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Research Article

Crustal melting vs. fractionation of basaltic magmas: Part 1, granites and paradigms

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ABSTRACT

Granitoids are a major component of the continental crust. They play a pivotal role in its evolution, either by adding new material (continental growth), or by reworking older continental crust. These two roles correspond to two main ways of forming granitic magmas, either by partial melting of pre-existing crustal rocks yielding granitic melts directly, or by fractionation of mantle-derived mafic to intermediate magmas. Both models represent endmembers, or paradigms that have shaped the way the geological community envisions granitoids, their occurrence, features, formation and meaning for crustal evolution and differentiation of the whole planet.

In this paper, we expose the two competing paradigms and their implications. We explore the evidence on which each model is based, and how each school of thought articulates a comprehensive view of granitic magmatism based on field geological, petrological, geochemical (including isotopes) and physical constraints; and how, in turn, each view shapes the thinking on crustal growth and evolution, and the interpretation of proxies such as age and Hf isotopic patterns in detrital zircon databases. We emphasize that both schools of thought build a different, but internally consistent view based on a large body of evidence, and we propose that each of them is, or has been, relevant to some portions of the Earth. Thus, the key question is not so much “which” model applies, but “where, when and to which extent”.

1. Introduction

“*This question of the origin of granite is perhaps the most lively of geological topics today—but we should remember that it always has been. About every twenty years or so, the problem has been firmly settled, and a sort of uneasy peace has broken out. This indicates to my mind that there is no unique solution of the problem—there are granites and granites.*” – Read, 1948 (p. 1)

These words, by H. Read, then one of the most influential granite[1] petrologists, neatly express the nature of the debates that structure, and perhaps polarize the granite community to this day. In Read’s time, the main controversy was between transformists and magmatists. Transformists (Perrin and Roubault, 1937; Raguin, 1976; Sederholm, 1923; Wegmann, 1935) proposed that granites were the product of solid-state, fluid-induced transformation of country rocks (“metasomatism”, in modern terms). Magmatists, who in the 1940s were winning the argument, held the view now universally admitted that granites are igneous rocks, crystallized from magmas. But this only displaced the controversy, as Read also wrote that "*Certain authorities consider therefore that a primary granitic magma could arise by melting, pure or partial, of the sialic crust, once it has been separated from the simatic layer. This magma is independent and not derived from a primary basaltic magma. This classic two-magma view that agrees with the distribution of rock types in the crust*

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[1] *This paper deals with granitoids (i.e. quartz-rich plutonic rocks, irrespective of the relative proportions of plagioclase to alkali feldspar, as implied by the IUGS classification). But for concision we often use the term “granite” as a synonym. We use “granite s.s.” when we need to refer to the exact rock type as defined in IUGS classification.*

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would be more acceptable to me—if I had to accept either—than the one-magma view, popular today in certain seminaries, that degrades granitic magma to the status of the dregs of the primary basaltic". Read was obliquely referring to his controversy with the experimental school, championed by N. Bowen (e.g. Bowen, 1947[2]). Bowen and his students were relying largely on experimental petrology, whereas the arguments of Read revolved around the association of granites with migmatites in the field, and offered generation of granites within the crust with no input from the mantle[3].

Read was prepared to accept, in his famous words, that there are "granites and granites", as was increasingly clear at the time. Indeed, an important difference had already been long recognised between "autochthonous anatectic granites" and "intrusive granites" (Meynier, 1942; Raguin, 1976). This old distinction already emphasized the difference between granites clearly associated with, and often grading into, migmatites vs. mid/upper crustal intrusives.

A more modern and systematic approach was taken by Pitcher (1987, 1997). Pitcher explained that orogenic granites can form either above subduction zones, by dominant fractionation of mantle-derived mafic melts and melting of mantle-derived mafic underplates or in collisional/post-collisional environments, by dominant crustal melting. We reproduce here (Fig. 1) his famous drawing. Pitcher then went on explaining differences between these environments in terms of geology, petrology, geochemistry, isotopes, emplacement modes, ore deposits, etc., neatly delineating most of the field of granite studies for the following years. A main conclusion from Pitcher (1997) is that supra-subduction arcs, notwithstanding petrogenetic complications (assimilation, etc.) "are likely to represent the simplest case of a single source located in the mantle". On the other hand, Pitcher (1997) considered granites from collisional orogens as dominantly reflecting reworking of older continental crust with limited, if any, direct involvement of the mantle.

Progressively, the granite community lost track of this balanced view. As the focus moved from descriptive to process-oriented, these studies led, quite naturally, to research focussing on case studies where said processes are in evidence, and less effort (if at all) has been dedicated to comparing granitoids, understanding their diversity, and in turn the probable petrogenetic nuances between the two defined end-member scenarios. Over the years, the situation evolved to a split in the granite community. Two schools of thought gradually emerged: on the one hand, people working on syn- to post-collisional granites (the "Hercynotype" association of Pitcher) and crustal melting, connected in their methods and approaches to the high-temperature metamorphic community; on the other hand, researchers focussing on arc-related granitoids (the "West Pacific" and "Andinotype" associations) and fractionation of basaltic magmas, linked with the volcanology community. If anything, the rift widened over the years, to the point that in many studies, either one of these end-members is taken for granted and not discussed, or even explained; and the other largely overlooked. Anecdotal evidence can be found in introduction statements, for instance: "*Partial melting has a profound effect on the continental crust. The formation of anatectic melt of granitic composition, its extraction and ascent is the main process by which the continental crust becomes differentiated (…)*" (Morfin et al., 2013), or even "*The production of granitic magmas by partial melting of metamorphic rocks and their consequent rise in the continental crust is one of the fundamental mechanisms in the evolution of the Earth*" (Schwindinger and Weinberg, 2017). Conversely, "*The composition of the continental crust of the Earth is unique in the Solar System and is the most accessible witness of differentiation processes. As initially proposed and demonstrated by Bowen (..) fractional crystallization [of primary liquids generated in the mantle] generates the entire range of silica contents ranging from mantle-derived basaltic magmas to rhyolites*" (Müntener and Ulmer, 2018) or "*it is widely accepted that the majority of the continental crust is formed in subduction zones (…) moderate-to-high pressure fractional crystallization, partial melting, and foundering of high-density cumulates/restites have the potential to produce upper continental crust and thereby strongly modify the lower and bulk continental crust*" (Jagoutz, 2010). Surely, the respective authors would acknowledge the possibility of alternative mechanisms, but these extracts put in clear light the implicit (and generally unchallenged) assumptions guiding their works: partial melting of metamorphic crust vs. differentiation of mantle-derived magmas.

The granite controversy has long been a specialist debate, mostly concerning "granitologists". However, in recent years, it has moved to a more central position in Earth Sciences. Granitoids are the main rock type hosting zircons – and zircons, in turn, are a key tracer of long-term crustal evolution, especially via U–Pb dating and O–Hf isotope tracing. Therefore, zircon-based studies tend to be heavily predicated on understanding of granite genesis. In this light, reviewing the evidence on the global meaning of granitic magmatism is of paramount importance for our perception of first-order questions in Earth Sciences. It is perhaps in the field of crustal growth that the most extreme, implicit and unchallenged assumptions can be found. Consider, for instance, the use of two-stage model ages in radiogenic (Nd or Hf) isotopic studies, implying that granites (such as those from which zircons crystallize) form by crustal melting (Liew and Hofmann, 1988 for Nd; Belousova et al., 2010; Dhuime et al., 2012 for Hf). Here, we highlight the presence of very strong paradigms, taken as axiomatic – and again never challenged, as another segment of the community takes equally strong views rooted in the opposite paradigm.

This paper explores the granite controversy proper, and its (unspoken) implications on conceptions of crustal growth and evolution. In the first section, we summarize some of the reasons why the controversy remains unsettled, and why the existing data are ambiguous. Then, we discuss how features of the granitic world are interpreted in different, and often totally opposed ways in the "mantle" and "crust" paradigms. We deliberately do not take sides in this section and try to faithfully convey the argumentation used in both sub-communities, focusing on the points that clearly depict the end-member models. In the following part, we see how the underlying paradigms are used, perhaps unconsciously, to discuss crustal evolution, beyond the "granite" community proper. Although most "granitologists" would surely advocate a more balanced and nuanced view, it is inevitable that outside of the granite community, many people settle for a much more clear-cut view, often without quite realizing that they are implicitly taking a very strong stance.

In a companion paper (Jacob et al., this issue), we explore conceptual possibilities to go beyond this dichotomy, and to quantify the global relevance of each paradigm by attempting to estimate the proportion of "crustal" and "mantle" contributions incorporated in granitoid rocks from different tectonic settings.

2. The root of a controversy

The core issue can be simply summarized by stating that Earth's magmas evolve to a handful of thermal minima (eutectic or similar). The most important ones correspond to granitic and basaltic compositions, and thus igneous rocks cluster around these. Therefore, the most common lines of magmatic evolution will connect these compositions, irrespective of the process involved: melting, fractionation or mixing. Thus, most petrologic and geochemical features of igneous rocks will be broadly similar in all petrogenetic scenarios.

[2] *"… We can indeed for rough purposes, separate petrologists into the 'pontiffs' and the 'soaks.' The pontiff bears the stigma of magma. The magma gives rise to emanations which yield a liquor. The difference between the 'pontiff' and the 'soak' is that the latter must have his liquor in lavish quantities on all occasions, but the former handles his liquor like a gentleman. He can take it or leave it, according to the indications of the individual occasion" (*Bowen, *1947).*

[3] *Read, in fact, was at least sympathetic with the transformist view, and accepted or even favoured the possibility of solid-state transformation.*

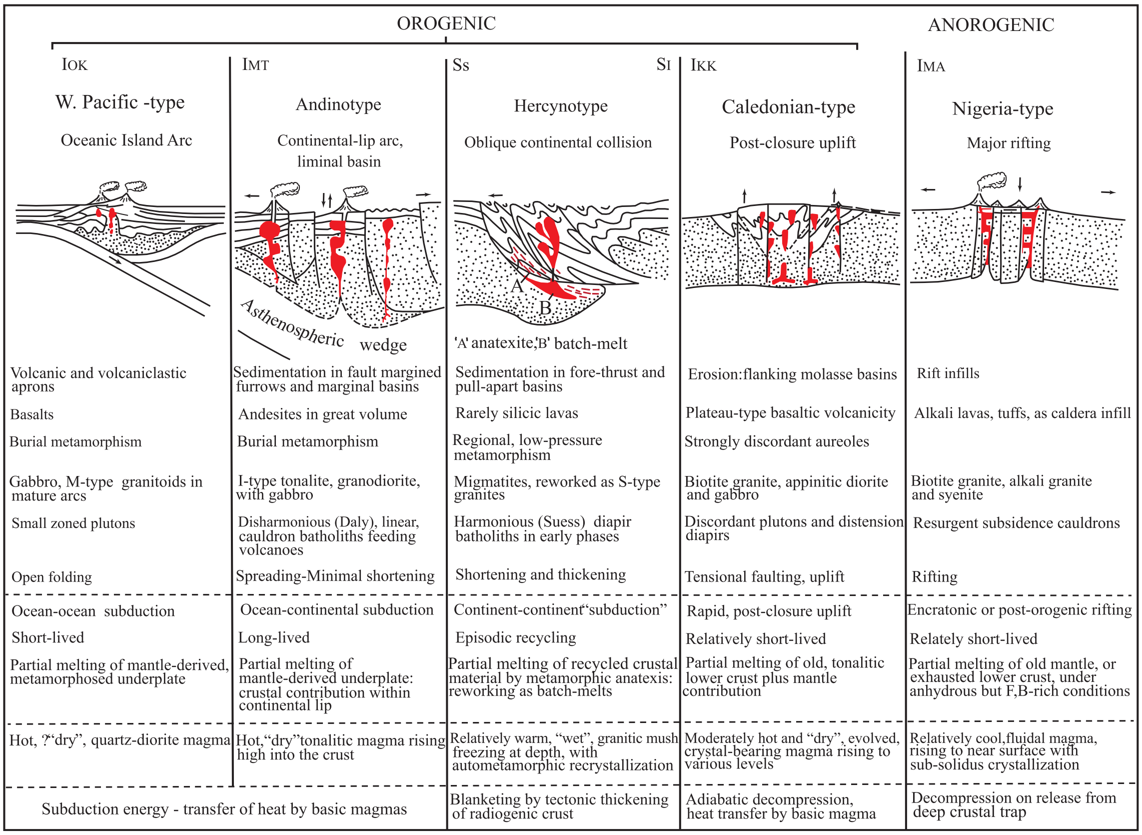

Fig. 1. Pitcher's (1987) overview of "granites and granites", summarizing the main features of granite magmatism in various settings, and their origin. A very similar view has been expressed, in more detail, by Barbarin (1999), where the different types of granites are referred to as ATG (Arc Tholeiitic Granites), ACG (Amphibole-rich Calc-alkaline Granites), MPG and CPG (Muscovite- and Cordierite-bearing Peraluminous Granites), KCG (K-rich Calc-alkaline Granites) and PAG (Per-Alkaline Granites). Redrawn by Y.-F. Zheng from original figure.

Moyen (2020) summarized how most of the petrogenetic evidence is ambiguous. Field observations essentially record solid–liquid equilibrium at P and T conditions connecting the liquidus and the solidus, or *vice versa*, and are broadly similar in both mantle-derived melt fractionation and crustal melting scenarios. Major-element-based diagrams display similar trends for melting, fractionation and mixing. Although in theory, different processes can yield distinct evolution lines for trace elements (and they do, to some degree, especially for strongly compatible or incompatible behaviours: Janoušek et al., 2016), this is seldom unambiguous. In any case, the process-related variation is small compared to the natural scatter of rock compositions. In addition, the fate of most trace elements tends to be governed by accessory minerals (Janoušek and Moyen, 2020, see also section below).

Of course, none of the above data is useless, and all do bring some constraints. It is often possible to build a model fitting all the observations. Sadly, the models tend to be non-unique such that, for instance, most of the observations fitting a model of melting of metabasic rocks would equally fit a scenario of basaltic magma fractionation (Jagoutz and Klein, 2018), and conversely. For example, the lack of inherited zircon in a granite may document an origin by mantle-derived magma fractionation, or equally result from high-temperature melting of a crustal protolith with attendant dissolution of all the older grains. Similarly, depleted mantle-like isotopic signatures can reflect either fractionation of mantle-derived basaltic melts or melting of juvenile mafic crust shortly after its extraction from the depleted mantle. Likewise, crustal-like isotopic signatures may result from melting of the crust or fractionation of a basalt generated, for instance, from the enriched subcontinental lithospheric mantle (SCLM).

Table 1 is an attempt to summarize some key evidence, and discuss what it actually corroborates (or contradicts). It is important to keep in mind the ambiguities and possible blind spots in our geological reasoning.

3. Two views of granitic systems

In this section, we describe the two dominant, end-member models that are proposed to describe the origin of granitic rocks. Our goal here is neither to undergo a critical examination of the competing models, nor to discuss their merits and flaws – but only to show the two logics at work.

Fig. 2 attempts to incorporate in a single sketch the key elements of the two end-member models (it is left as an exercise to the reader to decide which of the cartoons is closer to his/her understanding of what granites are – and, perhaps, to reflect on the merits of the opposite view). For clarity, they are not intended to depict any peculiar geotectonic setting and are voluntarily idealized and sketchy, in particular with respect to geometric and structural considerations. It is also worth keeping in mind that most of the time only a fraction of the whole system, corresponding to a certain crustal level, can be studied, and the rest is reconstructed (or imagined).

In **the basaltic magma fractionation paradigm** (Fig. 2a), the main driver is melting of the mantle and the formation of a parental mafic magma injected into the crust. This magma differentiates and interacts with lower crustal rocks (or their melts) in MASH zones (Melting, Assimilation, Storage, Homogenization; Hildreth and Moorbath, 1988) or Deep Crustal Hot zones (Annen et al., 2006). In both cases the product would be (ultra-) mafic cumulates, and differentiated intermediate–felsic melts, finally able to pierce the overlying crust of low density and to continue their ascent to shallow crustal levels. Ultimately, magmas could be stored in magma reservoirs where they may undergo physical-chemical processes including convection, prolonged crystallization, magma replenishment, and tapping of residual liquids. The eventual cooling and solidification of these reservoirs leads to formation of a future pluton, whereas extracted magmas are thought to erupt as complementary andesites–rhyolites.

