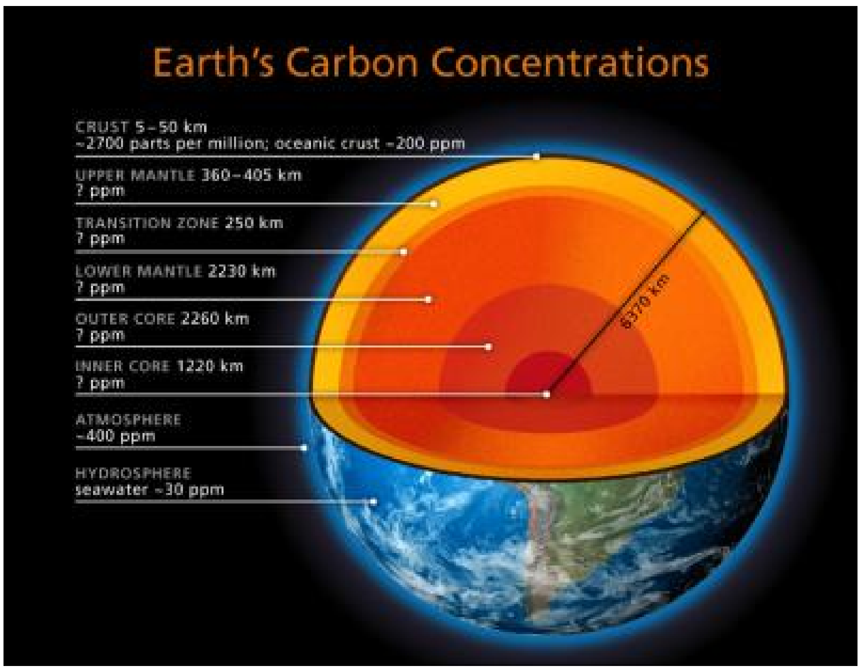
Deep Carbon: Quest underway to discover its quantity, movements, origins and forms in Earth

March 4 2013



While we know approximately the thickness of Earth�s layers, the quantities of carbon below the surface in each layer remain a mystery. Even estimates of carbon in the crust are uncertain. Fluxes between the layers complicate the mystery and the quest of the Deep Carbon Observatory. Credit: Deep Carbon Observatory

From Earth's surface to hundreds of kilometers deeper than oilmen drill, the Deep Carbon Observatory (DCO) is investigating the surprising quantity of carbon in the deep, dark Earth beyond photosynthesis.

The program is investigating deep carbon's movement in the slow convection of the mantle, the percolating fluids of the crust, and the violent emission from volcanoes. It searches for the ancient origin of the deep carbon, and the formation and transformation of its many forms, ranging from gas and oil to diamonds and deep microbes.

Ninety percent or more of Earth's carbon is thought to be locked away or in motion deep underground—a hidden dimension of the planet as poorly understood as it is profoundly important to life on the surface, according to scientists probing the world's innermost secrets in the decade-long, $500 million project.

In a landmark volume, DCO scientists say estimates of carbon bound in the metallic core alone range from 0.25 to 1 percent by weight. If 1 percent proves correct, the core by itself sequesters four times more carbon than all known carbon reservoirs in the rest of the planet—and 50,000,000 times as much as that held in the flora and fauna on Earth's relatively wafer-thin skin far above.

Studies of meteorites suggest that the material that first formed Earth contained about 3% by weight carbon. Confirmed sources of Earth's carbon, however—life, carbonate rocks like limestone, and carbon dioxide in the oceans and atmosphere—sum to only about 0.1% carbon content.

"Where is Earth's missing carbon?" asks Robert Hazen, Executive Director of the DCO, a global collaboration emerging as the largest ever conducted in this domain of science. "Significant amounts may be locked into minerals and melts in the mantle and core. If so, can we now find them?"

The DCO is expected to create profound new understanding of this planet and others, shedding unprecedented light on Earth's highly active subterranean environment—the globe's oldest ecosystem—including the secrets of volcanoes and diamonds, sources of oil and gas, and the origins of life itself.

Mysteries of deep carbon include:

Quantity:

- How much carbon is stored inside Earth?
- What are the reservoirs of that carbon?

Movements:

- How does carbon move among reservoirs?
- Where are the most significant carbon fluxes between Earth's deep interior and the surface?

