Primordial Deep Tech

taming the biochemistry of anaerobic life in reservoirs & oil geologies

A moonshot program[me] to reveal, simulate, and responsibly harness microbial life in the deep subsurface, with translational implications for primary energy, carbon storage, environmental remediation, and biotechnology. Within five years, this effort will establish a *UK-led, multi-site testbed network* and a *portfolio of high-impact R&D projects* to enable predictive, high-value biogeochemical engineering at scale.

The subsurface has been the dominant source of energy and materials for all modern history. Petroleum for fossil fuels and synthetic polymers, ores for structural metals, rare minerals for industrial catalysts and superalloys, uranium for nuclear reactors — all of it comes from the Earth's crust. *There is no substitute.* Mining & drilling operations operate at unfathomable scales and have cross-sectoral global environmental & financial ramifications, to the tune of gigatons of CO_2^e emissions and trillions in economic impact.

But our knowledge of the subsurface has always lagged our ability to extract from it. Anaerobic life in the deep subsurface (up to 5 km depths) has existed for the bulk of Earth's history, and it will exist long after we are gone. The biomass of microbes in the crust is estimated to exceed that of *all surface animal life combined* by 1–2 orders of magnitude and may comprise 90% of all prokaryotic genetic diversity.[1–3] Despite this fact, the mere existence of life in the deep subsurface was *not even widely accepted until the year 2000,* largely due to an inability to conduct controlled & sterile scientific studies.[4–6]

Our ignorance of subsurface biology has consequences. As we develop new ways to exploit resources from Earth's crust, we find ourselves fighting against subterranean microbiomes we *do not understand*. Sulfate-reducing bacteria, the principal culprits of gas souring, force fossil fuel companies around the world to spend billions every year managing microbial-induced corrosion and gas desulfurization.[7–9] CO_2 injections for enhanced oil recovery were thought to effect stable geologic carbon storage — but empirical studies show that *up to 20% of injected CO_2 may be converted to unmineralizable, planet-warming CH_4*, potentially offsetting any carbon drawdown benefit.[10–12] Subsurface hydrogen storage schemes, too, have observed unexpected microbial geomethanation events.[13,14] A burgeoning industry to harness geologic hydrogen as a new source of primary energy finds itself thwarted as >90% of produced H_2 is consumed by microbes before it reaches the surface.[15]

It's time to get smart about subsurface life.

For decades, scientific progress in this field has been stymied by high drilling costs, slow analytical capabilities, and a lack of driving motivation outside of the siloed & purely instrumental concerns of oil & gas. Through intelligent program design, we can demolish these roadblocks and transition the UK's relationship with the deep Earth from one of blind trial-and-error extraction to one of sustainable and informed biogeochemical exchange.

Programme Thesis: *faster, better, cheaper, deeper*

The Heilmeier Catechism

① *What are you trying to do?*
② *How is it done today?*
③ *What is new in your approach?*
④ *What is the impact if successful?*
⑤ *What are the risks?*
⑥ *How much will it cost?*
⑦ *How long will it take?*
⑧ *What tests will signal success?*

①② This programme will create the foundational science, biogeochemical tools, and integrated engineering platforms needed to systematically characterize, monitor, and harness the subsurface microbiome. The historical literature on biogeochemistry is fragmentary and fossil-centric. This is attributable to the financial & logistical cost of accessing the deep subsurface: **drilling a kilometer-deep borehole can cost tens of millions**. Historically, only O&G companies have had the incentive to do so, with little reason to publicize their data afterwards. Progress in the field is bottlenecked by the *noblesse oblige* of oil companies, placing onerous bureaucratic barriers to collaboration upon individual researchers — especially considering such research may well produce results that undermine fossil fuel companies' societal license to operate.

Meanwhile, public-sector and nonprofit attempts to drill independent research boreholes are confounded by high drilling costs and long timelines: the UK Geoenergy Observatories, announced in 2014, currently operate two access facilities, neither of which has drilled below 100m. The Agouron Institute has, for decades, funded biogeochemical core sampling; each borehole costs millions and, following successful sampling, was never used again.[16,17] The Agouron Institute is currently winding down operations with a targeted shutdown date in 2026.

