GRESHAM COLLEGE

17TH APRIL 2019

Mining Volcanoes: Diamonds, Copper and Hot Water

PROFESSOR RICHARD HERRINGTON

Volcanoes are ubiquitous features of a dynamic planet. They form as the Earth's dynamic processes cause magma to form deep below the Earth's surface, which then rises up to be extruded at the surface as a variable mixture of molten lava, fragments of volcanic material (known as pyroclastics) and often a range of gases. Volcanoes can erupt on land (terrestrial volcanoes) but much of the Earth's volcanic activity happens under the ocean or in rare cases beneath ice sheets. All of these volcanoes are testament to plate tectonic processes on the planet which serve to recycle the Earth's crustal and mantle material and as a result cause different elements that make up the mantle and crust to be either concentrated or depleted into specific rock associations. Many of the magmas forming under volcanoes are enriched in dissolved gases like carbon dioxide, water vapour, gases containing sulphur (like hydrogen sulphide or sulphur dioxide), chlorine and more exotic components. These geological and geochemical processes serve to concentrate elements under specific conditions and in some cases give rise to accumulations of economically important minerals. The presence of hot rocks close to the surface also presents an opportunity for heated water to circulate that can both carry metals to form mineral deposits or allow us to generate green energy from geothermal systems.

Active volcanoes are found in quite specific geological settings in the Earth's crust. These largely relate to the presence of tectonic plate boundaries, where crust is either newly formed or else destroyed, can cause magma bodies to form at depth which can feed overlying volcanoes at the surface. Through geological time, by using Charles Lyell's 19th century geological principle of 'the present being the key to the past', we are able to use our studies of active volcanoes to help unravel the mysteries of former volcanoes preserved in rocks from the geological record and vice versa. Because ancient systems get uplifted and then eroded through geological time, we can also study the kind of magma systems that exist deep below the modern volcanoes exposed at the Earth's surface. It is from the study of ancient rocks, we have found out that many of the world's giant copper deposits occur in rocks that are linked to formerly overlying volcanoes. Similarly, work on ancient volcanic rocks that formed on the ancient seafloor suggested to us that deep ocean volcanoes can be associated with large metal deposits. Finally, work in the geological record has discovered the presence of types of volcanism that we can't currently see actively forming at the Earth's surface today. These enigmatic types of ancient volcanoes also yield to us 'treasures from the deep' and at the same time tell us a lot about how the Earth formed and how things have changed through geological time.

A key to much of the Earth's tectonic and volcanic activity linked to mineral deposits is the role of water on the surface of the Earth and deep within. Water is an amazing compound, and in many ways it is the reason our planet 'works'. Without water, there is no life as we know it; frozen water, ice, happily floats on water which means that life can go on beneath icecaps. Water is an essential component for driving the forces of an active plant too as without water, many of the geological processes we see would not happen. Water also interacts with magmas where new crust is forming in the deep ocean and it has been estimated that the entire ocean volume is circulated through the mid-ocean ridges in a few millions of years; in a geological context this is a very short period of time. Subduction is the process by which old ocean crust gets returned to the mantle in the reverse process of new crust formation. Water makes the geological process of subduction happen, since seawater cools and hydrates the ocean crust leaving it cold and dense, able to be subducted below crustal rocks above it at subduction zones. Water is then liberated from the down-going plate and causes the overlying mantle rocks to melt, since adding water lowers the melting point of magmas. Water is also an amazing solvent, dissolving, transporting and then reprecipitating different elements including metals, into concentrations of minerals that can form economic mineral deposits.

On the Earth's modern surface, volcanoes forming along mid-ocean ridges and often hidden deep on the ocean floor, are testament to the formation of new crust from the upwelling mantle (so-called seafloor spreading) and the circulation of ocean water through the rocks. Tectonic forces stretch and break the thin crust on the ocean floor and melting leads to submarine and more rarely (in locations like Iceland) terrestrial volcanoes. At the zones of seafloor spreading where volcanoes erupt, heated circulating seawater dissolves many elements from the volcanic rocks which then rises out onto the ocean floor. On the ocean floor metals are redeposited from large vent chimneys (black smokers) and these chimneys, made of metal sulphide minerals, develop together with masses of sulphide-rich minerals forming below the surface of the seafloor. Such sites also emit hydrogen sulphide gas, toxic to us, but a source of energy to many forms of extreme bacteria living in the ocean close to the vents. Some larger organisms have also adapted to this life in the dark, utilising these extremophile bacteria in their feeding strategy in the absence of sunlight and photosynthesis. These sites are suggested by some scientists as being favourable environments for the start for the very start of life itself when the plant was young. On the ocean floor today, these sulphide deposits form in predictable regularity along the ocean ridges. In places where these deposits have been forming and access has been made possible using new technology, companies are even assessing whether such sites could be mined for their metals. Actually, we are already mining sulphide minerals from the (ancient) ocean floor, as many copper, zinc and lead mines around the world are mining such types of deposit from ancient seafloor systems. Really good examples are known from the Ural Mountain chain of Russia. Here, there is the record of an ancient ocean which closed around 350 million years ago, and exceptional preservation of the rocks has preserved the sulphide deposits formed and all their rock associations. The deposits are so well preserved that we even have fossils of vent animals preserved along with evidence for the bacteria that must have underpinned their ecosystem.