Table 1
Summary of the possible discriminant evidence cited in support of a basalt fractionation, or a crustal melting model. For each aspect listed in the table, it may be possible (at least in some cases) to find an alternative explanation, rooted in the opposite paradigm, or conversely, to find a justification for the absence of this feature, such that none is discriminant on its own.

	Fractionation of mantle melts			Crustal melting		
	Argument / key observation	Alternative explanation	Justification for absence	Argument/ key observation	Alternative explanation	Justification for absence
Field geology	Granites s.s. are associated with a range of mafic and intermediate rocks, including cumulates	Mafic rocks reflect unrelated episodes of mantle melting	Parental mafic rocks are not present at current level of exposure	Granites are associated with migmatites	Migmatites are incidental, with unrelated crustal melting (slightly older, or induced…), or can represent injection migmatites	Migmatites are not present at current level of exposure
Petrology, major elements	Compositions (and mineralogy: amphibole ± pyroxene, titanite) are consistent with liquids experimentally generated (or thermodynamically modelled) by fractionation of basaltic magmas	Melting of a metabasic source	Complex crystal–liquid dynamics (accumulation, segregation…), such that compositions do not represent liquids (and geochemical trends are not liquid lines of descent)	Compositions (and mineralogy: muscovite, cordierite, garnet, Al-silicates ± monazite) are analogous to experimental or thermodynamically modelled melts of crustal sources	Fractionation of a felsic–intermediate parental magma	Melting of non-sedimentary crustal sources, restite/ peritectic minerals entrainment
	Major-element trends similar to those determined experimentally (liquid line of descent with multiple saturation)	Partial melting with variable melt fractions		Major-element trends represent melting reactions and preserve the stoichiometry of melting	Fractionation trends	Incremental pluton assembly of batches of slightly different origins results in multiple, slightly different overlapping trends in a pluton
Trace elements	Arc-like signature (e.g. "VAG" of Pearce et al., 1984)	Melting of continental crustal source with an arc(-like) chemical signature	Non-arc environment	Syn-collisional ("COLG") signature (Pearce et al., 1984)	Differentiation of a mafic–intermediate parental magma with enriched trace-element signature	Melting of psammitic or non-sedimentary crustal sources, as the "COLG" signature corresponds only to pelite-derived, strongly peraluminous granites
Isotopes	Mantle-like isotopic signature	Melting of a young, juvenile metabasic source	Atypical mantle source (SCLM, metasomatized or crustally-contaminated orogenic mantle); crustal contamination upon ascent/ emplacement	Crust-like isotopic signature	Differentiation of melts derived from an enriched mantle; extensive assimilation	Melting of sources with strong juvenile igneous component (e.g., tuffites); rapid crustal recycling, not allowing the newly formed crust to develop a "mature" crustal radiogenic isotopic signature
Zircon inheritance	Lack of inherited zircons	Zircon dissolution by high-temperature crustal melting; melting of Zr-poor crustal sources	Crustal contamination, assimilation/hybridization (xenocrysts)	Abundance of inherited zircon	Assimilation, hybridization	High-temperature melting of the crust, whereby all zircons are dissolved

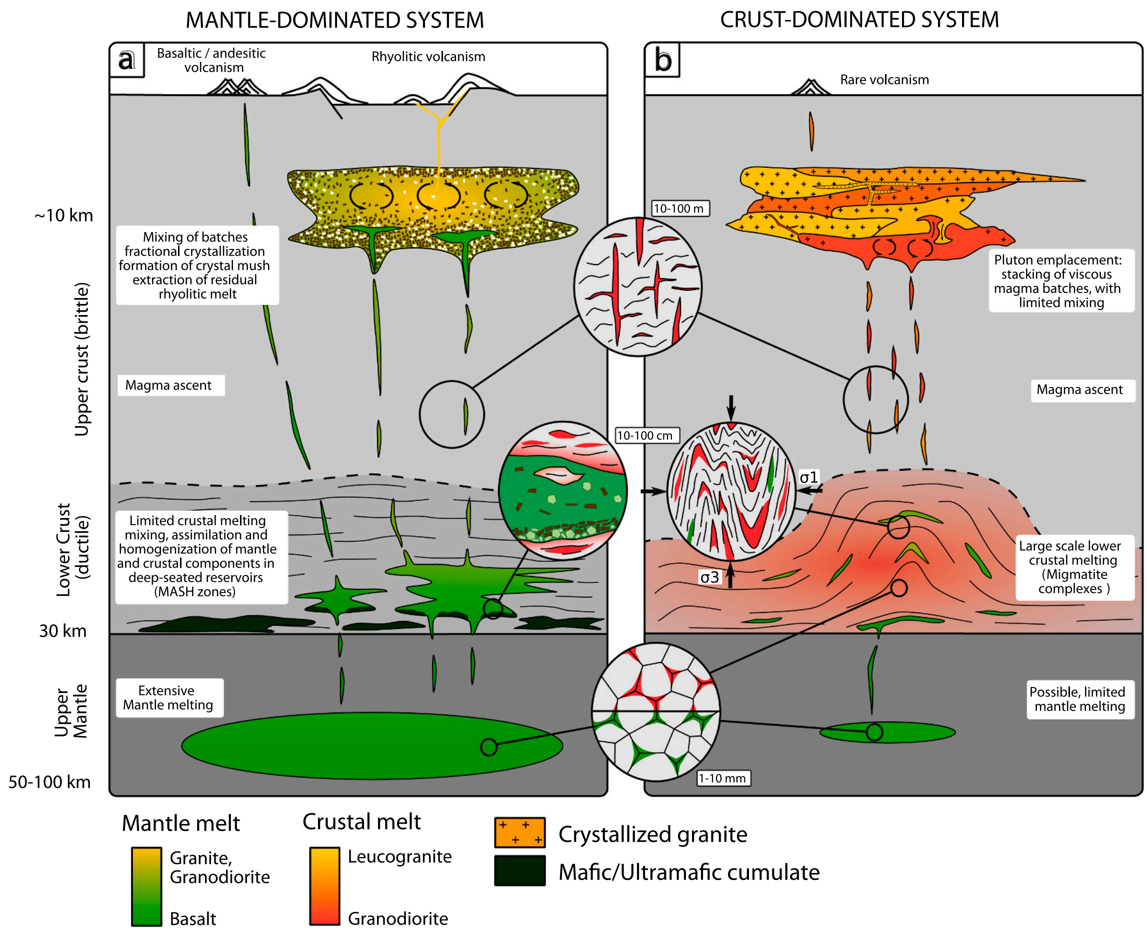

Fig. 2. Granitic systems. Left-hand side cartoon is inspired by an original drawing by B. Barbarin (pers. com). Modified from Jacob and Moyen (2021). In the basaltic melt fractionation model (left), the main driver is melting of the mantle to form a mafic melt. This magma is intruded into the crust, and evolves in a series of interconnected magma reservoirs in which the magma evolves by both closed-system (fractionation) and open-system (assimilation, mixing) processes, giving rise to progressively more felsic compositions. Magmas may feed upper-crustal magma reservoirs, that are periodically refilled by fresh, more mafic batches, and correspond to a dynamic magma chamber out of which melts are tapped to form volcanoes. In the crustal melting model (right), mantle melting is minimal. Most of the granitic magmas are formed by anatexis of the lower crust in migmatitic complexes, out of which small batches of not very hot magma are extracted and accreted to the future pluton, a zone of stacking with limited interactions of small batches of magma. Magmas seldom reach the surface, and volcanism is restricted (more comments and references in the text).

The **crustal melting model** (Fig. 2b) revolves around partial melting in the (lower) crust to produce granitic melts. Inputs of heat and fluids lead eventually to the formation of an anatectic lower crust, that undergoes a range of tectonic, petrological and chemical processes that can be summarized in terms of melting reactions, segregation, and extraction of magmas (melts + crystals) that rise towards emplacement sites. As individual batches of magma leak from the source, they will be trapped, and coalesce, progressively forming a pluton. Uncommonly, magma batches may reach the surface to form rhyolitic volcanoes. Mafic magmas from the mantle, if present, play an indirect role, supplying heat and fluids to assist melting (Collins et al., 2020a; Nabelek, 2020; Weinberg and Hasalová, 2015).

Some questions and concepts are common to both models. For instance, magma transfer through the crust can be studied and understood under both paradigms (Petford, 1996). Likewise, magma emplacement and the formation of plutons, including the ‘room problem’, strain control and physical processes responsible for the growth of plutons can all be discussed from the two perspectives, in essentially similar terms (Belcher and Kisters, 2006; Bouchez, 1997; Brown and Solar, 1999; Hecht and Vigneresse, 1999; Hutton and Reavy, 1992; Kisters et al., 2009; Paterson and Vernon, 1995; Petford et al., 2000; Român-Berdiel et al., 2000; Westraat et al., 2004). The formation of thermal aureoles or skarns around plutons, fluid segregation and origin of ore deposits are also largely disconnected from this controversy.

Sometimes, identical questions are framed differently in the two views. In all magmatic systems for instance, liquid–solid separation, two-phase flow and the dynamics of partially molten systems are key aspects (Schmeling, 2000; Schmeling et al., 2019; Spiegelman et al., 2001). However, although the underlying physics is the same, the systems are described in different terms and the relevant literature is largely disconnected. In crustal melting, this concept is understood in the context of melt extraction from the granulitic residue/strained migmatitic source and the dynamics of migmatitic complexes with progressively *increasing* degree of melting (Bons et al., 2004; Brown and Solar, 1999; Sawyer, 2008; Vanderhaeghe, 2001). The basaltic magma fractionation community rather describes it as mush dynamics in an initially convecting magma chamber with a *decreasing* melt fraction (Bachmann and Bergantz, 2008; Cashman et al., 2017; Wickham, 1987).

Likewise, the thermodynamics of liquid–solid equilibrium is the same in both cases. However, the crustal melting community envisions it in terms of melting reactions (e.g. Clark et al., 2011; Clemens and Vielzeuf, 1987) and accessory mineral solubility (Janoušek et al., 2016; Watson and Harrison, 1984), whereas in the magma fractionation community the concepts of liquid line of descent and mineral saturation (Jagoutz, 2010; Jagoutz et al., 2011; Leuthold et al., 2012; Müntener and Pistone, 2019) are more appropriate. Melt inclusions are an important aspect to both models, in that they preserve early compositions that once existed in the system. The melting community envisions them as primary liquids, directly reflecting the melting processes and conditions, with particular emphasis to inclusions trapped in peritectic minerals such as garnet, and thus likely to represent near-peak melting ("nanogranites": Bartoli et al., 2016; Cesare et al., 2009; Ferrero et al., 2012). To the fractionation community, melt inclusions of diverse compositions represent trapped melts that record the chemical differentiation of magmas in crustal reservoirs (Bouvet de Maisonneuve et al., 2012; Cioni et al., 1998; Fourmentraux et al., 2012; Reubi and Blundy, 2009).

In contrast, some other aspects are mostly investigated under one of the paradigms, either because they are of little relevance, or perhaps because they are not given enough consideration in the other. For instance, fluid regimes during melting (Clemens and Droop, 1998; Weinberg and Hasalová, 2015), entrainment of restite (Chappell et al., 1987) or peritectic mineral assemblages (Clemens et al., 2011; Stevens et al., 2007; Villaros et al., 2009), and generally source control on the chemistry of the melts (Mayne et al., 2020a) are all aspects that are little investigated outside of the crustal melting paradigm. Conversely, crystal settling and accumulation, the fate of the large volume of cumulates, the volcanic–plutonic connection (Bachmann and Bergantz, 2004, 2008; Miller et al., 2011) or MASH/Deep Hot Crustal Zones (Annen et al., 2006; Hildreth and Moorbath, 1988) are concepts developed in the fractionation framework and either not commonly explored in the crustal melting paradigm or considered as not efficient enough to produce significant volumes of granites (Collins et al., 2020a).

3.1. Field geology and rocks associated with granitoids

There are, more often than not, important geological differences between granitoid studies in the "basalt fractionation" and "crustal melting" worlds. Granitoids investigated in the magma fractionation community generally relate to magmatic arcs, where upper crustal to supracrustal rocks are found. Hence, volcanic rocks are common but lower crustal exposures are rarer. However, this is not always the case and deep crustal cumulates complementary to shallow level granites are well exposed in a handful of tilted sections of island and continental arcs, with the most important examples likely represented by the Kohistan arc in Pakistan (Jagoutz et al., 2006) and the Talkeetna arc in Alaska (Behn and Kelemen, 2006). These "crustal sections" are regarded as rare but critical examples of deep processes and, accordingly, attracted considerable attention. The crustal melting community, focussing on ancient, deeply eroded orogens, generally has better access to the deep crust and the roots of the magmatic systems. In this paradigm, deep crustal sections are rather common. On the other hand, high-level intrusives and volcanics are seldom preserved, or not produced at all. Thus, quite a few of the differences may simply relate to sampling bias as different objects and/or crustal levels are accessible.

3.1.1. Migmatites and other melt-bearing rocks

In the modern sense, 'migmatite' is a term strictly restricted to rocks in which the melting process can be documented (Sawyer, 2008). As such, their presence is a key evidence used in crustal melting models. However, liquid–solid mixtures may be preserved in a range of situations that do not all reflect in-situ melting, as would be emphasized in the fractionation community, such as injection of melts in a solid matrix, or extraction from a crystal mush. Such melt-bearing rocks technically should not be referred to as migmatites, although they would of course share many features with these. Further complications relate to the fact that leucosomes in migmatites, even if formed by melting, rarely represent pure crystallized melts but rather those "back reacted" during retrograde evolution (Kriegsman, 2001) or melts with accumulated crystals of early magmatic phases (Madlakana and Stevens, 2018; Nicoli et al., 2017; Taylor et al., 2014).

3.1.1.1. Mafic and ultramafic rocks. In the deep crust, it is common to find examples of mafic/ultramafic rocks (e.g. with amphibole, minor plagioclase, garnet and pyroxene(s)) showing evidence for solid–melt segregation. The basalt fractionation community, by analogy with cumulates in layered mafic intrusions, would interpret such rocks also as cumulates. Mafic cumulates are in fact abundant in some arc roots (Bouilhol et al., 2011; Davidson et al., 2007; Dessimoz et al., 2012; Ducea et al., 2015; Jagoutz et al., 2006), or as xenoliths in arc magmas (Saleeby et al., 2003; Yanagida et al., 2018). A garnet amphibolite would thus be interpreted petrographically as a garnet–amphibole cumulate, and the melt features would correspond to the incomplete extraction of the residual liquid (Bouilhol et al., 2011; Jagoutz et al., 2006). From a crustal point of view however, similar rocks would be viewed as partially molten meta-mafics, with peritectic garnet and evidence for extraction of anatectic melt (Johnson et al., 2012; Schwartz et al., 2017).

3.1.1.2. Intermediate orthogneisses. Migmatites with intermediate to felsic bulk composition are a rather common occurrence at active or fossil convergent plate boundaries. In many cases, there is robust evidence, for instance geochronologic, that a pre-existing orthogneiss was partially melted. Even so, melt may not be generated in-situ but injected from elsewhere, and such rocks may represent zones of melt flow through a solid gneissic framework (Hasalová et al., 2008; Závada et al., 2018). In the absence of the geochronological evidence, Jagoutz and Klein (2018) pointed out that it is often possible to interpret such assemblages as recording melt extraction from a dioritic to granodioritic magma crystallizing under strain, and of course the resulting mineral assemblages and textures would be similar.

3.1.1.3. Metasediments. A case for fractionation is harder to make in metasedimentary migmatites. What can be discussed, though, is the importance of the melting, its causes and connection with the granitoid system: was the granite intrusion the cause of the metamorphism producing the migmatites (e.g., Finger and Clemens, 1995; Pattison and Harte, 1988), or was it instead the consequence of the regional metamorphism leading to migmatization and magma extraction (Brown et al., 2016; Johannes et al., 2003; Vernon et al., 2001; Williams, 2001)? On a local scale, there is no doubt that melting can be induced in the contact aureole of intrusions (Sawyer, 2014). Whether this can be a large-scale process is more debatable. A somewhat extreme view has been offered by Castro (2014), proposing that large peraluminous granite bodies can be formed by intrusion of a mantle-derived melt in the crust, causing pervasive melting and assimilation.

