

GRANITE:
A PLANETARY RESPONSE TO LIQUID WATER

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Granite: A Planetary Response to Liquid Water

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ABOUT THE AUTHOR



John Douglas Clemens was born in 1953, in the now non-existent coal-mining town of Yallourn, in Victoria, Australia. In 1973 he obtained his Fellowship Diploma of Geology from the then Royal Melbourne Institute of Technology (now RMIT University). In 1982 he received his PhD in Geology from Monash University. From then until 1986 he was a postdoctoral fellow in the Department of Chemistry of Arizona State University, involved in research on nuclear waste disposal, experimental petrology and high-temperature calorimetry of geomaterials. In 1987 he moved to the Department of Geology at the Blaise Pascal University of Clermont-Ferrand (France) as an Associate Director of Research. There he continued his work in experimental petrology and modelling of crustal melting. In 1989 he joined Manchester University as lecturer in Geology. From 1994 to 2007 he held the Chair of Geosciences at Kingston University (London) and, from 2001, was also Associate Dean in the Faculty of Science. His present appointment is that of

Professor in Geology and Executive Head of Geology, Geography and Environmental Studies. He is editor-in-chief of the Springer book series *Electronic Geosciences*, and has published 55 papers, mostly in international journals, and several book chapters. The papers have accumulated over 2 500 citations. His most important work has been on the origin and evolution of granitic and silicic volcanic magmas, experimental studies and modelling of partial melting and the ascent and chemical evolution of granitic magmas. These continue to be his main interests.

GRANITE: A PLANETARY RESPONSE TO LIQUID WATER

ABSTRACT

Granites are coarse-grained igneous rocks, rich in quartz and feldspars and containing one or more hydrous minerals, such as micas and amphiboles. They have crystallised from silica-rich magmas that contained significant amounts of dissolved H_2O . Most such magmas are created when the pressures and temperatures, in hydrated rocks deep in the planet's crust, exceed those of the solidus, producing melt and crystalline residue. During this process H_2O need not be present in a free fluid, but the planet's near-surface environments do need to have abundant liquid water to produce weathered and hydrated rocks that ultimately melt to make the magmas. Liquid water in sufficient amounts (oceans) to trigger the chain of processes that leads to the formation of granites occurs on only one terrestrial planet, namely Earth. This explains why only Earth of all the planets in the solar system has plate tectonics, granites, continents and terrestrial life.

WHAT IS A GRANITE AND IS IT IMPORTANT?

A granite (s.l.) is a medium- to coarse-grained intrusive igneous rock, rich in quartz and feldspar-group minerals, and usually containing one or more hydrous minerals, such as muscovite or biotite mica, and amphiboles, such as hornblende. Granitic rocks solidified from silica-rich, hydrous magmas (naturally occurring

molten silicate-rich liquids with dissolved volatiles and possibly some suspended crystals). Consider Figure 1 below, taken from Le Maitre (2002).

This diagram is used to classify igneous rocks in terms of the relative proportions of quartz (Q), alkali (K-Na) feldspar (A), plagioclase (Ca-Na) feldspar (P) and the silica-undersaturated feldspar-like tectosilicate minerals collectively known as feldspathoids (F). Granite, being quartz-bearing, plots in the upper triangle, in the pink-shaded area. The rock types that could be described as 'granitic' include (from left to right in this diagram) alkali feldspar granite, syeno-

granite, monzogranite and granodiorite. Texturally, granitic rocks are typically what is known as hypidiomorphic granular, in which some of the crystals are well shaped, and others show no rational crystal faces at all. Consider the figure below, taken from Pivko (2005).

Figure 2 illustrates a typical granitic texture. The different minerals do not always show this exact arrangement, however, as the degree of perfection of a mineral's crystal shape is to a great extent dependent on its relative position in the crystallisation sequence. In turn, this is governed mainly by the composition of the particular granitic magma. For example, in more Si-rich granitic magmas, the quartz (SiO_2) is typically an early-saturating phase and forms large, well-shaped crystals, while the K-rich alkali feldspar, orthoclase, fills in the interstitial gaps between the earlier

