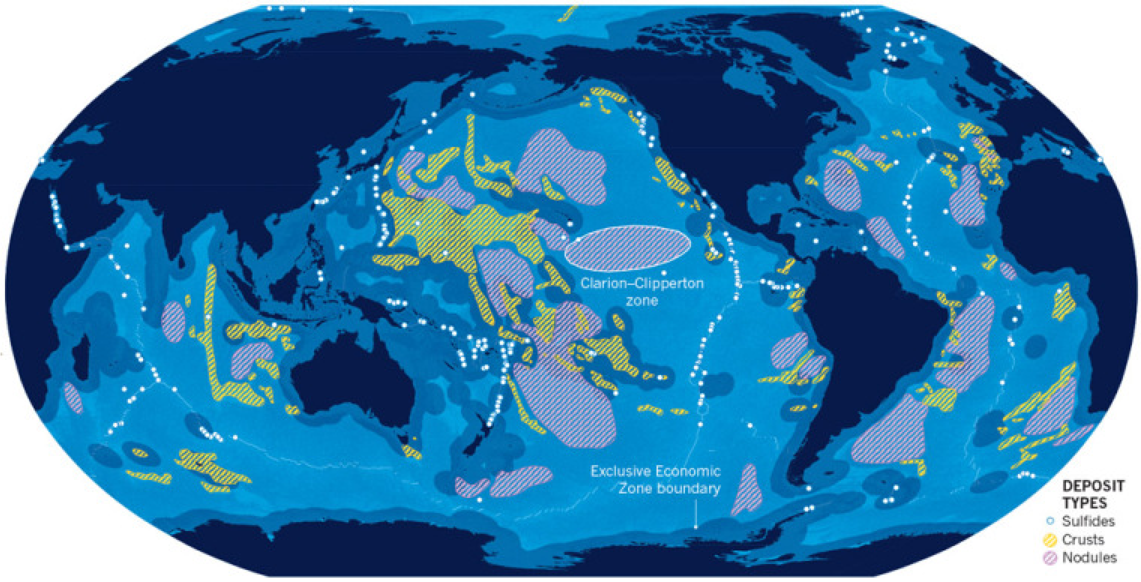
Physical resources

Ecological hazards of ocean-floor mining **(July 2019)**



The distribution of potential ocean-floor metal-rich resources (Credit: Hefferman 2019)

Spiralling prices for metals on the world market, especially those that are rare and involved in still-evolving technologies, together with depletion of onshore, high-grade reserves are beginning to make the opportunity of mining deep, ocean-floor resources attractive. By early 2018, fifteen companies had begun detailed economic assessment of one of the most remote swathes of the Pacific abyssal plains. In April 2018 (How rich are deep-sea resources?) I outlined the financial attractions and the ecological hazards of such ventures: both are substantial, to say the least. In Japan's Exclusive Economic Zone (EEZ) off Okinawa the potential economic bonanza has begun, with extraction from deep-water sulfide deposits of zinc equivalent to Japan's annual demand for that metal, together with copper, gold and lead. One of the most economically attractive areas lies far from EEZs, beneath the East Pacific Ocean between the Clarion and Clipperton transform faults. It is a huge field littered by polymetallic nodules, formerly known as manganese nodules because Mn is the most abundant in them. A recent article spelled out the potential environmental hazards which exploiting the resources of this region might bring (Hefferman, O. 2019. Seabed mining is coming – bringing mineral riches and fears of epic extinctions. *Nature*, v. **571**, p. 465-468; DOI: 10.1038/d41586-019-02242-y).

Recording of the ecosystem on the 4 km deep floor of the Clarion-Clipperton Zone (CCZ) began in the 1970s. It is extraordinarily diverse for such a seemingly hostile environment. Despite its being dark, cold and with little oxygen, it supports a rich and unique diversity of more than 1000 species of worms, echinoderms, crustaceans, sponges, soft corals and a poorly known but probably huge variety of smaller animals and microbes inhabiting the mud itself. In 1989, marine scientists simulated the effect on the ecosystem of mining by using an 8-metre-wide plough harrow to break up the surface of a small plot. A plume of fine sediment rained down to smother the inhabitants of the plot and most of the 11

km^2 surrounding it. Four subsequent visits up to 2015 revealed that recolonisation by its characteristic fauna has been so slow that the area has not recovered from the disturbance after three decades.

