Some notes on Limits to Knowledge for the Deep Carbon Observatory[1]

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One of the main strategies for winning improvements is by exploring the limits to our knowledge, that is, by asking what we know and why, what we could quite readily know, and what may be unknowable or very hard to learn. We tend to fill conferences, magazines, and airwaves with what we know. We much less often explore and disclose the limits to our knowledge. Few experts like or bother to write *terra incognita* on their maps. Yet, disclosing the limits to our knowledge is often among the most useful of acts. Such disclosure helps people choose where to explore and what to fund, and it helps people to hedge their bets. In this spirit, I will offer some generic comments and illustrations about the known, unknown, and unknowable and how they might bear on the disciplines and forms of expertise caring about deep carbon.

In considering deep carbon, the causes that separate the known, unknown and unknowable are numerous and diverse, falling into five families: the invisibility of the lost past, the vast expanse of Earth, difficulties of assembling parts into a whole, blinders we put on ourselves, and surprises from outside.

The *first family* of limits is the invisibility of the lost past. Some phenomena leave no traces or may have left traces we cannot find. This is perhaps the most fundamental problem in geology. We need imagination – and new tools - to explore the limits of our knowledge of the past. The Deep Carbon Observatory has cultivated instruments such as a quantum cascade lasers, large-radius high-mass-resolution multiple-collector isotope ratio mass spectrometers, and other forms of paleo thermometers to jump limits.

It is also difficult to see what is rare, diffuse, far, dark, deep, hot, or under pressure, the s*econd family* of limits. Expanse also challenges the timeliness and frequency of observations. We can afford to recover deep cores in only a few locations. Inclusions in diamonds sample tiny fractions of the mantle. Sonars (3D-seismic and other approaches) can probe large swathes but from most locations we will have no actual samples to verify interpretations of acoustic records. Vastness combines with variety, rarity, and patchiness, especially in the crust, to create limits to knowledge. Even when we have samples, as in core repositories, we may not have catalogued them or made them accessible.

The *third family* of limits, assembling parts into whole models and verifying them, encompasses both theoretical and statistical challenges. Statistics on, for example, properties of minerals at high pressures are inadequate. Lack of information on sizes of reservoirs and fluxes bedevils much deep carbon research and data. Even counted quantities, such as volcanic emissions, may be mismeasured. Mathematical models used to turn available data into systemic pictures misbehave or face challenges

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[1]This draws on JH Ausubel. A census of ocean life: On the difficulty and joy of seeing what Is near and far [external link]. *SGI Quarterly* April: 2010 ; and JH Ausubel. On the limits to knowledge of future marine biodiversity (PDF). *Electronic Journal of Sustainable Development* 1(2): 19-23, 2008

under extreme conditions or through the great lengths of geological time. Small mis-specifications in initial conditions magnify into tornadoes of error.

Scaling and simplification is also a paramount challenge. System dynamics involve interactions among processes acting on diverse scales of space, time, and organizational complexity. To what extent in deep carbon studies do we have ways to scale from small to large and back? Can we represent the dynamics of aggregates, for example, in terms of the statistical dynamics of populations of individual agents or units? As analysts and modelers, we must hope that not every detail of interaction, space, and time matters to "know" important behavior. Otherwise, many behaviors, both macroscopic and microscopic, appear unknowable. At the microscopic scale, the multiplicity and complexity of interactions can make detailed knowledge impossible. What do we understand in deep carbon science about how to define, identify, and suppress irrelevant detail? Need we study every igneous province to understand igneous provinces?

In some fields, including parts of biology and geophysics, data come from controlled experiments, allowing close matching between theory and experimental results. Experimental design is, of course, subject to a multitude of biases that may limit knowledge. At least as important is that in many aspects of deep carbon science, controlled experiments are impossible. Facts obtainable represent samples of what we would like to know in ways whose biases themselves may be hard to know. Thus, our models are themselves our limits, when we can experiment only within models.

The *fourth limit* is the blinders we put on ourselves, which stem from both economics and culture. The entities that survey carbon reservoirs, such as energy and gem companies and energy ministries, concentrate on commercial quantities and charismatic specimens. They mainly care to know enough to sign contracts. This favors knowing of the existence of a stock sufficient to meet market needs for, say, 10-20 years rather than exploring absolute or rare quantities. Blinded by commercial or disciplinary myopia, experts long overlook stocks, such as methane hydrates. We bring cultural biases that lead us to exclude or discount certain data and information, exemplified by abiotic carbon. We may have excluded the idea that minerals evolve and that life defines much mineralogy.

The Late Heavy Bombardment of Earth exemplifies surprise interventions from outside and stochastic perturbations, the *fifth family limiting knowledge*. Surprising events can harshly limit our knowledge. Abrupt changes disturb our orderly world. We tend to give little attention to abrupt changes, discontinuities. Can we know about whether systems are sufficiently adaptive to absorb such influences and thus survive in roughly similar form? At a more theoretical level, what we see or live with may reflect the capricious influence of historical events that cause bifurcations and thus represent but one realization of stochastic processes that admit many possibilities. Debated examples abound in consideration of the origins of life.

Finally, can we somehow rank the limits in these five families to help form strategies and priorities for exploration, instrument development, measurement, and analysis? Can we deploy tools of data science to understand more objectively the limits to knowledge and to demarcate the unknown? Can we, provisionally, define the unknowable, including future states of Earth's deep carbon?