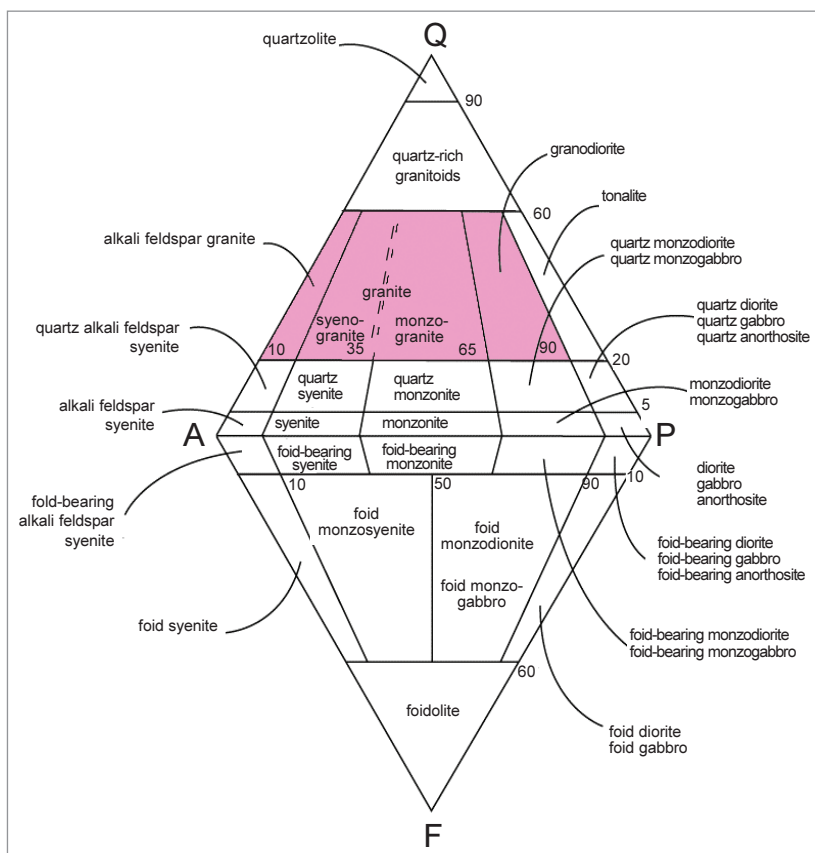


Figure 1: QAPF diagram used to give rocks their correct names, based on their mineral contents.

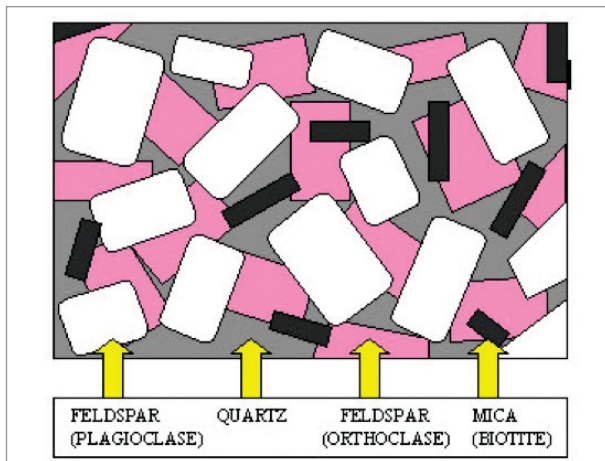


Figure 2: Drawing showing the texture of a typical granitic rock.

crystals. Some granites are even-grained, others have large alkali feldspar crystals set in a finer-grained matrix, and are said to be porphyritic in texture. Some have a gradation of crystal grain sizes, in textures known as seriate. These variations are normally not due to magma chemistry, but to variations in the rate of cooling and crystallisation of the magma.

Figure 3 below is an example of an actual granite texture, as seen in a 0.03 mm thick slice of the rock viewed at high magnification, between crossed polarising filters.

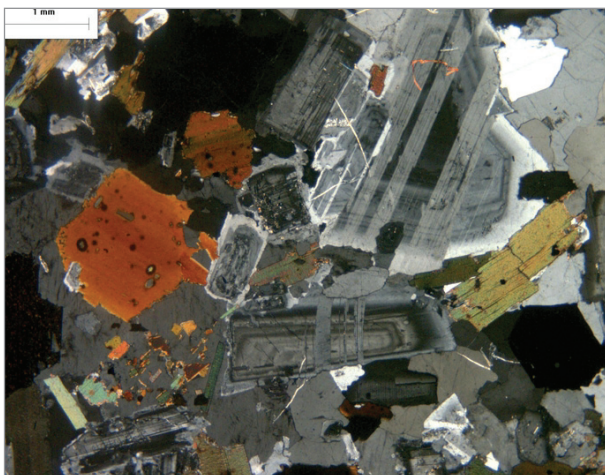


Figure 3: Photomicrograph of the texture of a monzogranite from Mount Disappointment, Victoria, Australia.

Earth scientists are well aware that, for a magma to be created, some pre-existing rock material must melt partially. Various rock reservoirs in the Earth can melt to produce a variety of chemically different magmas. That melting is incongruent. It produces a silicate liquid coexisting with a set of residual, refractory minerals. In the Earth Sciences this is typically called partial melting.