3.1.2. Mafic intrusions

Coeval mafic magmatic bodies are commonly found in association with granites. They are ubiquitous in magmatic arcs (Pitcher, 1987) but also occur in collisional orogens, even though in low proportions compared to the dominant granitoid rocks. They form mafic microgranular enclaves (MME; Didier and Barbarin, 1991; Vernon, 1984), small stocks, syn-plutonic to proper dykes and, more rarely, larger intrusions. In the same way as migmatites are taken in the crustal melting community as the ultimate proof for crustal melting, mafic intrusions are a crucial field evidence used in support of a basaltic magma fractionation model. In this view, such mafic rocks are easy to interpret – they are crystallization products of the parental magma, or of any intermediate magma differentiated therefrom. As such, they are key indicators of fractionation (liquid line of descent), as well as of mafic magma recharge. Crucially, it is often possible to use a series of mafic/intermediate rocks to build a complete differentiation series from basalts to granites, with all the intermediate compositions present (Jagoutz, 2010; Walker Jr. et al., 2015). The relative abundance of mafic igneous rocks in magmatic arcs is taken as evidence for the prevalence of such differentiation processes. The chemical affinity between MME and the granitic host is simply regarded as supporting their common origin.

In the crustal melting community, most authors would regard MME and minor mafic intrusions as small-volume, coeval mafic melts. Their chemically equilibrated nature is interpreted as reflecting various degrees of hybridization and equilibration with the host granitic magma (Castro et al., 1991; Didier and Barbarin, 1991; Elburg, 1996; Pin et al., 1990; Vernon, 1984). Their small proportion in anatectic plutons would be taken as evidence that they represent, at best, a very minor and accidental mantle contribution to the actual granite-forming process. Some more extreme views, relying more heavily on the chemical equilibrium between host and enclave, propose a purely crustal origin for the MME. For instance, Chappell (1978; also see Chappell et al., 1987) viewed such enclaves as fragments of restitic material entrained from the source, and equilibrated with the melt during magma cooling and crystallization. The MME have also been interpreted in terms of physical accumulation of early crystallized phases in the cooling pluton (Bea, 2010; Clemens and Wall, 1984; Donaire et al., 2005).

3.2. What is a pluton?

A consequence of the different views on granitic magmatism is that the very definition of what is considered a pluton differs depending on the point of view.

In the basaltic magma fractionation paradigm, a granitic pluton is a long-lived (fossil) magma reservoir. During their lifespan, such reservoirs are dominantly kept at high crystallinity (e.g., Huber et al., 2009; Koyaguchi and Kaneko, 1999), leading to a complex array of phase (crystals, melt, fluid) separation, and formation of cumulate layers with subsequent reworking (see Bachmann and Huber, 2019; Holness, 2018, and references therein). This leads to the concept of a mush (a reservoir of a partly crystallized magma, with a dynamics controlled by the triphasic nature of the system: solid, melt and fluid), that evolved into the notion of "mush column": a crustal-scale magma system, during its lifespan constituted by a series of interconnected bodies, each containing some melt (Cashman et al., 2017; Edmonds et al., 2019). Compositional heterogeneities in plutons are then taken as reflecting mush dynamics.

A pluton, from the crustal melting point of view, is best described as a site of accumulation of many incoming small batches of magma. Although it is acknowledged that fractionation can generate limited chemical evolution of the magma during and after ascent and emplacement (e.g., Chappell, 1999; Chappell et al., 2005), each new batch would crystallize to a large degree as soon as it accretes, limiting the possibility of mixing with subsequent batches or developing an active mush. Thus, the composition of batches mostly reflects that of unfractionated magmas (melt + possibly entrained solids) extracted from the source, and the heterogeneities in the pluton are interpreted as reflecting injection or accretion of individual magma batches (Clemens and Stevens, 2016a; Farina et al., 2012, 2014a; Fiannacca et al., 2017).

3.3. The volcanic–plutonic connection

Active continental margins host large granite batholiths, but they are also important volcanic provinces (e.g., Cawood et al., 2009; Collins et al., 2020b; Collins and Richards, 2008), offering the possibility to explore the connection between plutons and volcanoes. In the recent years, a combination of detailed field mapping (Bachmann et al., 2007; Colombini et al., 2011; Miller et al., 2005), geophysical evidence, modelling of melt extraction from partially crystallized mush systems (Bachmann and Bergantz, 2004) and petrological observations (Bachmann and Bergantz, 2004, 2008; Gelman et al., 2014), particularly from the western American continental arcs, has led to the conclusion that volcanoes and plutons in these environments are complementary parts of the same systems. Plutons are viewed as "crystal graveyards", melt-depleted magma reservoirs out of which melt has been extracted and erupted (Gelman et al., 2014; Gualda and Ghiorso, 2013; Lee and Morton, 2015). Thus, in the fractionation paradigm, silicic volcanoes are considered as the ultimate (and complementary) product of the process that forms granites.

In the crust melting world of collisional orogens, where plutons tend to be more abundant than volcanoes, the connection is far less obvious, perhaps partly due to preservation bias. Peraluminous rhyolites are rare (Barnes et al., 1970; Clemens et al., 2017; Clemens and Stevens, 2016b; Zeck and Williams, 2002), and not always synchronous with granites (Cesare et al., 2009). Even in provinces where both peraluminous rhyolites and granites are observed, such as the Pan-African S-type ignimbrites and granites from Western Cape (South Africa), rhyolites appear to have formed from hotter and drier magmas than granites (Clemens et al., 2017). This is in good agreement with phase relations in felsic magmatic systems, as the wet solidus has a negative P–T slope whereas the dry solidus has a positive one. Thus, rising wet magmas are expected to be trapped in the deep crust while dry magmas have the potential to erupt (Clemens and Droop, 1998; Miller et al., 2003). Consequently, volcanoes are mostly not directly related to the nearby plutons (although, of course, both likely reflect the same crustal melting event).

3.4. Tools

The followers of different paradigms attempt to solve distinct petrological problems, and hence use distinct tools for this purpose; or the same ones but with distinct strategies.

3.4.1. Major-element geochemistry

The major-element geochemistry of granitoids can be described by a handful of parameters that appear in different forms in most normative recalculation or classification schemes (Bonin et al., 2020; Debon and Le Fort, 1983; Frost et al., 2001). There parameters are indicators of (i) differentiation (e.g., SiO_2, FeOt + MgO); (ii) the molar balance between Ca, Na and K, or plagioclase and K-feldspar; (iii) the balance between Na and K; (iv) the excess or deficit of Al relative to the feldspar stoichiometry (Shand's A/CNK, normative corundum, etc.); (v) the balance between Fe and Mg (mg#, FeOt/MgO, etc.). The most successful diagrams combine several of these parameters.

In a fractionation paradigm, the main property that one typically wishes to portray is the evolution from mafic to felsic compositions. Thus, diagrams used in this context tend to include one of the differentiation-related indicators, Harker or Fenner diagrams (major-element oxides vs. SiO_2 or MgO, respectively) being the most common variants. In fact, A. Harker explicitly designed the former type for this use (Harker, 1909). Harker diagrams are, however, not very useful for highly silicic compositions, as they suffer from the closure effect (Aitchison, 1986; Pawlowsky-Glahn and Egozcue, 2006); variants based on Fe and Mg may be more appropriate in this case (Debon and Le Fort, 1983).

In a crust melting paradigm, there is of course no reason to look for a related basalt or a differentiation path. Rather, one tries to "strip off" the effects of differentiation and show the chemical affinities within a suite. This is done by projecting the data in a way that allows to group together cogenetic rocks irrespective of their degree of differentiation. The major-element chemical differences between granitoids are thus viewed as reflecting chiefly distinct sources: this is at the core of the S/I dichotomy (Chappell et al., 1987; Chappell and White, 1974). In this light, one of the most useful indicators is related to the aluminium balance in the rock. This parameter, especially when applied to rocks that plot away from the granitic minimum, is used to get insights into the type of source that melted (Moyen et al., 2017; Shand, 1943; Villaseca et al., 1998). So, to a point, the choice of diagrams made by the authors shapes the way information can be extracted from geochemistry, thus limiting the possible conclusions to a subset of possibilities at the very onset of the work.

3.4.2. Trace elements

In granitic rocks, trace-element variations are heavily influenced by accessory minerals (e.g., Bea, 1996; Evans and Hanson, 1993; Mittlefehldt and Miller, 1983). Apart from a handful of elements stored in the main rock-forming minerals (such as Ba, Rb, Sr and, to some extent, Eu, in feldspars and/or micas), the trace-element composition of a liquid needs to be described in terms of saturation/solubility of accessory minerals.

The fractionation community interprets this as saturation during crystallization, followed by the progressive formation (and removal) of accessory minerals such as apatite, zircon, monazite or allanite (Evans and Hanson, 1993; Hoskin et al., 2000; Lee and Bachmann, 2014). In the crustal melting community, the interpretation consists rather in progressive dissolution of the same accessory phases on the prograde path (Kelsey et al., 2008; Miller et al., 2003; Watson and Harrison, 1984; Yakymchuk and Brown, 2014). In both cases entrainment of solid crystals, forming inherited grains (or xenocrysts), complicates the matters further.

Both scenarios generate comparable chemical correlations (Janoušek et al., 2016). Consider for instance the case of Zr, an incompatible element unless zircon is involved (Miller et al., 2003). In a fractionation scenario, [Zr] (Zr concentration) passively increases with differentiation of mafic magma until the saturation point is reached, resulting in a clear maximum of [Zr] for intermediate compositions followed by a decrease with increasing SiO_2, reflecting zircon crystallization (see Hoskin et al., 2000; Lee and Bachmann, 2014).

In the case of crustal melting, low-temperature melts have only limited potential for zircon dissolution. At higher temperature, [Zr] saturation of melt increases (Watson and Harrison, 1983), resulting in more zircon being dissolved in the melt that, consequently, has higher [Zr]. If all the zircon in the source is consumed (which may happen at different temperatures and melt compositions, or not at all, depending on the nature of the source), further melting can only dilute the Zr in the melt, and [Zr] decreases (Watson and Harrison, 1984). Thus melting of lower [Zr] sources would yield a pattern resembling that produced by fractionation of a moderate-Zr melt. Practically however, such an inflexion is not commonly seen in granites related to melting of sediments, because of the overall high [Zr] content in their sources means that the residual zircon is never entirely consumed in course of crustal anatexis and such granites commonly include abundant inherited cores; in such granites [Zr] is the net result of both zircon dissolution in melt and residual zircons entrainment.

Both melting and fractionation scenarios can be complicated further by shielding by refractory phases, mechanical entrainment of crystals (inherited grains or xenocrysts), and kinetic effects (Watson, 1996).

Assuming that it is possible to filter out the effects of accessory minerals, the origin of trace-element anomalies in spidergrams can also be interpreted in various ways. In general, the geochemistry of any melt reflects that of its source (or parental liquid), degree of partial melting/fractional crystallization and the coexisting minerals present during evolution (e.g. feldspars for Ba, Eu and Sr, garnet for HREE, clinopyroxene, titanite or amphibole for MREE, K-feldspar/biotite for Ba, rutile for Nb–Ta, …).

Parental liquid composition or source can have different meanings. In the basaltic magma fractionation view, a granite with an 'arc' signature (i.e. LILE/HFSE decoupling, negative Nb–Ta anomalies in spiderplots, etc.) is best explained by an evolution from an arc-related primitive magma (this allows the distinction between volcanic-arc, oceanic-ridge and within-plate granites in discriminant diagrams such as those by Pearce et al., 1984). In the crust melting view, the similar signature is taken as reflecting melting of a continental crustal source that already featured prominent anomalies (Rudnick and Gao, 2014; Taylor and McLennan, 1985; Wedepohl, 1995). Since no extreme fractionation can occur during crustal melting, these anomalies are largely inherited by the melts (Janoušek et al., 2010). In both paradigms, the composition of the granitic melt reflects that of its 'source', but this term has distinct meanings – the parental magma that fractionates vs. the solid that melts.

Likewise, the role of key minerals can be envisioned during fractionation or melting. Good examples of contrasting views are found in the interpretation of the HREE depletion that is explained either by strong fractionation (in the garnet stability field) of mafic arc magmas (Alonso-Perez et al., 2003, 2009; Jagoutz and Schmidt, 2013) or by the presence of residual garnet during (deep) melting of metabasic rocks (Gao et al., 2016; Guo et al., 2007; Martin, 1986; Moyen and Stevens, 2006; Qian and Hermann, 2013).

3.4.3. Radiogenic isotopes

The interpretation of radiogenic isotopic signatures is, equally, dissimilar in both views. In the fractionation model, differences in isotopic compositions of granitoids can reflect (i) primary melts sampling different mantle domains (including perhaps portions of variably enriched sub-continental mantle or those contaminated by deeply subducted crustal material), and/or (ii) assimilation of local crust during ascent and emplacement of the magma (Becker et al., 1999; DePaolo, 1981; Faure, 2001; Fowler et al., 2008; Janoušek et al., 2020; Murphy, 2007; Powell, 1984; Schaltegger et al., 2019). Most common radiogenic tracers (Sr, Nd, Hf, Pb) occur in higher concentrations in the crust than in the chondritic or depleted mantle, or even basaltic melts derived by mantle melting. Thus, even a minor crustal contribution, possibly not visible using major or trace elements, or obscured by further fractionation, may largely control the isotopic composition of granitoids (Bohrson and Spera, 2007; Couzinié et al., 2016; DePaolo, 1981; Laurent and Zeh, 2015; Payne et al., 2016), and a crust-like isotopic signature is not seen as evidence for a dominantly crustal origin.

In a purely crustal concept, differences in isotopic compositions would be interpreted as reflecting distinct crustal sources/residence times or source materials (Clemens, 2019; Clemens and Phillips, 2014; Collins, 1998; Downes et al., 1997; Keay et al., 1997; Liew and Hofmann, 1988; McCulloch and Chappell, 1982; Pin and Duthou, 1990). Isotopes are a very potent tracer of e.g. old crustal domains or cryptic sutures (Blichert-Toft et al., 2016; Zeh et al., 2009). In this view, a mantle-like isotopic signature is not taken as an evidence against the crustal parentage, but rather for the involvement of young crust whose isotopic properties do no greatly depart from the mantle's (Collins, 1996; Collins et al., 2020a; Keay et al., 1997).

More recent interpretations, still from the crustal melting community, explore the possibility of non-equilibrium incongruent melting of the crust. The isotopic composition of each melt batch generated may reflect the compositions and actual contributions of the individual minerals involved in the specific melting reaction (Farina and Stevens, 2011; Iles et al., 2018; Knesel and Davidson, 1996, 2002; McLeod et al., 2012; Tang et al., 2014; Wolf et al., 2019). A corollary of this model is that the same source can produce magmas with different isotopic compositions during successive melting events at progressively higher temperatures (Farina et al., 2014b). As we have already mentioned, individual batches can be transferred to the pluton and crystallize there without much interaction, thus preserving most of their heterogeneity (Clemens et al., 2009; Farina et al., 2012, 2014a).

3.4.4. Thermodynamic modelling

Although the thermodynamics of solid–melt equilibrium is a problem common to any model of granite formation, different tools can be used to investigate it. Even more critically, several groups of models are in existence, and they were calibrated for different ranges of compositions and conditions (Ghiorso and Gualda, 2015).

In the fractionation community, the key tool is the MELTS family of algorithms and models (Ghiorso, 1997; Ghiorso and Sack, 1995). As the name suggests, MELTS is built around the concept of melt evolution and thus has built-in routines to calculate effects of fractionation of phases, isenthalpic or isentropic evolution, etc. Its main range of applicability is mafic systems. Even the more recent rhyolite-MELTS (Gualda et al., 2013) can be used only with caution in felsic systems as it struggles to adequately treat the biotite– (or amphibole–) melt equilibrium. It is hardly applicable in a crustal melting perspective as it does not include minerals such as muscovite or cordierite and does not treat well peraluminous melt compositions. This is not viewed as an issue since granites are, in this concept, only the very end of the differentiation process and the induced uncertainties affect only a small part of the evolution.

