Introduction

My engagement with the new field of deep carbon science began in September 2015, when Marie Edmonds of the Department of Earth Sciences at the University of Cambridge asked if I would be interested in researching a history of deep carbon science. By then I had been working in the history of science for some 15 years, following early retirement from Cambridge University Press. Much of my academic activity had been limited to the history of astronomy and cosmology in the twentieth century. In the geosciences, my knowledge of its pioneers was more or less limited to what had been achieved by people in Cambridge, particularly in tectonics, which was centre stage when I commenced my doctoral research at the Cavendish Laboratory in the radio astronomy group that had discovered pulsars. Over a working lunch at Queen's College, Marie told me about the exciting multidisciplinary mission of the Deep Carbon Observatory (DCO). I was immediately attracted by the vast transformative scope of this large-scale research programme with its focus on four clearly defined themes to be undertaken by four scientific communities working collegially. Through this framework the DCO had already completed six years of comprehensive exploration of deep carbon in Earth's crust, mantle and core. By this point in our conversation I was beginning to wonder how on Earth I could have anything to offer, given that my limited experience as a historian of science had been all about the pioneers who looked up in wonder at the mechanism of the heavens. So I was delighted to receive an invitation to participate as a historian of science at a DCO planning meeting soon to be held in a rural retreat at the University of Rhode Island in late 2015.

Next to a crackling campfire, Robert Hazen, through whose vision the concept of a large-scale enquiry on the multiple roles of carbon in Earth had emerged in 2007, passionately explained to me, "Simon, we need a proper history of deep carbon science." Such a history should identify 100 pioneers of deep carbon science; he would later give me a list of these, to which I would add another 50 or so. The narrative style should be one of telling engaging stories from history about how scientific enquiry is actually done: its contexts, circumstances, challenges and chance, as well as of the development of the scientific method. Could I identify sociological trends in the evolution of today's international interdisciplinary big science from the assortment of isolated individual scholars in the past? I have always liked unusual assignments that steer me along a new path of academic enquiry. This one could be fun. But more than that, I saw a door opening on a fabulous community of scholars deeply committed to research of the highest quality and wanting to share their discoveries with everyone immediately. Without reservation I agreed to give it a crack, which called for another beer while contemplating the embers of the campfire! I rose to the challenge, and this book is the result.

Historians work in the past – "a foreign country where they did things differently," as the saying goes. As a historian my task is to describe that foreign country and to account for how scholars and pioneering researchers made their discoveries under circumstances not at all like those that exist today. Mine is a deep history, by which I mean that I do begin at the beginning, insofar as that is possible. I decided that in order for us to a history of deep carbon science we need a narrative that outlines the long history of the discovery of the inner workings of our planet – the dynamics, the physics and the chemistry – and what we can learn about those things by measurements we can make at the surface, given that the interior is inaccessible. The slow accumulation of knowledge on the physical aspects of the interior set the scene for the twentieth century. In the geosciences, the tectonophysics revolution of the 1960s stands alongside the discovery of the structure of DNA in 1953 and the detection of the cosmic microwave background in 1965: all three were transformative for their fields. The stratigraphic column of my history tops out around the beginning of the third millennium. I have endeavoured to provide a solid platform from which future historians will survey the achievements of this century's pioneers of deep carbon science.

1 Why Carbon in Earth Matters

⦿ FOUNDATION OF THE DEEP CARBON OBSERVATORY

Carbon is the fourth most abundant element in the universe. It is outweighed by hydrogen, responsible for nine-tenths of the mass of ordinary matter in the cosmos, and by helium. Hydrogen and helium are remnants of the Big Bang: they are products of the first three minutes of our fireworks universe. Oxygen, the third most abundant element, and carbon are ashes from the explosive finale of the evolution of stars.