In considering the origins of granitic rocks, it is important to take into account one extremely significant geological observation – on Earth, the planet we know most about, granites, in any significant quantity, are found only on the continents. It is indeed the granitic rocks that make the existence of the continents possible. Oceanic crust (mainly composed of basaltic rocks and their coarser-grained equivalents) have densities of around $2\ 950\ \text{kg/m}^3$. The oceanic crust is born at the mid-ocean ridges as basaltic lava. It then spends a few millions of years travelling away from the ridges and is eventually subducted back into Earth's mantle – a kind of recycling conveyor belt. The relatively low density of the granitic rocks (around $2\ 650\ \text{kg/m}^3$) prevents the continental crust from being subducted and recycled. The continents owe their stability to this difference in density. Another consequence is that the geological history recorded by the continents is much longer than that of the ocean basins. Thus, the continents contain terranes that are older than 3 billion years.

So, granitic rocks gave us continents. They gave us a place where we could evolve and live. They give us most of the metal resources on which civilisation depends. They provide the materials that are weathered to produce the soils that allow us to grow food. In fact, we produce more than we need, and this excess food is the other factor that permits civilisation. Granites also provide for most of our energy requirements, directly in the form of granite-hosted uranium deposits, and indirectly by providing the foundations for the sedimentary environments in which coal and petroleum deposits are formed (river basins, lakes, deltas and continental shelves).

WHERE DO GRANITIC MAGMAS COME FROM?

Given the importance of this one rock type (granite), it is worth exploring and trying to understand the origins of the granitic magmas that solidify to granites. Several ideas have been put forward, and the three main processes can be summarised and assessed as follows:

1. As mantle-derived mafic (mainly basaltic) magmas crystallise, the residual liquid part of the magma becomes more and more enriched in Si and the alkali metals (mainly Na and K). Eventually this fractional crystallisation process leads to the residual liquid having a broadly granitic composition, and the crystallisation of this will produce a kind of granite. However, it takes a very large volume of original

mafic magma to form a relatively small volume of residual granitic liquid. Also, the isotopic characteristics of continental granites unequivocally rule out their derivation by simple fractionation from mantle-derived magmas. This is a relatively minor process that is responsible for the formation of small amounts of granitic rock with a rather special chemistry. The large volumes of granite on the continents are not formed in this way.

2. When pre-existing crustal rocks are heated to high temperatures, they first undergo a variety of devolatilisation reactions. However, if the heat source is powerful enough, the metamorphic conditions progress to what is known as the granulite facies. Here, rocks begin to melt. From observations of the rock record and from the results of high-pressure/high-temperature experimental work, we know that



Figure 4: Granite slab used as a foot bridge, Postbridge, Dartmoor, UK.

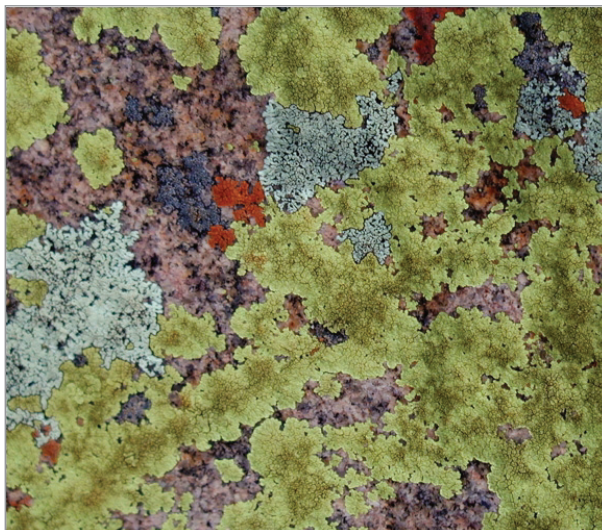


Figure 5: Lichens growing on the Heerenveen granite, Barberton Mountain Land, South Africa.

the partial melts formed at these conditions are granitic in composition. Derivation of granitic magmas by this mechanism satisfies all the observational data about granites, including the critical isotope constraints that demand the involvement of crust, rather than mantle, as the principle component in granitic magmas. Most granitic magmas are thus created when the pressures and temperatures, in hydrated rocks deep in the planet's crust, exceed those of the solidus, producing melt and crystalline residue.

3. In some cases there is clear physical evidence that mantle-derived and crust-derived melts have co-existed and interacted, physically and chemically. Some diffusive and mechanical mixing can indeed occur between the two sorts of magmas, leading to certain kinds of hybrid granitic rocks, enriched in Ca, Mg and Fe compared to purely crustal magmas. Thus, magma mixing and mingling are important secondary processes in some kinds of granitic rock series.