The International Seabed Authority (ISA), with reps from 169 maritime member-states, was created in 1994 by the United Nations to encourage and regulate ocean-floor mining; i.e. its function seems to be 'both poacher and gamekeeper'. In 25 years, the ISA has approved only exploration activities and has yet to agree on an environmental protection code, such is the diversity of diplomatic interests and the lack of ecological data on which to base it. Of the 29 approved exploration licences, 16 are in the CCZ and span about 20% of it, one involving British companies has an area of 55,000 km^2. ISA still has no plans to test the impact of the giant harvesting vehicles needed for commercial mining, and its stated intent is to keep only 30% of the CCZ free of mining 'to protect biodiversity'. The worry among oceanographers and conservationists is that ISA will create a regulatory system without addressing the hazards properly. Commercial and technological planning is well advanced but stalled by the lack of a regulatory system as well as wariness because of the huge start-up costs in an entirely new economic venture.

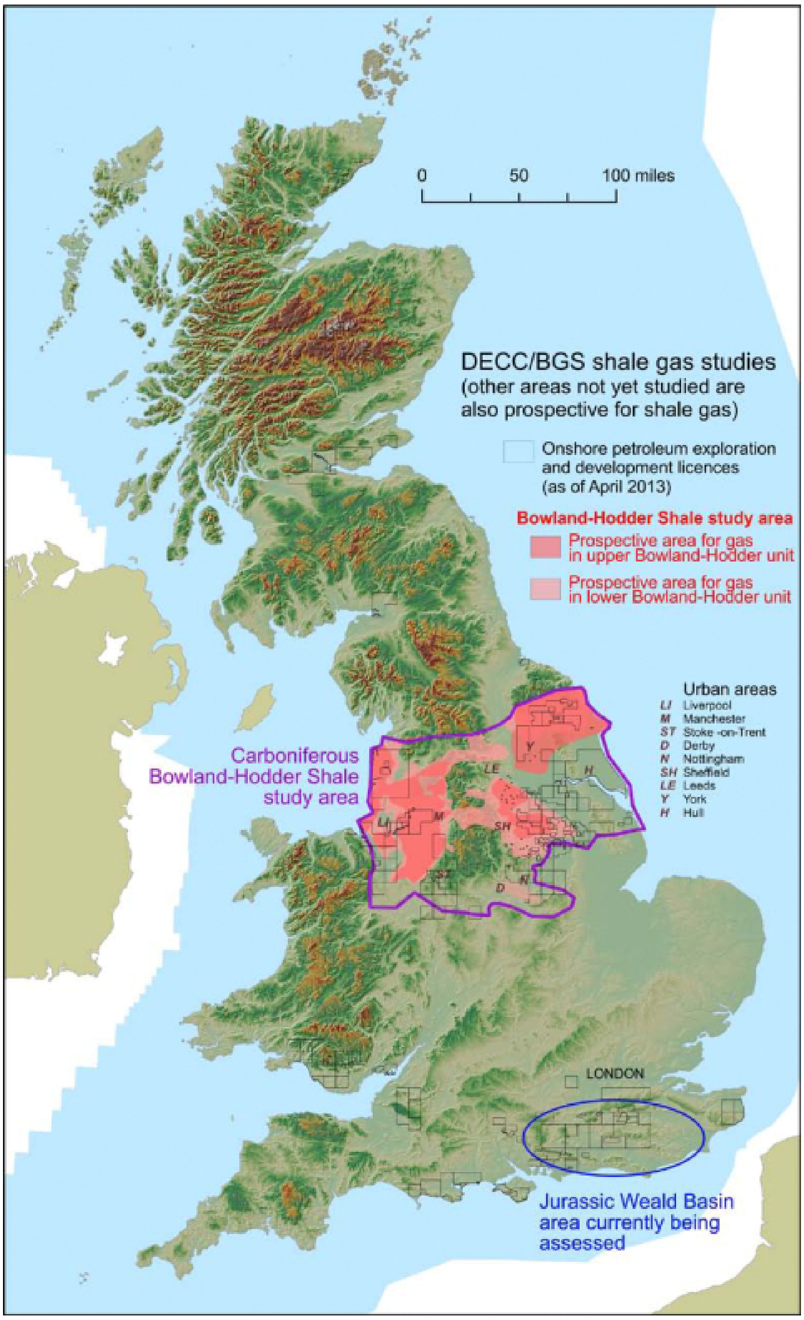
The obvious concern for marine ecosystems is the extent of disturbance and ecosystem impact, both over time and as regards scale. The main problem lies in the particles that make up ocean-floor sediments, which are dominated by clay-size particles. The size of sedimentary particles considered to be clays ranges between 2.0 and 0.06 µm. According to Stokes Law, a clay particle at the high end of the clay-size range with a diameter of 2 µm has a settling speed in water of 2 µm s^{-1}. The settling speed for the smallest clays is 1,000 time slower. So, even the largest clay particles injected only 100 m above the ocean floor would take 1.6 years to settle back to the ocean floor – if the water column was absolutely still. But even the 4,000 m deep abyssal plains are not at all stil, because of the ocean-water 'conveyor belt' driven by thermohaline circulation. An upward component of this flow would extend the time during which disturbed ocean-floor mud remains in suspension – if that component was a mere >2 µm s^{-1}, even the largest clay particles would remain suspended indefinitely. Deepwater currents, albeit slow, would also disperse the plume of fines over much larger areas than those being mined. Moreover such turbidity pollution is likely to occur at the ocean surface as well, if the mining vessels processed the ore materials by washing nodules free of attached clay. Plumes from shipboard processing would be dispersed much further because of the greater speed of shallow currents. This would impact the upper and middling depths of the oceans that support even more diverse and, in the case of mid-depths poorly known, ecosystems Such plumes may settle only after decades or even centuries, if at all.

