DEEP CARBON AND FALSE DICHOTOMIES

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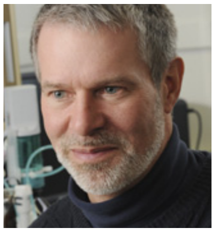


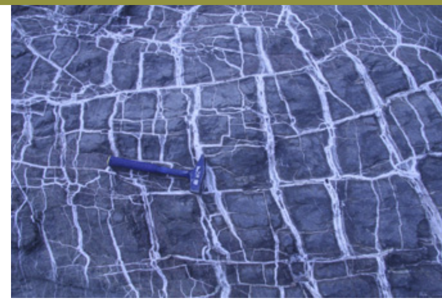
It's a quirk of human nature that we tend to think in dichotomies. Claude Lévi-Strauss, the 20th-century French anthropologist and philosopher-author of *The Savage Mind*, attributed such black-and-white perceptions as a throwback to primitive survival mechanisms: quickly recognizing friend versus enemy could prove a life versus death choice. Better not to equivocate when faced with mortal danger. Today's news is filled with the ongoing, modern consequences of such a rigid mindset, as racism, nationalism, and religious fundamentalism continue to divide the human population into fragments of "us" versus "them."

It would be gratifying to think that rational scientists come to their studies with a more nuanced and enlightened worldview, but one needs only to glance at the highlights of history to see that many scientists have fallen into the same trap. More than two centuries ago intense debates divided eighteenth-century uniformitarians and catastrophists—the former arguing that all geological processes are gradual and still in play today; the latter invoking brief and cataclysmic events (read Noah's Flood) as the cause of Earth's geological history. Today it's obvious that the truth lies somewhere in between. A similar rancorous debate raged between Abraham Gottlob Werner and his neptunist followers, who favored a watery origin for rocks, and James Hutton's plutonist disciples, who advocated heat as the principal causative agent of Earth's crust. Once again, both camps had it partially correct.

Over and over again, this storyline has been repeated by passionately committed scientists: the granite controversy (magma versus metasomatism); the nebular debate (gas clouds versus galaxies); the crater controversy (impact versus volcano, with echoes of the catastrophist–uniformitarian conflict); the mass extinction debate (again, impact versus volcano)—the list goes on and on. Textbooks from the time of my youth defined rigid boundaries between plants and animals, between single-celled and multicellular organisms, even between life and nonlife—all distinctions that have become blurred and confused as genomic data replace simplistic taxonomies.

Surely by now, as we rush headlong into the 21st century, we have outgrown such sloppy bimodal thinking. Haven't we?

Over the past five years I've had the pleasure of helping to organize and nurture the Deep Carbon Observatory (DCO)—a 10-year international research program with significant core support from the Alfred P. Sloan Foundation. With more than 1000 collaborators in 40 countries, the DCO is a microcosm of modern science.[2] It spans several scientific disciplines—astronomy, biology, chemistry, geology, and physics hold equal sway; the science of carbon knows no artificially imposed boundaries. Carbon is unique among elements: it forges the chemical backbone of all life; its compounds provide most of our energy needs; it plays the central chemical role in the discovery of new materials; and it lies at the root of some of society's most urgent concerns regarding climate, resources, health, and the environment. Yet, in spite of its fundamental importance to science and technology and its unparalleled influence on our planet's present and future habitability, we remain profoundly ignorant of carbon at the global scale, from crust to core. Many aspects of Earth's carbon cycle—its quantities, movements, forms, and origins—remain largely unknown. What are the types and extents of deep carbon reservoirs and fluxes? How do carbon's chemical behavior and physical properties change at extremes of temperature and pressure? What role has deep abiotic organic synthesis played in the formation of hydrocarbons and the origins of life? And how extensive and diverse is the hidden deep biosphere?



Serpentine + carbonate veins in partially serpentinized mantle peridotite, Wadi Fins, Oman. Such active subsurface alteration zones may host rich microbial ecosystems and could have played a role in life's origins. Photo by Peter Kelemen

Where there is ignorance or uncertainty, human nature creates false dichotomies, and so it is with deep carbon science. Consider just three of the potential traps that DCO has been confronting.

The first debate has raged for at least a century and a half, since Dmitri Mendeleev, the Russian geochemist of periodic table fame, posited an exclusively abiological origin of petroleum. Since that time, the "Russian-Ukranian" school of petroleum genesis has been unwavering in that stance. Meanwhile, geologists in America and much of the rest of the world came to the opposite conclusion, that oil is exclusively the alteration product of biomass—hence "fossil" fuel. For decades a geologic cold war simmered, with each side paying scant heed to the other.