Origins:

- How much rising carbon is primordial and how much is recycled from the surface?
- Are there deep abiotic sources of methane and other hydrocarbons?

Forms:

- What is the nature and extent of deep microbial life?

- Did deep organic chemistry play a role in life's origins?

"Of the 88 naturally occurring, long-lived elements on Earth, carbon stands alone," says Dr. Hazen. "No other element contributes so centrally to the well-being and sustainability of life on Earth, including our human species."

After the first three years of its 10-year life, the Observatory describes its quest to discover the quantity, movement, origin, and forms of deep carbon in a landmark 700-page volume. Published with open public access online in the influential series *Reviews in Mineralogy and Geochemistry*, the book Carbon in Earth outlines questions that will guide DCO's program through 2019 and beyond.

Dr. Hazen, Senior Staff Scientist, Geophysical Laboratory, Carnegie Institution of Washington, co-edited the book with John A. Baross of the Seattle-based University of Washington and Adrian Jones of University College, London. More than 50 experts from nine countries (US, UK, France, Germany, Belgium, Switzerland, Italy, Canada, and Russia) contribute to the volume.

The book and details of the ambitious global program are the focus of DCO's International Science Meeting 3-5 March 2013 at the US National Academy of Sciences, Washington, DC. Prior major meetings have taken place in China, Russia, Germany, France, and the UK.

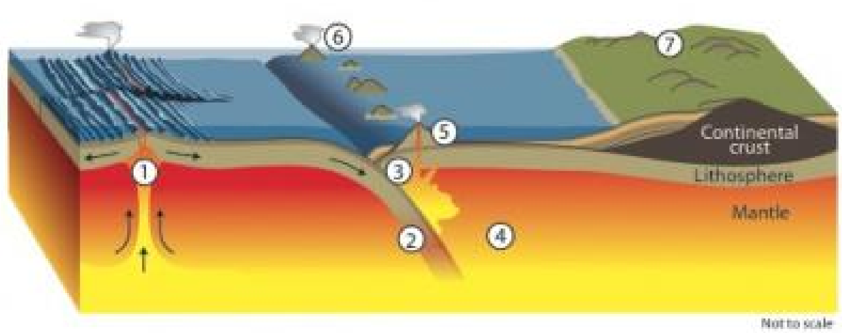
Among many highlights of the book:

Minerals made from life (Chapter 4): Four billion years ago, Earth featured few carbon-bearing minerals, and rocks were relatively uniform. Biological processes began to affect Earth's surface mineralogy as long as 3.8 billion years ago, when large-scale surface mineral deposits, including carbonate and iron formations, were precipitated.

Later, life and its carbon-rich skeletons irreversibly transformed Earth's surface mineralogy. Life accounts for much of the progressive separation and concentration of the elements from their original relatively uniform distribution in the planet.

The chalk of Britain's white cliffs near Dover formed from calcium carbonate—the skeletal remains of planktonic algae—famously illustrates life making minerals. But the DCO is revealing a far richer array of carbon-based minerals derived from ancient life, from reefs formed by marine animals and microbes to the crystal lenses of the eyes of trilobites (extinct marine invertebrates)—biomineralization that underscores the intricate co-evolution of the geosphere and the biosphere.

"An old guessing game began: 'animal, vegetable or mineral'? We're learning now that for some types of rock the answer may be, 'all three'," says Dr. Hazen.



Left to Right shows: Cross section of the modern plate tectonic cycle, including (1) creation of oceanic crust at mid-ocean ridges, (2) subduction at ocean trenches, (3) dehydration and melting beneath subduction volcanoes, (4) carbon storage in the upper mantle, (5) carbon transport in island arc volcanoes where oceanic crust is subducted beneath oceanic crust, (6) carbon emissions from volcanoes, and (7) diffuse carbon sources. Several features such as hotspot volcanoes and convergent margin volcanoes (where oceanic crust is subducted beneath continental crust) are not pictured here. Credit: Credit: Deep Carbon Observatory

Where does the carbon go? (Chapter 7): The stately process of plate tectonics drives Earth's deep carbon cycle, as dense carbon-rich crust sinks at subduction zones, while carbon returns to the surface through volcanism, primarily through the release of carbon dioxide. Thus, the familiar near-surface parts of the global carbon cycle—the atmosphere, the oceans, and the biosphere—are intimately linked to Earth's deep interior.

