Physics and Chemistry, Reservoirs and Fluxes, Deep Energy, and Deep Life (Table 1). The program also emphasizes four crosscutting activities that bridge community boundaries—namely, data science, instrumentation, field studies, and modeling and visualization—and several cross-community groups that provide essential services to the entire DCO community (Fig. 1).

In addition to its scientific advances, DCO has created an enduring legacy of interdisciplinary and international community building, successfully establishing a diverse, dynamic, and collaborative community of geologists, physicists, chemists, and biologists in more than 50 countries. In particular, DCO has focused on cultivating the next generation of deep carbon researchers by supporting early career scientists who will carry on the tradition of exploration and discovery for decades to come.

The vision, guiding questions, and scientific goals of DCO were initially framed at an international Deep Carbon Cycle Symposium at the Carnegie Institution for Science in 2008. This symposium led to a successful proposal to the Alfred P. Sloan Foundation to establish a decadal research program on deep carbon science from 2009 to 2019. The Alfred P. Sloan Foundation pledged seed funding of 50 million USD over ten years to foster DCO. DCO has leveraged the support from the Alfred P. Sloan Foundation with more than 500 million USD in support from other sources, including international organizations, national science agencies, foundations, and the private sector.

2. The Extreme Physics and Chemistry Community

DCO's Extreme Physics and Chemistry Community is dedicated to improving our understanding of the physical and chemical behavior of carbon at extreme conditions, as found in the deep interiors of Earth and other planets. This Community is making transformational advances in our understanding of carbon in minerals, magmas and melts, and aqueous fluids at extreme conditions. DCO scientists have published new results on the properties of carbon-bearing minerals at high pressures and temperatures, including the structure, compressibility, and elasticity of carbonate minerals, carbides, carbon dioxide (CO_2) ices, and clathrates. One discovery is the formation of phases with sp^3 hybridization of carbon to yield tetrahedral coordination of carbon by oxygen at elevated pressure and temperature. Under ambient conditions, CO_2 is a linear molecule; however, at sufficiently high pressure, CO_2 transforms into a polymerized framework structure in which carbon is tetrahedrally coordinated with four oxygen atoms [3]. Dense forms of polymeric CO_2 are potential reservoirs of carbon in planetary interiors. The stabilization of tetrahedrally coordinated carbon has profound implications if this carbon substitutes for tetrahedrally coordinated silicon in silicate minerals. This substitution mechanism has been verified experimentally [4], and indicates a potential reservoir for carbon in Earth and planetary interiors. DCO scientists have also conducted extensive research on carbonate minerals under extreme conditions. Under ambient conditions, carbon forms trigonal planar structural units in carbonate minerals. At high pressure, carbonate minerals transform into denser structures in which carbon is tetrahedrally coordinated with four oxygen atoms [5–11]—a discovery that has important implications for the stability and properties of carbonates in the deep carbon cycle [12,13]. Complementary experimental studies of carbon in iron at extreme conditions provide conflicting evidence about the elusive role of carbon in Earth's core [14–16].

Magma ocean processes set the initial distribution of carbon and conditions for further development of Earth's deep carbon cycle [17]. Magmas are also the main agent for transporting carbon from Earth's interior to its surface [18]. Conversely, carbon influences deep Earth dynamics by inducing melting and mobilization

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Table 1
DCO decadal goals.

DCO Science Community	Decadal goals
Extreme Physics and Chemistry	• Seek and identify possible new carbon-bearing materials in Earth and planetary interiors • Characterize the structural and dynamical properties of materials and identify their reactions and transformations at conditions relevant to Earth and planetary interiors • Develop, extend, combine, and exploit experimental tools to investigate carbon-bearing samples in new regimes of pressure, temperature, and bulk composition • Develop, extend, and improve databases and simulations of deep carbon material properties, reactions, and transport for integration with quantitative models of global carbon cycling
Reservoirs and Fluxes	• Establish open access, continuous information streams on volcanic gas emission and related activity • Determine the chemical forms and distribution of carbon in Earth's deepest interior • Determine the seafloor carbon budget and global rates of carbon input into subduction zones • Estimate the net direction and magnitude of tectonic carbon fluxes from the mantle and crust to the atmosphere • Develop a robust overarching global carbon cycle model through deep time, including the earliest Earth and coevolution of the geosphere and biosphere • Produce quantitative models of global carbon cycling at various scales, including the planetary scale (mantle convection), tectonic scale (subduction zone, orogeny, rift, volcano), and reservoir scale (core, mantle, crust, hydrosphere)
Deep Energy	• Utilize field-based investigations of approximately 25 globally representative terrestrial and marine environments to determine processes controlling the origin, form, quantities, and movements of abiotic gases and organic species in Earth's crust and uppermost mantle • Implement the use of DCO-sponsored instrumentation, especially revolutionary isotopologue measurements, to discriminate the abiotic versus biotic origin of methane gas and organic species sampled from global terrestrial and marine field sites • Quantify as a function of temperature, pressure, fluid and solid compositions, and redox state the mechanisms and rates of fluid-rock interactions that produce hydrogen (H_2), abiotic forms of hydrocarbon gases, and more complex organic compounds • Integrate our quantitative understanding of the processes that control the origins, forms, quantities, and movements of abiotic vs. biotic carbon compounds with quantitative models of global carbon cycling
Deep Life	• Determine the processes that define the diversity and distribution of deep life as it relates to the carbon cycle • Determine the environmental limits of deep life • Determine the interactions between deep life and carbon cycling on Earth