Looking now at the sites in the crust where we have the geological process of subduction, where oceans are closing and oceanic crust is being recycled, we find large volcanoes developed as cold ocean crust descends down below the overlying plate, to be heated to the point where it loses its water and many other mobile elements locked up in the rocks, leading to the formation of an ascending magma body in the crust above. In these so-called arc volcanoes, water controls the eruption processes. Many of the volcanoes in arcs are very gassy, erupting large amounts of water, sulphur and chlorine-bearing gases along with direct products of the magma. As large bodies of magma rise up through faults and fissures in the crust, they pond at specific crustal levels where they begin to crystallise and some of the dissolved components like water and other gases come out of solution. This type of unmixing, somewhat akin to removing the cork from a champagne bottle, can be the trigger for water-rich fluids to leave the otherwise sticky silicate melt, taking with it many dissolved metals (like copper, molybdenum, iron and gold) which can form large ore deposits either in the cooled magma chamber at depth or else rising up to form mineral deposits close to surface where they can be accompanied by fumaroles or hot springs.

Many of the world's volcanic arcs are the sources of much of the world's copper and much of its gold. Our greening of the energy industry has ironically increased the demand for copper, the major enabling metal for the transmission infrastructure for renewable power generation as well as connecting our use of stored electricity for vehicles and other technologies. These often-giant deposits of metals formed in the roots of volcanoes are known as porphyry copper deposits and they now account for 60% of the world's current needs for the orange metal. We have key evidence of the link between such deposits and volcanoes, we can find many modern volcanoes erupting significant metals and gases along with the more expected volcanic products like lava and pyroclastic deposits. In addition, the fringes of volcanic systems are often active geothermally, with surface groundwaters percolating into volcanic systems to give rise to hydrothermal systems that can be tapped for the steam for power generation. These same geothermal systems can give rise to significant gold and silver deposits where the precious metals are moved from the volcanic rocks to be precipitated elsewhere.

There are some volcanoes that we only know from the geological record. Kimberlites are one such type of volcanic rock. Kimberlite volcanoes are unusual as they arise from magmas formed very deep inside the earth, at least 140 and down to 450km deep in the mantle. As a result of this, such magmas are rather unusual in composition, containing many minerals that are only stable under intense pressure and high temperature. Although they are not known to be forming today, the youngest-known kimberlites found in Tanzania are between 100 and 200,000 years old, well within human history. The reason we are so interested in kimberlites is that they often carry diamonds and as such are the main host rock know for this most precious of all gems. Many of the mines in South Africa and Canada are mining kimberlite for their contained diamonds. The unusual thing about the diamonds in kimberlite is that they did not form as part of the cooling magma process. Diamonds are exotic and the kimberlite magma serves as the carrying agent for diamonds that had previously formed in the mantle. Diamond is simply the stable form of elemental carbon present in the Earth at depths more than 150km. Above this depth, diamonds break down and revert to other forms of carbon. From the evidence found at the surface, kimberlites were likely to be extremely violent eruptions, there is plenty of evidence in more recent deposits that fossil wood (Redwood tree) is found deep in the kimberlite suggesting that explosive eruption was followed by infilling of the crater with fall-back deposits.

Other more ancient volcanoes last erupted on the surface of Earth around 2 billion years ago. These volcanic lava flows, known as komatiites, after the Komati river in South Africa where they were first described, are the product of an earlier Earth when the planet had a much higher heat-flow in the mantle. During those times, very high temperature magmas, more than 1600 degrees C, could find their way up and flow out onto the Earth's surface as lavas. Such lavas are both magnesium and iron-rich yet would have had a viscosity similar to water but a density similar to that of rock. As a result, these magmas would aggressively melt the surface of the rock over which they flowed, forming lava channels rather like river systems. Chemical changes resulting from the melting of the rocks over which they flowed would change the composition of the lava, leading to the unmixing of a sulphide liquid from the lava, analogous to oil and vinegar settling apart in a bottle of salad dressing. This liquid sulphide then crystallised to form mineral deposits rich in nickel, copper and sometimes platinum-group metals, examples of which are mined in ancient rocks in Western Australia and Canada.

While we can't study this process on Earth today, there are other parts of the planetary system where these types of very hot lavas are common. Jupiter's moon Io is located so close to the large planet that gravity forces keep its core and mantle very hot. On Io's surface, scientists have detected evidence for these high-temperature komatiite flows, and we might suspect that mineral deposits like those in ancient rocks on Earth might be forming there. We know that other planetary bodies may also host volcanic activity. Venus has active volcanoes and, another of Jupiter's moons, Europa shows indirect evidence for volcanic activity under an extensive ice cover, with speculation that seafloor black smokers might be forming deep below and even more tenuous speculation that vent life might be continuing using the power of sulphur. NASA have plans to visit Europa and a sub-ice explorer has already been designed. Sadly, despite the extensive giant and likely extinct volcanoes visible on Mars, the new seismic probe landed recently on the planet shows little evidence for the kind of tectonic activity we would expect to detect on an active volcanic planet. Mars likely lost most of its atmosphere early in its geological history along with the bulk of its water and these may be factors partly responsible for tectonic activity ceasing. Mars may yet yield important evidence for volcanic activity of the sort we would expect early in the Earth's history.

Volcanoes are the manifestation of a geologically active planet, evidence of a planet both maturing and recycling material between the mantle and the crust and back again. The magmatic processes that underlie the formation of volcanoes are often responsible for recycling and concentrating metals and other elements into economic concentrations that we can exploit for all of our technological advances. Water is an important component in many of the geological processes linked to formation of volcanoes. Water helps to drive some volcanic systems and in many cases is essential for the formation of many the useful mineral deposits formed.

Barnes & Lightfoot (2005) Economic Geology 100th Anniversary Volume 179-214
Sparks et al. (2006) Journal of Volcanology and Geothermal Research 155: 18-48
Tosdal et al. (2009) Elements, vol. 5, pp.289-295
White NC & Herrington RJ (2000) Encyclopaedia of Volcanoes, 1st Edition, 897-914
Wilkinson (2013) Nature Geoscience 6, 917-925