From Crust to Core

Carbon plays a fundamental role on Earth. It forms the chemical backbone for all essential organic molecules produced by living organisms. Carbon-based fuels supply most of society's energy, and atmospheric carbon dioxide has a huge impact on Earth's climate. This book provides a complete history of the emergence and development of the new interdisciplinary field of deep carbon science. It traces four centuries of history during which the inner workings of the dynamic Earth were discovered, and it documents the extraordinary scientific revolutions that changed our understanding of carbon on Earth forever: carbon's origin in exploding stars; the discovery of the internal heat source driving the Earth's carbon cycle; and the tectonic revolution. Written with an engaging narrative style and covering the scientific endeavors of about 150 pioneers of deep geoscience, this is a fascinating book for students and researchers working in Earth system science and deep carbon research.

SIMON MITTON is a life fellow at St. Edmund's College, University of Cambridge. For more than 50 years he has passionately engaged in bringing discoveries in astronomy and cosmology to the general public. He is a fellow of the Royal Historical Society, a former vice-president of the Royal Astronomical Society and a fellow of the Geological Society. The International Astronomical Union designated asteroid 4027 as Minor Planet Mitton in recognition of his extensive outreach activity and that of Dr. Jacqueline Mitton.

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A Chronicle of Deep Carbon Science

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For Marie Edmonds

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Foreword

I came to know the curious, absorbent and learned Simon Mitton in 2012, when Simon completed the editing and publication of *Taking the Back off the Watch: A Personal Memoir* of the scientist Thomas Gold. As a graduate student of Nobel Prize-winning astronomer Martin Ryle during a rather turbulent time and a historian of science at the University of Cambridge, Simon knew Tommy, who was conjecturing about the origin of very distant radio signals. Following Tommy's death in 2004, Simon worked closely with Tommy's widow, Carvel, to bring the memoir to fruition.

In 1995, grants from the Alfred P. Sloan Foundation supported Gold in writing a book based on his path-breaking 1992 paper in the *Proceedings of the National Academy of Sciences* paper, "The Deep, Hot Biosphere." Gold's 1999 book, *The Deep Hot Biosphere: The Myth of Fossil Fuels*, addressed controversial questions, including the possibility that life originated deep in Earth rather than in a warm little pond on its surface or extraterrestrially, arriving from space on a comet or meteorite. It also argued that a large fraction of Earth's hydrocarbons (natural gas, oil and coal) had primordial, abiotic origins and accumulated in the crust from upward outgassing rather than forming as "fossil fuels" from the shallow burial of biomass during the Jurassic and other epochs.

While the Foundation took no position on Gold's propositions, Sloan president Ralph Gomory (1990–2007), mathematician and former chief of research for IBM, believed that big questions of the kind Gold raised usefully stimulated science. Sloan also supported *Renegade Genius*, a television documentary on Gold that appeared in 2009, five years after Gold had passed away.

In 2007, geologist Robert Hazen (Carnegie Institution for Science, Washington, DC) published the book *Genesis*, aimed at

public understanding of questions associated with the origins of life. The book came to my attention as a Sloan program manager who had handled Sloan's grants with Gold. Hazen's book dispassionately weighed evidence for and against several of Gold's propositions, as well as pointing to other major unanswered questions in the geosciences, including the ecology and evolution of minerals.

Sloan invited and provided funds to Hazen to organize a May 2008 conference to explore the limits of knowledge (the known, unknown and unknowable) of deep carbon science, which Hazen did together with his colleague, Russell Hemley, then director of Carnegie's Geophysical Laboratory and an expert in materials under extremely high pressures, as in Earth's interior. In the interim, MIT microeconomist Paul Joskow had assumed the presidency of Sloan. President Joskow had a keen interest in energy resources and a long-standing relationship with Richard Meserve, president of the Carnegie Institution and former head of the US Nuclear Regulatory Commission. The May 2008 meeting proved very lively. President Joskow asked me to consult experts and stakeholders and to prepare an internal strategy paper for a 10-year international initiative about deep carbon science to be anchored by funding from Sloan and to convene an expert group to vet the strategy.

Among those consulted and immediately enthusiastic were earthquake expert, former Sloan Trustee and National Academy of Sciences president Frank Press and also Walter Munk (Scripps Institution of Oceanography), who helped start the international program for drilling in the seafloor during the 1960s, about which Simon writes in Chapters 8 and 9. Gold's former colleague John Saul (geologist) and student Steven Soter (astronomer) also provided advice and impetus. Favorable vetting resulted in an invitation in early 2009 from Sloan to Carnegie for a three-year US$4 million grant to initiate a major program in deep carbon science, spanning biology as well as solid-earth sciences. Hemley suggested the framework of a "Deep Carbon Observatory" (DCO) to emphasize the importance of making new measurements. The Sloan Trustees approved the grant in

June 2009, and the DCO officially came into existence on July 1, 2009, with Hazen as lead scientist and Hemley chairing a distinguished international steering committee. Founding members included John Baross (USA), Taras Bryndzia (Australia/USA), Claude Jaupart (France), Adrian Jones (UK), Barbara Sherwood Lollar (Canada), Eiji Ohtani (Japan) and Sergei Stishov (Russia). An administrative secretariat was established at Carnegie. Assuming the DCO proceeded very well, the Sloan Trustees committed to provide about US$5 million a year for 10 years, a total of about $50 million.

