

Post-Archean granitic rocks: contrasting petrogenetic processes and tectonic environments



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Abstract: Granitic rocks represent a ubiquitous component of upper continental crust but their origin remains highly controversial. This controversy stems from the fact that the granites may result from fractionation of mantle-derived basaltic magmas or partial melting of different crustal protoliths at contrasting pressure–temperature conditions, either water-fluxed or fluid-absent. Consequently, many different mechanisms have been proposed to explain the compositional variability of granites ranging from whole igneous suites down to mineral scale. This Special Publication presents an overview of the state of the art and envisages future avenues towards a better understanding of granite petrogenesis.

Granite (*sensu lato*) represents a ubiquitous rock type dominating the upper–middle continental crust (Taylor & McLennan 2009; Rudnick & Gao 2014). For this reason, the granites have attracted a plethora of studies, some dating back to the dawn of modern igneous geology in the mid-eighteenth century. Ever since, the controversy regarding the origin of granites has been raging more or less continuously, even though focusing on various aspects of the ‘granite problem’ (e.g. see Pitcher 1987, 1993; Clarke 1996; Cobbing 2000; Young 2003 for reviews).

The ‘great debate’

The modern dispute on the origin of granites dates back to James Hutton who, based on carefully

made observations of textures, field relationships, as well as the presence of country-rock meta-sedimentary xenoliths in granitic intrusions of the Scottish Highlands, proposed the revolutionary idea that granite had to be a product of crystallization from a ‘fluidal substance’ (i.e. magma) (Hutton 1788, 1794). This was in sharp contrast with the then governing Wernerian theory (Werner 1787) in which the granites belonged to the ‘Primitive foundation’, precipitated from the primeval ocean.

The other flare-up in the heated debate was centred on the so-called ‘room problem’, considering the way in which large granitic batholiths can be accommodated within crust, especially in cases when the country rock did not show evidence of strong deformation. The other disputed observation

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came from the study of migmatite terrains, especially in Nordic countries, where the contacts between intrusions, partially molten and residual rocks are often transitional.

An apparent remedy was offered by the ‘transformists’, who proposed *in situ* conversion of pre-existing rocks by metasomatic fluids or other mechanisms (Read 1957; Mehnert 1968). However, the ‘magmatists’ assumed that granites were a product of crystal differentiation from a primary basaltic magma. Indeed, the eutectic and cotectic compositions of common granites, reproduced by water-present melting experiments, represent a powerful argument against the metasomatic models (Bowen 1948; Tuttle & Bowen 1958).

Another breakthrough came in the late 1960s and early 1970s when it was recognized that many granites are crustally derived, having originated by partial melting of metasediments (Winkler 1965). These publications were followed by the first experiments that generated granites by dehydration melting of metapelitic starting materials (Brown & Fyfe 1970).

With the advancement of geochemistry, new source-orientated paradigms emerged. Most notably, it was the classification of Chappell & White (1974), further elaborated over the years (Chappell & White 1992, 2001). Mainly based on modal composition and major-element whole-rock geochemistry, it distinguished granites generated by partial melting of lower-crustal meta-igneous rocks (thus termed I-type) from those originating by anatexis of metasedimentary sources (S-type). As a result of the popularity of this scheme, the ‘alphabetic soup’ terminology was supplemented by anorogenic A-types (Loiselle & Wones 1979), mantle-derived M-types (White 1979), charnockitic C-types (Kilpatrick & Ellis 1992) and hybrid H-types (Castro *et al.* 1991), eventually leading to a considerable confusion (Clarke 1992).

Nowadays, it is widely believed that a significant number of granites, including those occurring at active continental margins, may result from fractionation of mantle-derived basaltic magmas (Grove *et al.* 2003; Ulmer *et al.* 2018). Many others, especially those in collisional orogens, are the ultimate product of regional metamorphism, leading to partial melting of different crustal protoliths at contrasting pressure–temperature conditions, either water-fluxed or fluid-absent (Clemens 2003, 2005, 2012; Brown 2010, 2013; Weinberg & Hasalová 2015; Collins *et al.* 2016; Yakymchuk 2019).