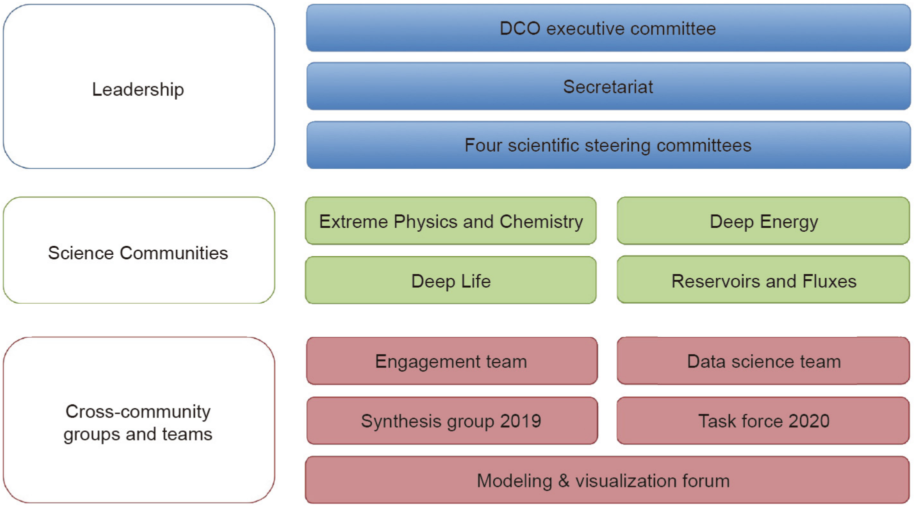

Fig. 1. DCO organizational structure.

of structurally bound mineral water [19]. Melting may also have a major impact on the recycling of subducted carbon into the deep mantle. The melting-phase relations of recycled oceanic crust suggest that slabs undergo melting and loss of carbonate components in the transition zone, creating a barrier to deep carbon subduction [20]. Recent experimental studies indicate that carbonatitic liquids provide a potentially significant pathway for carbon recycling at shallow depths beneath arcs [21].

DCO is making rapid advances in our understanding of the role of aqueous fluids in the deep carbon cycle. Until recently, thermodynamic models developed to understand water-rock interactions in Earth's upper and middle crust could not be extended to deeper environments, largely because the dielectric constant of water at extreme conditions was unknown. DCO scientists removed this barrier by conducting first-principles calculations of the dielectric constant of water under extreme conditions and the transport of carbonates in the deep Earth [22]. These calculations were used in combination with experimental results [23] to develop the Deep Earth Water (DEW) model [24]. Initial results from the DEW model demonstrate that organic carbon plays an important role in subduction zone fluids [25] and that diamonds can form due to pH shifts in deep fluids [26]. The role of carbon in setting the pH of subduction zone fluids can now be assessed, with implications for volatile and metal cycles [27]. This approach is transforming our view of global geochemical transport [28].

3. The Reservoirs and Fluxes Community

DCO's Reservoirs and Fluxes Community is dedicated to identifying the principal deep carbon reservoirs, determining the mechanisms and rates by which carbon moves among these reservoirs, and assessing the total carbon budget of Earth.

Its Diamonds and Mantle Geodynamics of Carbon (DMGC) group has created an international infrastructure to study Earth's deep interior through the unique record preserved in diamonds. DMGC aims to advance deep Earth exploration by studying natural diamonds and diamond-forming fluids and melts in order to elucidate carbon mobility in Earth through geologic time [29]. Because this effort hinges, in part, on sample availability and a coordinated effort toward sample research, DMGC is developing registered sample collections and a geochemical database of diamonds and diamond inclusions.

The discovery of native metals, metal carbides, and reduced volatiles in large gem-quality diamonds indicates that these diamonds formed from metallic liquid in Earth's deep mantle, and provides broad implications for Earth's evolution [30]. In contrast, highly saline fluids from a subducting slab are the source for certain fluid-rich fibrous diamonds; the data imply a strong association between subduction, mantle metasomatism, and fluid-rich diamond formation, as well as pointing to the important effect of subduction-derived fluids on the composition of the deep lithospheric mantle [31]. The discovery of hydrous ringwoodite included within an ultradeep diamond provides direct evidence of a hydrous mantle transition zone, which may have a key role in terrestrial magmatism and plate tectonics [32]. The discovery of calcium silicate perovskite in a diamond that formed 780 km below Earth's surface provides the first direct observation of Earth's fourth most abundant mineral; the isotopic composition of carbon in the surrounding diamond, together with the pristine high-pressure $CaSiO_3$ structure, indicate the recycling of oceanic crust into the lower mantle [33]. Blue boron-bearing diamonds contain mineral inclusions indicating that these diamonds formed in oceanic lithosphere that was subducted into Earth's lower mantle. Blue diamonds indicate a pathway for the ultradeep recycling of carbon, water, and other materials from the crust to the lower mantle and back to the surface [34].

