Magma

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Magma (from Ancient Greek μάγμα (*mágma*) meaning "thick unguent") is a mixture of molten or semi-molten rock, volatiles and solids[1] that is found beneath the surface of the Earth, and is expected to exist on other terrestrial planets and some natural satellites. Besides molten rock, magma may also contain suspended crystals, dissolved gas and sometimes gas bubbles. Magma often collects in magma chambers that may feed a volcano or solidify underground to form an intrusion. Magma is capable of intruding into adjacent rocks (forming igneous dikes and sills), extrusion onto the surface as lava, and explosive ejection as tephra to form pyroclastic rock.

Lava flow on Hawaii. Lava is the extrusive equivalent of magma.

Contents

Description

Magma is a complex high-temperature fluid substance. Temperatures of most magmas are in the range 700 °C to 1300 °C (or 1300 °F to 2400 °F), but very rare carbonatite magmas may be as cool as 600 °C, and komatiite magmas may have been as hot as 1600 °C. Most magmas are silicate mixtures.[2]

Environments of magma formation and compositions are commonly correlated. Environments include subduction zones, continental rift zones,[3] mid-ocean ridges and hotspots. Despite being found in such widespread locales, the bulk of the Earth's crust and mantle is not molten. Except for the liquid outer core, most of the Earth takes the form of a rheid, a form of solid that can move or deform under pressure. Magma, as liquid, preferentially forms in high temperature, low pressure environments within several kilometers of the Earth's surface.

Magma compositions may evolve after formation by fractional crystallization, contamination, and magma mixing. By definition rock formed of solidified magma is called igneous rock.

While the study of magma has historically relied on observing magma in the form of lava outflows, magma has been encountered in situ three times during geothermal drilling projects—twice in Iceland (see #Magma usage for energy production below), and once in Hawaii.[4][5][6]

Sources

Partial melting

Melting of solid rocks to form magma is controlled by three physical parameters: temperature, pressure, and composition. Mechanisms are discussed in the entry for igneous rock.

When rocks melt they do so incrementally and gradually; most rocks are made of several minerals, all of which have different melting points, and the physical/chemical relationships controlling melting are complex. As a rock melts, its volume changes. When enough rock is melted, the small globules of melt (generally occurring in between mineral grains) link up and soften the rock. Under pressure within the earth, as little as a fraction of a percent partial melting may be sufficient to cause melt to be squeezed from its source. Melts can stay in place long enough to melt to 20% or even 35%, but rocks are rarely melted in excess of 50%, because eventually the melted rock mass becomes a crystal and melt mush that can then ascend *en masse* as a diapir, which may then cause further decompression melting.

Geochemical implications of partial melting

The degree of partial melting is critical for determining what type of magma is produced. The degree of partial melting required to form a melt can be estimated by considering the relative enrichment of incompatible elements versus compatible elements. Incompatible elements commonly include potassium, barium, cesium, and rubidium.

Rock types produced by small degrees of partial melting in the Earth's mantle are typically alkaline (Ca, Na), potassic (K) and/or peralkaline (high aluminium to silica ratio). Typically, primitive melts of this composition form lamprophyre, lamproite, kimberlite and sometimes nepheline-bearing mafic rocks such as alkali basalts and essexite gabbros or even carbonatite.

Pegmatite may be produced by low degrees of partial melting of the crust. Some granite-composition magmas are eutectic (or cotectic) melts, and they may be produced by low to high degrees of partial melting of the crust, as well as by fractional crystallization. At high degrees of partial melting of the crust, granitoids such as tonalite, granodiorite and monzonite can be produced, but other mechanisms are typically important in producing them.

Magma usage for energy production

The Iceland Deep Drilling Project, while drilling several 5,000m holes in an attempt to harness the heat in the volcanic bedrock below the surface of Iceland, struck a pocket of magma at 2,100m in 2009. Being only the third time in recorded history that magma had been reached, IDDP decided to invest in the hole, naming it IDDP-1.