In 2009, Robert (Bob) Hazen and his colleagues of the Carnegie Institution of Washington promoted the following connection between carbon in the universe and human existence on Earth:

> Carbon plays an unparalleled role in human life. It is the element of life, providing the chemical backbone for all essential biomolecules. Carbon-based fuels supply most of society's energy, while small carbon-containing molecules in the atmosphere play a major role in our variable and uncertain climate. Yet in spite of carbon's importance scientists remain largely ignorant of the physical, chemical, and biological behavior of the carbon-bearing systems more than a few hundred meters beneath Earth's surface.[1]

Hazen et al. observed that we know neither how much deep carbon is stored in Earth's interior as a whole nor how deep carbon migrates along the pathways between the reservoirs. Furthermore, our ignorance of the deep microbial system – that by some estimates rivals the total surface biomass – is profound. In short, our knowledge of deep carbon is seriously incomplete. To address this knowledge deficit, in 2009 the Carnegie Institution of Washington launched a decade-long program of research and discovery: the Deep Carbon Observatory (DCO). Its mission was to lay the groundwork for a new scientific discipline devoted to element number six – carbon – and its place in our lives and world. The emergence of this new collaboration in the geoscience community has changed how science is conducted across time zones, cultures and disciplines to bring global thinking to bear on the role and properties of carbon inside Earth.

In 2007, a chance encounter between Bob Hazen and Jesse Ausubel, a faculty member of Rockefeller University and a project officer at the Alfred P. Sloan Foundation, led to the concept of the DCO. Hazen, an accomplished writer of exhilarating science books at the cutting edge of research, was on a promotional tour. Hazen gave an after-dinner talk at the Century Association, a club for "congenial companions in a society of authors and artists" on Manhattan's West 43rd Street. At this literary salon, Hazen spoke of his latest book, *Genesis: The Scientific Quest for Life's Origins*, in which he suggested that geophysical reactions might have played a critical role in getting life started. Ausubel's presence at this fundraising dinner was due to a last-minute cancellation by another participant. The presentation on the emergence of the first life on Earth made a deep impression on Ausubel. Hazen had developed a thinking style that envisaged life inevitably emerging as a consequence of chemistry, starting with water, organic molecules and a source of energy. His experiments in prebiotic chemistry showed the circumstances through which organic molecules could progress from structural simplicity to considerable complexity. This research was focused on how a prebiotic world rich in organic molecules could transition to the so-called RNA world of self-replicating genetic molecules. But above all, Hazen had emphasized the daunting gaps that existed in our knowledge of the origin of life and the special role of carbon. What Ausubel did next was to seek out Hazen's book and read it.

Three months later, Ausubel contacted Hazen about the possibility of the Alfred P. Sloan Foundation supporting an integrated science approach to the pursuit of life's origins. It would be a 10-year

Cambridge University Press & Assessment
978-1-108-42669-5 — From Crust to Core
Simon Mitton
Excerpt
More Information

mission that drew on several branches of science – geology, biology, chemistry, physics and astronomy – in order to coordinate a multifaceted project to investigate early life on Earth and the role of the deep carbon cycle in its emergence. The first step was to convene an international workshop on the deep carbon cycle at the Carnegie Institution in May 2008. By this stage, Ausubel and Hazen were no longer focused solely on life's origins: they felt that, in order to further human understanding of Earth and our place here, they needed to place the element carbon center stage. In his opening address at the three-day workshop, Hazen set out what he wanted the 110 participants to achieve:

> A rare and important opportunity awaits us to define a new field. Collectively we need to assess what we don't know. We will succeed in this endeavor if we accomplish three things, which I now charge all of you with. First, we have to look beyond our individual interdisciplinary expertise and see the subject in an integrated context: geology, chemistry, biology, physics – they are all going to play central roles. Second, we have to identify the key questions we want to have answered to understand the deep carbon cycle. That's really what we're here to do. And finally, we have to imagine what it's going to take – what field observations, what key experiments, what new instruments, what theoretical advances are required to move this endeavor forward? I am tremendously excited to be here with you! I welcome you all! Let's get started!

All three tasks contributed to the publication three years later of *Carbon in Earth*, a monumental book that is the benchmark for our present understanding of Earth's carbon and a comprehensive review of what we already knew in 2009 and what we would have to learn in the DCO decade of discovery, 2009–2019.

