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Post-Archean granitic rocks: contrasting petrogenetic Q1 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, as well as 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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59 came from the study of migmatite terrains, especially
60 in Nordic countries, where the contacts between
61 intrusions, partially molten and residual rocks were
62 often transitional.

63 An apparent remedy was offered by the ‘trans-
64 formists’, who proposed *in situ* conversion of
65 pre-existing rocks by metasomatic fluids or other
66 mechanisms (Read 1957; Mehnert 1968). However,
67 the, ‘magmatists’ assumed that granites were a prod-
68 uct of crystal differentiation from a primary basaltic
69 magma. Indeed, the eutectic and cotectic composi-
70 tions of common granites, reproduced by water-
71 present melting experiments, represent a powerful
72 argument against the metasomatic models (Bowen
73 1948; Tuttle & Bowen 1958).

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

81 With the advancement of geochemistry, new
82 source-orientated paradigms emerged. Most notably,
83 it was the classification of Chappell & White (1974),
84 further elaborated over the years (Chappell & White
85 1992, 2001). Mainly based on modal composition
86 and major-element whole-rock geochemistry, it
87 distinguished granites generated by partial melting
88 of lower-crustal meta-igneous rocks (thus termed
89 I-type) from those originating by anatexis of meta-
90 sedimentary sources (S-type). As a result of
91 the popularity of this scheme, the ‘alphabetic soup’
92 terminology was supplemented by anorogenic
93 A-types (Loiselle & Wones 1979), mantle-derived
94 M-types (White 1979), charnockitic C-types (Kilpa-
95 trick & Ellis 1992) and hybrid H-types (Castro *et al.*
96 1991), eventually leading to a considerable confu-
97 sion (Clarke 1992).

98 Nowadays, it is widely believed that a significant
99 number of granites, including those occurring at
100 active continental margins, may result from fractiona-
101 tion of mantle-derived basaltic magmas (Grove
102 *et al.* 2003; Ulmer *et al.* 2018). Many others, espe-
103 cially those in collisional orogens, are the ultimate
104 product of regional metamorphism, leading to partial
105 melting of different crustal protoliths at contrasting
106 pressure–temperature conditions, either water-fluxed
107 or fluid-absent (Clemens 2003, 2005, 2012; Brown
108 2010, 2013; Weinberg & Hasalová 2015; Collins
109 *et al.* 2016; Yakymchuk 2019).

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

quickly exhumed, still hot, lower-crustal meta-
morphitic 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 gran-
ites (*sensu lato*) do not represent pure melts. They
rather are mixtures of cumulus phase(s) or even crys-
tal 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 car-
ried 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 incremen-
tal 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 com-
monly 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 composi-
tional data require machine processing but sophisti-
cated 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 relation-
ships, petrology and/or the composition of granitic
rocks. Given the number of mineral phases, includ-
ing accessories, (nearly) all trace elements behave

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

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

130 As previous disputes have shown, the large com-
131 munity tends to buffer changes in the long-term sta-
132 tus quo; any innovative approach has to struggle with
133 tradition, or even rigidity, and most workers tend to
134 stick to existing paradigms. Moreover, geologists
135 typically believe and apply their own experience;
136 thus, depending on the country of origin and terrains
137 they have worked in, they prefer certain ideas and
138 models over the others. Nowadays, it is unthinkable
139 that Hutton, for the sake of being unbiased, inten-
140 tionally sought field evidence for his influential the-
141 ory on the origin of granites only after its first
142 public presentation.

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

160 Ways ahead

161 From the above it follows that the origin of granitic
162 rocks is likely to remain a matter of passionate debate
163 for years to come. It will certainly be fuelled by
164 an increasing demand for raw materials, increasing
165 computer power and progress in analytical tech-
166 niques. The latter will secure a never-finishing flux
167 of increasingly affordable, high-quality compo-
168 sitional data, including non-traditional isotopic sys-
169 tems such as Fe, Ca, Li, Mg, Si, Cr or stable Sr
170 (Johnson *et al.* 2004; Foden *et al.* 2015; Tomascak
171 *et al.* 2016; Teng *et al.* 2017), as well as *in situ* ele-
172 mental and isotopic data for both individual minerals
173 and melt inclusions. To tackle the flood of data, an

increasing role will be played by statistical and com-
puting 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 compre-
hensive 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 indis-
pensable even in the twenty-first century.

In this Special Publication the Editors aim to pre-
sent an overview of the state of the art, as well as
envisaging future avenues towards a better under-
standing 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 gener-
ated in contrasting geodynamic settings during the
Proterozoic–Phanerozoic periods.
- Main permissible mechanisms producing subduc-
tion-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 dis-
criminant 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 individ-
ual rock-forming minerals.

A-type granitoids, less abundant than the other
granite types, have generated no worldwide consen-
sus 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

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

183 Whether large batholiths originate from magmas
184 occurring at the end of fractionation trends defining
185 a basalt–(basaltic) andesite–dacite–rhyolite series,
186 or form by partial melting of older crustal litho-
187 logies (amphibolites or intermediate igneous rocks)
188 remains a contentious issue (see [Castro 2019](#)).
189 [Moyen \(2019\)](#) explores the thermal implications of
190 both scenarios, two situations appear equally favour-
191 able for generating large volumes of granites: short-
192 lived high basaltic flux, where granites result mostly
193 from basalt differentiation, and long-lived systems
194 with no or only minimal basalt flux, where granites
195 are chiefly a product of crustal melting.

196 In the original alphabetical classification ([Chap-
197 pell & White 1974](#)), I-type granitoids were defined
198 as having originated from partial melting of igneous
199 rocks located within the Earth's lower crust. Geo-
200 logical and geochemical features provide evidence
201 that other formations may be involved, such as
202 immature quartzo-feldspathic metasedimentary
203 suites. In a review of experimental data, [Castro
204 \(2019\)](#) shows that I-type granitoids should be sub-
205 divided into two classes: 'primary granitoids' that
206 are directly related to subduction and composed of
207 fractionated liquids from intermediate magma sys-
208 tems of broadly andesitic composition, and 'second-
209 ary granitoids' that are crustal melts produced by
210 fluid-fluxed melting of older subduction-related
211 igneous rocks that resided in the continental crust.

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

220 [Nabelek \(2019\)](#) provides an overview of compo-
221 sitional variability and possible genesis of peralumi-
222 nous leucogranites that are ubiquitous in collisional
223 orogens, such as the Variscides and Himalayas. Based
224 mainly on phase-equilibria and whole-rock
225 geochemical considerations, it is concluded that
226 most of these syn- to post-collisional leucogranites
227 are characterized by the presence of muscovite,
228 biotite and tourmaline, and formed under vapour-
229 poor conditions involving a peritectic breakdown
230 of muscovite.

231 In their first contribution, [Mayne et al. \(2019b\)](#)
232 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 investiga-
tions, 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.
\(2019a\)](#) 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 soft-
ware 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 chemi-
cal variability of this normally-zoned pluton, homo-
geneous in terms of whole-rock Sr–Nd isotopic
compositions, could have been generated by crystal-
lization 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 gran-
itoids, may be deciphered by whole-rock geochemi-
cal 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 petro-
logical 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 modelling of igneous rocks.

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