The Reservoirs and Fluxes Community's Deep Earth Carbon Degassing (DECADE) initiative aims to determine accurate global fluxes of volcanic CO_2 to the atmosphere. To achieve this goal, DECADE has launched an intensive field-based effort to install CO_2-monitoring networks on 20 of the world's 150 most actively degassing volcanoes. DECADE also conducts laboratory-based studies, which focus on using gas samples and melt inclusions to provide empirical constraints on carbon degassing to the atmosphere.

High-frequency gas monitoring at Turrialba Volcano in Costa Rica revealed CO_2 precursors to eruptions, which lays the foundation for improved volcanic eruption forecasts [35]. An international team led by DECADE members demonstrated that the Ambrym basaltic volcano in the Vanuatu Arc in the southwest Pacific Ocean ranks among the top-three known persistent emitters of volcanic gas at the global scale [36]. There is growing evidence that continental rifts represent a major source of deep carbon released to Earth's surface from both volcanoes and fault zones [37–40]. New measurements of olivine-hosted melt inclusions from the Mid-Atlantic Ridge indicate that upper mantle carbon content varies by almost two orders of magnitude globally, which can affect the dynamics of melting, the style of volcanism, and the evolution of Earth's atmosphere via planetary outgassing [41]. For the first time in a global study, DCO scientists found evidence for higher carbon output ($m(CO_2)/m(S_{total})$, where $m(CO_2)$ and $m(S_{total})$ are the amounts of CO_2 and total sulfur, respectively) in volcanic arcs where carbonate sediment subducts on the seafloor [42]. A synthesis of global carbon and helium isotopic data from arc volcanoes concludes that the carbon isotope composition of mean global volcanic gas is considerably heavier than the canonical mid-ocean ridge basalt value; this result indicates that reworking of crustal limestone is an important source of volcanic carbon, which has implications regarding the return of carbon to the deep mantle and for Earth's past climate [43].

Modeling and visualization of Earth's deep carbon cycle through deep time contributes significantly to DCO's overall goals. A reevaluation of carbon fluxes in subduction zones indicates that almost all of the carbon in subducting sediments and oceanic plates may be extracted in fluids and melts, with relatively little carbon being returned to the convecting mantle [44]. Plate tectonic reconstructions establish connections between the deep carbon cycle and the concentration of CO_2 in the atmosphere over geologic time scales [45–47]. Numerical models of the role of volatiles in reactive melt transport in the asthenosphere indicate that CO_2 and water, despite their low concentration, have an important control on the extent and style of magma genesis, as well as on the dynamics of melt transport and the stranding of carbon at the lithosphere–asthenosphere boundary; these findings have significant implications for deep Earth degassing [48,49].

4. The Deep Energy Community

DCO's Deep Energy Community is dedicated to developing a fundamental understanding of environments and processes that regulate the volume and rates of the production of abiogenic hydrocarbons and other organic species in the crust and mantle through geological time. This research is transforming our understanding of methane (CH_4) and includes novel information about its origin, provenance, and formation temperature. Revolutionary advances in instrumentation make it possible to discriminate between methane produced by abiotic synthesis and that produced by biological processes.

The Panorama mass spectrometer is the first instrument capable of resolving the two doubly substituted mass-18 isotopologues of methane ("clumped isotopes")—$^{13}CH_3D$ and $^{12}CD_2H_2$—at natural abundances [50]. A paper by Edward Young and 23 co-authors from 14 institutions in eight countries [51] reports the first resolved measurements of two doubly substituted isotopologues of methane in gases collected from diverse geologic settings around the globe, including major natural gas fields, ultramafic complexes, and ancient waters from deep underground mines in Precambrian Cratons. If thermodynamic equilibrium is achieved, then $\Delta^{13}CH_3D$ and $\Delta^{12}CD_2H_2$ serve as two independent, intramolecular thermometers. If thermodynamic equilibrium is not achieved, then temperature cannot be determined by this method; however, the data may provide the means for distinguishing between abiotic and biotic origins of methane. Disequilibrium isotopologue ratios can provide information about methane formation mechanisms and serve as tracers that provide insights into mixing, diffusion, kinetics, and other processes [51].

Ubiquitous dissolved methane in hot-spring fluids emanating from submarine hydrothermal vents is a potential carbon source for microbial communities living at and below the seafloor and in the water column. Methane clumped isotope analyses indicate a hot (270–360 °C), deep, and abiotic origin for methane at seafloor hot springs in unsedimented oceanic crust [52]. This important finding was made possible by a novel tunable infrared laser direct absorption spectroscopy instrument [53], which was developed with DCO support. Using the same instrument, microbial methane from a broad range of natural and cultured samples produced nonequilibrium clumped isotope signals [54]. The clumped isotope anomalies place new constraints on biogeochemical sources, sinks, and budgets of methane.

Computational studies have identified a novel mechanism for abiotic methane formation: The effects of confinement on carbon dioxide methanation in nanopore-controlled chemical reactions can shift thermodynamic equilibrium toward methane production [55]. This mechanism for producing abiotic methane may be applicable to interactions between seawater and oceanic crust, and could explain the origin of methane observed in some submarine hydrothermal vent systems.

Experimental studies have been conducted on abiotic methane formation under a wide range of conditions, including reducing environments that develop during serpentinization of ultramafic rocks. Using isotopically labeled CO_2, some experiments have shown that earlier claims of CH_4 production by serpentinization at low temperatures were incorrect [56]. However, other experiments have shown that CO_2 reduction in the presence of extant hydrogen (H_2) vapor leads to significant methane production at low temperatures [56]. Similarly, the production of methane in serpentinized ultramafic rocks can be catalyzed at low temperatures by ruthenium (Ru)-bearing chromite minerals [51,57].