A cemented steel case was constructed in the hole with a perforation at the bottom close to the magma. The high temperatures and pressure of the magma steam were used to generate 36MW of power, making IDDP-1 the world's first magma-enhanced geothermal system.[7]

Evolution of magmas

Primary melts

When a rock melts, the liquid is a *primary melt*. Primary melts have not undergone any differentiation and represent the starting composition of a magma. In nature it is rare to find primary melts. The leucosomes of migmatites are examples of primary melts. Primary melts derived from the mantle are especially important, and are known as *primitive melts* or primitive magmas. By finding the primitive magma composition of a magma series it is possible to model the composition of the mantle from which a melt was formed, which is important in understanding evolution of the mantle.

Parental melts

Where it is impossible to find the primitive or primary magma composition, it is often useful to attempt to identify a parental melt. A parental melt is a magma composition from which the observed range of magma chemistries has been derived by the processes of igneous differentiation. It need not be a primitive melt.

For instance, a series of basalt flows are assumed to be related to one another. A composition from which they could reasonably be produced by fractional crystallization is termed a *parental melt*. Fractional crystallization models would be produced to test the hypothesis that they share a common parental melt.

At high degrees of partial melting of the mantle, komatiite and picrite are produced.

Migration

Magma develops within the mantle or crust when the temperature-pressure conditions favor the molten state. Magma rises toward the Earth's surface when it is less dense than the surrounding rock and when a structural zone allows movement. Magma develops or collects in areas called magma chambers. Magma can remain in a chamber until it cools and crystallizes forming igneous rock, it erupts as a volcano, or moves into another magma chamber.

Cooling of magmas

There are two known processes by which magma ceases to exist: by volcanic eruption, or by crystallization within the crust or mantle to form a pluton. In both cases the bulk of the magma eventually cools and forms igneous rocks.

When magma cools it begins to form solid mineral phases. Some of these settle at the bottom of the magma chamber forming cumulates that might form mafic layered intrusions. Magma that cools slowly within a magma chamber usually ends up forming bodies of plutonic rocks such as gabbro, diorite and granite, depending upon the composition of the magma. Alternatively, if the magma is erupted it forms volcanic rocks such as basalt, andesite and rhyolite (the extrusive equivalents of gabbro, diorite and granite, respectively).

Volcanism

During a volcanic eruption the magma that leaves the underground is called lava. Lava cools and solidifies relatively quickly compared to underground bodies of magma. This fast cooling does not allow crystals to grow large, and a part of the melt does not crystallize at all, becoming glass. Rocks largely composed of volcanic glass include obsidian, scoria and pumice.

Before and during volcanic eruptions, volatiles such as CO_2 and H_2O partially leave the melt through a process known as exsolution. Magma with low water content becomes increasingly viscous. If massive exsolution occurs when magma heads upwards during a volcanic eruption, the resulting eruption is usually explosive.

Composition, melt structure and properties

Silicate melts are composed mainly of silicon, oxygen, aluminium, alkalis (sodium, potassium, calcium), magnesium and iron. Silicon atoms are in tetrahedral coordination with oxygen, as in almost all silicate minerals, but in melts atomic order is preserved only over short distances. The physical behaviours of melts depend upon their atomic structures as well as upon temperature and pressure and composition.[8]

Viscosity is a key melt property in understanding the behaviour of magmas. More silica-rich melts are typically more polymerized, with more linkage of silica tetrahedra, and so are more viscous. Dissolution of water drastically reduces melt viscosity. Higher-temperature melts are less viscous.

Generally speaking, more mafic magmas, such as those that form basalt, are hotter and less viscous than more silica-rich magmas, such as those that form rhyolite. Low viscosity leads to gentler, less explosive eruptions.

Characteristics of several different magma types are as follows:

Ultramafic (picritic)
- SiO_2 < 45%
- Fe–Mg > 8% up to 32%MgO
- Temperature: up to 1500°C
- Viscosity: Very Low
- Eruptive behavior: gentle or very explosive (kimberilites)
- Distribution: divergent plate boundaries, hot spots, convergent plate boundaries; komatiite and other ultramafic lavas are mostly Archean and were formed from a higher geothermal gradient and are unknown in the present

Mafic (basaltic)
- SiO_2 < 50%
- FeO and MgO typically < 10 wt%
- Temperature: up to ~1300°C
- Viscosity: Low
- Eruptive behavior: gentle
- Distribution: divergent plate boundaries, hot spots, convergent plate boundaries