③ **There is a better way.** By selecting a diverse portfolio of bleeding-edge biogeochemistry R&D projects, we can form a *government-backed research consortium* which can collectively negotiate testbed access with multiple industry partners on far more favorable terms. The benefits for researchers are obvious: separating the cost of access from the cost of research solves the CAPEX problem at the heart of deep biogeochemistry, with access to varying geologies, pooled instrumentation, and opportunities for collaboration and data-sharing across the portfolio. Industrial partners benefit too, both from direct talent pool & cost sharing and access to a smörgåsbord of cutting-edge biogeochemical analysis tuned precisely to their geological context.

The time is right. The emergence of the carbon sequestration, geologic hydrogen, and enhanced geothermal industries, enabled by advances in drilling technology, has broken the O&G monopoly on deep subsurface exploration. Recent breakthroughs in amplicon sequencing and metagenomics enable rapid sampling of microbiomes where previous generations of biogeochemists could only observe what species they could culture.

④⑤ In the long term, innovations in this field could enable large-scale circular industry in the form of massive subsurface *biogeoreactors*, applying the chemical potential of the crust to produce not merely geologic hydrogen but ammonia, propane, ethylene, and other **valuable net-zero chemicals**. However, even if stimulated biogeochemistry is found to be technoeconomically intractable (likely due to some combination of slow reaction rates, high CAPEX, and low product recovery), in the near term the tools and knowledge gained in this programme can be brought to bear to establish **better greenhouse gas inventories** for O&G and carbon sequestration, new ***in situ*** **bioremediation techniques** for subsurface 'forever chemicals', and entirely **new extremophile genomes** and proteins of interest to the biotech industry.

Programme Structure: *two parts science, one part enablers*

⑥ We envision a **£50M ARIA-style moonshot funding programme** to simultaneously convene a diverse and synergistic R&D cohort of high-impact biogeochemical technologists and negotiate public-private partnerships enabling that portfolio to access an equally wide variety of commercially relevant downhole environments.

- **Direct R&D Funding (£35M):** We will fund a portfolio of big-if-true science and engineering projects to discover, characterize, model, and apply deep microbial processes. Example projects include:
  - Discovery of microbes to produce valuable chemicals such as ethylene, propane, or ammonia
  - Microbial engineering for *in situ* bioremediation of contaminants such as PFAS, TCE, & PCBs
  - Metagenomic–geology correlation mapping using AI to predict microbiomes *before* drilling
  - Ecosystem perturbation to mitigate undesired metabolisms (methanogenesis, hydrogenotrophy)

- **Distributed Testbed Consortium (£15M):** We will establish a cross-cutting [inter]national effort with centralized sampling and instrumentation, leveraging the R&D portfolio to negotiate consolidated, low-cost access to deep boreholes across various geologies and industrial use cases. Example sites include:
  - O&G wells *(e.g., Dorset, North Sea)* offering a well-to-research offtake scheme for EOL boreholes
  - Carbon storage sites *(e.g., Humber, Teesside)* with capacity for pre- and post-injection studies
  - Deep geothermal wells *(e.g., Cornwall, Eden)* with potential to discover new hyperthermophiles
  - Geologic hydrogen *(e.g., Australia, Canada)* may help develop domestic UK geoH_2 capabilities

⑦⑧ The R&D portfolio will be structured in three overlapping phases over 5 years, enabled by the Testbed Consortium, to move projects from foundational discovery to real-world application. Remaining Testbeds will transition to a self-sustaining national facility with a handoff plan to a permanent operator (e.g., BGS, UKRI).

	Phase	Duration	R&D Milestones	Testbed Enabler
1	***Discovery & Mapping***	*Years 0-3*	Performers will collect and analyze samples for deep geochemical gas tracing & metagenomic, proteomic, and amplicon sequencing to identify novel phyla (like CPR bacteria or DPANN archaea) and new extremophiles.	Provides performers with the essential high-depth samples from diverse geologies, required for foundational bioprospecting and metagenomic sequencing
2	***Validation & Modeling***	*Years 2-4*	Performers will build computational and physical biogeoreactor mimics to (1) model critical gas-rock interactions; (2) investigate syntrophic interactions and biofilm formation on different geologies; (3) develop predictive *in silico* models for biogeochemical cycling.	Supplies live microbial consortia, core samples, and empirical data needed to validate high-pressure lab mimics and model how deep biomes function and react to industrial stressors
3	***Translation & Demonstration***	*Years 3-5+*	Performers will develop and test commercial applications for engineered biogeochemistry, enhanced O&G/CCS GHG inventories, etc.	Provides access to real-world operational sites so performers can test and validate *in situ* applications

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