For the melting community, the main phase equilibria modelling tools belong to the Thermocalc family (Powell and Holland, 1988). These include the Thermocalc program itself, as well as other programs using different minimization strategies, such as Perple_X (Connolly, 2009; Connolly and Petrini, 2002) or Theriak-Domino (de Capitani and Petrakakis, 2010). The Thermocalc database has initially been designed to investigate metamorphic assemblages, and melt phase is a relatively late addition (White et al., 2001), to extend the range of applicability to high-grade metamorphism and migmatites. The situation is improving (Holland et al., 2018), but even relatively recent models (Green et al., 2016) still suffer from original calibrations meant for melt compositions close to the granite minimum. Fractionation is hard to treat with any of these tools (although recent software developments make it easier: Mayne et al., 2020b), that instead excel at calculating "pseudosections" (i.e. isochemical phase assemblage maps), and thus explore the effect of melting conditions on melt compositions (Mayne et al., 2020a).

3.5. Concepts and questions

Moving on to more conceptual questions, we discuss here how the two communities are tackling some petrological problems, and which are the key issues as viewed from either side.

3.5.1. Exploring the whole range of granite compositions

Both models struggle to fully explain the global range of granitic compositions, and need to resort to tweaks and alterations of the core model.

In the mantle-derived melt fractionation view, the chief difficulty is formation of peraluminous magmas without resorting to melting of an aluminous, crustal source. Simply put, the problem is that feldspar being, by definition, Al-neutral (A/CNK = 1), its fractionation is unable by itself to cross the Al saturation line, A/CNK = 1 (see fig. 6 in Bonin et al., 2020; Chappell, 1999). In a pure fractionation model this would require fractionation of Al-poor, and, or alkali/Ca-rich phases (amphibole or pyroxene) (Miller, 1985; Ulmer et al., 2008; Zen, 1986); but even this fails to generate very high (> 1.2) A/CNK values, and to reproduce trends of decreasing A/CNK with increasing SiO_2 observed in strongly peraluminous granites (Chappell and White, 2001; Clemens and Stevens, 2012; Debon and Le Fort, 1983; Miller, 1985; Stussi and De la Roche, 1984; Villaseca et al., 1998).

The crustal model has difficulties to explain the less siliceous compositions. Some authors have proposed that felsic–intermediate rock types down to c. 56 wt. % SiO_2, such as tonalites and quartz diorites, can be produced by partial melting of metabasaltic sources (e.g. Fiannacca et al., 2015; Gao et al., 2016; Jung et al., 2002, 2009; Zhao et al., 2007), after 10–60% melting at 900–1000 °C (Qian and Hermann, 2013; Rapp and Watson, 1995; Skjerlie and Patiño-Douce, 2002; Springer and Seck, 1997; Wolf and Wyllie, 1994). Nevertheless, experimental melts of continental crustal materials at realistic temperatures (≤ 950 °C) seldom contain less than 65 wt. % SiO_2 (based on compilations from Laurent et al., 2014 and Moyen and Stevens, 2006; Moyen et al., 2017). Generating the low-SiO_2 end of the trends seen in many granites, even crustal S-types, is therefore a challenge. Several solutions have been proposed, such as (i) mixing with mafic magmas (Castro et al., 1991; Kemp et al., 2007; Patiño-Douce, 1999), (ii) entrainment of material from the solid source, either in bulk (the classic "restite unmixing" model: Chappell et al., 1987), or only some minerals (the "peritectic assemblage entrainment" model: Clemens et al., 2011; Stevens et al., 2007) or (iii) crystal accumulation/melt drainage from a crystal-rich mush (Chappell and Wyborn, 2004; Fiedrich et al., 2017; Gelman et al., 2014).

3.5.2. The heat budget

Latent heat of crystallization is about 400 kJ/kg for crustal rocks (Spera and Bohrson, 2001), which has to be compared to typical heat capacities in the range of 1.0 to 1.5 kJ/kg/K. Thus, crystallization of 1 kg of melt releases an energy equivalent to heating of the same 1 kg of rock by 300–400 °C. Likewise, in a partial melting system, forming 25 wt. % of melt from a rock at a temperature just below the solidus uses as much heat as heating it by 100 °C. These simple calculations show that heat availability is clearly an important limiting factor in the evolution of granitic systems.

In the mafic magma fractionation paradigm, the problem is largely pushed back to the mantle. The injection of basaltic melts at > 1000 °C in a much cooler crust, plus the latent heat of crystallization, means that the system is very energetic and has abundant heat to spare and to shed as it cools down (see fig. 2 in Collins et al., 2020a). Granites crystallize from cooler melts than basalts, and if they are mostly formed by fractionation of these basalts, there is no thermal issue involved.

The thermal issue becomes much more critical in a crustal melting situation. In this case, one needs to find appropriate heat sources to heat the crust to its solidus, and then add energy equivalent to another 100–200 °C. Calculations show that this is feasible, and even unavoidable in favourable situations such as a crust with a high radioactive heat production (sediment-rich, or during earlier periods of Earth's history, e.g. in the Archaean), a thickened crust, and an increased conductive flux from the mantle (Bea, 2012; England and Thompson, 1984; Gerdes et al., 2000; Moyen, 2020; Thompson and Connolly, 1995). Even so, the maximum temperature of the partially molten systems will never be as high above the wet granite solidus as in the case of basaltic magma fractionation, so that the resulting granitic magmas will have far less thermal manoeuvring room to permit processes such as assimilation (Bohrson and Spera, 2007; Roberts and Clemens, 1995; Spera and Bohrson, 2001). The granitic liquids will also be chemically close to the haplogranitic minimum (e.g., Holtz and Johannes, 1991), having little scope for further evolution of their modal (or major-element) compositions.

In past decades, part of the debate focussed on whether it is actually possible to melt the crust without injecting mantle-derived melts (e.g., Clark et al., 2011; Zheng and Zhao, 2017), and if mafic melts are injected, how much melting is expected. The problem then is that if most of the heat in the crust is added by advection of mafic melts, the basaltic magmas would differentiate to granitic ones (Annen et al., 2006; Annen and Sparks, 2002; Dufek and Bergantz, 2005; Huppert and Sparks, 1988; Moyen, 2020; Petford and Gallagher, 2001). In this case thermal constraints impose that crustal melting is limited by the amount of basaltic magmas advected – and thus, crustal melts cannot volumetrically exceed basalt fractionates (melting efficiency being likely below 10 %; see table 2 of Dufek and Bergantz, 2005).

There are yet other alternatives to gather enough heat to permit crustal melting (Bea, 2012; Casini et al., 2015; Devès et al., 2014; Finger et al., 2009; Gerdes et al., 2000; Henk et al., 2000; Laurent et al., 2017; Moyen, 2020; Nabelek et al., 2010): (i) gradual accumulation of radiogenic heat (for instance in a thickened orogenic crust); (ii) localized shear heating along shear zones, (iii) conduction of heat from a hot mantle (even in the absence of mantle melting), either because it has anomalous composition rich in heat-producing elements or because of processes such as delamination of a crustal/lithospheric mantle root, slab break-off, asthenosphere upwelling or a rise of a mantle plume.

Finally, several mechanisms may alleviate the heat requirement by moving the solidus to lower temperatures: (i) influx of water into the crust, for instance via crystallization of mafic melts releasing hydrous fluids (Collins et al., 2020a) or by dehydration of underlying metamorphic complexes after thrusting/crustal stacking (Fiannacca et al., 2020; Le Fort et al., 1987; Nabelek, 2020); (ii) exhumation and decompression of an already hot middle/lower crust in gneiss/migmatite domes and core complexes (Collins et al., 1998; Vanderhaeghe and Teyssier, 2001).

Table 2
What is a typical granite? Two concepts of the (granitic) world.

	Mantle model (basalt fractionation)	Crust model (crustal melting)
A typical granitoid is…	Metaluminous (quartz) diorite–tonalite–granodiorite–granite	Peraluminous granodiorite to leucogranite
Granites most commonly occur in…	Magmatic arcs	Syn- to post-collisional domains
Granites mostly form by…	Differentiation of basalts (originally mantle-derived)	Partial melting of variable crustal lithologies
Plutons are…	Solidified, largely homogenized magma chambers where differentiation (± crystal/melt segregation including crystal accumulation) operated	A collection of countless (anatectic) magma batches
Volcanoes are…	An ordinary end-product of the melt evolution/extraction	Rare to absent, possibly the product of a different process than the granites
Coeval mafic rocks are…	The forerunner of the granitoid magmas	Accidental
Melts in the crust are…	Hot, with lots of potential for fractionation, assimilation/AFC, mixing etc.	Near-solidus, and their major-element composition can hardly evolve further

All of these scenarios are rather complex and difficult to model accurately. Unsurprisingly, the two communities using calculations based on slightly different assumptions reach opposite conclusions. While the fractionation community mostly focuses on arc crust and concludes on the impossibility to trigger abundant crustal melting without a direct involvement of voluminous mantle-derived injections, the melting community finds that slow maturation and in-situ radioactive heat production in a fertile thickened orogenic pile, followed by exhumation, makes intracrustal melting unavoidable (Moyen, 2020).

3.5.3. *Importing foreign concepts*

As we have noted, some concepts and ways of thinking belong to one of the paradigms. Yet, they offer fruitful lines of evidence, worth being considered under the other one.

The concept of differentiation of magmas during crystallization, for instance, is rather alien to the crustal point of view, for reasons on which we have elaborated. Yet, near-eutectic crystallization will cover a large interval of melt fractions, and can thus permit some liquid–solid segregation (Chappell and Wyborn, 2004; Lee and Morton, 2015). Taking such processes into account may offer interesting insights even on the evolution of peraluminous plutons (Miller, 1985; Mittlefehldt and Miller, 1983; Weinberg, 2006). Melt evolution close to the granite minimum is not eutectic *sensu stricto* but occurs over a narrow range of temperatures and modal compositions. Even though it produces limited major-element variations in the resulting granites, it will profoundly influence the trace-element patterns of the residual melts, with potentially critical consequences for the concentration of economically valuable elements (e.g., Li, Sn, W, Nb, Ta; Černý et al., 2005; Sial et al., 2011).

Likewise, the crustal melting community has evolved a sound understanding of melting processes and their possible complications, such as the entrainment of solids (peritectic minerals or restite) and their role in shaping the chemistry and isotopic signatures of magmas. Much in the same way as crystallization above, the complexities of the melting process and its potential to generate a range of magmas with possibly disparate chemical and isotopic signatures – even in the mantle – are perhaps under-appreciated in the fractionation community.

4. In summary: the “typical” granite defined

In a somewhat provocative way, one may try to articulate how both schools of thought imagine an archetypical granite. Although these views are seldom expressed as clearly and as strongly, it is nevertheless clear, when reading the literature or listening to conference presentations, that these two views underlie and frame the thinking of most of the researchers. More often than not, these are unspoken assumptions, taken for granted but never discussed or questioned.

In the basalt fractionation community, the “ordinary” granite occurs at a supra-subduction continental arc. Western America (from the Andes to Alaska) would be the archetypical granite locality. An ordinary granitoid is seldom a granite s.s., but is rather a granodiorite or a tonalite, often accompanied by (quartz) diorite or gabbro. It is metaluminous, and hornblende-bearing, only the most silicic rocks being weakly peraluminous (A/CNK generally < 1.1, and typically lacking muscovite or cordierite). Strongly peraluminous, cordierite or muscovite bearing granites (A/CNK >1.1) are only acknowledged as a petrological curiosity. Thus, the main chemical properties investigated, or considered in classifications, are not related to aluminosity, but rather to evolution with increasing SiO_2. Radiogenic isotopes are useful to trace the characteristics of the mantle source(s) and/or contamination by crustal material. Granitoids are part of a magmatic series, and they are understood in the context of crustal-scale magma differentiation and the dynamics of magma reservoirs. Therefore, there is a strong connection to the mafic/ultramafic community, comparisons with layered mafic intrusions, and so on. The magmas involved are both hot enough, and chemically remote from the minimum composition, to permit processes such as closed-system magmatic differentiation, assimilation, or magma mixing.

The “ordinary” granite, as viewed from the crustal melting community, is a granite s.s., even a leucogranite, less commonly a granodiorite. It is typically exposed in collisional orogens (e.g. European Variscides, Himalayan Belt), often in conjunction with migmatites and HT–HP metamorphic complexes. Peraluminous, muscovite/cordierite- and biotite-bearing varieties dominate, but hornblende-bearing, weakly peraluminous to metaluminous types are also present. They reflect melting of different crustal rocks and are often described as S- vs. I-type granites, respectively. Isotopes (whole-rock Sr–Nd, Hf–O in zircon most commonly) are a critical tool, as they hold the key to understanding the source of the granitoids and the preceding evolution of the terrain where they are hosted. Granitoids relate to partial melting and their study is therefore connected to investigations on migmatites, melting reactions, and in general to the HT metamorphism community. The magmas involved are frequently close to the granite minimum, both chemically and thermally, so they have little scope for major-element evolution.

5. The nature and evolution of continental crust – implicit models linked to granite paradigms

Implicit assumptions on what is a granite, and how it forms, have consequences on related key topics in Earth Sciences. This is a critical aspect, as other communities use the findings of granite studies, in a digested form, to base their further thinking – commonly, without even realizing that they rely on a very strong paradigm that may or may not be globally relevant. Nowhere is this more obvious than in debates connected to the origin and growth of Earth’s continental crust. It has long been recognized that, since the continental crust is dominated by granitoids, there has to be a link between granitic magmatism and crustal growth. The way this link is articulated does, however, depend on each individual's preferred views on granite formation.

5.1. The nature of the lower crust

In a basaltic magma differentiation paradigm, the lower crust is mostly inferred (and drawn) as dominated by (ultra-) mafic plutonic rocks and related cumulates (Cashman et al., 2017; Ducea et al., 2015). Since all of these components are thought to originate by the differentiation of the same parental mafic magma, the averaged composition has to equal that of the latter (Hacker et al., 2011; Jagoutz, 2010). The discrepancy between the primary mafic input and the final andesitic–dacitic bulk crust composition (Hacker et al., 2011; Rudnick and Gao, 2014) can be ascribed either to removing portions of the dense (ultra-) mafic lower crust via delamination of dense cumulates (Ducea and Saleeby, 1998; Jagoutz and Schmidt, 2013; Kay and Kay, 1993; Zandt et al., 2004), or to deep addition of felsic material by "relamination" (Castro et al., 2013; Hacker et al., 2011, 2015; Schulmann et al., 2014).

From the "crustal melting" perspective, many good sections offer excellent exposure of exhumed lower crust (> 8—10 kbar; e.g., Harley, 2016). Whereas some of these include mafic rocks, they are neither systematically occurring nor a dominant rock type, and in fact large portions of the exposed lower crust are made of older granulitic gneisses (both ortho- and paragneisses) that have been partially molten and melt-depleted with minor or no mafic intrusions (Brown, 2010; Harley, 2016; Sawyer et al., 2011). Of course, in a crustal melting logic, this is fully expected: the existence of granites requires the presence of a complementary melt-depleted zone that is observed in granulite terrains. Thus, the lower crust is expected to be mostly restitic and melt-depleted, but does not have to be particularly mafic (Hacker et al., 2011, 2015). Here again, some delamination of the lower crust may assist in adjusting the final bulk composition (Arndt and Goldstein, 1989).

5.2. Mechanisms of crustal growth

In the "basalt differentiation" paradigm, granites are chiefly the product of differentiation of basaltic arc magmas above subduction zones. The difference between the bulk andesitic composition of the crust and the primary basaltic composition of regular mantle melts is accounted for by recycling of the dense lower crustal cumulates by delamination (Jagoutz and Behn, 2013). Alternatively, if the primary magmas generated by melting of hydrous mantle peridotite are basaltic andesite to andesite in composition (Castro et al., 2013; Castro and Gerya, 2008; Grove et al., 2012), this removes the need for a cumulate delamination. Either way, crustal formation is viewed as a process of intrusion of mafic to intermediate melts into the crust, differentiation, and possibly some recycling of cumulate (Arndt, 2013; Jagoutz, 2010; Jagoutz et al., 2011; Ulmer et al., 2008). This model is not always as clearly expressed but nevertheless underlies large portions of the literature on crustal growth (e.g., Arndt, 2013).