Granitic rock terranes afford some of the most beautiful scenery and interesting ecological habitats, world-wide (e.g. Figures 4 and 5).

They also produce many interesting geological features and structures, as well as varied petrology and geochemistry for igneous geologists to study. However, we should ask the question: Why do we have granites on Earth, since not all planetary bodies have granites?

WHERE DO WE GET GRANITES AND WHY?

The first thing we need to know is that partial melting of any kind of rock occurs at much lower temperatures when there is a free aqueous fluid phase present. This is because H_2O has a powerful depolymerising effect on silicates at high temperature, allowing the breaking of strong Si-O-Si and Si-O-Al bonds. The hydrous melts formed in this process have much lower viscosities and higher diffusion coefficients, due to the depolymerising effects of H_2O . For example, at a pressure of 0.5 GPa (about 5 000 atmospheres), an anhydrous granite would melt at about 1 020 °C. The same mineral mixture would begin to melt at only 645 °C if a pure H_2O fluid were also present. So, to produce granitic magmas at the sorts of temperatures that are possible within the Earth's crust, and probably in many planetary crusts, (< 1 000 °C) we need to have a source of H_2O .

However, H₂O need not be present in a free fluid during this process. The theoretical pressure-temperature phase diagram below (from Clemens, 2006) shows the univariant reaction in a two-component system A-H₂O, where there can be an anhydrous mineral A, a fluid of nearly pure H₂O (Fl), a crystalline hydrate mineral H and a variety of possible H₂O-bearing melt compositions (M) that all have more H₂O in them than the mineral H.

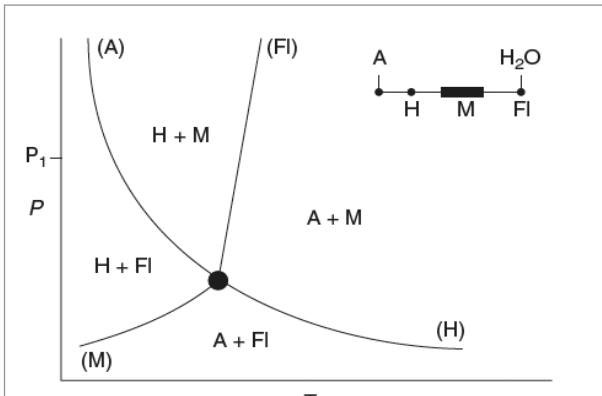


Figure 6: Phase diagram illustrating the kinds of reactions that can occur in a simple chemical system with an anhydrous crystalline solid (A), a crystalline hydrate (H) and H₂O.

The ‘wet’ solidus (beginning of melting) is defined by the reactions: $H + H_2O = M$ and $A + H_2O = M$.

Note, however, that there is another type of melting reaction, known as the fluid-absent reaction because it does not involve the H₂O fluid: $H = A + M$.

In this type of melting reaction, the hydrous mineral H breaks down to the anhydrous mineral A, with the co-production of a melt that now contains the H₂O that was once in the crystalline hydrate.

Through comparing the crystallisation sequences of natural granitic rocks (as determined from textural observations) with the results of experimental determinations of the melting and crystallisation phase relations of these rocks, petrologists have been able to determine the temperatures of formation and initial H₂O contents of the magmas. The results of this work were compiled by Scaillet et al. (1998). These data are represented by the points in Figure 7, from Clemens (2006).

Note that the distribution of the data points is narrowly dispersed in a band in which the melt H₂O content and the temperature are negatively correlated. The cooler magmas are more hydrous and the hotter ones are less hydrous. Analysis and modelling have shown that this relationship and this distribution of the data can only occur if the melting reactions that

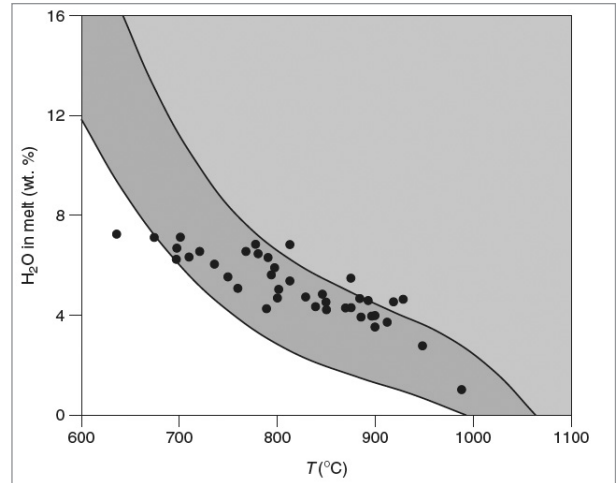


Figure 7: Graph showing the temperatures and H₂O contents of some granitic magmas, as inferred from comparison between experimentally determined phase relations and the order of crystallisation of minerals determined from studies of texture.