Iconoclast astrophysicist Tommy Gold stirred the pot with his controversial "deep hot biosphere" hypothesis, first published in the *Wall Street Journal* on June 8, 1977, and subsequently expanded into articles and ultimately a popular book in 1999. His initial shocking, heretical little piece, "Rethinking the Origins of Oil and Gas," espoused the optimistic view that we will never run out of hydrocarbon fuels. Petroleum, he argued, is produced in prodigious quantities deep within Earth, synthesized not by biology but rather by Earth's inner heat and pressure. Hydrocarbons incessantly rise from the distant mantle, refilling oil reservoirs from below, where a host of hungry microbes impart their biological overprint, thus fooling an army of western geologists. Such processes, operating for billions of years, have generated thousands of years' supply of oil.

The scientific community was quick to express outrage. Some decried Gold's end run around the convention of peer review: newspapers are not the place to spring novel ideas on the experts. Others railed against the unsubstantiated premise of Gold's deep oil model, which flew in the face of textbook orthodoxy. And the Soviets were furious, too, claiming that they had had the idea first.

Gold's publications brought the old debate to the fore, and it became one of the core questions to be addressed by the fledgling DCO. The starkness of the disagreement was revealed at a 2010 DCO forum on the subject, where a prominent Russian geochemist, when asked what percentage of petroleum is nonbiological in origin, answered without hesitation, "100%." An American expert, who espoused the polar-opposite 100% biotic petroleum orthodoxy, threatened to walk away if DCO even contemplated adopting a more nuanced point of view.

It should come as little surprise that both camps have valid arguments, and that hydrocarbons, both deep and shallow, undoubtedly have varied origins. That petroleum is predominantly derived from biology remains the majority opinion, but mounting evidence points to significant deep repositories of abiogenic methane, with lesser amounts of other varied organic species, as well. After all, the origins of life must have been preceded by a robust period of abiotic organic synthesis.

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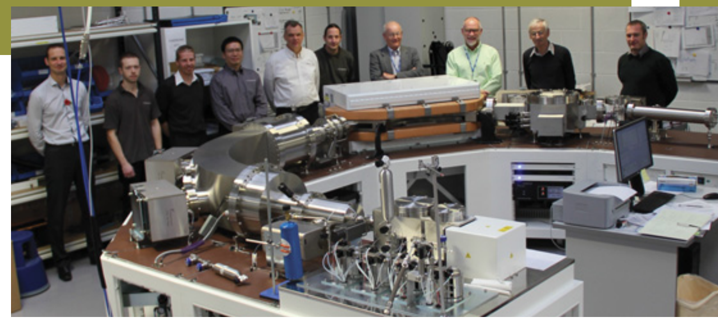
2 We welcome readers to check out deepcarbon.net to learn more and to join the expanding DCO network.

As in all scientific debates, data trump shouting. New DCO-sponsored instrumentation, including high-resolution mass spectrometers and infrared laser techniques, are being designed and constructed specifically to measure diagnostic ratios of the rare methane isotopologues $^{12}CH_2D_2$ and $^{13}CH_3D$, and thus to address this question. If these instruments work as hoped, we'll soon have the means to distinguish some biotic from abiotic methane, and a long-standing polarizing debate will fall by the wayside.

A second false dichotomy involves the possible role of the element carbon in nominally acarbonaceous mantle silicates. This ongoing investigation mirrors the past three decades of astonishing discoveries about water in nominally dry mantle minerals, such as the high-pressure ringwoodite form of olivine [$(Mg,Fe)_2SiO_4$], which can incorporate up to three weight percent "water" in the form of OH groups replacing oxygen atoms. This finding points to the possible storage of several oceans' worth of water in Earth's transition zone, roughly 400 to 600 km deep. This possibility has received a quantitative boost from a DCO-sponsored study of a remarkable ringwoodite inclusion with 1.5% "water" in a diamond host. Clearly, the nominally dry mantle is in reality rather wet. Might the same story hold for carbon?

Such an idea has been championed since the 1980s by NASA Ames scientist Friedemann Freund, who claims to find significant carbon in natural olivine—carbon contents in excess of 1000 ppm, enough to make Earth's mantle a dominant repository of carbon. Freund's findings have been rebuffed by several researchers, including Hans Keppler and colleagues at the German Bayerisches Geoinstitut, who counter with high-temperature crystal-growth experiments that place an upper limit on carbon in mantle silicates of no more than 1 ppm. The debate continues—1 versus 1000 ppm—and neither side has budged.