The "crustal melting" paradigm implies a different concept of crustal growth, which is seen as mostly accomplished by increasing crustal thickness during collision of continental plates and resulting melting (e.g. Zheng, 2021). Within this framework, as granitoids result from crustal melting, they do not correspond *per se* to the product of new crust formation. Granite magmatism leads instead to differentiation of pre-existing continental crust into a melt-depleted granulitic lower crust and a low-density middle-upper granitoid crust, resulting in purely intracrustal redistribution of elements and components (Couzinié et al., 2017; Fiannacca et al., 2015; Villaseca et al., 2012). In this case, bulk crust composition is largely inherited from the two merging plates, each one comprising in turn either old igneous and metamorphic basements, or newly accreted arcs, back-arcs, accretionary prisms, oceanic plateaux, etc.

5.3. Reading the zircon record: the role of granitoids in crustal growth

Zircons chiefly form in granitoids, and they can be preserved through erosion, sedimentation, metamorphism and even further partial melting. By compiling U–Pb ages of igneous zircons, or by investigating detrital populations, it is possible to gain a regional, continental-scale or planetary view on crustal evolution (e.g., Arndt, 2013; Belousova et al., 2010; Cawood et al., 2013; Cawood and Hawkesworth, 2019; Condie, 1998; Condie and Aster, 2010; Dhuime et al., 2011, 2018; Goldstein et al., 1997; Hawkesworth et al., 2019; Roberts and Spencer, 2015). One of the most robust features of zircon U–Pb age compilations is the presence of peaks and troughs, pointing to some form of episodicity in zircon formation (and/or preservation) record. The ages of these peaks correspond roughly to the periods of supercontinents assembly on Earth. However, the interpretation of zircon peaks, and their implications for the history of the terrestrial continental crust, are intimately linked to opinions on granitoid formation.

A first family of interpretations (Fig. 3a–c) posits that zircon peaks primarily reflect crustal growth, and that most of the zircons crystallized in the very material that was extracted from the mantle and freshly added to the crust (e.g. Arndt, 2013; Condie, 1998; Goldstein et al., 1997; Spencer et al., 2017). This is not always explicitly interpreted in terms of granitoid petrogenesis, but when it is, the assumption is that granitoids form mostly by the differentiation of basaltic arc magmas (e.g. Jagoutz et al., 2011; Müntener and Ulmer, 2018) or at least that zircons from such granitoids are preferentially preserved in the record. Any non-juvenile isotopic signature in zircons would be interpreted as minor amounts of contamination by older crust, either in the mantle source, or during emplacement of the host granitoids. More than actual supercontinent amalgamation, then, the zircon age peaks would reflect the enhanced felsic magmatism during the subduction of the intervening oceanic lithosphere between parts of the future supercontinent. Often, this goes with the unspoken assumption that subduction, seen as the main agent of continental crustal growth, was operating during most of Earth's history, at least since the Neoarchaean.

In contrast (Fig. 3d–f), the investigation of Hf–O isotope systematics has led to the conclusion that a sizable proportion of the zircons is formed by crustal reworking. From a purely granitic point of view, the implication is that most of the granites, at least those recorded in zircon databases, are the product of crustal reworking. This leads to the use of two-stage model ages (introduced for Nd initially, e.g. Liew and Hofmann, 1988, and now applied to Hf, Belousova et al., 2010; Dhuime et al., 2011, 2012; Kemp et al., 2006; etc.) to see through the reworking phase and constrain the age of crustal extraction from the mantle. The apparently paradoxical observation that Hf model ages (even when using O isotopes to remove the most obviously recycled contributions, i.e."O filtered" databases: Dhuime et al., 2011) imply continuous crustal growth, whereas the zircon U–Pb age distribution remains episodic (Hawkesworth et al., 2009, 2010) is resolved with the concept of (selective) preservation. In this view, granitoids formed during continental collision (or post-collisional, which is unresolvable at the scale of the supercontinent cycle) stages of supercontinent amalgamation (Condie and Aster, 2010) have a better preservation potential than those formed in active continental margins or in oceanic island arcs. Therefore, despite representing lower produced volumes, they should be over-represented in the geological record (Hawkesworth et al., 2009, 2010).

6. Conclusions

In this paper, we reviewed the main paradigms for granite formation, and the key pieces of evidence that support each of them. Two main views, or two end-member models, on the origin of granites coexist in the community. One end-member situation (typified in oceanic arcs and to some extent highlighted by the community working on the link between plutonism and volcanism) is differentiation of mantle-generated mafic melts, resulting in a series of liquids evolving along a line of

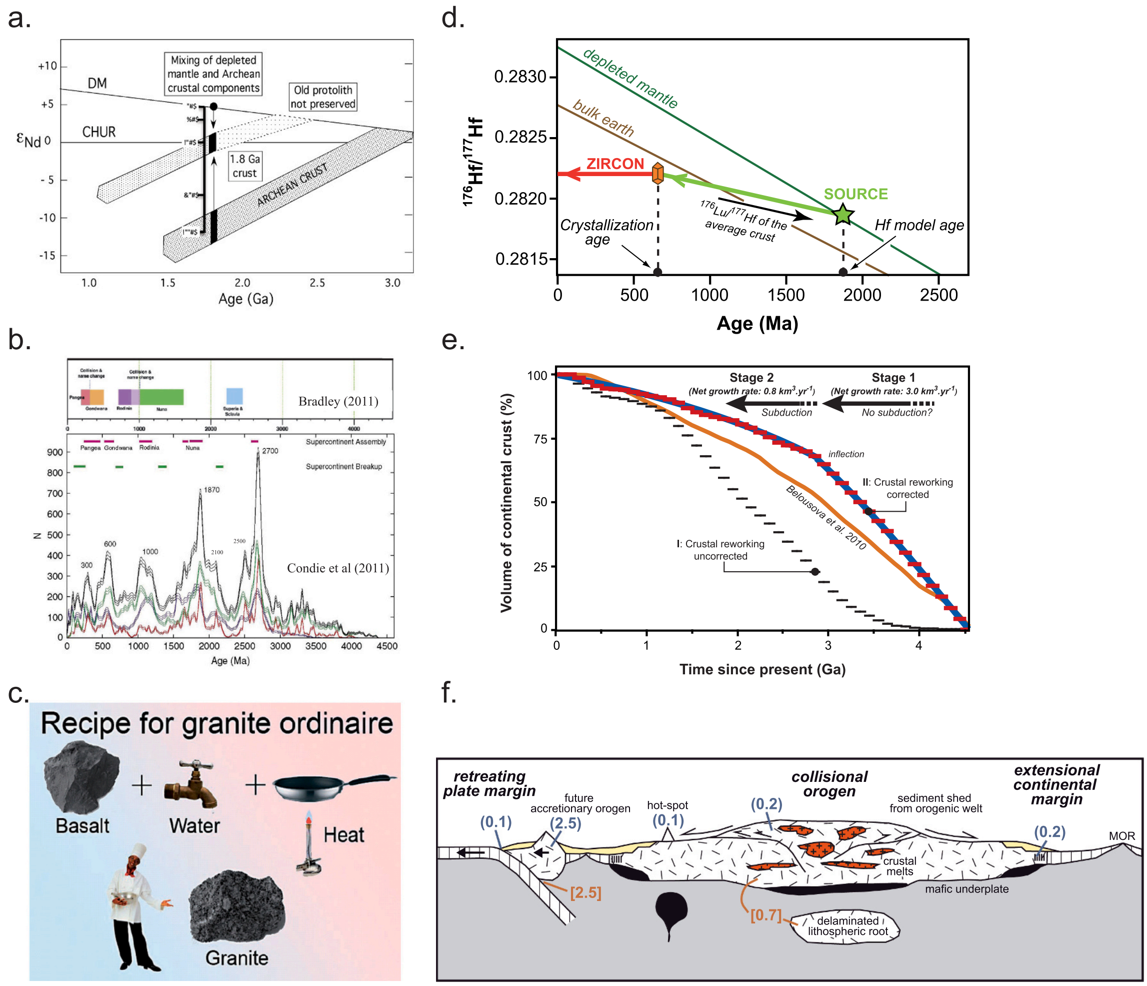

Fig. 3. Contrasting, implicit models for granite formation and their implications for the interpretation of isotopic patterns and crustal growth models, after Arndt (2013) (a–c) and Hawkesworth et al. (2010) and Dhuime et al. (2012) (d–f). (a). Arndt's (2013) view is based on the interpretation of granitoids as reflecting primarily mantle extraction, with isotopic deviations corresponding to volumetrically minor contamination. Thus (b) age peaks should reflect (with minor qualification) periods of crustal growth. As a result (c), his "recipe for ordinary granite" is rooted in a fractionation paradigm. In contrast (d), Hawkesworth et al. (2010) viewed the isotopic signature of granitoids (or their zircons) as the result of reworking of older crustal material and interpreted them using two-stage model ages. The growth curve of Dhuime et al. (2012) (e) is therefore built on two-stage model ages more than emplacement ages, and (f) granitoids (or at least those from which zircons are preserved) are thought to form mostly in orogenic cores during supercontinents assembly. The numbers in parentheses (above surface) and brackets (below surface) in (f) represent the rates of crustal addition and removal, respectively, expressed in $km^3\ yr^{-1}$.

descent, and leaving behind solid mafic cumulates at various levels in the crust and stages of their evolution. The other end-member (exemplified by "S-type" granites and the community working on the link between granite plutons and migmatites or granulites), is melting of pre-existing crust and extraction of nearly undifferentiated liquids, rising and solidifying in sites of pluton assembly. Perhaps surprisingly, deciding between these two models is not simple, as the features of granitic systems, including field observations/relations, petrology, mineralogy, major- and trace-element geochemistry, and isotopic composition, are more often than not equivocal and can be reconciled with both views. Of course, some examples are unambiguous or very close to one of the end-member, but a large number of granitoids (e.g., many granitoids from cordilleras or post-collisional to post-orogenic environments) can equally be explained under either model.

Each sub-community (crustal melting vs. mantle fractionation) has a tendency to expand its favourite model into the "no man's land" in between, and view all granites (except, perhaps, rare and acknowledged exceptions close to the opposite end-member) as formed by their preferred paradigm. However, beyond these mundane factors, this is also, chiefly, a reflection of the fact that each sub-community focusses on a distinct geodynamic environment: magmatic arcs for the fractionation group, and collisional orogens or fertile back-arcs for the crustal melting group. To some degree, more than a matter of competing models, it is therefore a matter of studying distinct geological objects.

We stress that each of the two paradigms is legitimate and built on a robust body of evidence that cannot be overlooked or brushed aside, and each applies to some granites – the main problem being, in which proportion. This triggers several interesting questions:

- In which proportion does an individual granite originate from the crust, or from the mantle?
- Are all granites, or all granitic provinces, similar in that respect?
- What are the factors that control the balance between crust and mantle contributions in granitoids on the regional scale?
- What is the long-term balance of these contributions?
- Finally, in which proportions do granites represent crustal growth or crustal reworking?

We explore all of these questions in the companion paper (Jacob et al., this issue).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Such a paper took many years to mature. An important milestone was a workshop on Granites, held in Roscoff (France) in July 2019, which several of us attended – and where we were forced to confront our ideas and reflect on our differences. Before and beyond, we thank all the colleagues whose discussions and (sometimes very strongly expressed) opinions over the years led us to articulate this summary. Acknowledging all of them would in effect duplicate the reference list.

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References

Aitchison, J., 1986. The Statistical Analysis of Compositional Data. Methuen, New York.
Alonso-Perez, R., Ulmer, P., Müntener, O., Thompson, A.B., 2003. Role of garnet fractionation in H_2O undersaturated andesite liquids at high pressure. Lithos 73, S116.
Alonso-Perez, R., Müntener, O., Ulmer, P., 2009. Igneous garnet and amphibole fractionation in the roots of island arcs: experimental constraints on andesitic liquids. Contrib. Mineral. Petrol. 157, 541–558.
Annen, C., Sparks, R.S.J., 2002. Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust. Earth Planet. Sci. Lett. 203, 937–955.
Annen, C., Blundy, J.D., Sparks, R.S.J., 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. J. Petrol. 47, 505–539.
Arndt, N.T., 2013. The formation and evolution of the continental crust. Geochem. Perspectiv. 2-3, 405–533.
Arndt, N.T., Goldstein, S.L., 1989. An open boundary between lower continental crust and mantle: its role in crust formation and crustal recycling. Tectonophysics 161, 201–212.
Bachmann, O., Bergantz, G.W., 2004. On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. J. Petrol. 45, 1565–1582.
Bachmann, O., Bergantz, G.W., 2008. Rhyolites and their source mushes across tectonic settings. J. Petrol. 49, 2277–2285.
Bachmann, O., Huber, C., 2019. The inner workings of crustal distillation columns; the physical mechanisms and rates controlling phase separation in silicic magma reservoirs. J. Petrol. 60, 3–18.
Bachmann, O., Miller, C.F., De Silva, S., 2007. The volcanic–plutonic connection as a stage for understanding crustal magmatism. J. Volcanol. Geotherm. Res. 167, 1–23.
Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. Lithos 46, 605–626.
Barnes, V.E., Edwards, G., McLaughlin, W.A., Friedman, I., Joensuu, O., 1970. Macusanite occurrence, age, and composition, Macusani, Peru. Geol. Soc. Am. Bull. 81, 1539–1546.
Bartoli, O., Acosta-Vigil, A., Ferrero, S., Cesare, B., 2016. Granitoid magmas preserved as melt inclusions in high-grade metamorphic rocks. Am. Mineral. 101, 1543–1559.
Bea, F., 1996. Residence of REE, Y, Th and U in granites and crustal protoliths; implications for the chemistry of crustal melts. J. Petrol. 37, 521–552.
Bea, F., 2010. Crystallization dynamics of granite magma chambers in the absence of regional stress: multiphysics modeling with natural examples. J. Petrol. 51, 1541–1569.
Bea, F., 2012. The sources of energy for crustal melting and the geochemistry of heat-producing elements. Lithos 153, 278–291.
Becker, H., Wenzel, T., Volker, F., 1999. Geochemistry of glimmerite veins in peridotites from Lower Austria – implications for the origin of K-rich magmas in collision zones. J. Petrol. 40, 315–338.
Behn, M.D., Kelemen, P.B., 2006. Stability of arc lower crust: insights from the Talkeetna arc section, south central Alaska, and the seismic structure of modern arcs. J. Geophys. Res. Solid Earth 111, B11207.
Belcher, R.W., Kisters, A.F.M., 2006. Progressive adjustments of ascent and emplacement controls during incremental construction of the 3.1 Ga Heerenveen Batholith, South Africa. J. Struct. Geol. 28, 1406–1421.
Belousova, E., Kostitsyn, Y., Griffin, W.L., Begg, G.C., O'Reilly, S.Y., Pearson, N.J., 2010. The growth of the continental crust: constraints from zircon Hf-isotope data. Lithos 119, 457–466.
Blichert-Toft, J., Delile, H., Lee, C.-T., Stos-Gale, Z., Billström, K., Andersen, T., Hannu, H., Albarède, F., 2016. Large-scale tectonic cycles in Europe revealed by distinct Pb isotope provinces. Geochem. Geophys. Geosyst. 17, 3854–3864.
Bohrson, W.A., Spera, F.J., 2007. Energy-Constrained Recharge, Assimilation, and Fractional Crystallization (EC-RAcFC): a Visual Basic computer code for calculating trace element and isotope variations of open-system magmatic systems. Geochem. Geophys. Geosyst. 8, Q11003.
Bonin, B., Janoušek, V., Moyen, J.F., 2020. Chemical variation, modal composition and classification of granitoids. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 9–51.
Bons, P., Arnold, J., Elburg, M., Kalda, J., Soesoo, A., van Miligen, B.P., 2004. Melt extraction and accumulation from partially molten rocks. Lithos 78, 25–42.
Bouchez, J.-L., 1997. Granite is never isotropic: an introduction to AMS studies of granitic rocks. In: Bouchez, J.-L., Hutton, D.H.W., Stephens, W.E. (Eds.), Granite: From Segregation of Melt to Emplacement Fabrics. Kluwer Academic Publications, Dordrecht, pp. 95–112.
Bouilhol, P., Connolly, J.A.D., Burg, J.P., 2011. Geological evidence and modeling of melt migration by porosity waves in the sub-arc mantle of Kohistan (Pakistan). Geology 39, 1091–1094.
Bouvet de Maisonneuve, C., Dungan, M., Bachmann, O., Burgisser, A., 2012. Insights into shallow magma storage and crystallization at Volcán Llaima (Andean southern volcanic zone, Chile). J. Volcanol. Geotherm. Res. 211, 76–91.
Bowen, N.L., 1947. Magmas. Geol. Soc. Am. Bull. 58, 263–280.
Brown, M., 2010. Melting of the continental crust during orogenesis: the thermal, rheological, and compositional consequences of melt transport from lower to upper continental crust. Can. J. Earth Sci. 47, 655–694.
Brown, M., Solar, G.S., 1999. The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. Tectonophysics 312, 1–33.
Brown, C.R., Yakymchuk, C., Brown, M., Fanning, C.M., Korhonen, F.J., Piccoli, P.M., Siddoway, C.S., 2016. From source to sink: petrogenesis of Cretaceous anatectic granites from the Fosdick migmatite–granite complex, West Antarctica. J. Petrol. 57, 1241–1278.
Cashman, K.V., Sparks, R.S.J., Blundy, J.D., 2017. Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science 355 eaag3055.
Casini, L., Cuccuru, S., Puccini, A., Oggiano, G., Rossi, P., 2015. Evolution of the Corsica–Sardinia Batholith and late-orogenic shearing of the Variscides. Tectonophysics 646, 65–78.
Castro, A., 2014. The off-crust origin of granite batholiths. Geosci. Front. 5, 63–75.
Castro, A., Gerya, T.V., 2008. Magmatic implications of mantle wedge plumes: experimental study. Lithos 103, 138–148.
Castro, A., Moreno-Ventas, I., de la Rosa, J.D., 1991. H-type (hybrid) granitoids: a proposed revision of the granite-type classification and nomenclature. Earth Sci. Rev. 31, 237–253.
Castro, A., Vogt, K., Gerya, T., 2013. Generation of new continental crust by sublithospheric silicic-magma relamination in arcs: a test of Taylor's andesite model. Gondwana Res. 23, 1554–1566.
Cawood, P.A., Hawkesworth, C.J., 2019. Continental crustal volume, thickness and area, and their geodynamic implications. Gondwana Res. 66, 116–125.
Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009. Accretionary orogens through Earth history. In: Cawood, P., Kröner, A. (Eds.), Earth Accretionary Systems in Space and Time, Geological Society, London, Special Publications, 318, pp. 1–36.
Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2013. The continental record and the generation of continental crust. Geol. Soc. Am. Bull. 125, 14–32.
Černý, P., Blevin, P.L., Cuney, M., London, D., 2005. Granite-related ore deposits. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.), Economy Geology 100th Anniversary Volume, 1905–2005. Littleton, Co., Society of Economic Geologists, pp. 337–370.
Cesare, B., Ferrero, S., Salvioli-Mariani, E., Pedron, D., Cavallo, A., 2009. "Nanogranite" and glassy inclusions: the anatectic melt in migmatites and granulites. Geology 37, 627–630.
Chappell, B.W., 1978. Granitoids from the Moonbi district, New England Batholith, eastern Australia. J. Geol. Soc. Aust. 25, 267–283.
Chappell, B.W., 1999. Aluminium saturation in I- and S-type granites and the characterization of fractionated haplogranites. Lithos 46, 535–551.
Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. Pac. Geol. 8, 173–174.
Chappell, B.W., White, A.J.R., 2001. Two contrasting granite types: 25 years later. Aust. J. Earth Sci. 48, 489–499.
Chappell, B.W., Wyborn, D., 2004. Cumulate and cumulative granitic and associated rocks. Resour. Geol. 54, 227–240.