DCO researchers have studied the production of H_2 and CH_4 during serpentinization at field sites around the world. For example, International Ocean Discovery Program (IODP) Expedition 357: Atlantis Massif Serpentinization and Life successfully cored a transect across the Atlantis Massif on the flank of the Mid-Atlantic Ridge. This expedition examined the role of serpentinization in driving seafloor hydrothermal systems, sustaining microbial communities, and sequestering carbon [58].

In a remarkable paper, DCO scientists documented abiotic synthesis of amino acids in the oceanic lithosphere [59]. Amino acids formed abiotically during a late alteration stage of massif serpentinites beneath the Atlantis Massif. This discovery has significant implications for the origins of life, ancient metabolisms, and the functioning of the present-day deep biosphere.

Ancient groundwaters in Precambrian Cratons are now recognized as important sources of H_2, which is available to support the subsurface biosphere to depths of several kilometers [60]. The contribution of Precambrian continental crust to global H_2 production had been greatly underestimated. If H_2 production via both radiolysis and hydration reactions is taken into account, H_2 production rates from the Precambrian continental lithosphere are comparable to estimates from marine systems [61]. Incorporating H_2 production from the Precambrian continental lithosphere could double existing estimates of global H_2, increasing the habitable volume of Earth's crust.

Research on molecular hydrogen is not limited to Earth. DCO scientists are members of the teams that discovered molecular hydrogen and higher hydrocarbons escaping from Saturn's moon Enceladus, which has a layer of ice covering a subsurface ocean [62,63]. The discovery of molecular hydrogen indicates that water is reacting with rocks on the floor of the alien ocean [62]. The process responsible for producing molecular hydrogen on Enceladus might resemble hydrothermal vents on Earth's seafloor. The discovery of complex carbon compounds emanating from Enceladus [63] suggests that the moon's ocean may contain the raw ingredients necessary for life.

5. The Deep Life Community

DCO's Deep Life Community is dedicated to assessing the nature and extent of the deep microbial and viral biosphere. This Community has expanded the known boundaries of Earth's microbial and viral biosphere, and investigated the interactions and processes that govern how ecosystems survive and evolve. DCO has united researchers approaching overarching deep life questions from varying perspectives by: ① studying the subsurface biosphere in the sediments and rocks of both the continents and the seafloor; ② exploring what genomes can reveal about the limits and possible origins of life; and ③ investigating the response of deep life to a range of physical and chemical extremes.

The lower boundary of the deep sedimentary biosphere was explored by DCO researchers participating in IODP Expedition 337: Deep Coalbed Biosphere off Shimokita. They discovered a microbial ecosystem producing methane from Miocene coalbeds nearly 2.5 km below the seafloor [64]. The assemblages appear to be the descendants of microbes buried in terrigenous sediments up to 20 million years ago. Despite low cell numbers, these microbes are actively growing at rates that range from months to over 100 years—some of the slowest microbial biosynthesis rates ever directly measured by incubation [65]. Other DCO researchers found microbial communities exhibiting aerobic respiration in sediments 75 m below the seafloor in the South Pacific Gyre, a finding that suggests that oxygen and aerobic communities may occur in sediments over 15%–44% of the Pacific and perhaps 9%–37% of the global seafloor [66].

The select survival of taxa capable of coping with the severe energy stresses characteristic of subsurface environments may cause these taxa to become the founders of more common communities such as Bathyarchaeota, which may play an important role in carbon cycling [67]. Therefore, microbial communities existing at extremes, such as the elevated temperatures in hydrogen-rich hydrothermal vent systems on the Mid-Cayman Rise, are critical to understanding the limits of deep life [68]. For example, members of the Bathyarchaeota are among the most abundant, diverse, and widely distributed Archaea in marine subsurface habitats globally. A metagenomic study has shown that Bathyarchaeotal subgroups employ versatile metabolisms, which in turn supply substrates for heterotrophic and methanogenic community members [69]. Another metagenomic study indicates that distinct evolutionary pressures correlate with genes related to nutrient uptake, biofilm formation, or viral invasion, a finding that is consistent with distinct evolutionary histories between geochemically different hydrothermal vent fields [70].

Based on observations of Archaea and bacteria at 77 worldwide locations with different marine ecosystems, DCO researchers determined that methane seep communities exhibit lower diversity than communities in other ecosystems. The surviving assemblages reflect the most favorable microbial metabolisms at methane seeps and distinguish the seep microbiome from other seafloor microbiomes [71]. Although only a few species of methanotrophs occur at all seeps worldwide, these microorganisms seem to greatly influence the methane budget of the ocean.

DCO also investigates the deep terrestrial continental biosphere. Based on a compilation of cell concentration and microbial diversity data from continental subsurface localities around the globe, DCO researchers estimated that the continental subsurface hosts $(2–6) \times 10^{29}$ cells, and found that bacteria are more abundant than Archaea and that their community composition is correlated to sample lithology [72].