produce granites are of the fluid-absent type. Reference to the phase diagram above shows the reason why. At a pressure p , the fluid-absent melting reaction occurs at a particular temperature. At any fixed P and T along such a univariant reaction, the activity of H₂O is also fixed, leading to a unique melt H₂O content. The narrow band, rather than a line, in the figure above reflects the fact that in real, chemically complex rock systems the reactions are bands with higher variance than in the simple model presented here. The low negative slope of the trend in the graph reflects the fact that fluid-absent melting reactions have steep positive slopes in P - T space, which means that the activity of H₂O and melt H₂O contents do not vary widely. These fluid-absent melting reactions certainly occur at higher T than the fluid-saturated solidus reaction, but experiments have shown that they still occur at temperatures accessible within the crust (700 to 900 °C). So, we do not need free aqueous fluid to accomplish partial melting of the crust and production of granitic magmas. All we need is for rocks with hydrous minerals in the crust to be heated by whatever drives high- T metamorphism (radioactive heat production in thickened crust and introduction of mantle heat through the intrusion of mantle magma at depth).

Nevertheless the planet’s near-surface environments do need to have abundant liquid water to produce weathered and hydrated rocks that can ultimately melt to make the magmas. If we look at some of the rock planetary bodies in our own solar system, we can perhaps see why Earth appears to be unique in having granitic rocks.

GRANITES ON PLANETS?

The Jovian satellite Io is geologically very active. It has silicate volcanoes, but it is too hot, has no H₂O (certainly none in liquid form), no oceans, no granites, no continents and no plate tectonics. The image below (Figure 8), as well as the next four, was taken from the Jet Propulsion Laboratory web site (<http://pds.jpl.nasa.gov/planets/>).

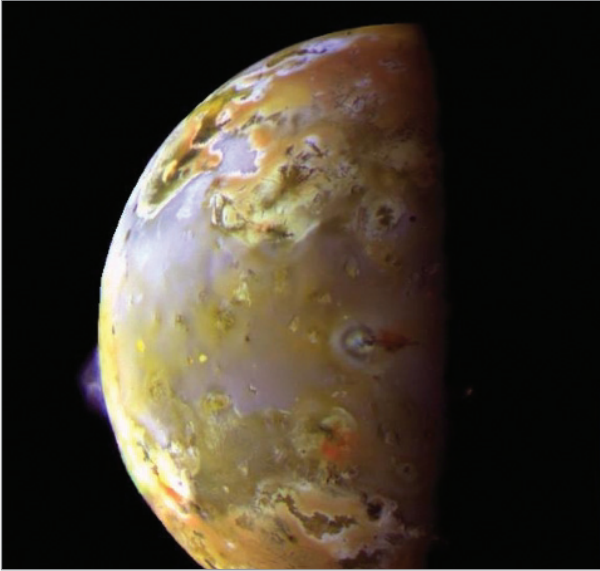


Figure 8: *Io (with volcanic plume on the horizon).*

Our own captured satellite, Moon (Figure 9) is too cold, probably has no or extremely little H₂O, and none in liquid form, no oceans, no granites, no continents and no plate tectonics.



Figure 9: *Moon.*

Venus (Figure 10) is Earth's virtual twin sister, but has undergone a runaway greenhouse effect. It is too hot and, although some H₂O vapour is present, there is no clay formation on the surface, no granites, no continents and no plate tectonics.

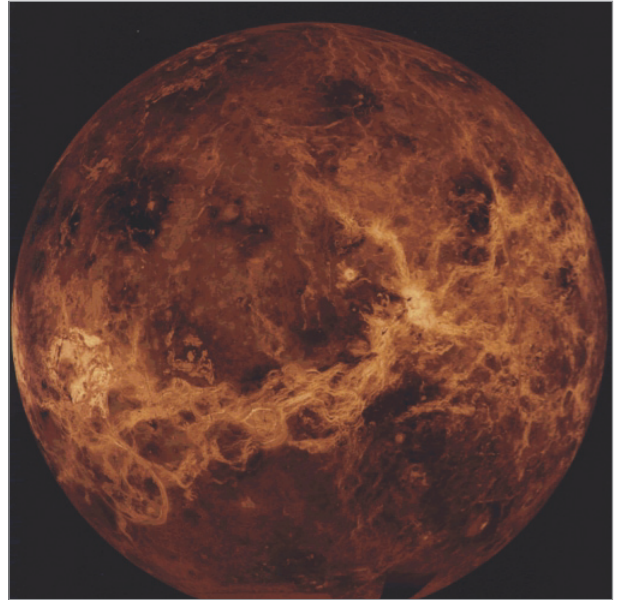


Figure 10: *Coloured composite radar image of Venus.*

Mars (Figure 11) is smaller and more Fe-rich than Earth, and is too cold. It does have some H₂O ice at the poles, possibly some under its dusty soil and it occasionally melts and floods out onto the surface in catastrophic torrents. However, it has no oceans, no granites, no continents and no plate tectonics.