Over the next two years, a series of workshops led to the emergence of four communities to carry out the work of the DCO: Deep Life; Deep Energy; Reservoirs and Fluxes; and Extreme Physics and Chemistry. Each community prepared a set of "decadal goals" to achieve by the end of 2019 and agreed to organize the work along the four themes of origins, quantities, movements and forms. Cross-community teams concerned with data science and with engagement (communications and community building) were formed in 2011–2012. Early grant-making focused on instrument development, using both open, competitive calls for proposals and invited proposals. Subsequently, the majority of Sloan DCO funding was used to support a global network of graduate students and postdocs. Much effort went into community building: for example, cultivation of DCO support in Germany, France, Italy, the UK, Russia, China and Japan, as well as the USA; development of a website for both internal and external purposes; and giving the DCO a recognizable identity and family feeling. The program used the major international meetings in geosciences (especially the annual meeting of the American Geophysical Union and the annual Goldschmidt conference in geochemistry) to bring together the growing network of participants in the DCO.

At the outset of the program, Sloan asked the DCO to prepare a report that would describe the baseline of knowledge about deep carbon and that could be used to help measure progress achieved by 2019. The DCO leadership chose to try to create not only a

benchmark, but a landmark, and in 2013, they published the 20-chapter, 698-page open access volume, *Carbon in Earth*. Released at an "all-program" meeting of close to 200 people at the US National Academy of Sciences in Washington, DC (March 2013), along with a press release summarizing the DCO's goals, the volume also served to attract many more scientists to the DCO network, which grew to about 500 by the end of 2013. A December 2013 press release highlighted early discoveries. The December 2014 Mid-term Scientific Report by Hemley summarized the first five years of the program. Subsequent all-program meetings took place in Munich (April 2015) and St. Andrews (March 2017).

A question early in the DCO decade was whether to foster an effort to drill through the crust into the mantle, as was strongly advocated by Japanese members. After the spring 2011 Tohoku earthquake, Japan deferred interest in this "Mohole."

During 2014, Sloan organized a far-reaching mid-term review by an external group of experts who had no stake in the DCO. The review led to major additions and changes in the program, including formation of a new group to take responsibility for synthesis, led by Cambridge volcanologist Professor Marie Edmonds, to whom Simon dedicates this book. The Synthesis Group and much of the strategic management of the DCO were handled by a team at the University of Rhode Island led by Sara Hickox and later Darlene Trew Crist. The Rhode Island team skillfully organized an October 2015 workshop that formulated most of the synthesis activities of the DCO. Creatively, they invited Simon to offer a historian's perspective on the DCO, which he did during a lively and provocative evening session. Sloan then invited Simon to submit a proposal to write a history of deep carbon science to place the DCO in context. The happy result is this book, which spans from the center of Earth to faraway habitable planets, with rich intervals in Europe during the Renaissance and Enlightenment, as well as the contemporary archipelagos of global research.

During 2015–2019, the active membership of the DCO network reached a total of about 1200 scientists from about 50 nations. In the later years, the substantial flow of DCO peer-reviewed publications included numerous papers in *Science*, *Nature* and other prestigious outlets. Under Edmonds and Trew Crist's leadership, a 50-page decadal report, press releases, special issues of journals and hundreds of other articles, as well as videos and blogs and two other books reachable at deepcarbon.net, summarize the work of the program. Although tracking matching and leveraged funds is difficult because of different forms of funding in different nations and for other reasons, a cautious estimate is that US$200–$250 million in funds from other sources complemented US$57 million that Sloan spent on the DCO program between 2009 and the culminating events in the fall of 2019.

I first met Tommy Gold in about 1983. In subsequent years, he would appear unexpectedly at my office at The Rockefeller University, having arrived on the Big Red Bus that shuttles Cornell University faculty and students between the main campus in rural Ithaca, New York, and the Manhattan campus. He would speak for an hour or so about abiotic methane, or the possible deep origin of life, or the formation of diamonds, and then abruptly depart. I believe Tommy was a Renegade Genius, and that even Tommy, who was schismatic, would have admired the contributions of the DCO, of which he was the progenitor. And he would especially have liked this book of Simon Mitton, which shows vividly how the matter of deep carbon has arrived as a science through the overthrow of received ideas.

Jesse H. Ausubel

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