Groundbreaking work

Smart ways to seek metals PART II

Sully Vent in the Main Endeavour Vent Field, north-east Pacific. Hydrothermal vents occur where tectonic plates are drawing apart, and in some cases where subduction is creating weaknesses in the crust. They're the underwater equivalent of land features that we find more familiar: hot springs, fumaroles and geysers.

National Oceanic and Atmospheric Administration Earth–Ocean Interactions Program

Thinking outside the box – in places under the sea or outside the atmosphere – creates new paths into the metals cycle.

BY **DAVE SAMMUT**

The Earth has a problem. It's really not that big a space to support more than seven billion humans, especially when that population is growing at more than 200 000 per day (and accelerating), especially when our global average intensity of use of every kind of resource is growing and especially when all of these resources are held within a band about 12 kilometres thick (a couple of kilometres in the crust and the rest in the atmosphere).

Within that infinitesimally small percentage of the world's volume, the vast majority of the resources we need currently come from the land, which itself is less than 30% of the surface area. Ultimately, while the mathematics might play out on a vast scale, the conclusions are inevitable: we need to maximise the efficiency with which we extract, process, transport and utilise our finite resources, and then we must ensure that every practical scrap is returned to the beginning of that cycle.

In the first part of this series (September, p. 20), I wrote about some really interesting initiatives being undertaken within the land-based metals cycles, with a particular emphasis on 'above ground resources' – metalliferous materials that offer excellent opportunities for recycling, up-cycling, industrial ecology and every other term that might apply.

From 'urban mines' (landfill) to

sewage sludge residues, those present-day opportunities are emerging as realistic, incremental improvements to efficiency in the global metals cycles. But what about the really interesting ideas for tomorrow, and what of the questions and challenges these raise?

Seabed mining

Fortunately for most people, the majority of geological activity from plate tectonics occurs where nobody wants to live. While I'd be willing to extend that statement to include Los Angeles, I am of course mostly referring to the ocean floor. In the past 50 years, we have made exotic and fascinating discoveries about what was for a long time considered a lifeless wasteland.

The ocean floor is on average higher in iron and nickel content than the land, which is higher in aluminium and silicon. In a gross oversimplification, one of the factors that makes 'land' land is that the lighter elements 'float' higher on the molten magma of the Earth, and the ocean floor 'hangs' between the stretches of land. Occasionally, as in parts of Newfoundland and Labrador, the subduction of one tectonic plate will push an area of seabed up, and so Labrador is now host to one of the world's biggest nickel mines.

In the 1960s, it was discovered that nickel- and manganese-rich balls were just lying on the abyssal plains of the Pacific Ocean. There was a flurry of news just this year, when huge versions of the same were found in the Atlantic. Measuring from golfball to bowling ball size, these grow incredibly slowly – at a rate of just millimetres per million years. The discovery (then and now) sparked serious investigations and expenditure into the possibility of their recovery.

The other big discovery of the 1960s was 'black smokers', or hydrothermal vents. Superheated water emerges from these vents heavily laden with dissolved minerals – copper, zinc, lead, nickel, silver and gold. On contact with the near-freezing water at the deep oceanic floor, these minerals immediately precipitate. The typical depth at which active sites are being found is around 2100 metres, but black smokers have been found as deep as 5000 metres, for example in the Cayman Trough.

In fast-growing, active areas, black smokers can reach 40–60 metres in height, growing at up to 30 centimetres per day. However, it has more recently been found that some of the largest 'massive sulfide' deposits may actually form from slower-growing sites. The substantial Mount Isa ore body is actually an example of a formerly seafloor massive sulfide mineral deposit.

A combination of economic and technical factors means that the seabed mining of minerals is an idea whose time has come, 'ready or not'. High-grade land-based mineral resources in politically stable areas are becoming less common. Even with incremental efficiencies in mining and minerals processing techniques, metals prices creep inexorably upwards. Decades of petroleum experience have honed deep-sea technologies. Inevitably, companies have started seriously looking at the opportunities afforded by offshore resources.