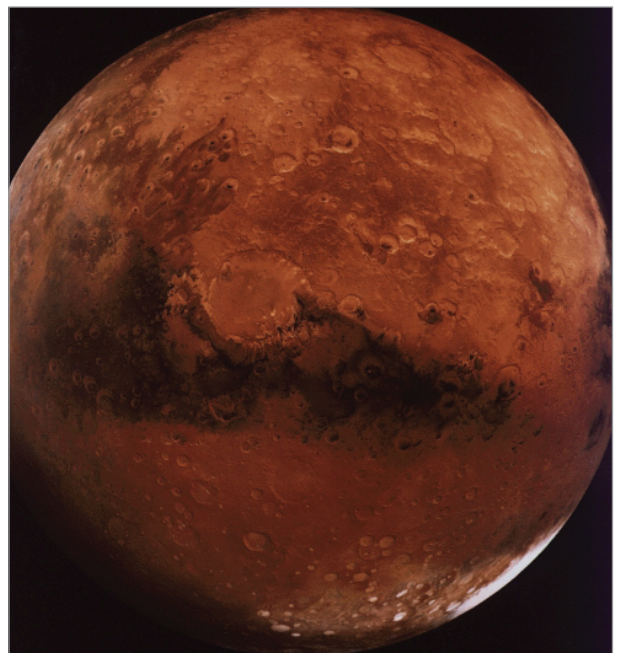


Figure 11: *Mars, showing the southern polar ice cap.*

Earth (Figure 12) is just right, with some H₂O ice (for the moment), a large quantity of water, large oceans, granites, continents, plate tectonics and life.



Figure 12: Earth.

The rules appear to be: no water, no granites – no oceans, no continents (Campbell & Taylor, 1983). But why these the rules? How does this work? The answer to these questions is that the presence of liquid water on a planet's surface allows submarine weathering and hydrothermal alteration of the primitive basaltic crust. Clays and hydromicas are formed in these altered rocks, during their long journey from the mid-ocean ridges toward their “destruction” in the yawning chasms of the subduction zones. Low-*T* partial melting of these hydrated rocks can occur in shallow subduction zones (Foley et al., 2002) or possibly in oceanic plateaux heated by mantle plumes (huge hot upwellings said to originate at the core-mantle boundary). The products of this partial melting of the altered oceanic crust are Na-rich granitic magmas that crystallised, in the Archaean era, to form Earth's first granitic crust. As a low-density material, this sodic granite was buoyant and could therefore resist subduction and so remain at the planet's surface to form the protocontinental nuclei. So, without the liquid water there would be no oceans, no hydrothermal alteration of the ocean floor, no possibility of low-*T* partial melting, no formation of granitic magmas and therefore no continents would be built up over time. Only one terrestrial planet has liquid water in sufficient amounts (oceans) to trigger this critical chain of processes that leads to the formation of granites. This is why Earth alone in the solar system has plate tectonics, granites, continents and terrestrial life. Of course, these

same processes continue today, but it is generally accepted that most of the continental masses were in place by 1.8 Ga (1.8 billion years ago; see Taylor & McLennan, 1985) and that a large proportion of the more recent granitic magma production represents a recycling and refinement of the existing continental crust. This has resulted in the episodic enrichment of the upper continental crust in K, U and Th – the main radioactive heat-producing elements.

Most granitic magmas contain a large component of crustal material. This is evident in their chemistry and isotopic compositions, with enrichment in mantle-incompatible elements (e.g. K, Rb, Th, Zr), radiogenic Sr and Nd and heavy O. In a variety of tectonic situations, hydrated crustal rocks can undergo high-grade (high-*T*) metamorphism. Provided that the rocks are of suitable (fertile) composition, when metamorphic temperatures become high enough (roughly > 750 °C), corresponding to the upper amphibolite and granulite facies of regional metamorphism, they can become partially melted. Experiments have shown that the melts (hydrous silicate liquids) are granitic (*s.l.*) in composition, and that they form the volumetrically dominant portions of a variety of granitic magmas that can ascend through the crust and be emplaced at shallower levels.