The Panorama Mass Spectrometer development team. A Deep Carbon Observatory team led by Edward Young (UCLA) and Douglas Rumble (Geophysical Laboratory) is working with Nu Instruments to design and build a new mass spectrometer capable of unprecedented measurements of isotopic bond ordering in methane gas. This instrument will help to resolve the origins of deep hydrocarbons.

A possible nuanced resolution now comes from Rensselaer Polytechnic geoscientist Bruce Watson, who employed a new approach by measuring the diffusion of carbon-13 into olivine and quartz crystals at high temperature. In unpublished work presented at the Fall 2014 meeting of the Geological Society of America in Vancouver, British Columbia, Watson reported measurements of carbon as high as 1000 ppm in olivine and 4000 ppm in quartz. The key to resolving the debate may be the carbon species, which appears to be a neutral carbon–oxygen molecule, perhaps CO. If these diffusion experiments stand up to scrutiny, then it is likely that both Freund and Keppler are right. Silicates can incorporate significant amounts of carbon by diffusion, but the neutral CO species is not easily incorporated during crystal growth.

A third false dichotomy, one triggered by an experiment that was almost too successful, has dogged the origins-of-life community for decades. In the early 1950s, when Stanley Miller discovered the abundant, facile synthesis of amino acids in a simulated early-Earth atmosphere laced with simulated lightning, he and most of the budding origins-of-life community concluded that a key piece of the biogenesis problem had been solved. “If God didn’t do it in this way,” quipped the influential biochemist Leslie Orgel, “then He missed a good bet.” The easy, early success proved seductive; the “Millerite” orthodoxy prevailed for more than three decades.

The 1987 discovery of black smoker volcanic vents, with their rich microbially hosted ecosystems, on the deep, dark ocean floor offered an alternative origins scenario—one based on the chemical energy of minerals and familiar redox chemistry rather than the disruptive ionizing effects of lightning. This alternative origins model was appealing to some of us (including NASA, which was given a fresh impetus to explore nearby terrestrial bodies lacking an atmosphere but with plausible hydrothermal activity). Miller and company fought the hydrothermal origins idea with a vengeance, publishing paper after paper explaining why the “Ventists” were wrong.

It’s taken more than 20 years of experiments and debate, but DCO scientists in a half dozen countries are now showing a rich, plausible prebiotic chemistry associated with deep hydrothermal zones, which must have complemented above-ground synthesis mechanisms. Of special note, many DCO researchers are focusing on the ubiquitous serpentinization reaction, by which basalt and other mafic rocks alter to the clay mineral serpentine while releasing hydrogen. Serpentinization is coming into focus as yet another environment that must have contributed to the origins story. And the misleading “Millerite” versus “Ventist” debate is quickly entering the annals of science history as just one more example of an unproductive polarization of nature’s subtlety.

The lesson to be learned is obvious. The imposition of false dichotomies on questions about the natural world serves not only to polarize researchers but perhaps actually to impede scientific progress by ignoring the intricacies of complex systems. Nature is rarely painted in black and white. By shunting aside false and arbitrary divisions, we make more rapid progress towards a nuanced truth.

Ironically, the Deep Carbon Observatory program has found itself criticized on the basis of a false dichotomy—the debate that was explored by science historian Derek de Solla Price in his influential 1963 book, *Little Science, Big Science*. For reasons that remain obscure to me, many geologists take great pride in doing “little science,” while eschewing those who do “big science.” I’ve found that some scientists, when pressed, define “big” as anything bigger than their program. The researcher with one postdoc sees two postdocs as “big science,” while the researcher with two postdocs makes the same claim for anyone with four or more. “Big,” it seems, is in the eye of the beholder.

Admittedly, by anyone’s standards 1000 researchers in 40 countries is a big program. But DCO is hardly monolithic; we’re not a billion-dollar particle accelerator or a giant telescope. All DCO research emerges from grassroots efforts, led by individuals pursuing their own ambitions. The collective result may be grand and global, but the research advances are individual and local. So is that big science or little science? I would argue the dichotomy is, once again, specious—a senseless distraction at a time when important questions about our planet’s present and future remain unanswered, and the answers, if revealed, could profoundly benefit the entire world.