Intermediate (andesitic)
- SiO_2 ~ 60%
- Fe–Mg: ~ 3%th
- Temperature: ~1000°C
- Viscosity: Intermediate
- Eruptive behavior: explosive or effusive
- Distribution: convergent plate boundaries, island arcs

Felsic (rhyolitic)
- SiO_2 > 70%
- Fe–Mg: ~ 2%
- Temp: < 900°C
- Viscosity: High
- Eruptive behavior: explosive or effusive
- Distribution: common in hot spots in continental crust (Yellowstone National Park) and in continental rifts

Temperature

At any given pressure and for any given composition of rock, a rise in temperature past the solidus will cause melting. Within the solid earth, the temperature of a rock is controlled by the geothermal gradient and the radioactive decay within the rock. The geothermal gradient averages about 25 °C/km with a wide range from a low of 5–10 °C/km within oceanic trenches and subduction zones to 30–80 °C/km under mid-ocean ridges and volcanic arc environments.

Pressure

As magma buoyantly rises it will cross the solidus-liquidus and its temperature will reduce by adiabatic cooling. At this point it will liquefy and if erupted onto the surface will form lava. Melting can also occur due to a reduction in pressure by a process known as decompression melting.[9]

Density

Type	Density [kg/m³]
Basalt magma	2650–2800[10]
Andesite magma	2450–2500[10]
Rhyolite magma	2180–2250[10]

Composition

It is usually very difficult to change the bulk composition of a large mass of rock, so composition is the basic control on whether a rock will melt at any given temperature and pressure. The composition of a rock may also be considered to include *volatile* phases such as water and carbon dioxide.

The presence of volatile phases in a rock under pressure can stabilize a melt fraction. The presence of even 0.8% water may reduce the temperature of melting by as much as 100 °C. Conversely, the loss of water and volatiles from a magma may cause it to essentially freeze or solidify.

Also a major portion of almost all magma is silica, which is a compound of silicon and oxygen. Magma also contains gases, which expand as the magma rises. Magma that is high in silica resists flowing, so expanding gases are trapped in it. Pressure builds up until the gases blast out in a violent, dangerous explosion. Magma that is relatively poor in silica flows easily, so gas bubbles move up through it and escape fairly gently.

References

1. Spera, Frank J. (2000), "Physical Properties of Magma", in Sigurdsson, Haraldur (editor-in-chief), *Encyclopedia of Volcanoes*, Academic Press, pp. 171–190, ISBN 978-0126431407
2. Popp, B. N. (September 2007). "Igneous Rocks" (PDF). *Geology Course Lecture in PowerPoint*. School of Ocean and Earth Science and Technology, University of Hawaiʻi at Manoa. Retrieved 16 October 2015.
3. Foulger, G.R. (2010). *Plates vs. Plumes: A Geological Controversy*. Wiley–Blackwell. ISBN 978-1-4051-6148-0.
4. Scientists' Drill Hits Magma: Only Third Time on Record (http://www.news.ucdavis.edu/search/news_detail.lasso?id=9174), UC Davis News and Information, June 26, 2009.
5. Magma Discovered in Situ for First Time (http://www.physorg.com/news148664988.html). Physorg (December 16, 2008)
6. Puna Dacite Magma at Kilauea: Unexpected Drilling Into an Active Magma Posters (http://www.agu.org/meetings/fm08/fm08-sessions/fm08_V23A.html), 2008 Eos Trans. AGU, 89(53), Fall Meeting.
7. Wilfred Allan Elders, Guðmundur Ómar Friðleifsson and Bjarni Pálsson (2014). *Geothermics Magazine, Vol. 49 (January 2014)*. Elsevier Ltd.
8. Watson, E. B.; Hochella, M. F. and Parsons, I. (editors), *Glasses and Melts: Linking Geochemistry and Materials Science*, *Elements*, volume 2, number 5, (October 2006) (http://www.elementsmagazine.org/) pp. 259–297
9. Geological Society of America, *Plates, Plumes, And Paradigms*, p. 590 ff., 2005, ISBN 0-8137-2388-4
10. usu.edu - GEOLOGY 326, PHYSICAL PROPERTIES OF MAGMAS (http://www.usu.edu/geo/shervais/G4500_PDF/45Week1B_Magmas.pdf), 2005-02-11