In collisional orogens, granitic crustal melts can be produced due to both crustal thickening and thinning, as well as decompression of high-grade, metamorphic terrains. The heat necessary for anatexis can be: (1) produced *in situ*, due to radioactive decay in a thickened continental crust rich in U, Th and K; (2) advected from basic intrusion(s) or from

quickly exhumed, still hot, lower-crustal metamorphic complexes; (3) conducted from a thermal anomaly in the mantle (originating due to slab break-off, thermal boundary layer detachment, mantle delamination, asthenosphere upwelling in extensional settings or ascent of a mantle plume); or (4) come from an underlying metasomatized/crustally-contaminated lithospheric mantle where it is produced by *in situ* radioactive decay (Henk *et al.* 2000; Clark *et al.* 2011; Bea 2012).

Why the ‘granite problem’ is still there

Granites are difficult to study for four main reasons. The first problem is that granitic melts, regardless of their parental composition, tend to evolve towards the granite minimum in the course of crystallization or are often minimal melts to start with (Johannes & Holtz 1996). Secondly, the generally high viscosity of siliceous melts, especially the low-temperature S-type ones (Dingwell 1999), means that many granites (*sensu lato*) do not represent pure melts. They rather are mixtures of cumulus phase(s) or even crystal mushes, from which liquids were extracted and erupted as dacites or rhyolites (Bachmann & Bergantz 2004, 2008; Bachmann & Huber 2016; Cashman *et al.* 2017), or partial melts that have carried entrained material from the source, either restite or peritectic phases (Chappell *et al.* 1987; Stevens *et al.* 2007; Clemens *et al.* 2010, 2011). Moreover, during its construction, a granitic pluton may also incorporate extra material either from the country rock (xenocrysts) or the previous pulses of the same magmatism (antecrysts) (Streck 2008; Jerram *et al.* 2018). A distinct (third) possibility remains of mixing or mingling with some other magma pulse(s), either broadly cogenetic, during incremental construction commonly invoked for the granitic plutons (Bartley *et al.* 2006; Farina *et al.* 2012; Chen & Nabelek 2017; Hines *et al.* 2018), or even coming from a contrasting, mantle source (Hibbard 1995; Perugini & Poli 2000; Didier & Barbarin 1991). Last, but not least, granitic plutons are commonly associated with hydrothermal systems, and the water-rich fluid unmixed during crystallization inevitably results in alterations.

To obscure things further, the methods we are using are not flawless. The large sets of compositional data require machine processing but sophisticated statistical methods very often cannot decipher any useful patterns beyond the analytical or natural noise. Alternatively, they may yield undisputed truths and obvious conclusions, apparent to anyone with a good working knowledge of field relationships, petrology and/or the composition of granitic rocks. Given the number of mineral phases, including accessories, (nearly) all trace elements behave

as compatible ones, complicating whole-rock-based geochemical modelling (Janoušek *et al.* 2016). Of course, these techniques are also difficult to apply when not dealing with pure melts.

Frustratingly, progress in understanding granite genesis often has not seemed to advance in step with the effort invested. As in other branches of science, the existence of a large community of active researchers also has its downside, as the relevant literature is massive and impossible to follow in its entirety. Any progressive or even ground-breaking ideas can thus be swamped by work that represents only incremental, if any, advancement.

As previous disputes have shown, the large community tends to buffer changes in the long-term status quo; any innovative approach has to struggle with tradition, or even rigidity, and most workers tend to stick to existing paradigms. Moreover, geologists typically believe and apply their own experience; thus, depending on the country of origin and terrains they have worked in, they prefer certain ideas and models over the others. Nowadays, it is unthinkable that Hutton, for the sake of being unbiased, intentionally sought field evidence for his influential theory on the origin of granites only after its first public presentation.