Researchers investigating a subsurface lithoautotrophic microbial ecosystem (SLiME) in the ancient Witwatersrand Basin found, to their surprise, that sulfur-driven autotrophic denitrifiers were the dominant microbial group. Further analysis revealed that metabolic community cooperation enabled less typical metabolic reactions to prevail and stabilize the ecosystem [73]. Modeling also suggests that food—not dissolved oxygen—limits eukaryotic population growth at 1.4 km depths in 12 300-year-old palaeometeoric fissure water in South African mines [74,75]. Microbial communities occurring in connection with hydraulic fracturing during hydrocarbon resource development in the deep subsurface also provide clues to the deep terrestrial biosphere [76]. Microbes exist as deep as 2500 m below land surface and exhibit salt tolerance, metabolic capacity without electron acceptors, and evidence of active viral infection.

Through the DCO Census of Deep Life (CoDL), DNA sequencing has provided new and value-added information about carbon cycling, deep biosphere evolution, and the connection between ecosystems and environments both continental and marine. For example, CoDL researchers used 16S DNA sequencing to identify bacterial and archaeal taxa associated with eight minerals from a sub-seafloor microbial observatory on the Juan de Fuca Ridge, 280 m below the seafloor. They confirmed that distinct communities colonize different minerals, and that these communities group by mineral chemistry [77].

DCO's Extreme Biophysics group has approached the challenges of life existing in these extreme environments from a completely different angle. By focusing on molecular-level adaptation to life under extreme conditions, these researchers are advancing our knowledge of the basic chemistry and physics of the component biological structures and systems that define the limits of life [78,79].

6. Synthesis and future opportunities

DCO is synthesizing and integrating research across its four Science Communities to realize a new understanding of deep carbon science and fully capture DCO's achievements. This synthesis process aims to elevate the collaborative efforts of the global research initiative. Synthesis products and activities include cross-community research projects, such as Biology Meets Subduction and Carbon Mineral Evolution, as well as workshops, meetings, visualizations, special issues of journals, and books. The culmination of these activities will occur at an international conference, Deep Carbon 2019: Launching the Next Decade of Deep Carbon Science.

To help launch the next decade of deep carbon science, DCO scientists are developing a broad portfolio of activities that will extend beyond the culmination of the initial decadal program in 2019. A biennial Gordon Research Conference on Deep Carbon Science is planned as a sustainable successor to DCO international science meetings. A biennial Gordon Research Seminar on Deep Carbon Science for early career scientists could become a successor to DCO Summer Schools and DCO Early Career Scientist Workshops. Carbonates at High Pressures and Temperatures (CarboPaT), a research consortium supported by the German Research Foundation to study carbonates at extreme conditions, will continue to provide a platform for deep carbon science in Germany. In the United Kingdom, the Natural Environment Research Council has established a research program on Volatiles, Geodynamics, and Solid Earth Controls on the Habitable Planet. Science for Clean Energy is a European consortium led by DCO researchers with support from the European Union's Horizon 2020 program. The next decade of deep life research will be facilitated by a new International Center for Deep Life Investigation at Shanghai Jiao Tong University in China as well as a cluster of excellence titled The Ocean Floor—Earth's Uncharted Interface in Germany. These and other initiatives will help propel the next decade of deep carbon science.

7. Conclusion

In 2009, DCO was an ambitious experiment in scientific programs with no guarantee of success. Since then, DCO has evolved into a network of more than 1200 scientists that spans the globe and transcends traditional scientific disciplines. DCO is a science incubator that has launched new research groups, science communities, international scientific collaboration and partnerships, major research projects, field expeditions, scientific instruments, and companies. Perhaps most importantly, DCO has built an enduring legacy in its diverse, dynamic, and collaborative community of interdisciplinary scientists. DCO's management and community-building innovations are keys to the program's scientific success. Based on its success in achieving fundamental advances in deep carbon science, DCO may serve as an effective model for tackling large-scale, interdisciplinary, and international science questions.

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References

[1] Hazen RM, Schiffries C. Why deep carbon? Rev Mineral Geochem 2013;75:1–6.

[2] Hazen RM, Jones AP, Baross JA, editors. Carbon in Earth, reviews in mineralogy and geochemisty. Chantilly: Mineralogical Society of America and Geochemical Society; 2013.

[3] Santoro M, Gorelli FA, Bini R, Haines J, Cambon O, Levelut C, et al. Partially collapsed cristobalite structure in the non molecular phase V in CO_2. Proc Natl Acad Sci USA 2012;109(14):5176–9.

[4] Santoro M, Gorelli FA, Bini R, Salamat A, Garbarino G, Levelut C, et al. Carbon enters silica forming a cristobalite-type CO_2-SiO_2 solid solution. Nat Commun 2014;5(3761):3761.

[5] Boulard E, Gloter A, Corgne A, Antonangeli D, Auzende AL, Perrillat JP, et al. New host for carbon in the deep Earth. Proc Natl Acad Sci USA 2011;108 (13):5184–7.

[6] Boulard E, Pan D, Galli G, Liu Z, Mao WL. Tetrahedrally coordinated carbonates in Earth's lower mantle. Nat Commun 2015;6(6311):6311.

[7] Cerantola V, Bykova E, Kupenko I, Merlini M, Ismailova L, McCammon C, et al. Stability of iron-bearing carbonates in the deep Earth's interior. Nat Commun 2017;8(15960):15960.