Much of the heat for this metamorphism and partial melting commonly comes through emplacement of hot, mantle-derived basaltic magma deep in the crust. Over time, the formation and ascent of granitic magmas causes the continental crust to become differentiated. The lower part becomes more mafic by additions of mantle-derived magma and the removal of the lower-density granitic component, which rises to enrich the upper crust in SiO₂, K, U, Th, etc. (see e.g., Clemens, 1990).

As we have seen above, H₂O is necessary, as a component, to allow partial melting at the sorts of temperatures that can be realised in Earth's crust. However, because rocks can partially melt by fluid-absent reactions, free H₂O fluid is not required. This means that rocks deep in Earth's crust, where there is no significant reservoir for H₂O fluid, can still produce up to some 10s of per cent of granitic melt, provided that *T* is sufficiently high.

FLUID-ABSENT PARTIAL MELTING OF CRUSTAL ROCKS

It is worth examining the types of fluid-absent partial melting reactions that can occur in common types of rocks. In the section below, the following mineral abbreviations are used: Ms = muscovitic white mica

(hydrous K, Al sheet silicate), Pl = plagioclase (Ca-Na) feldspar (framework silicate), Qtz = quartz, Als = Al_2SiO_5 , Kfs = alkali (K-Na) feldspar (framework silicate), Bt = biotitic dark mica (hydrous Mg, Fe, Al sheet silicate), Grt = garnet (Mg, Fe, Al island silicate), Crd = cordierite (Al-rich Fe, Mg ring silicate), Opx = orthorhombic pyroxene (Ca-free, Mg, Fe single-chain silicate), Cpx = monoclinic pyroxene (Ca-bearing, Mg, Fe single-chain silicate), Hbl = hornblende (hydrous Ca, Na, Mg, Fe, Al double-chain silicate).

- In metapelites (former clay-rich sediments such as shales and mudstones):
 $\text{Ms} + \text{Pl} + \text{Qtz} = \text{Als} + \text{Kfs} + \text{S-type leucogranitic melt}$
 $\text{Bt} + \text{Pl} + \text{Als} + \text{Qtz} = \text{Grt/Crd} + \text{S-type granitic melt}$
- In metagreywackes (former clay-bearing sandstones) and metatonalites (relatively low-Si granitoid rocks):
 $\text{Bt} + \text{Pl} + \text{Qtz} = \text{Opx} (+ \text{Cpx} + \text{Grt}) + \text{S- or I-type granitic melt}$
- In metabasalts and meta-andesites (former basaltic and andesitic lavas):
 $\text{Hbl} + \text{Qtz} = \text{Pl} + \text{Opx} + \text{Cpx} + \text{I-type granitic melt}.$

SOME FUNDAMENTAL THINGS WE THINK WE KNOW ABOUT GRANITIC MAGMAS

The following physicochemical parameters are what we currently believe are inherited by granitic magmas (see e.g., Clemens, 1998; Clemens & Mawer, 1992; Clemens & Petford, 1999), in their mostly molten state, prior to significant cooling and crystallisation:

- Temperatures = ~ 650 to 1 100 °C
- Initial dissolved H_2O contents = 2 to 7 wt%
- Densities = all close to 2 250 kg/m^3 , even with up to 50 vol.% crystals present
- Viscosities = 10^3 to 10^6 Pa.s across the whole compositional range
- Magma ascent mechanisms = mainly self-propagating fractures, at $\sim 10^{-2}$ m/s
- Crystallisation kinetics = quite rapid – hours to years to grow large crystals.

SOME CURRENT DEBATES AND A KIND OF CONCLUSION

Although we are quite knowledgeable about many aspects of the phenomenon of granite formation, there remain considerable uncertainties, debates and issues. The following questions summarise these concerns:

- How fast are batholiths (aerially extensive granitic bodies) built? We know, from structural geology, that there are many different mechanisms that can be responsible for the emplacement of granitic bodies. However, the theoretical ascent rates of magmas in dykes may not tell us much about pluton growth rates. At the lower end these are controlled by the magma supply rate in the source region and, at the upper end, by the rates of the tectonic processes responsible for space creation. Neither of these controlling factors is well constrained, at present.
- Are plutons and batholiths built in a single pulse of homogeneous magma that then differentiates in a huge magma chamber, or are they heterogeneous accumulations of multiple, small, chemically distinct pulses? The geochemical and isotopic data on granitic complexes is beginning to suggest that the big liquid chamber model is fundamentally flawed and that many granitic magmas do not differentiate into their compositional spectra, but inherit their compositional heterogeneities from pulsed magma formation in heterogeneous source regions (Figure 13).