Processing on land, obviously, presents the same risk for near-shore waters. It may be said that such pollution could be controlled easily by settling ponds, as used in most conventional mines on land. But the 'fines' produced by milling hard ores are mainly silt-sized particles (2.0 to 60 µm) of waste minerals, such as quartz, whose settling speeds are proportional to the square of their diameter; thus a doubling in particle size results in four-times faster settling. The mainly clay-sized fines in deep-ocean ores would settle far more slowly, even in shallow ponds, than the rate at which they are added by ongoing ore processing; chances are, they would eventually be released either accidentally or deliberately

A mining code is expected in 2020, in which operating licences are likely to be for 30 years. Unlike the enforced allowance of environmental restoration once a land-based mining operation is approved, the sheer scale, longevity and mobility of fine-sediment plumes seem unlikely to be resolvable, however strong such environmental-protection clauses are for mining the ocean floor.

UK shale gas: fracking potential dramatically revised downwards **(August 2019)**

In 2013, much to the joy of the British government and the fracking industry, the British Geological Survey (BGS) declared that there was likely to be between 24 and 68 trillion m^3 (TCM) of gas available to fracking ventures in the Carboniferous Bowland Shale, the most promising target in Britain. That is equivalent to up to about 90 years' supply at the current UK demand for natural gas. The BGS estimate was based on its huge archives of subsurface geology, including that of the Bowland Shale; they know where the rock is present and how much there is. But their calculations of potential gas reserves used data on the gas content of shales in the US where fracking has been booming for quite a while. Fracking depends on creating myriad cracks in shale so that gas can escape what is an otherwise impermeable material.



Areas in Britain underlain by the Bowland Shale formation (credit: British Geological Survey)

How much gas might be available from a shale deposit depends on its content of solid hydrocarbons (kerogen), whether it has thermally matured and produced gas, which remains locked within the rock. So a shale may be very rich in kerogen, but if it has not been heated to 'maturity' during burial it may contain no gas at all, and is therefore worthless for fracking. Likewise, a shale from which the gas has leaked away over millions of years. A reliable means of checking has only recently emerged. High-pressure water pyrolysis (HPWP) mimics the way in which oil and gas are generated during deep burial and then expelled as once deep rock is slowly uplifted (Whitelaw, P.*et al*. 2019. Shale gas reserve evaluation by laboratory pyrolysis and gas holding capacity consistent with field data. *Nature Communications*, v. **10**, article 3659; DOI: 10.1038/s41467-019-11653-4). The authors from the University of Nottingham, BGS and a geochemical consulting company show that two samples of the Bowland Shale are much less promising than originally thought. Based on the HPWP results, it seems that the Bowland Shale as a whole may have gas reserves of only around 0.6 TCM of gas that may be recoverable from the estimated 4 TCM of gas that may reside in the shale formation as a whole. This is 'considerably below 10 years supply at the current [UK] consumption'.