[8] Liu J, Lin JF, Prakapenka VB. High-pressure orthorhombic ferromagnesite as a potential deep-mantle carbon carrier. Sci Rep 2015;5(7640):7640.

[9] Lobanov SS, Dong X, Martirosyan NS, Samtsevich AI, Stevanovic V, Gavryushkin PN, et al. Raman spectroscopy and X-ray diffraction of sp^3 $CaCO_3$ at lower mantle pressures. Phys Rev B 2017;96(10):104101.

[10] Merlini M, Cerantola V, Gatta GD, Gemmi M, Hanfland M, Kupenko I, et al. Dolomite-IV: candidate structure for a carbonate in the Earth's lower mantle. Am Mineral 2017;102(8):1763–6.

[11] Merlini M, Crichton WA, Hanfland M, Gemmi M, Müller H, Kupenko I, et al. Structures of dolomite at ultrahigh pressure and their influence on the deep carbon cycle. Proc Natl Acad Sci USA 2012;109(34):13509–14.

[12] Dorfman S, Badro J, Nabiei F, Prakapenka VB, Cantoni M, Gillet P. Carbonate stability in the reduced lower mantle. Earth Planet Sci Lett 2018;489:84–91.

[13] Fu S, Yang J, Lin JF. Abnormal elasticity of single-crystal magnesiosiderite across the spin transition in Earth's lower mantle. Phys Rev Lett 2017;118 (3):036402.

[14] Wood B, Li J, Shahar A. Carbon in the core: its influence on the properties of core and mantle. Rev Mineral Geochem 2013;75:231–50.

[15] Shahar A, Schauble EA, Caracas R, Gleason AE, Reagan MM, Xiao Y, et al. Pressure-dependent isotopic composition of iron alloys. Science 2016;352(6285):580–2.

[16] Chen B, Li Z, Zhang D, Liu J, Hu MY, Zhao J, et al. Hidden carbon in Earth's inner core revealed by shear softening in dense Fe_7C_3. Proc Natl Acad Sci USA 2014;111(50):17755–8.

[17] Dasgupta R. Ingassing, storage, and outgassing of terrestrial carbon through geologic time. Rev Mineral Geochem 2013;75:183–229.

[18] Ni H, Keppler H. Carbon in silicate melts. Rev Mineral Geochem 2013;75:251–87.

[19] Dasgupta R, Hirschmann M. The deep carbon cycle and melting in Earth's interior. Earth Planet Sci Lett 2010;298(1–2):1–13.

[20] Thomson AR, Walter MJ, Kohn SC, Brooker RA. Slab melting as a barrier to deep carbon subduction. Nature 2016;529(7584):76–9.

[21] Poli S. Carbon mobilized at shallow depths in subduction zones by carbonatitic liquids. Nat Geosci 2015;8(8):633–6.

[22] Pan D, Spanu L, Harrison B, Sverjensky DA, Galli G. Dielectric properties of water under extreme conditions and transport of carbonates in the deep Earth. Proc Natl Acad Sci USA 2013;110(17):6646–50.

[23] Facq S, Daniel I, Sverjensky D. *In situ* Raman study and thermodynamic model of aqueous carbonate speciation in equilibrium with aragonite under subduction zone conditions. Geochim Cosmochim Acta 2014;132:375–90.

[24] Sverjensky D, Harrison B, Azzolini D. Water in the deep Earth: the dielectric constant and the solubilities of quartz and corundum to 60 kb and 1200 °C. Geochim Cosmochim Acta 2014;129:125–45.

[25] Sverjensky D, Stagno V, Huang F. Important role for organic carbon in subduction-zone fluids in the deep carbon cycle. Nat Geosci 2014;7(12):909–13.

[26] Sverjensky DA, Huang F. Diamond formation due to a pH drop during fluid-rock interactions. Nat Commun 2015;6(8702):8702.

[27] Galvez ME, Connolly JA, Manning CE. Implications for metal and volatile cycles from the pH of subduction zone fluids. Nature 2016;539(7629):420–4.

[28] Dolejš D. Geochemistry: ions surprise in Earth's deep fluids. Nature 2016;539(7629):362–4.

[29] Shirey S, Cartigny P, Frost D, Keshav S, Nestola F, Pearson G, et al. Diamonds and the geology of mantle carbon. Rev Mineral Geochem 2013;75:355–421.

[30] Smith EM, Shirey SB, Nestola F, Bullock ES, Wang J, Richardson SH, et al. Large gem diamonds from metallic liquid in Earth's deep mantle. Science 2016;354(6318):1403–5.

[31] Weiss Y, McNeill J, Pearson DG, Nowell GM, Ottley CJ. Highly saline fluids from a subducting slab as the source for fluid-rich diamonds. Nature 2015;524(7565):339–42.

[32] Pearson DG, Brenker FE, Nestola F, McNeill J, Nasdala L, Hutchison MT, et al. Hydrous mantle transition zone indicated by ringwoodite included within diamond. Nature 2014;507(7491):221–4.

[33] Nestola F, Korolev N, Kopylova M, Rotiroti N, Pearson DG, Pamato MG, et al. $CaSiO_3$ perovskite in diamond indicates the recycling of oceanic crust into the lower mantle. Nature 2018;555(7695):237–41.