This history of science book, *From Crust to Core*, complements *Carbon in Earth* by exploring four centuries of philosophical and scientific inquiry on the nature of Earth's interior, its cycles and mechanisms and the particular roles of deep carbon. My aim has been to present a layered story of remarkably rich discovery. The narrative thread encounters about 150 pioneers of deep geoscience, several dozen research institutions and universities and more than 20 ships and research vessels. Many of these pioneers started their inquiries from points of view that at first sight might seem far away from the history of deep carbon science. On the other hand, such personal journeys of discovery are central to the philosophy of science, showing how science is actually done and the importance of asking the right questions and of understanding what the data are actually telling us.

⦿ SPHERES BELOW AND HEAVENS ABOVE

Before commencing the historical narrative about the scientific discovery of Earth's deep interior, I shall introduce the architecture of Earth from crust to core as we understand it today. Readers already familiar with the concepts may wish to skip this section. The first point to make is that everything that is deeper than about 10 kilometres is inaccessible to direct view. Furthermore, the temperature rises surprising quickly. In the world's deepest gold mine, TauTona in South Africa, the temperature of the rock face is 60°C. At the bottom of the deepest borehole, 12 kilometres down, on the Kola Peninsula in Finland, the temperature reached 180°C, and which point further drilling became impossible.

Earth's interior is divided into layers with different chemical compositions and mechanical properties. To picture the internal structure of Earth, we can begin with simple models. It can be likened to a stone fruit such as an avocado: both have a solid core surrounded by a thick mantle, with a crinkly surface skin or crust. For geophysical purposes, however, the core–mantle–crust model is too crude. To improve on that, we must think of Earth as being made up of a number of layers, like an onion: we can peel them off one by one, starting with the crust, below which there are two layers for the upper mantle and the lower mantle, separated by the transition zone between depths of 410 and 660 kilometres. The transition zones (or boundaries) are where phase changes occur in minerals as we proceed

Cambridge University Press & Assessment
978-1-108-42669-5 — From Crust to Core
Simon Mitton
Excerpt
More Information

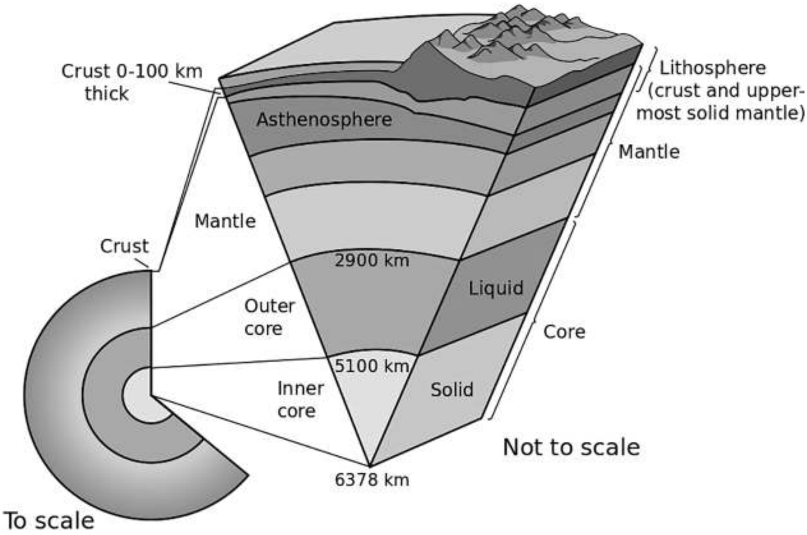

FIGURE 1.1 A conventional radial section of Earth's interior showing the major divisions used in geophysics.
Source: Adapted from the United States Geological Survey. Public domain

to greater pressures and higher temperatures. The boundary between the lower mantle and the outer core lies at a depth of 2900 kilometres. Below this is a liquid outer core, with a thickness of about 2300 kilometres, composed mainly of iron and nickel. The outer core is the seat of Earth's magnetic field, which is generated through a self-induced dynamo process. The transition to a solid inner core is located 5100 kilometres below the surface. We're going to examine these layers by working down from crust to core and then upwards from the surface to space.