Chappell, B.W., White, A.J.R., Wyborn, D., 1987. The importance of residual source material (restite) in granite petrogenesis. J. Petrol. 28, 1111–1138.
Chappell, B.W., White, A., Williams, I., Wyborn, D., 2005. Low- and high-temperature granites. Trans. Royal Soc. Edinburgh Earth Sci. 95, 125–140.
Cioni, R., Marianelli, P., Santacroce, R., 1998. Thermal and compositional evolution of the shallow magma chambers of Vesuvius: evidence from pyroxene phenocrysts and melt inclusions. J. Geophys. Res. Solid Earth 103, 18277–18294.
Clark, C., Fitzsimons, I.C.W., Healy, D., Harley, S.L., 2011. When the continental crust melts: how does the continental crust get really hot? Elements 7, 235–240.
Clemens, J.D., 2019. The You Yangs Batholith in southeastern Australia, the sources of its magmas and inferences for local crustal architecture. Aust. J. Earth Sci. 66, 247–264.
Clemens, J.D., Droop, G.T.R., 1998. Fluids, P–T paths and the fates of anatectic melts in the Earth's crust. Lithos 44, 21–36.
Clemens, J.D., Phillips, G.N., 2014. Inferring a deep-crustal source terrane from a high-level granitic pluton: the Strathbogie Batholith, Australia. Contrib. Mineral. Petrol. 168, 1070.
Clemens, J., Stevens, G., 2012. What controls chemical variation in granitic magmas? Lithos 134, 317–329.
Clemens, J.D., Stevens, G., 2016a. Melt segregation and magma interactions during crustal melting: breaking out of the matrix. Earth Sci. Rev. 160, 333–349.
Clemens, J.D., Stevens, G., 2016b. The Saldanha Bay Volcanic Complex: clarifying the Cambrian geology of the Postberg–Saldanha area, West Coast, South Africa. S. Afr. J. Geol. 119, 347–358.
Clemens, J.C., Vielzeuf, D., 1987. Constraints on melting and magma production in the crust. Earth Planet. Sci. Lett. 86, 287–306.
Clemens, J.D., Wall, V.J., 1984. Origin and evolution of a peraluminous silicic ignimbrite suite: the Violet Town Volcanics. Contrib. Mineral. Petrol. 88, 354–371.
Clemens, J.D., Helps, P.A., Stevens, G., 2009. Chemical structure in granitic magmas – a signal from the source? Trans. Royal Soc. Edinburgh Earth Sci. 100, 159–172.
Clemens, J.D., Stevens, G., Farina, F., 2011. The enigmatic sources of I-type granites: the peritectic connexion. Lithos 126, 174–181.
Clemens, J.D., Stevens, G., Frei, D., Joseph, C.S.A., 2017. Origins of cryptic variation in the Ediacaran–Fortunian rhyolitic ignimbrites of the Saldanha Bay Volcanic Complex, Western Cape, South Africa. Contrib. Mineral. Petrol. 172, 99.
Collins, W.J., 1996. Lachlan Fold Belt granitoids: products of three-component mixing. Trans. Royal Soc. Edinburgh Earth Sci. 87, 171–181.
Collins, W.J., 1998. Evaluation of petrogenetic models for Lachlan Fold Belt granitoids: implications for crustal architecture and tectonic models. Aust. J. Earth Sci. 45, 483–500.
Collins, W.J., Richards, S.W., 2008. Geodynamic significance of S-type granites in circum-Pacific orogens. Geology 36, 559–562.
Collins, W.J., Van Kranendonk, M.J., Teyssier, C., 1998. Partial convective overturn of Archaean crust in the east Pilbara Craton, Western Australia: driving mechanisms and tectonic implications. J. Struct. Geol. 20, 1405–1424.
Collins, W.J., Murphy, J.B., Johnson, T.E., Huang, H.Q., 2020a. Critical role of water in the formation of continental crust. Nat. Geosci. 13, 331–338.
Collins, W.J., Huang, H.Q., Bowden, P., Kemp, A.I.S., 2020b. Repeated S–I–A-type granite trilogy in the Lachlan Orogen and geochemical contrasts with A-type granites in Nigeria: implications for petrogenesis and tectonic discrimination. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 53–76.
Colombini, L.L., Miller, C.F., Gualda, G.A., Wooden, J.L., Miller, J.S., 2011. Sphene and zircon in the Highland Range volcanic sequence (Miocene, southern Nevada, USA): elemental partitioning, phase relations, and influence on evolution of silicic magma. Mineral. Petrol. 102, 29.
Condie, K.C., 1998. Episodic continental growth and supercontinents: a mantle avalanche connection? Earth Planet. Sci. Lett. 163, 97–108.
Condie, K.C., Aster, R.C., 2010. Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and continental growth. Precambrian Res. 180, 227–236.
Connolly, J.A.D., 2009. The geodynamic equation of state: what and how. Geochem. Geophys. Geosyst. 10, Q10014 https://doi.org/10.1029/2009GC002540.
Connolly, J.A.D., Petrini, K., 2002. An automated strategy for calculation of phase diagram sections and retrieval of rock properties as a function of physical conditions. J. Metamorph. Geol. 20, 697–708.
Couzinié, S., Moyen, J.F., Laurent, O., Zeh, A., Bouilhol, P., Villaros, A., Gardien, V., 2016. Post-collisional magmatism: crustal growth not identified by zircon Hf–O isotopes. Earth Planet. Sci. Lett. 456, 182–195.
Couzinié, S., Laurent, O., Poujol, M., Mintrone, M., Chelle-Michou, C., Moyen, J.F., Bouilhol, P., Vézinet, A., Marko, L., 2017. Cadomian S-type granites as basement rocks of the Variscan belt (Massif Central, France): implications for the crustal evolution of the north Gondwana margin. Lithos 286-287, 16–34.
Davidson, J., Turner, S., Handley, H., Macpherson, C., Dosseto, A., 2007. Amphibole "sponge" in arc crust? Geology 35, 787–790.
de Capitani, C., Petrakakis, K., 2010. The computation of equilibrium assemblage diagrams with Theriak/Domino software. Am. Mineral. 95, 1006–1016.
Debon, F., Le Fort, P., 1983. A chemical–mineralogical classification of common plutonic rocks and associations. Trans. Royal Soc. Edinburgh Earth Sci. 73, 135–149.
DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth Planet. Sci. Lett. 53, 189–202.
Dessimoz, M., Müntener, O., Ulmer, P., 2012. A case for hornblende dominated fractionation of arc magmas: the Chelan Complex (Washington Cascades). Contrib. Mineral. Petrol. 167, 567–589.
Devès, M.H., Tait, S.R., King, G.C., Grandin, R., 2014. Strain heating in process zones; implications for metamorphism and partial melting in the lithosphere. Earth Planet. Sci. Lett. 394, 216–228.
Dhuime, B., Hawkesworth, C., Cawood, P., 2011. When continents formed. Science 331, 154–155.
Dhuime, B., Hawkesworth, C.J., Cawood, P.A., Storey, C.D., 2012. A change in the geodynamics of continental growth 3 billion years ago. Science 335, 1334–1336.
Dhuime, B., Hawkesworth, C.J., Delavault, H., Cawood, P.A., 2018. Rates of generation and destruction of the continental crust: implications for continental growth. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 376, 20170403.
Didier, J., Barbarin, B. (Eds.), 1991. Enclaves and Granite Petrology. Elsevier, Amsterdam.
Donaire, T., Pascual, E., Pin, C., Duthou, J.L., 2005. Microgranular enclaves as evidence of rapid cooling in granitoid rocks: the case of the Los Pedroches granodiorite, Iberian Massif, Spain. Contrib. Mineral. Petrol. 149, 247–265.
Downes, H., Shaw, A., Williamson, B.J., Thirlwall, M.F., 1997. Sr, Nd and Pb isotopic evidence for the lower crustal origin of Hercynian granodiorites and monzogranites, Massif Central, France. Chem. Geol. 136, 99–122.
Ducea, M., Saleeby, J., 1998. A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California. Int. Geol. Rev. 40, 78–93.
Ducea, M.N., Saleeby, J.B., Bergantz, G., 2015. The architecture, chemistry, and evolution of continental magmatic arcs. Annu. Rev. Earth Planet. Sci. 43, 299–331.
Dufek, J., Bergantz, G.W., 2005. Lower crustal magma genesis and preservation: a stochastic framework for the evaluation of basalt–crust interaction. J. Petrol. 46, 2167–2195.
Edmonds, M., Cashman, K.V., Holness, M., Jackson, M., 2019. Architecture and dynamics of magma reservoirs. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 377, 20180298.
Elburg, M.A., 1996. Evidence of isotopic equilibration between microgranitoid enclaves and host granodiorite, Warburton Granodiorite, Lachlan Fold Belt, Australia. Lithos 38, 1–22.
England, P.C., Thompson, A.B., 1984. Pressure–temperature–time paths of regional metamorphism. Part I: Heat transfer during the evolution of regions of thickened continental crust. J. Petrol. 25, 894–928.
Evans, O.C., Hanson, G.N., 1993. Accessory-mineral fractionation of rare-earth element (REE) abundances in granitoid rocks. Chem. Geol. 110, 69–93.
Farina, F., Stevens, G., 2011. Source controlled $^{87}Sr/^{86}Sr$ isotope variability in granitic magmas: the inevitable consequence of mineral-scale isotopic disequilibrium in the protolith. Lithos 122, 189–200.
Farina, F., Stevens, G., Villaros, A., 2012. Multi-batch, incremental assembly of a dynamic magma chamber: the case of the Peninsula Pluton granite (Cape Granite Suite, South Africa). Mineral. Petrol. 106, 193–216.
Farina, F., Stevens, G., Gerdes, A., Frei, D., 2014a. Small-scale Hf isotopic variability in the Peninsula Pluton (South Africa): the processes that control inheritance of source $^{176}Hf/^{177}Hf$ diversity in S-type granites. Contrib. Mineral. Petrol. 168, 1065.
Farina, F., Dini, A., Rocchi, S., Stevens, G., 2014b. Extreme mineral-scale Sr isotope heterogeneity in granites by disequilibrium melting of the crust. Earth Planet. Sci. Lett. 399, 103–115.
Faure, G., 2001. Origin of Igneous Rocks: The Isotopic Evidence. Springer, Berlin.
Ferrero, S., Bartoli, O., Cesare, B., Salvioli-Mariani, E., Acosta-Vigil, A., Cavallo, A., Groppo, C., Battiston, S., 2012. Microstructures of melt inclusions in anatectic metasedimentary rocks. J. Metamorph. Geol. 30, 303–322.
Fiannacca, P., Cirrincione, R., Bonanno, F., Carciotto, M.M., 2015. Source-inherited compositional diversity in granite batholiths: the geochemical message of Late Paleozoic intrusive magmatism in central Calabria (southern Italy). Lithos 236, 123–140.
Fiannacca, P., Williams, I.S., Cirrincione, R., 2017. Timescales and mechanisms of batholith construction: constraints from zircon oxygen isotopes and geochronology of the late Variscan Serre Batholith (Calabria, southern Italy). Lithos 277, 302–314.
Fiannacca, P., Basei, M.A.S., Cirrincione, R., Pezzino, A., Russo, D., 2020. Water-assisted production of late-orogenic trondhjemites at magmatic and subsolidus conditions. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 147–178.
Fiedrich, A., Bachmann, O., Ulmer, P., Deering, C., Kunze, K., Leuthold, J., 2017. Mineralogical, geochemical, and textural indicators of crystal accumulation in the Adamello Batholith (Northern Italy). Am. Mineral. 102, 2467–2483.
Finger, F., Clemens, J.D., 1995. Migmatization and "secondary" granitic magmas: effects of emplacement and crystallization of "primary" granitoids in Southern Bohemia, Austria. Contrib. Mineral. Petrol. 120, 311–326.
Finger, F., Gerdes, A., René, M., Riegler, G., 2009. The Saxo-Danubian Granite Belt: magmatic response to post-collisional delamination of mantle lithosphere below the southwestern sector of the Bohemian Massif (Variscan Orogen). Geol. Carpath. 60, 205–212.
Fourmentraux, C., Métrich, N., Bertagnini, A., Rosi, M., 2012. Crystal fractionation, magma step ascent, and syn-eruptive mingling: the Averno 2 eruption (Phlegraean Fields, Italy). Contrib. Mineral. Petrol. 163, 1121–1137.
Fowler, M.B., Kocks, H., Darbyshire, D.P.F., Greenwood, P.B., 2008. Petrogenesis of high Ba–Sr plutons from the Northern Highlands Terrane of the British Caledonian Province. Lithos 105, 129–148.
Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. J. Petrol. 42, 2033–2048.
Gao, P., Zheng, Y.F., Zhao, Z.F., 2016. Experimental melts from crustal rocks: a lithochemical constraint on granite petrogenesis. Lithos 266, 133–157.
Gelman, S.E., Deering, C.D., Bachmann, O., Huber, C., Gutierrez, F.J., 2014. Identifying the crystal graveyards remaining after large silicic eruptions. Earth Planet. Sci. Lett. 403, 299–306.
Gerdes, A., Wörner, G., Henk, A., 2000. Post-collisional granite generation and HT–LP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. J. Geol. Soc. 157, 577–587.