[34] Smith EM, Shirey SB, Richardson SH, Nestola F, Bullock ES, Wang J, et al. Blue boron-bearing diamonds from Earth's lower mantle. Nature 2018;560(7716):84–7.

[35] de Moor JM, Aiuppa A, Avard G, Wehrmann H, Dunbar N, Muller C, et al. Turmoil at Turrialba Volcano (Costa Rica): degassing and eruptive processes inferred from high-frequency gas monitoring. J Geophys Res Solid Earth 2016;121(8):5761–75.

[36] Allard P, Aiuppa A, Bani P, Métrich N, Bertagnini A, Gauthier PJ, et al. Prodigious emission rates and magma degassing budget of major, trace and radioactive volatile species from Ambrym basaltic volcano, Vanuatu island Arc. J Volcanol Geotherm Res 2015;304:378–402.

[37] Foley SF, Fischer TP. An essential role for continental rifts and lithosphere in the deep carbon cycle. Nat Geosci 2017;10(12):897–902.

[38] Lee H, Muirhead JD, Fischer TP, Ebinger CJ, Kattenhorn SA, Sharp ZD, et al. Massive and prolonged deep carbon emissions associated with continental rifting. Nat Geosci 2016;9:145–9.

[39] Hunt JA, Zafu A, Mather TA, Pyle DM, Barry PH. Spatially variable CO_2 degassing in the Main Ethiopian Rift: implications for magma storage, volatile transport and rift-related emissions. Geochem Geophys Geosyst 2017;18(10):3714–37.

[40] Brune S, Williams SE, Müller RD. Potential links between continental rifting, CO_2 degassing and climate change through time. Nat Geosci 2017;10(12):941–6.

[41] Le Voyer M, Kelley KA, Cottrell E, Hauri EH. Heterogeneity in mantle carbon content from CO_2-undersaturated basalts. Nat Commun 2017;8:14062.

[42] Aiuppa A, Fischer T, Plank T, Robidoux P, Di Napoli R. Along-arc, inter-arc and arc-to-arc variations in volcanic gas CO_2/S_T ratios reveal dual source of carbon in arc volcanism. Earth Sci Rev 2017;168:24–47.

[43] Mason E, Edmonds M, Turchyn AV. Remobilization of crustal carbon may dominate volcanic arc emissions. Science 2017;357(6348):290–4.

[44] Kelemen PB, Manning CE. Reevaluating carbon fluxes in subduction zones, what goes down, mostly comes up. Proc Natl Acad Sci USA 2015;112(30):E3997–4006.

[45] Johansson L, Zahirovic S, Müller RD. The interplay between the eruption and weathering of Large Igneous Provinces and the deep-time carbon cycle. Geophys Res Lett 2018;45(11):5380–9.

[46] Pall J, Zahirovic S, Doss S, Hassan R, Matthews KJ, Cannon J, et al. The influence of carbonate platform interactions with subduction zone volcanism on palaeo-atmospheric CO_2 since the Devonian. Clim Past 2018;14(6):857–70.

[47] Müller RD, Dutkiewicz A. Oceanic crustal carbon cycle drives 26-million-year atmospheric carbon dioxide periodicities. Sci Adv 2018;4(2):q0500.

[48] Keller T, Katz R. The role of volatiles in reactive melt transport in the asthenosphere. J Petrol 2016;57(6):1073–108.

[49] Keller T, Katz R, Hirschmann M. Volatiles beneath mid-ocean ridges: deep melting, channelised transport, focusing, and metasomatism. Earth Planet Sci Lett 2017;464:55–68.

[50] Young ED, Rumble III D, Freedman P, Mills M. 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. Int J Mass Spectrom 2016;401:1–10.

[51] Young ED, Kohl IE, Sherwood Lollar B, Etiope G, Rumble D, Li S, et al. 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. Geochim Cosmochim Acta 2017;203:235–64.

[52] Wang DT, Reeves EP, McDermott JM, Seewald JS, Ono S. Clumped isotopologue constraints on the origin of methane at seafloor hot springs. Geochim Cosmochim Acta 2018;223:141–58.

[53] Ono S, Wang DT, Gruen DS, Sherwood Lollar B, Zahniser MS, McManus BJ, et al. Measurement of a doubly substituted methane isotopologue, $^{13}CH_3D$, by tunable infrared laser direct absorption spectroscopy. Anal Chem 2014;86(13):6487–94.

[54] Wang DT, Gruen DS, Sherwood Lollar B, Hinrichs KU, Stewart LC, Holden JF, et al. Methane cycling. Nonequilibrium clumped isotope signals in microbial methane. Science 2015;348(6233):428–31.

[55] Le T, Striolo A, Turner CH, Cole DR. Confinement effects on carbon dioxide methanation: a novel mechanism for abiotic methane formation. Sci Rep 2017;7(1):9021.

[56] McCollom TM. Abiotic methane formation during experimental serpentinization of olivine. Proc Natl Acad Sci USA 2016;113(49):13965–70.

[57] Etiope G, Ifandi E, Nazzari M, Procesi M, Tsikouras B, Ventura G, et al. Widespread abiotic methane in chromitites. Sci Rep 2018;8(1):8728.

[58] Früh-Green GL, Orcutt BN, Green SL, Cotterill C, Morgan S, Akizawa N, et al. Expedition 357 summary. Proceed Inter Ocean Discov Prog 2017:375.