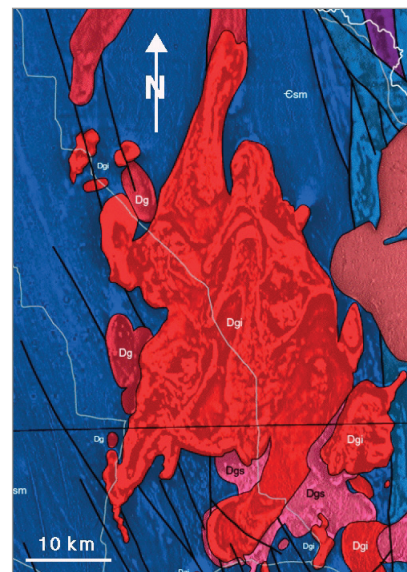


Figure 13: Map of a section of north-western Victoria (Australia) showing the first vertical derivative of total magnetic intensity.

The type of magnetic survey used to produce Figure 13 “sees” several kilometres into the ground/rock. The lighter the colour, the more magnetic the rocks are. The map shows some of the internal structure of Devonian granitic plutons and the surrounding and Ordovician metasediments. This is an enlargement of a section of the 1:1 000 000 scale map of Simons and Moore (1999), published as an enclosure in Van den Berg et al. (2000). The lobate and concentric ring patterns are strongly

reminiscent of flow features in lavas. The higher and lower susceptibility bands could indicate sub-pulses of magma within the tongues or lobes that may correspond to the main pulses of magma (rather like flow units in lavas). The interpretation of patterns like this remains uncertain, but they are undeniably spectacular and clearly of some importance and interest.

Apart from ongoing academic debate on their

origins, what can granites provide us with in the energy- and resource-hungry human world? Many ore deposits are either hosted by granitic rocks or associated with granitic intrusions. Some oil deposits are hosted in highly fractured granites.

This all assumes that we recognise that, without granites, there would have been no continents and no terrestrial life, and, therefore, nobody to ask the above question in the first place!

REFERENCES CITED

- Campbell, I.H. & Taylor, S.R. 1983. No water, no granites – no oceans, no continents. *Geophysical Research Letters* 10, 1061–1064.
- Clemens, J.D. 1990. The granulite – granite connexion. In: *Granulites and Crustal Differentiation* (eds Vielzeuf, D. & Vidal, P.) NATO ASI Series. Dordrecht: Kluwer Academic Publishers. 25–36.
- Clemens, J.D. 1998. Observations on the origins and ascent mechanisms of granitic magmas. *Journal of the Geological Society of London* 155, 843–851.
- Clemens, J.D. 2006. Melting of the continental crust: fluid regimes, melting reactions and source-rock fertility. In: *Evolution and Differentiation of the Continental Crust* (eds Brown, M. & Rushmer, T.). Cambridge University Press. 297–331.
- Clemens, J.D. & Mawer, C.K. 1992. Granitic magma transport by fracture propagation. *Tectonophysics* 204, 339–360.
- Clemens, J.D. & Petford, N. 1999. Granitic melt viscosity and silicic magma dynamics in contrasting tectonic settings. *Journal of the Geological Society of London* 156, 1057–1060.
- Foley, S., Tiepolo, M., & Vannucci, R. 2002. Growth of early continental crust controlled by melting of amphibolite in subduction zones. *Nature* 417, 837–840.
- Jet Propulsion Laboratory [Online 2005/10/05]. Available: <http://pds.jpl.nasa.gov/planets> [2008/08/26]
- Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Wolley, A.R., & Zanettin, B. 1989. *A Classification of Igneous Rocks and Glossary of Terms*. Oxford: Blackwell.
- Pivko, D. 2005. *The world's most popular granites – updated and extended to 180 granites* [2005/01/01]. Department of Geology and Paleontology, Comenius University, Bratislava, Slovakia. Available: <http://www.findstone.com/daniel1.htm> [2008/08/26]
- Scaillet, B., Holtz, F. & Pichavant, M. 1998. Phase equilibrium constraints on the viscosity of silicic magmas – I. Volcanic-plutonic association. *Journal of Geophysical Research-Solid Earth* 103, 27257–27266.
- Simons, B.A. & Moore, D.H. 1999. Victoria 1:1 000 000 Pre-Permian Geology. Geological Survey of Victoria.
- Taylor, S.R. & McLennan, S.M. 1985. *The Continental Crust: its Composition and Evolution*. Oxford: Blackwell Scientific Publications.
- Van den Berg, A.H.M., Willman, C.E., Maher, S., Simons B.A., Cayley, R.A., Taylor, D.H., Morand, V.J., Moore, D.H. & Radojkovic, A. 2000. *The Tasman Fold Belt System in Victoria*. Geological Survey of Victoria Special Publication.



Figure 14: The author in Namibia (Khan River valley)