Ghiorso, M.S., 1997. Thermodynamic models of igneous processes. Annu. Rev. Earth Planet. Sci. 25, 221–241.
Ghiorso, M.S., Gualda, G.A., 2015. Chemical thermodynamics and the study of magmas. In: Sigurdsson, H., Houghton, B., McNutt, S., Rymer, H., Stix, J. (Eds.), The Encyclopedia of Volcanoes. Academic Press, Amsterdam, pp. 143–161.
Ghiorso, M.S., Sack, R.O., 1995. Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid–solid equilibria in magmatic systems at elevated temperatures and pressures. Contrib. Mineral. Petrol. 119, 197–212.
Goldstein, S., Arndt, N., Stallard, R., 1997. The history of a continent from U–Pb ages of zircons from Orinoco river sand and Sm–Nd isotopes in Orinoco basin river sediments. Chem. Geol. 139, 271–286.
Green, E.C.R., White, R.W., Diener, J.F.A., Powell, R., Holland, T.J.B., Palin, R.M., 2016. Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. J. Metamorph. Geol. 34, 845–869.
Grove, T.L., Till, C.B., Krawczynski, M.J., 2012. The role of H_2O in subduction zone magmatism. Annu. Rev. Earth Planet. Sci. 40, 413–439.
Gualda, G.A., Ghiorso, M.S., 2013. Low-pressure origin of high-silica rhyolites and granites. J. Geol. 121, 537–545.
Gualda, G.A.R., Ghiorso, M.S., Lemons, R.V., Carley, T.L., 2013. Rhyolite-MELTS: a modified calibration of MELTS optimized for silica-rich, fluid-bearing magmatic systems. J. Petrol. 53, 875–890.
Guo, Z., Wilson, M., Liu, J., 2007. Post-collisional adakites in South Tibet: products of partial melting of subduction-modified lower crust. Lithos 96, 205–224.
Hacker, B.R., Kelemen, P.B., Behn, M.D., 2011. Differentiation of the continental crust by relamination. Earth Planet. Sci. Lett. 307, 501–516.
Hacker, B.R., Kelemen, P.B., Behn, M.D., 2015. Continental lower crust. Annu. Rev. Earth Planet. Sci. 43, 167–205.
Harker, A., 1909. A Natural History of Igneous Rocks. Methuen and Co., London.
Harley, S.L., 2016. A matter of time: the importance of the duration of UHT metamorphism. J. Mineral. Petrol. Sci. 111, 50–72.
Hasalová, P., Štípská, P., Powell, R., Schulmann, K., Janoušek, V., Lexa, O., 2008. Transforming mylonitic metagranite by open-system interactions during melt flow. J. Metamorph. Geol. 26, 55–80.
Hawkesworth, C., Cawood, P., Kemp, T., Storey, C., Dhuime, B., 2009. A matter of preservation. Science 323, 49–50.
Hawkesworth, C.J., Dhuime, B., Pietranik, A.B., Cawood, P.A., Kemp, A.I.S., Storey, C.D., 2010. The generation and evolution of the continental crust. J. Geol. Soc. 167, 229–248.
Hawkesworth, C., Cawood, P.A., Dhuime, B., 2019. Rates of generation and growth of the continental crust. Geosci. Front. 10, 165–173.
Hecht, L., Vigneresse, J.L., 1999. A multidisciplinary approach combining geochemical, gravity and structural data: implications for pluton emplacement and zonation. In: Castro, A., Fernandez, C., Vigneresse, J.L. (Eds.), Understanding Granites: Integrating New and Classical Techniques, Geological Society, London, Special Publications, 168, pp. 95–110.
Henk, A., von Blanckenburg, F., Finger, F., Schaltegger, U., Zulauf, G., 2000. Syn-convergent high-temperature metamorphism and magmatism in the Variscides: a discussion of potential heat sources. In: Franke, W., Haak, V., Oncken, O., Tanner, D. (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt, Geological Society, London, Special Publications, 179, pp. 387–399.
Hildreth, W., Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of central Chile. Contrib. Mineral. Petrol. 98, 455–489.
Holland, T.J., Green, E.C., Powell, R., 2018. Melting of peridotites through to granites: a simple thermodynamic model in the system KNCFMASHTOCr. J. Petrol. 59, 881–900.
Holness, M.B., 2018. Melt segregation from silicic crystal mushes: a critical appraisal of possible mechanisms and their microstructural record. Contrib. Mineral. Petrol. 173, 48.
Holtz, F., Johannes, W., 1991. Genesis of peraluminous granites I. Experimental investigation of melt compositions at 3 and 5 kbar and various H_2O activities. J. Petrol. 32, 935–958.
Hoskin, P.W., Kinny, P.D., Wyborn, D., Chappell, B.W., 2000. Identifying accessory mineral saturation during differentiation in granitoid magmas: an integrated approach. J. Petrol. 41, 1365–1396.
Huber, C., Bachmann, O., Manga, M., 2009. Homogenization processes in silicic magma chambers by stirring and mushification (latent heat buffering). Earth Planet. Sci. Lett. 283, 38–47.
Huppert, H.E., Sparks, R.S.J., 1988. The generation of granitic magmas by intrusion of basalt into continental crust. J. Petrol. 29, 599–624.
Hutton, D.H.W., Reavy, R.J., 1992. Strike-slip tectonics and granite petrogenesis. Tectonics 11, 960–967.
Iles, K.A., Hergt, J.M., Woodhead, J.D., 2018. Modelling isotopic responses to disequilibrium melting in granitic systems. J. Petrol. 59, 87–113.
Jacob, J.-B., Moyen, J.F., 2021. Granite and related rocks. In: Alderton, D., Elias, S.A. (Eds.), Encyclopedia of Geology, 2nd edition. Academic Press, Oxford, pp. 170–183.
Jacob, J.-B., Moyen, J.-F., Fiannacca, P., Laurent, O., Bachmann, O., Janoušek, V., Farina, F., Villaros, A. [This issue]. Crustal melting vs. fractionation of basaltic magmas: Part 2, Attempting to quantify mantle and crust contributions in granitoids. Lithos 106292. https://doi.org/10.1016/j.lithos.2021.106292.
Jagoutz, O.E., 2010. Construction of the granitoid crust of an island arc. Part II: a quantitative petrogenetic model. Contrib. Mineral. Petrol. 160, 359–381.
Jagoutz, O., Behn, M.D., 2013. Foundering of lower island-arc crust as an explanation for the origin of the continental Moho. Nature 504, 131–134.
Jagoutz, O., Klein, B., 2018. On the importance of crystallization–differentiation for the generation of SiO_2-rich melts and the compositional build-up of arc (and continental) crust. Am. J. Sci. 318, 29–63.
Jagoutz, O., Schmidt, M.W., 2013. The composition of the foundered complement to the continental crust and a re-evaluation of fluxes in arcs. Earth Planet. Sci. Lett. 371, 177–190.
Jagoutz, O., Müntener, O., Burg, J.-P., Ulmer, P., Jagoutz, E., 2006. Lower continental crust formation through focused flow in km-scale melt conduits: the zoned ultramafic bodies of the Chilas Complex in the Kohistan island arc (NW Pakistan). Earth Planet. Sci. Lett. 242, 330–342.
Jagoutz, O., Müntener, O., Schmidt, M.W., Burg, J.-P., 2011. The roles of flux- and decompression melting and their respective fractionation lines for continental crust formation: evidence from the Kohistan arc. Earth Planet. Sci. Lett. 303, 25–36.
Janoušek, V., Moyen, J.F., 2020. Whole-rock geochemical modelling of granite genesis: the current state of the play. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 267–291.
Janoušek, V., Konopásek, J., Ulrich, S., Erban, V., Tajčmanová, L., Jeřábek, P., 2010. Geochemical character and petrogenesis of Pan-African Amspoort suite of the Boundary Igneous Complex in the Kaoko Belt (NW Namibia). Gondwana Res. 18, 688–707.
Janoušek, V., Moyen, J.F., Martin, H., Erban, V., Farrow, C.M., 2016. Geochemical Modelling of Igneous Processes – Principles and Recipes in the R Language. Springer, Berlin.
Janoušek, V., Hanžl, P., Svojtka, M., Hora, J.M., Erban Kochergina, Y.V., Gadas, P., Holub, F.V., Gerdes, A., Verner, K., Hrdličková, K., Daly, J.S., Buriánek, D., 2020. Ultrapotassic magmatism in the heyday of the Variscan Orogeny – the story of the Třebíč Pluton, the largest durbachitic body in the Bohemian Massif. Int. J. Earth Sci. 109, 1767–1810.
Johannes, W., Ehlers, C., Kriegsman, L.M., Mengel, K., 2003. The link between migmatites and S-type granites in the Turku area, southern Finland. Lithos 68, 69–90.
Johnson, T.E., Fischer, S., White, R.W., Brown, M., Rollinson, H.R., 2012. Archaean intracrustal differentiation from partial melting of metagabbro – field and geochemical evidence from the central region of the Lewisian Complex, NW Scotland. J. Petrol. 53, 2115–2138.
Jung, S., Hoernes, S., Mezger, K., 2002. Synorogenic melting of mafic lower crust: constraints from geochronology, petrology and Sr, Nd, Pb and O isotope geochemistry of quartz diorites (Damara Orogen, Namibia). Contrib. Mineral. Petrol. 143, 551–566.
Jung, S., Masberg, P., Mihm, D., Hoernes, S., 2009. Partial melting of diverse crustal sources – constraints from Sr–Nd–O isotope compositions of quartz diorite–granodiorite–leucogranite associations (Kaoko Belt, Namibia). Lithos 111, 236–251.
Kay, R.W., Kay, S.M., 1993. Delamination and delamination magmatism. Tectonophysics 219, 177–189.
Keay, S., Collins, W.J., McCulloch, M.T., 1997. A three-component Sr–Nd isotopic mixing model for granitoid genesis, Lachlan Fold Belt, eastern Australia. Geology 25, 307–310.
Kelsey, D.E., Clark, C., Hand, M., 2008. Thermobarometric modelling of zircon and monazite growth in melt-bearing systems: examples using model metapelitic and metapsammitic granulites. J. Metamorph. Geol. 26, 199–212.
Kemp, A., Hawkesworth, C., Paterson, B., Kinny, P., 2006. Episodic growth of the Gondwana supercontinent from hafnium and oxygen isotopes in zircon. Nature 439, 580–583.
Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt, J. M., Gray, C.M., Whitehouse, M.J., 2007. Magmatic and crustal differentiation history of granitic rocks from Hf–O isotopes in zircon. Science 315, 980–983.
Kisters, A.F.M., Ward, R.A., Anthonissen, C.J., Vietze, M.E., 2009. Melt segregation and far-field melt transfer in the mid-crust. J. Geol. Soc. 166, 905–918.
Knesel, K.M., Davidson, J.P., 1996. Isotopic disequilibrium during melting of granite and implications for crustal contamination of magmas. Geology 24, 243–246.
Knesel, K.M., Davidson, J.P., 2002. Insights into collisional magmatism from isotopic fingerprints of melting reactions. Science 296, 2206–2208.
Koyaguchi, T., Kaneko, K., 1999. A two-stage thermal evolution model of magmas in continental crust. J. Petrol. 40, 241–254.
Kriegsman, L.M., 2001. Partial melting, partial melt extraction and partial back reaction in anatectic migmatites. Lithos 56, 75–96.
Laurent, O., Zeh, A., 2015. A linear Hf isotope–age array despite different granitoid sources and complex Archean geodynamics: example from the Pietersburg Block (South Africa). Earth Planet. Sci. Lett. 430, 326–338.
Laurent, O., Martin, H., Moyen, J.-F., Doucelance, R., 2014. The diversity and evolution of late-Archaean granitoids: evidence for the onset of "modern-style" plate tectonics between 3.0 and 2.5 Ga. Lithos 205, 208–235.
Laurent, O., Couzinié, S., Zeh, A., Vanderhaeghe, O., Moyen, J.F., Villaros, A., Gardien, V., Chelle-Michou, C., 2017. Protracted, coeval crust- and mantle melting during Variscan late-orogenic evolution: zircon U–Pb dating in the eastern French Massif Central. Int. J. Earth Sci. 106, 421–451.
Le Fort, P., Cuney, M., Deniel, C., France-Lanord, C., Sheppard, S.M.F., Upreti, B.N., Vidal, P., 1987. Crustal generation of the Himalayan leucogranites. Tectonophysics 134, 39–57.
Lee, C.T.A., Bachmann, O., 2014. How important is the role of crystal fractionation in making intermediate magmas? Insights from Zr and P systematics. Earth Planet. Sci. Lett. 393, 266–274.

Lee, C.T.A., Morton, D.M., 2015. High silica granites: terminal porosity and crystal settling in shallow magma chambers. Earth Planet. Sci. Lett. 409, 23–31.

Leuthold, J., Müntener, O., Baumgartner, L.P., Putlitz, B., Ovtcharova, M., Schaltegger, U., 2012. Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia). Earth Planet. Sci. Lett. 325, 85–92.

Liew, T.C., Hofmann, A.W., 1988. Precambrian crustal components, plutonic associations, plate environment of the Hercynian Fold Belt of Central Europe: indications from a Nd and Sr isotopic study. Contrib. Mineral. Petrol. 98, 129–138.

Madlakana, N., Stevens, G., 2018. Plagioclase disequilibrium induced during fluid-absent biotite-breakdown melting in metapelites. J. Metamorph. Geol. 36, 1097–1116.

Martin, H., 1986. Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. Geology 14, 753–756.

Mayne, M., Stevens, G., Moyen, J.F., 2020a. A phase equilibrium investigation of selected source controls on the composition of melt batches generated by sequential melting of an average metapelite. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 223–241.

Mayne, M., Stevens, G., Moyen, J.F., Johnson, T., 2020b. Performing process-oriented investigations involving mass transfer using Rcrust: a new phase equilibrium modelling tool. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 209–221.

McCulloch, M.T., Chappell, B.W., 1982. Nd isotopic characteristics of S- and I-type granites. Earth Planet. Sci. Lett. 58, 51–64.

McLeod, C.L., Davidson, J.P., Nowell, G.M., de Silva, S.L., 2012. Disequilibrium melting during crustal anatexis and implications for modeling open magmatic systems. Geology 40, 435–438.

Meynier, A., 1942. Les granites. Presented at the Annales de géographie. Société de géographie 227–228.

Miller, C.F., 1985. Are strongly peraluminous magmas derived from pelitic sedimentary sources? J. Geol. 93, 673–689.

Miller, C.F., McDowell, S.M., Mapes, R.W., 2003. Hot and cold granites? Implications of zircon saturation temperatures and preservation of inheritance. Geology 31, 529–532.

Miller, C.F., Miller, J.S., Faulds, J.E., Stevens, C., Cooper, C., 2005. Miocene volcano–plutonic systems, southern Nevada: a window into upper crustal magmatic processes. In: Stevens, C., Cooper, C. (Eds.), Western Great Basin Geology: Fieldtrip Guidebook and Volume, 99. GSA Cordilleran Section, Pacific Section SEPM publications, pp. 37–66.