The most successful to date is diamond mining. De Beers already has multiple dedicated vessels that effectively suction diamonds from the shallow seabed, typically in the alluvial zones where rivers passing through land-based diamond fields empty into the sea (for example off the west coast of South Africa). Its vessel *MV Mafuta* (formerly the *Peace in Africa*, as seen in the Discovery Channel's documentary series *Mighty Ships*) mines 10 000 m^3 of water and gravel per hour, to produce roughly 240 000 carats (~48 kg) of diamonds annually.

The emerging entrants into the seabed mining of massive sulfides are Nautilus Minerals and Neptune Metals. Of these, Nautilus is closer to production, having recently settled a

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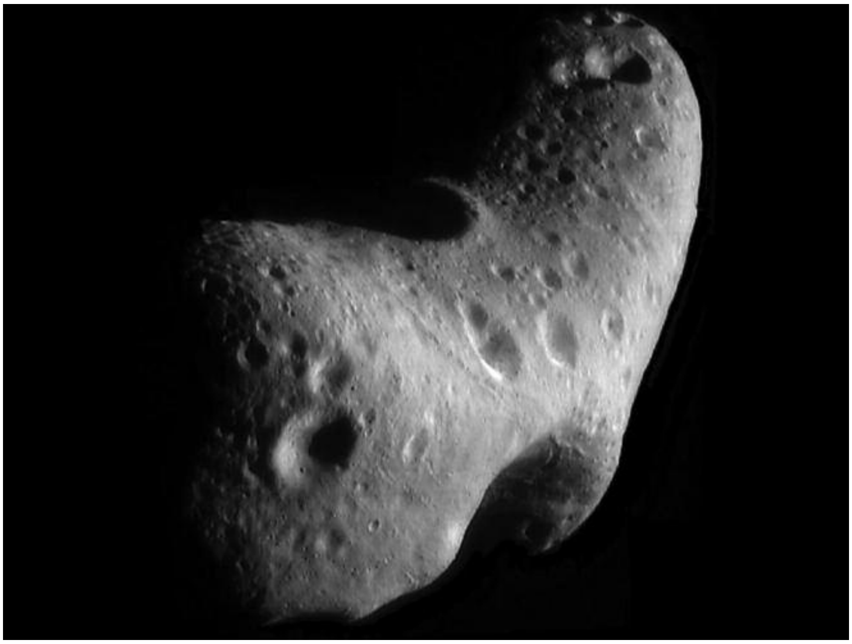
long-running dispute with the government of Papua New Guinea over costs. The mineral grades in Nautilus' primary site, Solwara 1 in the Bismarck Archipelago, are roughly ten times the typical grade of a land-based copper deposit: 6.8% Cu, as compared to 0.7%.

Proponents argue that there are many advantages to seabed mining: less tonnage to be mined per unit metal recovered, no impact on food production, surface freshwater or groundwater, pollination, soil formation or erosion, historic or cultural values, and 'no significant risk of disaster', such as mine tailings collapse.

However, there are justifiable reservations about the concept of seabed mining. The third big discovery in ocean geology was the astounding presence and diversity of life surrounding these active smokers. Far from light and oxygen, entire ecologies of previously unsuspected organisms exist, as chemosynthetic bacteria and archaea form the basis of a food chain supporting diverse higher organisms, including giant tube worms, clams, limpets and shrimp.