Lastly, all of us are, to varying degrees, ignorant or careless regarding the original definitions and proper meaning of even the most elementary terms. Over time, some of them (e.g. the adjective ‘calc-alkaline’) have lost their original meaning and should be either redefined or dropped. Moreover, granite petrologists, like other igneous petrologists, have introduced a plethora of historical and parochial names for essentially the same rock types that still persist in the current literature despite the sterling efforts of the IUGS Subcommittee on Systematics of Igneous Rocks (Streckeisen 1976; Le Maitre 2002). Thus, we all should strive to use the approved terminology with as much rigour as possible.

Ways ahead

From the above it follows that the origin of granitic rocks is likely to remain a matter of passionate debate for years to come. It will certainly be fuelled by an increasing demand for raw materials, increasing computer power and progress in analytical techniques. The latter will secure a never-finisher flux of increasingly affordable, high-quality compositional data, including non-traditional isotopic systems such as Fe, Ca, Li, Mg, Si, Cr or stable Sr (Johnson *et al.* 2004; Foden *et al.* 2015; Tomascak *et al.* 2016; Teng *et al.* 2017), as well as *in situ* elemental and isotopic data for both individual minerals and melt inclusions. To tackle the flood of data, an

increasing role will be played by statistical and computing methods, data mining and online databases, shared through the World Wide Web. There is also a clear trend towards the increased application of ever-improving tools for phase-equilibria modelling (Ghiorso & Sack 1995; Asimow & Ghiorso 1998; Holland & Powell 1998, 2011; Connolly 2005; Gualda *et al.* 2012; Green *et al.* 2016) that will become integrated into larger packages for comprehensive modelling of igneous rocks (Bohrson *et al.* 2014; Mayne *et al.* 2016). But at the same time, we should not forget that we ultimately try to describe and explain natural phenomena, and thus detailed and careful field and petrological work remain indispensable even in the twenty-first century.

In this Special Publication the Editors aim to present an overview of the state of the art, as well as envisaging future avenues towards a better understanding of granite petrogenesis. As such, it is a follow-up of the excellent GSL Special Publication *Understanding Granites: Integrating New and Classical Techniques* of Castro *et al.* (1999), which is now exactly 20 years old. The current Special Publication contains 10 papers, covering four main themes:

- Compositional variability of granitic rocks generated in contrasting geodynamic settings during the Proterozoic–Phanerozoic periods.
- Main permissible mechanisms producing subduction-related granites.
- Crustal anatexis of different protoliths, and the role of water in granite petrogenesis.
- Theoretical tools available for modelling whole-rock geochemical evolution and phase-mineral equilibria to decipher the evolution of granitic suites in P – T – t space.

Granitoids are the most common rocks in the Earth’s continental crust and display many varieties, and thus require classification. After a historical review of previous schemes suggested on various grounds, Bonin *et al.* (2020) state that classification should preferentially link the bulk chemical composition to the stoichiometry of the constituent minerals. Based on statistical analysis of a large database of granitic compositions, they identify the most discriminant geochemical variables. They suggest the winning strategy is to use simple atomic parameters (e.g. millication-based) that can be linked to modal proportions and compositions/structure of individual rock-forming minerals.

A-type granitoids, less abundant than the other granite types, have generated no worldwide consensus about their origins. Collins *et al.* (2019) compare A-type granitoids in two classical type localities: the Mesozoic Younger Granites province (northern Nigeria) and the Paleozoic Lachlan Fold Belt (eastern Australia). They show that rocks of the

anorogenic Nigerian province crystallized from hotter and drier liquids than those of the post-orogenic A-types of the Lachlan Fold Belt province, which were situated in a distal back-arc setting. In the latter case, A-type granites are not strictly within-plate, as generally assumed, but nonetheless were hotter and more anhydrous than the associated S- and I-type granites.

Whether large batholiths originate from magmas occurring at the end of fractionation trends defining a basalt–(basaltic) andesite–dacite–rhyolite series, or form by partial melting of older crustal lithologies (amphibolites or intermediate igneous rocks) remains a contentious issue (see [Castro 2019](#)). [Moyen \(2019\)](#) explores the thermal implications of both scenarios. Two situations appear equally favourable for generating large volumes of granites: short-lived high basaltic flux, where granites result mostly from basalt differentiation, and long-lived systems with no or only minimal basalt flux, where granites are chiefly a product of crustal melting.