Unsurprisingly, the most prominent of the fracking companies, Cuadrilla, have dismissed the findings brusquely, despite having published analyses of other samples that consistent with results in this paper. Opinion in broader petroleum circles is that the only way of truly putting a number to potential reserves is to drill and frack many wells … The British government may well have a collective red face only a week after indicating that they were prepared to review regulation of fracking, which currently forces operations to stop if it causes seismic events above magnitude 0.5 on the Richter scale. A spokesperson for Greenpeace UK said that, 'Fracking is our first post-truth industry, where there is no product, no profit and no prospect of either.'

See also: McGrath, M. 2019. Fracking: UK shale reserves may be smaller than previously estimated. (BBC News 20 August); Ambrose, J. 2019. Government's shift to relax shale gas fracking safeguards condemned (Guardian 15 August); Fracking in the UK; will it happen? (Earth-logs June 2014)

Ancient oil migration (October 2019)

In order for petroleum deposits to form, the first requirement is a source of abundant hydrocarbons, most usually from a mudstone that was deposited under highly reducing conditions. In such an environment dead organic matter can accumulate without complete decay and oxidation to form a source rock or black shale. The next step comes from burial and heating until the dead matter matures to release liquid and gaseous hydrocarbons. In turn these fluids, along with heated water, must leave the impermeable source rock and migrate through more porous and permeable strata, such as sandstone or limestone reservoir rocks. Either they reach the surface to escape or become trapped in some kind of geological structure. In migrating, the hydrocarbons induce reducing condition in the rocks through which they flow, often bleaching them as the colouring agents based on insoluble iron-3 compounds are reduced to iron-2 that dissolves and is carried out of the system along with the hydrocarbons.

Throughout the Precambrian, the Earth was lacking in free or dissolved oxygen, even after the Great Oxidation Event at around 2.4 to 2.1 billion years ago; ideal conditions for the formation of black-shale source rocks. And indeed there are huge volumes of them going back to the Palaeoarchaean Era (>3.25 Ga). The Earth's heat flow having be greater then, due to less decay of radioactive heat-producing elements in the mantle, petroleum must have been generated in volumes at least as large as that released during the Phanerozoic. Yet there are few oilfields of Precambrian age, and geologists usually don't bother looking for oil in very ancient rocks, largely because the older a rock sequence is the more likely it has been deeply buried and heated above the temperature at which oil breaks down into hydrocarbon gases (~130°C), which in turn are destroyed above about 250°C. Moreover, many such ancient rocks have generally been deformed by many phases of brittle tectonic processes that formed zones of fracturing that give lines of easy escape for pressurised fluids.

Interleaved chert (white) and ironstone of the Palaeoproterozoic Gunflint Iron Formation of Ontario, Canada and Minnesota, USA.

So, looking for telltale signs of oil formation and migration in Precambrian strata is pretty much a matter of academic curiosity. Solid, bituminous hydrocarbons granules and veins are not uncommon in Precambrian sediments, although their relationships do not rule out later introduction into ancient rocks. Birger Rasmussen of the University of Western Australia has been tracking down such signs for over 30 years, his best known discovery – in 2005 – being in Archaean rocks (3.2 to 2.6 Ga) of the Pilbara craton in Western Australia. Recently, he and Janet Muhling of the same institution reported stunning evidence of migration in the Palaeoproterozoic Era (Rasmussen, B. & Muhling, J.R. 2019. Evidence for widespread oil migration in the 1.88 Ga Gunflint Formation, Ontario, Canada. *Geology*, v. **47**, p. 899-903; DOI: 10.1130/G46469.1). The sedimentary unit is a banded iron formation containing interleaved cherts (famous for their content of some of the oldest incontrovertible microfossils), a granular variant of which is pervaded by solid bitumen in both granules and former pore spaces. This is interpreted as the result of oil migration during the actual cementation of the ironstone by silica; i.e. during diagenesis below the seabed rather than through solid sedimentary rock. Bitumen also fills later fractures. Rasmussen and Muhling consider the most likely scenario for this undoubted Palaeoproterozoic reservoir to have formed. They conclude that it coincided with the tectonic burial of the BIF basin beneath an exotic thrust block about 20 Ma after its formation. This generated petroleum from older source rocks, remote from the site of BIF deposition, that migrated away and up-dip from the thrust belt following the unconsolidated BIF formation.

