Magmatism

Magma rushed into largest layered intrusion (*April 2015*)

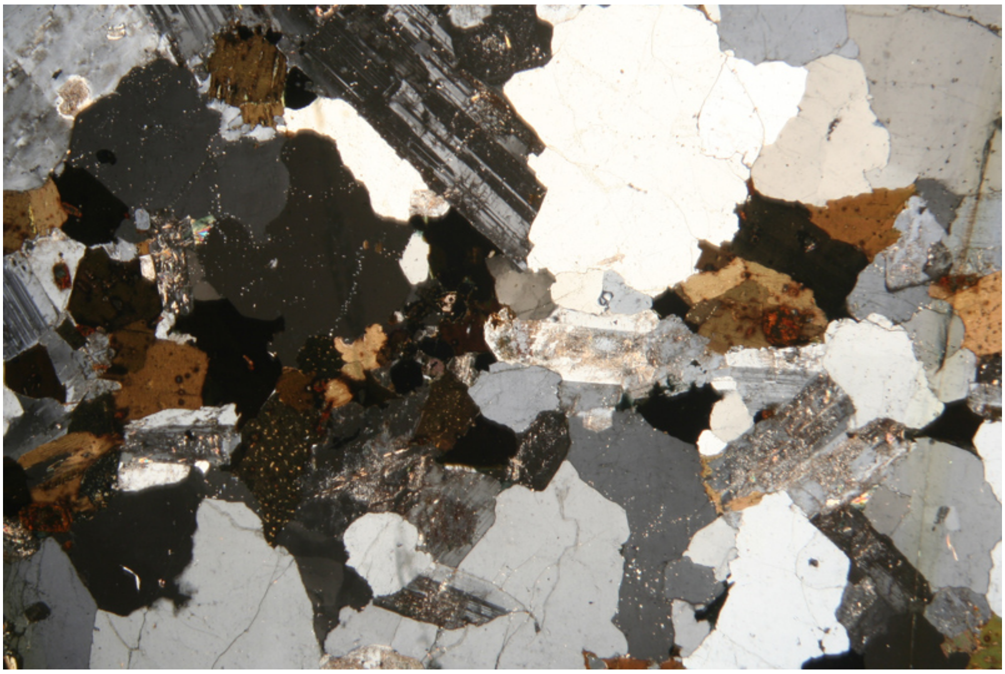
Chances are that the platinum in the catalytic converter that helps prevent your car emitting toxic gases in its exhaust fumes came from a vast igneous intrusion in South Africa known as the Bushveldt complex. The world's most important source of noble metals formed by repeated differentiation of huge volumes of mafic magma to form thin, dense layers rich in sulfides, platinum group metals and chromium ore set in very thick layers of barren gabbro and other mafic to ultramafic rock. The intrusion is exposed over an area the size of Ireland and formed about 2 billion years ago. Its 370 000 to 600 000 km^3 volume suggests that it was the magma chamber that fed flood basalts that erosion has since eroded away. Successive pulses of basaltic magma built up a total thickness of about 8 kilometres of layered rock.

Layered igneous rocks in the Bushveld Complex (credit: Wikipedia)

The final product of the Bushveldt differentiation process was minute pockets of material of more felsic composition trapped within overwhelmingly larger amounts of gabbro. One of the elements that ended up in these roughly granitic inclusions was zirconium that mafic minerals are unable to accommodate while basaltic magma is crystallising. That formed minute crystals of the mineral zircon ($ZrSiO_4$) in the residual pockets, which in turn locked up a variety of other elements, including uranium. Zircon can be dated using uranium's radioactive decay to form lead isotopes, its refusal to enter chemical reactions after its crystallisation makes U/Pb dates of zircon among the most reliable available for geochronology and the precision of such dates has become increasingly exquisite as mass spectrometry has improved. So, the Bushveldt complex now has among the best records of magma chamber evolution (Zeh, A. *et al*. 2015. The Bushveld Complex was emplaced and cooled in less than one million years – results of zirconology, and geotectonic implications. *Earth and Planetary Science Letters*, v. **418**, p. 103-114; DOI: 10.1016/j.epsl.2015.02.035).

Like a number of younger large igneous provinces, the Bushveldt complex took a very short time to form, about 950 thousand years 2055 Ma ago. That is from magma emplacement to final crystallization when the zircon ages were set, so the accumulation of magma probably took only 100 thousand years. This suggests that magma blurted into the lower crust at an average rate of around 5 $km^3\ a^{-1}$, and quite probably even faster if the magmatism was episodic. It requires a major stretch of the imagination to suggest that this could have occurred by some passive process. Instead, the authors have suggested that while a plume of mantle material rose from well below the lithosphere a large slab of lower lithosphere, formed from dense eclogite, broke off and literally fell into the deeper mantle. The resulting changes in stress in the lower lithosphere would have acted as a pump to drive the plume upwards, causing it to melt as pressure dropped, and to squirt magma into the overlying continental crust. Although the authors do not mention it, this is reminiscent of the idea of large igneous provinces having sufficient power to eject large masses from the Earth's surface: the Verneshot theory, recently exhumed in late 2014. The main difference is that the originators of the Verneshot theory appealed to explosive gas release.