Figure 1.1 shows the major divisions used in geophysics. The surface rocks are part of the crustal layer, which is rich in silica (silicon dioxide, SiO_2). Its average thickness is about 38 kilometres beneath the continents and around 8 kilometres beneath the oceans. The five commonest elements in Earth's crust are oxygen (47 percent), silicon (27 percent), aluminum (8.1 percent), iron (6.3 percent) and calcium (5 percent). Carbon (0.18 percent) is ranked tenth by its natural abundance in the crust. The thinner oceanic crust and the thicker continental crust are formed by entirely different processes and have different histories.

The crust and the uppermost mantle, considered as a mechanical entity, is known as the lithosphere (from the Greek *lithos*, meaning "rock"). It is the hard and rigid outer layer of Earth that has fractured into a dozen major plates (plus a handful of minor ones). Each tectonic plate is a layer of continental crust or oceanic crust supported by the viscous upper mantle. The oceanic lithosphere ranges in thickness from 50 to 150 kilometres, being at its thinnest at the mid-ocean ridges. The continental lithosphere is altogether a bulkier affair at a thickness of 40–280 kilometres or so, with a 30–50-kilometre veneer of crust. The boundary between the crust and the mantle is referred to as the Moho, a convenient contraction derived from the name of the pioneering Croatian seismologist Andrija Mohorovičić (1857–1936). In 1909, he first noticed a discontinuity in the behavior of seismic waves crossing the Moho.

The 100–200-kilometre-thick semi-fluid layer of hot plastic rock in the upper mantle is known as the asthenosphere (from the Greek *asthenēs*, meaning "weak"). Earth's layers vary in thickness, mechanical strength and chemical composition. Actually, there are two different concepts of layering in the outer part of Earth: the crust and the mantle have different compositions (geochemistry), whereas the lithosphere and asthenosphere have different mechanical strengths (geophysics). Under the influence of long-term stress, the lithosphere exhibits rigidity, but deforms elastically and through brittle failure, whereas the asthenosphere deforms like a highly viscous fluid. The multiple layers of the mantle arise because as we go from crust to core we encounter ever-increasing temperatures and pressures. Minerals in the mantle adjust their atomic structures and chemical compositions in reaction to different temperature and pressure regimes. Such phase changes are detectable because they alter the velocities at which earthquake waves travel through the interior. A transition zone between 410 and 660 kilometres marks the boundary of the lower mantle and the upper mantle. Much of our knowledge of the mineralogy and composition of the mantle has also come from experiments with diamond anvil cells and from microscopic examination of inclusions in diamonds.

To complete this introductory survey of our dynamic planet, we need to rise above the interior and consider four interconnected spheres: lithosphere, hydrosphere, biosphere and atmosphere. Together these make up the complete system in which life on Earth exists. The system is a physical and biological domain that is the subject of many great debates on environmental issues, climate change and the origin and evolution of life. The hydrosphere encompasses the water on, under or above the surface. So, it includes the water in the oceans and seas, the liquid and frozen groundwater, the water locked in glaciers, icebergs and ice caps and the moisture in the atmosphere. Three-quarters of Earth's surface is covered by oceanic saltwater – freshwater accounts for only 2.5 percent of Earth's surface, and just a tenth of that is readily available from lakes, reservoirs and rivers. The hydrosphere is an intricate closed system in which water and other volatiles are continuously driven around in a cycle powered by solar energy and Earth's gravity. This cycle moves water between the biosphere, atmosphere and lithosphere.

The atmosphere is the gaseous layer – commonly known as air – that surrounds Earth and is retained by gravity. By volume, dry air is 78 percent nitrogen, 21 percent oxygen, almost 1 percent argon and 0.04 percent carbon dioxide. Atmospheric scientists distinguish several layers in the atmosphere according to temperature and composition, as illustrated in Figure 1.2. The origin and evolution of the atmosphere is intimately connected to the interior dynamics of our planet. With the exception of the abundant oxygen released by photosynthesis, the atmospheric gases came from Earth's interior and were released through volcanic eruptions. Carbon dioxide is abundant in volcanic gases, which raises the question: Which emits more carbon dioxide – Earth's volcanoes or human activities? Terry Gerlach, a retired expert on volcanic emissions and formerly of the