Sedimentary deposits of the 'Anthropocene' **(November 2019)**

Economic activity since the Industrial Revolution has dug up rock – ores, aggregate, building materials and coal. Holes in the ground are a signature of late-Modern humanity, even the 18th century borrow pits along the rural, single-track road that passes the hamlet where I live. Construction of every canal, railway, road, housing development, industrial estate and land reclaimed from swamps and sea during the last two and a half centuries involved earth and rock being pushed around to level their routes and sites. The world's biggest machine, aside from CERN's Large Hadron Collider near Geneva, is Hitachi's Bertha the tunnel borer (33,000 t) currently driving tunnels for Seattle's underground rapid transit system. But the record muck shifter is the 14,200 t MAN TAKRAF RB293 capable of moving about 220,000 t of sediment per day, currently in a German lignite mine. The scale of humans as geological agents has grown exponentially. We produce sedimentary sequences, but ones with structures that are very different from those in natural strata. In Britain alone the accumulation of excavated and shifted material has an estimated volume six times that of our largest natural feature, Ben Nevis in NW Scotland. On a global scale 57 billion t of rock and soil is moved annually, compared with the 22 billion t transported by all the world's rivers. Humans have certainly left their mark in the geological record, even if we manage to reverse terrestrial rapacity and stave off the social and natural collapse that now pose a major threat to our home planet so that there are geologists around to appreciate the point.

A self propelled MAN TAKRAF bucketwheel excavator (Bagger 293) crossing a road in Germany to get from one lignite mine to another. (Credit: u/loerez, Reddit)

The holes in the ground have become a major physical resource, generating substantial profit for their owners from their infilling with waste of all kinds, dominated by domestic refuse. Unsurprisingly, large holes have become a dwindling resource in the same manner as metal ores. Yet these stupendous dumps contain a great deal of metals and other potentially useful material awaiting recovery in the eventuality that doing so would yield a profit, which presently seems a remote prospect. Such infill also poses environmental threats simply from its composition which is totally alien compared with common rock and sediment. Three types of infill common in the Netherlands, of which everyone is aware, have recently been assessed (Dijkstra, J.J. *et al*. 2019. The geological significance of novel anthropogenic materials: Deposits of industrial waste and by-products. *Anthropocene*, v. **28**, Article 100229; DOI: 10.1016/j.ancene.2019.100229). These are: ash from the incineration of household waste; slags from metal smelting; builders' waste. What unites them, aside from their sheer mass, is the fact that are each products of high-temperature conditions: anthropogenic metamorphic rocks, if you like. That makes them thermodynamically unstable under surface conditions, so they are likely to weather quickly if they are exposed at the surface or in contact with groundwater. And that poses threats of pollution of soil-, surface- and groundwater

All are highly alkaline, so they change environmental pH. Ash from waste incineration is akin to volcanic ash in that it contains a high proportion of complex glasses, which easily break down to clays and soluble products. Curiously, old dumps of ash often contain horizons of iron oxides and hydroxides, similar to the 'iron pans' in peaty soils. They form at contacts between oxidising and reducing conditions, such as the water table or at the interface with natural soils and rocks. Soluble salts of a variety of trace elements, such copper, antimony and molybdenum, may accumulate. Slags not only contain anhydrous silicates rich in the metals of interest and other trace metals, which on weathering may yield soluble chromium and vanadium, but they also have high levels of calcium-rich compounds from the limestone flux used in smelting, i.e. agents able to create high alkalinity. Portland cement, perhaps the most common material in builders' waste, is dominated by hydrated calcium-aluminium silicates that break-down if the concrete is crushed, again with highly alkaline products. Another component in demolition debris is gypsum from plaster, which can be a source of highly toxic hydrogen sulfide gas generated in anaerobic conditions by sulfate-sulfide reducing bacteria