How far has geochemistry led geology? (July 2015*)*



Thin section of a typical granite: clear white and grey grains are quarts; feldspars are striped black and white; coloured minerals are micas

In the Solar System the Earth is unique in having a surface split into two distinct categories according to their relative elevation; one covered by water, the other not. More than 60% of its surface – the ocean-basin floors – falls between 2 to 11 km below sea level with a mean around 4 to 5 km deep. A bit less than 40% – land and the continental shelves – stands higher than 1 km below sea level up to almost 9 km above, with a mean around 1 km high. Between 1 and 2 km below sea level is represented by only around 3 % of the surface area. This combined hypsography and wetness is reckoned to have had a massive bearing on the course of climate and biological evolution, as far as allowing our own emergence. The Earth's bimodal elevation stems from the near-surface rock beneath each division having different densities: continental crust is less dense than its oceanic counterpart, and there is very little crustal rock with an intermediate density. Gravitational equilibrium ensures that continents rise higher than oceans. That continents were underpinned mainly by rocks of granitic composition and density, roughly speaking, was well known by geologists at the close of the 19th century. What lay beneath the oceans didn't fully emerge until after the discovery of plate tectonics in the 1960s and the associated notion of simple basaltic magmas pouring out as plates became detached.

In 1915 Canadian geologist Norman Levi Bowen resolved the then-current knowledge of the field relations, mineralogy and, to a much lesser extent, the chemistry of igneous rocks, predominantly those on the continents in a theory to account for the origin of continents. This involved a process of distillation or fractionation in which the high-temperature crystallisation of mafic (magnesium- and iron-rich) minerals from basaltic magma left a residual melt with lower Mg and Fe, higher amounts of alkalis and alkaline earth elements and especially enriched in SiO_2 (silica). A basalt with ~50% silica could thereby give rise to rocks of roughly granitic composition (~60% SiO_2) – the 'light' rocks that buoy-up the continental surface – through Bowen's hypothetical fractional crystallisation. Later authors in the 1930s, including Bowen's teacher Reginald Aldworth Daly, came up with the idea that granites may form by basalt magma digesting older SiO_2-rich rocks or by partially melting older crustal rocks as suggested by British geologist Herbert Harold Read. But, of course, this merely shifted the formation of silica-rich crust further back in time

Since the emergence of plate theory and the discovery of the predominance of basalt beneath ocean floors, a great deal of field-, microscope- and, more recently, geochemical study has been spent since on to-ing and fro-ing between these hypotheses, as well as on the petrology of basaltic magmas. By the 1990s one of the main flaws seen in Bowen's hypothesis was removed, seemingly at a stroke. Surely, if a basalt magma split into a dense Fe- Mg-rich cumulate in the lower crust and a less dense, SiO_2-rich residual magma in the upper continental crust, then the bulk density of that crust ought to remain the same as the original basalt. But if the dense part somehow fell back into the mantle what remained would be more able to float proud. Although a neat idea, outside of proxy indications that such delamination had taken place, it could not be proved.

Since the 1960s geochemical analysis has became steadily easier, quicker and cheaper, using predominantly X-ray fluorescence and mass-spectrometric techniques. So geochemical data steadily caught up with the traditional analysis of thin sections of rock using petrological microscopes. Beginning in the late 1960s igneous geochemistry became almost a cottage industry and millions of rocks have been analysed. Recently, about 850 thousand multi-element analyses of igneous rocks have been archived with US NSF funding in the EarthChem library. A group from the US universities of Princeton, California – Los Angeles and Wisconsin – Madison extracted 123 thousand plutonic and 172 thousand volcanic igneous rocks of continental affinities from EarthChem to 'sledgehammer' the issue of continent formation into a unified theory (Keller, C.B. *et al*. 2015. Volcanic-plutonic parity and the differentiation of the continental crust. *Nature*, v. **523**, p. 301-307; DOI: 10.1038/nature14584).

In a nutshell, Keller *et al* compared the two divisions in this vast data bank; the superficial volcanic with the deep-crustal plutonic kinds of continental igneous rock. The gist of their approach is a means of comparative igneous geochemistry with an even longer pedigree, which was devised in 1909 by British geologist Alfred Harker. The Harker Diagram plots all other elements against the proportionally most variable major component of igneous rocks, SiO_2. If the dominant process involved mixing of basalt magma with or partial melting of older silica-rich rocks such simple plots should approximate straight lines. It turns out – and this is not news to most igneous geochemists with far smaller data sets – that the plots deviate considerably from straight lines. So it seems that old Bowen was right all along; the differing deviations from linearity stemming from subtleties in the process of initial melting of mantle to form basalt and then its fractionation at crustal depths. Keller and colleagues found an unexpected similarity between the plutonic rocks of subduction-related volcanic arcs and those in zones of continental rifting. Both record the influence of water in the process, which lowers the crystallisation temperature of granitic magma so that the melt freezes before the bulk of it can migrate to the surface and extrude as lava. Previously, rift-related magmas had been thought to be drier than those formed in arcs so that silica-rich magma should tend to be extruded.

But there is a snag, the EarthChem archive hosts only data from igneous rocks formed in the Phanerozoic, most being less than 100 Ma old. It has long been known that continental crust had formed as far back as 4 billion years ago, and many geologists believe that most of the continental crust was in place by the end of the Precambrian about half a billion years ago. Some even reckon that igneous process may have been fundamentally different before 3 billion years ago(see: Dhuime, B., Wuestefeld, A. & Hawkesworth, C. J. 2015. Emergence of modern continental crust about 3 billion years ago. *Nature Geoscience*, v. **8**, p. 552–555; DOI: 10.1038/ngeo2466).

So big-science data mining may flatter to deceive and leave some novel questions unanswered

Related article: Till, C. 2015. Big geochemistry. Nature, v. **523**, p. 293-294; DOI: 10.1038/523293a.