The effects of seabed mining on these ecologies is largely unknown. It is possible that each site may be unique, and their mining creates multiple risks: disturbance or destruction of species and the balance of species; the effects of stirred-up sediments on filter feeder populations;



Close-up image, taken by NASA's Near Earth Asteroid Rendezvous mission in 2000, of Eros, an S-type asteroid with an orbit that takes it somewhat close to Earth.
NASA/JHUAPL

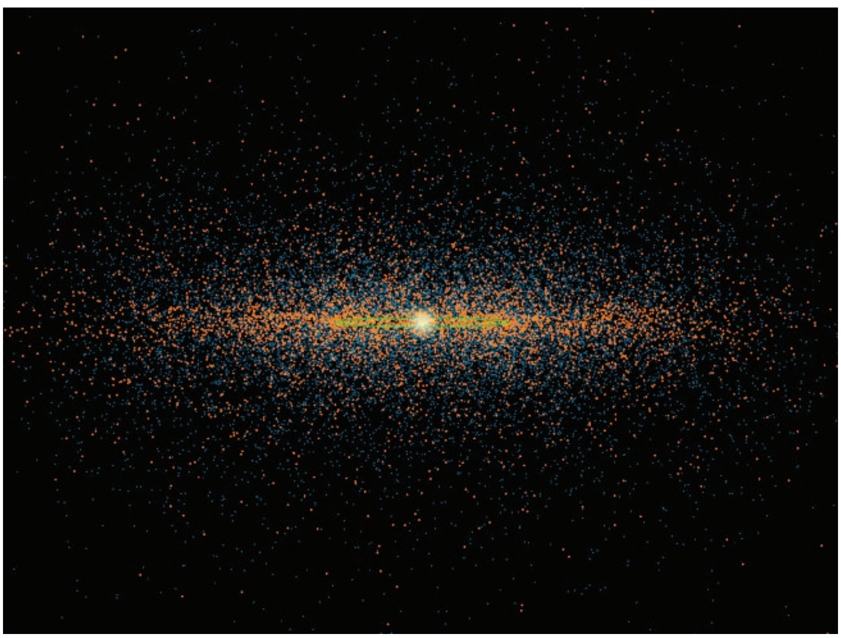


Diagram showing an edge-on view of our solar system. The dots represent a snapshot of the population of near-Earth asteroids (blue) and potentially hazardous asteroids (orange) that scientists think are likely to exist on a typical day based on the asteroid-hunting portion of the Wide-field Infrared Survey Explorer (WISE) mission. Earth's orbit is green.
NeoWISE

methane clathrate release; the potential for sub-oceanic landslides; acidification of the water; and more.

To address these concerns, a three-year research project involving 25 European research institutions kicked off in January this year. Among its studies, the EU Joint Program healthy and Productive Seas (JPI Oceans) initiative will visit a seafloor area in the Peru Basin that was disturbed by ploughing in 1989 to investigate the scale of recovery, the ecosystem status and the biogeochemical situation after 26 years.

While I think the science is fascinating, I agree with project coordinator Dr Matthias Haeckl of GEOMAR: 'We should get to know the deep sea better before we start to change it on [a] potentially large scale'.

Asteroid mining

An avid reader of science fiction from a young age, I have grown up with the excitement, adventure and challenges of life in space. And after a decade or more of relative dormancy in space exploration, the news as I write this article is filled with space. The New Horizons flyby has transformed poor, unloved Pluto from a fuzzy dot to a treasure trove of new information. The European Space Agency's Rosetta mission soft-landed its Philae probe on comet 67P carrying alpha-particle X-ray and IR–vis spectrometers, and a GC–MS. And in July, private company Planetary Resources has successfully launched its Arkyd 3 spacecraft on a test mission to the International Space Station.

Planetary Resources is one of two US companies that are currently vying to be the first to mine economic resources from asteroids. Both have ambitions to be doing so within the next ten years. This is particularly interesting because asteroid mining has implications both for returning metals to Earth, and for supplying further space-based missions.

Approximately 70–75% of objects in the asteroid belt beyond Mars' orbit are expected to be carbonaceous 'C-type' asteroids, rich in organic compounds, ammonia and water, as well as potentially useful isotopes of hydrogen and helium. The material is expected to be extremely friable, able to be crushed between thumb and forefinger, making it readily recoverable. And it could be critical to supplying further space missions, where each tonne lifted from Earth's gravity well into low orbit currently costs more than $20 million.