[59] Ménez B, Pisapia C, Andreani M, Jamme F, Vanbellingen QP, Brunelle A, et al. Abiotic synthesis of amino acids in the recesses of the oceanic lithosphere. Nature 2018;564(7734):59–63.

[60] Holland G, Sherwood Lollar B, Li L, Lacrampe-Couloume G, Slater GF, Ballentine CJ. Deep fracture fluids isolated in the crust since the Precambrian era. Nature 2013;497(7449):357–60.

[61] Sherwood Lollar B, Onstott TC, Lacrampe-Couloume G, Ballentine CJ. The contribution of the Precambrian continental lithosphere to global H_2 production. Nature 2014;516(7531):379–82.

[62] Waite JH, Glein CR, Perryman RS, Teolis BD, Magee BA, Miller G, et al. Cassini finds molecular hydrogen in the Enceladus plume: evidence for hydrothermal processes. Science 2017;356(6334):155–9.

[63] Postberg F, Khawaja N, Abel B, Choblet G, Glein CR, Gudipati MS, et al. Macromolecular organic compounds from the depths of Enceladus. Nature 2018;558(7711):564–8.

[64] Inagaki F, Hinrichs KU, Kubo Y, Bowles MW, Heuer VB, Hong WL, et al. Exploring deep microbial life in coal-bearing sediment down to ~2.5 km below the ocean floor. Science 2015;349(6246):420–4.

[65] Trembath-Reichert E, Morono Y, Ijiri A, Hoshino T, Dawson KS, Inagaki F, et al. Methyl-compound use and slow growth characterize microbial life in 2-km-deep subseafloor coal and shale beds. Proc Nat Acad Sci USA 2017;114(44):E9206–15.

[66] D'Hondt S, Inagaki F, Zarikian C, Abrams LJ, Dubois N, Engelhardt T, et al. Presence of oxygen and aerobic communities from seafloor to basement in deep-sea sediment. Nat Geosci 2015;8(4):299–304.

[67] Starnawski P, Bataillon T, Ettema TJG, Jochum LM, Schreiber L, Chen X, et al. Microbial community assembly and evolution in subseafloor sediment. Proc Natl Acad Sci USA 2017;114(11):2940–5.

[68] Reveillaud J, Reddington E, McDermott J, Algar C, Meyer JL, Sylva S, et al. Subseafloor microbial communities in hydrogen-rich vent fluids from hydrothermal systems along the Mid-Cayman Rise. Environ Microbiol 2016;18(6):1970–87.

[69] He Y, Li M, Perumal V, Feng X, Fang J, Xie J, et al. Genomic and enzymatic evidence for acetogenesis among multiple lineages of the archaeal phylum Bathyarchaeota widespread in marine sediments. Nat Microbiol 2016;1(6):16035.

[70] Anderson RE, Reveillaud J, Reddington E, Delmont TO, Eren AM, McDermott JM, et al. Genomic variation in microbial populations inhabiting the marine subseafloor at deep-sea hydrothermal vents. Nat Commun 2017;8(1):1114.

[71] Ruff SE, Biddle JF, Teske AP, Knittel K, Boetius A, Ramette A. Global dispersion and local diversification of the methane seep microbiome. Proc Natl Acad Sci USA 2015;112(13):4015–20.

[72] Magnabosco C, Lin LH, Dong H, Bomberg M, Ghiorse W, Stan-Lotter H, et al. The biomass and biodiversity of the continental subsurface. Nat Geosci 2018;11(10):707–17.

[73] Lau MCY, Kieft TL, Kuloyo O, Linage-Alvarez B, van Heerden E, Lindsay MR, et al. An oligotrophic deep-subsurface community dependent on syntrophy is dominated by sulfur-driven autotrophic denitrifiers. Proc Natl Acad Sci USA 2016;113(49):E7927–36.

[74] Borgonie G, García-Moyano A, Litthauer D, Bert W, Bester A, van Heerden E, et al. Nematoda from the terrestrial deep subsurface of South Africa. Nature 2011;474(7349):79–82.

[75] Borgonie G, Linage-Alvarez B, Ojo AO, Mundle SOC, Freese LB, Van Rooyen C, et al. Eukaryotic opportunists dominate the deep-subsurface biosphere in South Africa. Nat Commun 2015;6(1):8952.

[76] Daly RA, Borton MA, Wilkins MJ, Hoyt DW, Kountz DJ, Wolfe RA, et al. Microbial metabolisms in a 2.5-km-deep ecosystem created by hydraulic fracturing in shales. Nat Microbiol 2016;1:16146.

[77] Smith A, Fisk M, Thurber A, Flores GE, Mason O, Popa R, et al. Deep crustal communities of the Juan de Fuca Ridge are governed by mineralogy. Geomicrobiol J 2016:147–56.

[78] Bourges AC, Torres Montaguth OE, Ghosh A, Tadesse WM, Declerck N, Aertsen A, et al. High pressure activation of the Mrr restriction endonuclease in Escherichia coli involves tetramer dissociation. Nucleic Acids Res 2017;45(9):5323–32.

[79] Gao M, Harish B, Berghaus M, Seymen R, Arns L, McCallum SA, et al. Temperature and pressure limits of guanosine monophosphate self-assemblies. Sci Rep 2017;7(1):9864.