Rajdeep Dasgupta of Rice University in Houston, Texas, notes: "Sinking and in-gassing of carbon, as well as its storage and out-gassing, dynamically transform our planet. We are discovering more and more ways that modern Earth differs from its past on all time scales."

How old is your diamond? (Chapter 12): Carbon can form the cheap black graphite of a pencil or the superlatively hard, transparent crystal of a precious diamond. Jewelers and gemologists might enhance the financial value and significance of diamonds far beyond their clarity or size in carats through new technologies and techniques that can determine the age, depth and the part of Earth from which the precious stones came. Inclusions—bits of minerals trapped where diamonds formed—and the structure and composition of the diamond itself provide direct evidence of deep carbon's home and rank among the most valuable tools of scientists looking into the forbidding underground frontier. Diamonds, in short, are sparkling "eyes" offering a glimpse into Deep Earth.

Hydrogen as primal food and fuel (Chapter 18): Hydrogen fed primordial life, scientists suspect. DCO's intriguing investigations include the process called "serpentinization" during which basalt rock—the foundation stone of the ocean floor—erupts from deep-sea volcanoes and is exposed to seawater, causing a chemical reaction that produces both hydrogen and the mineral serpentine, characterized by long colorful veins. Was this energy-releasing process part of life's original recipe?

"Drill a hole one or two kilometers deep just about anywhere and you will find a sparse but hardy microbial community," says Isabelle Daniel of l'Université Claude Bernard Lyon 1, France. "These deep microbes, which live in the tiniest cracks and fissures in rocks, survive on the chemical energy of minerals."

Deep viruses (Chapter 20): Perhaps most enigmatic of all deep life forms are viruses in the crust and subsea sediment, which may play a profound role in microbial diversity. Wikipedia does not even have an article yet on the viriosphere, much less the deep viriosphere. Genetic material from viruses is passively inserted into the genome of microbes and may simply reside there for years before finding expression in some way, just as people who get shingles suffer from a chickenpox virus left over from childhood.

The lateral transfer of genes by viruses—5,000 of which in a line would fit across a fingernail—"is an intriguing part of evolution," says Dr. Baross. "The deep subsurface may have acted as a natural laboratory for the origin of life, in which multiple 'experiments' could have been carried out in tandem." Viruses, he adds, "may manipulate the genomes of the hosts they infect throughout the subsurface, effectively resulting in a mutualistic, symbiotic relationship between host and virus that transcends traditional notions of viruses as parasites."

Galapagos of the Deep (Chapter 17): The variety of bacterial life at extreme high-pressure depths worldwide constitutes a subterranean "Galapagos," DCO scientists say, adding that such subsurface life comprises a large portion of Earth's total biomass—estimated in the late 1990s to be a third to a half of all life, though that figure is now considered high.

DNA has unearthed a marvel of diversity among deep single-celled micro-organisms, notably Archaea. And deep fungi—organisms with complex cell structures (eukaryotes) in the marine subsurface, have been a scientific surprise.

"Given the extraordinarily low rates of respiration, subsurface microbes must reproduce very slowly, if at all," says Steven D'Hondt of the University of Rhode Island. "They take at least hundreds to thousands of years to reproduce and it's conceivable that they live without dividing for millions to tens of millions of years," he says. Still to be determined, Dr. D'Hondt notes, is the extent to which these organisms are "microbial zombies, incapable of being revived to a normal state."

Selected program goals

Earth's carbon recycling program: Parts of the ocean floor are constantly refreshed in a process by which material from Deep Earth is upwelled at mid-Ocean ridges. New rocks at ocean ridges replace denser old crust that sinks at subduction zones, where they are swallowed back into Deep Earth—a recycling process that sequesters carbon under high temperature and pressure and hydrates rock kilometers deep. The DCO aims to multiply the precision of our estimates of the quantities and speeds of these processes.

Left to Right: Cross section of the modern plate tectonic cycle, including (1) creation of oceanic crust at mid-ocean ridges, (2) subduction at ocean trenches, (3) dehydration and melting beneath subduction volcanoes, (4) carbon storage in the upper mantle, (5) carbon transport in island arc volcanoes where oceanic crust is subducted beneath oceanic crust, (6) carbon emissions from volcanoes, and (7) diffuse carbon sources. Several features such as hotspot volcanoes and convergent margin volcanoes (where oceanic crust is subducted beneath continental crust) are not pictured here.