In the original alphabetical classification ([Chappell & White 1974](#)), I-type granitoids were defined as having originated from partial melting of igneous rocks located within the Earth's lower crust. Geological and geochemical features provide evidence that other formations may be involved, such as immature quartzo-feldspathic metasedimentary suites. In a review of experimental data, [Castro \(2019\)](#) shows that I-type granitoids should be subdivided into two classes: 'primary granitoids' that are directly related to subduction and composed of fractionated liquids from intermediate magma systems of broadly andesitic composition, and 'secondary granitoids' that are crustal melts produced by fluid-fluxed melting of older subduction-related igneous rocks that resided in the continental crust.

[Fiannacca *et al.* \(2019\)](#) describe Late Paleozoic peraluminous granites and trondhjemites from southern Italy, demonstrating the contrasting roles of water-fluxed and fluid-absent (dehydration) melting during magma genesis. They also explain an unusual low-Ca trondhjemite suite by metasomatic alteration, highlighting the need for petrographical analysis in conjunction with geochemical modelling.

[Nabelek \(2019\)](#) provides an overview of compositional variability and possible genesis of peraluminous leucogranites that are ubiquitous in collisional orogens, such as the Variscides and Himalayas. Based mainly on phase-equilibria and whole-rock geochemical considerations, it is concluded that most of these syn- to post-collisional leucogranites are characterized by the presence of muscovite, biotite and tourmaline, and formed under vapour-poor conditions involving a peritectic breakdown of muscovite.

In their first contribution, [Mayne *et al.* \(2019a\)](#) present the background, overall philosophy and

explore full potential of their new software (RCRUST) ([Mayne *et al.* 2016](#)) which allows phase-equilibria modelling along pressure–temperature paths with composition as a variable. To demonstrate the utility of RCRUST for process-orientated investigations, the authors briefly present four possible fields of application. In the first, they explore the evolution of the water content in a fully-hydrated but fluid-absent rock composition along pressure–temperature trajectories that evolve towards granulite- and eclogite-facies peak metamorphic conditions. The second and third cases investigate the effect of melt loss during partial melting and the role of peritectic crystals entrained from the source. The last of the open-system processes presented deals with melt–crystal separation during crystallization, mimicking processes like crystal settling or filter pressing in magma reservoirs.

In their second contribution, [Mayne *et al.* \(2019b\)](#) apply RCRUST to investigate the control exerted by the source on the bulk composition of anatectic melts derived by partial melting of an average pelite under both water-deficient and water in excess conditions. The initial magnesium, iron, sodium and calcium contents of the source are varied, as are the pressure–temperature path followed by the system and the melt extraction threshold. The resulting melt compositions are compared to those of natural S-type granites. The work confirms that the strongest control on melt composition is exerted by the availability of a water-rich fluid in the source, while bulk-rock composition and the degree of melt retention in the source have only a minor influence.

Another interesting application of the path-dependent phase-equilibria modelling using the software RCRUST is presented in the case study of the Buddusò Pluton in NE Sardinia by [Farina *et al.* \(2019\)](#). The authors propose that the internal chemical variability of this normally-zoned pluton, homogeneous in terms of whole-rock Sr–Nd isotopic compositions, could have been generated by crystallization differentiation of the same hydrous tonalitic parental magma. The inferred mechanism invokes compaction in a rheologically locked crystal-rich magma chamber ([Bachmann & Bergantz 2004](#)).

Petrogenesis of igneous suites, including granitoids, may be deciphered by whole-rock geochemical modelling. [Janoušek & Moyen \(2019\)](#) provide an overview of the current approaches and argue that petrogenetic modelling is a powerful tool to rule out impossible scenarios and to constrain likely processes inferred from geological and petrological observations. Particularly promising seems to be the development of integrated, coherent and comprehensive software, using the R and Python languages ([Shen 2014](#); [Janoušek *et al.* 2016](#); [Mayne *et al.* 2016](#)), that combines thermodynamic and

whole-rock geochemistry-based petrogenetic modeling of igneous rocks.

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