The other two types of asteroids identified in spectral studies are silicate 'S-type' and metal-rich 'M-type'. Both are considered to be relatively rich in metals, particularly valuable and useful metals: Au, Ir, Ag, Os, Pd, Pt, Rh, Ro, Ru, W, Fe, Co, Mn, Mo, Ni, Al and Ti. And these metals are likely to be distributed quite evenly through the asteroid, making them readily accessible.

Some scientists have advanced the theory that while Earth's gravity would have pulled the siderophilic (iron-loving) elements to the molten core of the planet during its formation roughly 4.5 billion years ago, much of the available near-surface resources that we now mine actually came to Earth during the subsequent period of asteroid bombardment after the Earth had largely cooled.

Astronomysource.com estimates that a single 1-killometre-diameter M-type asteroid could alone contain roughly 7000 tonnes of platinum, with a value of more than $200 billion at today's prices. Given that this is more than 50 times the annual global consumption, a single asteroid would be enough to significantly disrupt global markets. Successfully mining asteroids on a commercial scale could potentially affect markets in much the way that the invention of the Bayer and Hall–Heroult processes catastrophically devalued aluminium in the late 19th century. But then, the sudden change in the cost of aluminium created entire new uses that ultimately revolutionised a range of industries, including food and construction. What opportunities would a change in the cost of platinum group metals have on our industries?

There are plenty of challenges in the concept of mining asteroids. With little or no gravity, you don't so much 'land' on an asteroid as 'dock' with it. Means will have to be found to securely anchor the mining equipment to the surface, or Newton's third law will make the job pretty difficult. For C-type and S-type asteroids, a simple scoop or something akin to a snowblower – technologies that exist already – should serve admirably, and some target metals might be magnetically separable from the regolith. However, new cutting technologies might be needed for denser M-type asteroids. That remains an unknown at this stage.

The extreme temperature gradients in space are another major challenge. In a July 2015 proposal funded by NASA's Emerging Space office, NexGen Space LLC posed a novel solution for moon colonisation. The short description is that large robotically controlled mirrors will reflect the sun's rays into a crater, where it will create a less hostile micro-environment for a small army of other terraforming robots that will mine water and minerals from the moon's surface, while fixed equipment will hydrolyse the water for fuel and air for future colonists.

Other NASA-funded technologies are examining 3D printing of metal components in situ, and the repurposing of a host of other current technologies for real advancement of space-based development.

However, the *Nostromo* of Hollywood's 1979 classic *Aliens* was a mining ship returning from an asteroid. While the possibility of life on an asteroid is unlikely to be quite as scary, the seabed experience tells us that life can exist where we least expect. We may need to literally tread carefully in our progress.

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Possession is nine tenths of the law

For both seabed and asteroid mining, the law is scrambling to catch up with technology. With substantial expenditure from private companies to recovering resources from non-territorial areas, there is a huge question mark over how value is to be shared.

A 1994 United Nations Convention on the Law of the Sea yielded the International Seabed Authority, which notionally polices and licenses the seabed (but not the waters above it). In principle, the value of resources falling outside the exclusive economic zones of individual nations is to be shared globally, including with developing and landlocked nations. However, even with 159 member nations, there is one prominent holdout (a country that has perfected the 'self' in 'self-interest'), contenting itself with 'observer' status.

Space is even more of a cowboy paradise. While the Outer Space Treaty was signed in 1967, which declares the moon and other celestial bodies as the 'Common Heritage of Mankind', there are multiple ambiguities in the practice of the law. The US refused to join more than 100 other countries in ratifying the 1984 Moon Agreement, and more recently its Congress passed the *Asteroid Act*, granting ownership of any resources extracted from asteroids to the company that mined them. This sort of unilateral declaration is strongly akin to America's 1856 Guano Islands Act, and it might be expected to cause the same sort of legal trouble.

Ultimately, these issues probably won't be tested at law until long after mining has begun. Until then, asteroids are likely to be a big game of 'finders keepers'.