Deep Earth's exhalations: Another of the project's decade-long objectives: better tracking of carbon exhaled from Deep Earth. DCO scientists aim to establish round-the-clock automated, web-accessible observatories measuring CO2 emissions from 25 of the world's 150 most actively out-gassing volcanoes on five continents.

Other colleagues, meanwhile, are creating a systematic, internationally consistent way to measure and inventory carbon out-gassed from hot springs and other small, diffuse sources worldwide. Though they lack the dramatic flare of volcanoes, these small sources of carbon out-gassing collectively may represent a significant source from the deep interior.

DCO researchers will also estimate the volume of CO2 released as great plates of Earth crush together, for example in the still-rising Himalayan mountains, where thick layers of old carbon-rich rocks are squeezed, tortured, and broken down.

Distinguishing biotic and abiotic gas: Exploratory deep drill holes routinely find methane deposits but the source of some of this natural gas and other out-gassing methane (for example, for sea floor vents) is a matter of debate. Is it almost all recycled surface life? How much might come from deep abiotic processes—methane formed by chemical reactions in the lower crust or mantle? A radically new high-resolution mass spectrometer now under construction for the DCO may reliably distinguish biotic (or fossil) methane from abiotic methane within a couple of years.

New tools

Learning quantity, movements, origin, and forms of deep carbon requires new tools, such as the spectrometer mentioned above.

Using technology similar to medicine's three-dimensional x-ray CT scan, DCO scientists can study the way carbon-bearing fluids migrate through rocks under ultra high temperature and pressure, as in Earth's fractured crust.

New high-temperature and high-pressure devices feature a tiny space encased by diamonds. Scientists can use lasers to heat samples of different elements squeezed between these tiny anvils to temperatures and pressures (to 10 million atmospheres), mimicking Deep Earth and giant gas planets. Study of the altered properties of elements at extreme conditions may unlock secrets of both the origin and forms of carbon minerals, while possibly leading to a new generation of useful technological materials.

The program will also design and construct the next generation of bioreactor, to study microbial populations at high temperature and pressure to help determine the temperature, pressure, and environmental limits to microbial survival, growth, and reproduction.

Another crucial tool—and major lasting legacy of the DCO—will be an integrated open-access database of many kinds of information about Deep Earth and its carbon-bearing materials.

Areas of the world from which the DCO expects especially important field results include Oman, the Songliao Basin of China, South Africa, Siberia, and the deep sea floor. The DCO is cooperating with the International Continental Drilling Program and the International Ocean Drilling Program to deepen exploration.

Says Jesse Ausubel, at the Rockefeller University and Science Advisor to the Alfred P. Sloan Foundation, DCO's founding sponsor: "Earth is a steaming carbon pudding. The DCO will sniff and measure all our deep carbon emanations, and drastically revise our estimates of the abundance and fluxes of carbon."

Says Craig Schiffries, Director of the DCO: "We are already partnering with many academic institutions, professional societies, and government agencies, and some private sector enterprises. The Deep Carbon Observatory can succeed only as an international collaboration of many disciplines and all sectors—public, private and academic."

Says co-editor John Baross: "The DCO may find totally new kinds of life as we reach greater depths, higher temperatures and pressures. And quite possibly Earth's deepest life doesn't use DNA and proteins the way normal cells do. Living biofilms may just spread out along deep cracks and fissures—perhaps as a growing layer of biomolecules. And, since efforts to detect deep life are based on looking for DNA and proteins, we must develop new techniques to search for deep and potentially weird life."

Adds co-editor Adrian Jones: "Our interest dives below the reach of oil and gas company drills down to depths where diamonds form. If they were alive today, we would welcome both Jules Verne and J.R.R. Tolkien on the program's steering committee. We aim to find the limits of life and come back to tell the tale."

"Carbon in Earth identifies a vast amount we know we don't know," concludes Dr. Hazen, "but we will also discover entirely unanticipated phenomena. Even a year ago we did not anticipate the book would have a chapter on the viriosphere."

More information: Deep Carbon Observatory, International Science

Meeting
US National Academy of Sciences
2101 Constitution Ave. N.W., Washington, DC 20001

Provided by Deep Carbon Observatory