Miller, C.F., Furbish, D.J., Walker, B.A., Claiborne, L.L., Koteas, G.C., Bleick, H.A., Miller, J.S., 2011. Growth of plutons by incremental emplacement of sheets in crystal-rich host: evidence from Miocene intrusions of the Colorado River region, Nevada, USA. Tectonophysics 500, 65–77.

Mittlefehldt, D.W., Miller, C.F., 1983. Geochemistry of the Sweetwater Wash Pluton, California; implications for "anomalous" trace element behavior during differentiation of felsic magmas. Geochim. Cosmochim. Acta 47, 109–124.

Morfin, S., Sawyer, E.W., Bandyayera, D., 2013. Large volumes of anatectic melt retained in granulite facies migmatites: an injection complex in northern Quebec. Lithos 168, 200–218.

Moyen, J.F., 2020. Granites and crustal heat budget. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 77–100.

Moyen, J.-F., Stevens, G., 2006. Experimental constraints on TTG petrogenesis: implications for Archean geodynamics. In: Benn, K., Mareschal, J.C., Condie, K.C. (Eds.), Archean Geodynamics and Environments, AGU Special Publications, 164, pp. 149–175.

Moyen, J.F., Laurent, O., Chelle-Michou, C., Couzinié, S., Vanderhaeghe, O., Zeh, A., Villaros, A., Gardien, V., 2017. Collision vs. subduction-related magmatism: two contrasting ways of granite formation and implications for crustal growth. Lithos 277, 154–177.

Müntener, O., Pistone, M., 2019. Bulk crustal composition and modulations by magmatic additions. Geophys. Res. Abstr. 21, EGU2019–17243.

Müntener, O., Ulmer, P., 2018. Arc crust formation and differentiation constrained by experimental petrology. Am. J. Sci. 318, 64–89.

Murphy, J.B., 2007. Igneous rock associations 8. Arc magmatism II: Geochemical and isotopic characteristics. Geosci. Can. 34, 7–35.

Nabelek, P.I., 2020. Petrogenesis of leucogranites in collisional orogens. In: Janoušek, V., Bonin, B., Collins, W.J., Farina, F., Bowden, P. (Eds.), Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments, Geological Society, London, Special Publications, 491, pp. 179–207.

Nabelek, P.I., Whittington, A.G., Hofmeister, A.M., 2010. Strain heating as a mechanism for partial melting and ultrahigh temperature metamorphism in convergent orogens: implications of temperature-dependent thermal diffusivity and rheology. J. Geophys. Res. Solid Earth 115, B12417.

Nicoli, G., Stevens, G., Moyen, J.F., Vézinet, A., Mayne, M., 2017. Insights into the complexity of crustal differentiation from K_2O-poor leucosomes within metapelitic migmatites: Southern Marginal Zone of the Limpopo Belt, South Africa. J. Metamorph. Geol. 35, 999–1022.

Paterson, S.R., Vernon, R.H., 1995. Bursting the bubble of ballooning plutons – a return to nested diapirs emplaced by multiple processes. Geol. Soc. Am. Bull. 107, 1356–1380.

Patiño-Douce, A.E., 1999. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas? In: Castro, A., Fernandez, C., Vigneresse, J.L. (Eds.), Understanding Granites: Integrating New and Classical Techniques, Geological Society, London, Special Publications, 168, pp. 55–75.

Pattison, D.R.M., Harte, B., 1988. Evolution of structurally contrasting anatectic migmatites in the 3 kbar Ballachulish aureole, Scotland. J. Metamorph. Geol. 6, 475–494.

Pawlowsky-Glahn, V., Egozcue, J.J., 2006. Compositional data and their analysis: an introduction. In: Buccianti, A., Mateu-Figueras, G., Pawlowsky-Glahn, V. (Eds.), Compositional Data Analysis in the Geosciences: From Theory to Practice, Geological Society, London, Special Publications, 264, pp. 1–10.

Payne, J.L., McInerney, D.J., Barovich, K.M., Kirkland, C.L., Pearson, N.J., Hand, M., 2016. Strengths and limitations of zircon Lu–Hf and O isotopes in modelling crustal growth. Lithos 248, 175–192.

Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol. 25, 956–983.

Perrin, R., Roubault, M., 1937. Les réactions à l'état solide et la géologie. Gouvernement général de l'Algérie Service de la carte géologique de l'Algérie, Algiers.

Petford, N., 1996. Dykes or diapirs? Trans. Royal Soc. Edinburgh Earth Sci. 87, 105–114.

Petford, N., Gallagher, K., 2001. Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. Earth Planet. Sci. Lett. 193, 483–489.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.L., 2000. Granite magma formation, transport and emplacement in the Earth's crust. Nature 408, 669–673.

Pin, C., Duthou, J.L., 1990. Sources of Hercynian granitoids from the French Massif Central: inferences from Nd isotopes and consequences for crustal evolution. Chem. Geol. 83, 281–296.

Pin, C., Binon, M., Belin, J.M., Barbarin, B., Clemens, J.D., 1990. Origin of microgranular enclaves in granitoids – equivocal Sr–Nd evidence from Hercynian rocks in the Massif Central (France). J. Geophys. Res. 95, 17821–17828.

Pitcher, W.S., 1987. Granites and yet more granites forty years on. Geol. Rundsch. 76, 51–79.

Pitcher, W.S., 1997. The Nature and Origin of Granite. Springer Science & Business Media, Dordrecht.

Powell, R., 1984. Inversion of the assimilation and fractional crystallization (AFC) equations; characterization of contaminants from isotope and trace element relationships in volcanic suites. J. Geol. Soc. 141, 447–452.

Powell, R., Holland, T.J.B., 1988. An internally consistent thermodynamic dataset with uncertainties and correlations: 3. Applications to geobarometry, worked examples and a computer program. J. Metamorph. Geol. 6, 173–204.

Qian, Q., Hermann, J., 2013. Partial melting of lower crust at 10–15 kbar: constraints on adakite and TTG formation. Contrib. Mineral. Petrol. 165, 1195–1224.

Raguin, E., 1976. Géologie du Granite. Masson, Paris.

Rapp, R.P., Watson, E.B., 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust-mantle recycling. J. Petrol. 36, 891–931.

Read, H.H., 1948. Granites and granites. In: Gilluly, J. (Ed.), Origin of Granite, Geological Society of America Memoirs, 28, pp. 1–19.

Reubi, O., Blundy, J., 2009. A dearth of intermediate melts at subduction zone volcanoes and the petrogenesis of arc andesites. Nature 461, 1269–1273.

Roberts, M.P., Clemens, J.D., 1995. Feasibility of AFC models for the petrogenesis of calc-alkaline magma series. Contrib. Mineral. Petrol. 121, 139–147.

Roberts, N.M., Spencer, C.J., 2015. The zircon archive of continent formation through time. In: Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S., Clift, P.D. (Eds.), Continent Formation Through Time, Geological Society, London, Special Publications, 389, pp. 197–225.

Romàn-Berdiel, T., Aranguren, A., Cuevas, J., Tubia, J.M., Gapais, D., Brun, J.-P., 2000. Experiments on granite intrusion in transtension. In: Vendeville, B., Mart, Y., Vigneresse, J.L. (Eds.), Salt, Shale and Igneous Diapirs in and around Europe, Geological Society, London, Special Publications, 174, pp. 21–42.

Rudnick, R.L., Gao, S., 2014. Composition of the continental crust. In: Holland, H.D., Heinrich, D., Turekian, K.K. (Eds.), Treatise on Geochemistry, 2nd edition. Elsevier, Amsterdam, pp. 1–51.

Saleeby, J., Ducea, M., Clemens-Knott, D., 2003. Production and loss of high-density batholithic root, southern Sierra Nevada, California. Tectonics 22, 1064.

Sawyer, E.W., 2008. Atlas of Migmatites. In: The Canadian Mineralogist Special Publications 9. NRC Research Press, Ottawa.

Sawyer, E.W., 2014. The inception and growth of leucosomes: microstructure at the start of melt segregation in migmatites. J. Metamorph. Geol. 32, 695–712.

Sawyer, E.W., Cesare, B., Brown, M., 2011. When the continental crust melts. Elements 7, 229–234.

Schaltegger, U., Nowak, A., Ulianov, A., Fisher, C.M., Gerdes, A., Spikings, R., Whitehouse, M.J., Bindeman, I., Hanchar, J.M., Duff, J., Vervoort, J.D., 2019. Zircon petrochronology and $^{40}Ar/^{39}Ar$ thermochronology of the Adamello Intrusive Suite, N. Italy: monitoring the growth and decay of an incrementally assembled magmatic system. J. Petrol. 60, 701–722.

Schmeling, H., 2000. Partial melting and melt segregation in a convecting mantle. In: Bagdassarov, N., Laporte, D., Thompson, A.B. (Eds.), Physics and Chemistry of Partially Molten Rocks. Petrology and Structural Geology, 11. Springer, Dordrecht, pp. 141–178.

Schmeling, H., Marquart, G., Weinberg, R., Wallner, H., 2019. Modelling melting and melt segregation by two-phase flow: new insights into the dynamics of magmatic systems in the continental crust. Geophys. J. Int. 217, 422–450.

Schulmann, K., Lexa, O., Janoušek, V., Lardeaux, J.M., Edel, J.B., 2014. Anatomy of a diffuse cryptic suture zone: an example from the Bohemian Massif, European Variscides. Geology 42, 275–278.

Schwartz, J.J., Klepeis, K.A., Sadorski, J.F., Stowell, H.H., Tulloch, A.J., Coble, M.A., 2017. The tempo of continental arc construction in the Mesozoic Median Batholith, Fiordland, New Zealand. Lithosphere 9, 343–365.

Schwindinger, M., Weinberg, R.F., 2017. A felsic MASH zone of crustal magmas – feedback between granite magma intrusion and in situ crustal anatexis. Lithos 284, 109–121.

Sederholm, J.J., 1923. On migmatites and associated Precambrian rocks of southwestern Finland. Bull. Comm. géol. Finl. 58, 1–153.

Shand, S.J., 1943. In: Eruptive Rocks: Their Genesis, Composition, Classification, and Their Relation to Ore-Deposits with a Chapter on Meteorite. John Wiley & Sons, New York.

Sial, A.N., Bettencourt, J.S., De Campos, C.P., Ferreira, V.P. (Eds.), 2011. Granite-Related Ore Deposits. Geological Society, London, Special Publications 350.

Skjerlie, K., Patiño-Douce, A.E., 2002. The fluid-absent partial melting of a zoisite-bearing quartz eclogite from 1.0 to 3.2 GPa; implications for melting in thickened continental crust and for subduction-zone processes. J. Petrol. 43, 291–314.

Spencer, C., Roberts, N., Santosh, M., 2017. Growth, destruction, and preservation of Earth's continental crust. Earth Sci. Rev. 172, 87–106.

Spera, F.J., Bohrson, W.A., 2001. Energy constrained open-system magmatic processes I: general model and Energy-Constrained Assimilation and Fractional Crystallization (EC-AFC) formulation. J. Petrol. 42, 999–1018.

Spiegelman, M., Kelemen, P., Aharonov, E., 2001. Causes and consequences of flow organization during melt transport: the reaction infiltration instability in compactible media. J. Geophys. Res. 106, 2061–2077.

Springer, W., Seck, H.A., 1997. Partial fusion of granulites at 5 to 15 kbar: implications for the origin of TTG magmas. Contrib. Mineral. Petrol. 127, 30–45.

Stevens, G., Villaros, A., Moyen, J.-F., 2007. Selective peritectic garnet entrainment as the origin of geochemical diversity in S-type granites. Geology 35, 9–12.

Stussi, J.-M., De la Roche, A., 1984. Le magmatisme orogénique granitique de la chaîne varisque française. Typologie chimique et répartition spatiale. C. R. Acad. Sci. – Ser. II 298, 43–48.

Tang, M., Wang, X.-L., Shu, X.-J., Wang, D., Yang, T., Gopon, P., 2014. Hafnium isotopic heterogeneity in zircons from granitic rocks: geochemical evaluation and modeling of "zircon effect" in crustal anatexis. Earth Planet. Sci. Lett. 389, 188–199.

Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell, Oxford.

Taylor, J., Nicoli, G., Stevens, G., Frei, D., Moyen, J.F., 2014. The processes that control leucosome compositions in metasedimentary granulites: perspectives from the Southern Marginal Zone migmatites, Limpopo Belt, South Africa. J. Metamorph. Geol. 32, 713–742.

Thompson, A.B., Connolly, J.A.D., 1995. Melting of the continental-crust – some thermal and petrological constraints on anatexis in continental collision zones and other tectonic settings. J. Geophys. Res. 100, 15565–15579.

Ulmer, P., Müntener, O., Perez, R.A., 2008. Differentiation of mantle-derived calc-alkaline magmas at mid to lower crustal levels: experimental and petrologic constraints. Geochim. Cosmochim. Acta 72, A966.

Vanderhaeghe, O., 2001. Melt segregation, pervasive melt migration and magma mobility in the continental crust; the structural record from pores to orogens. Physics of the Earth and Planetary Interiors, Part A: Solid Earth and Geodesy 26, 213–223.

Vanderhaeghe, O., Teyssier, C., 2001. Partial melting and the flow of orogens. Tectonophysics 342, 451–472.

Vernon, R.H., 1984. Microgranitoid enclaves in granites – globules of hybrid magma quenched in a plutonic environment. Nature 309, 438–439.

Vernon, R.H., Richards, S.W., Collins, W.J., 2001. Migmatite–granite relationships: origin of the Cooma granodiorite magma, Lachlan Fold Belt, Australia. Phys. Chem. Earth Solid Earth Geod. 26, 267–271.

Villaros, A., Stevens, G., Buick, I.S., 2009. Tracking S-type granite from source to emplacement: clues from garnet in the Cape Granite Suite. Lithos 112, 217–235.

Villaseca, C., Barbero, L., Herreros, V., 1998. A re-examination of the typology of peraluminous granite types in intracontinental orogenic belts. Trans. Royal Soc. Edinburgh Earth Sci. 89, 113–119.

Villaseca, C., Orejana, D., Belousova, E.A., 2012. Recycled metaigneous crustal sources for S- and I-type Variscan granitoids from the Spanish Central System Batholith: constraints from Hf isotope zircon composition. Lithos 153, 84–93.

Walker Jr., B.A., Bergantz, G.W., Otamendi, J.E., Ducea, M.N., Cristofolini, E.A., 2015. A MASH zone revealed: the mafic complex of the Sierra Valle Fértil. J. Petrol. 56, 1863–1896.

Watson, E.B., 1996. Dissolution, growth and survival of zircons during crustal fusion; kinetic principles, geological models and implications for isotopic inheritance. Trans. Royal Soc. Edinburgh Earth Sci. 87, 43–56.

Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magmas types. Earth Planet. Sci. Lett. 64, 295–304.

Watson, E.B., Harrison, T.M., 1984. Accessory minerals and the geochemical evolution of crustal magmatic systems: a summary and prospectus of experimental approaches. Phys. Earth Planet. Inter. 35, 19–30.

Wedepohl, K.H., 1995. The composition of the continental crust. Geochim. Cosmochim. Acta 59, 1217–1232.

Wegmann, C.E., 1935. Zur Deutung der Migmatite. Geol. Rundsch. 26, 305–350.

Weinberg, R.F., 2006. Melt segregation structures in granitic plutons. Geology 34, 305–308.

Weinberg, R.F., Hasalová, P., 2015. Water-fluxed melting of the continental crust: a review. Lithos 212, 158–188.

Westraat, J.D., Kisters, A.F.M., Poujol, M., Stevens, G., 2004. Transcurrent shearing, granite sheeting and the incremental construction of the tabular 3.1 Ga Mpuluzi Batholith, Barberton granite–greenstone terrane, South Africa. J. Geol. Soc. 161, 1–16.

White, R.W., Powell, R., Holland, T.J.B., 2001. Calculation of partial melting equilibria in the system $CaO–Na_2O–K_2O–FeO–MgO–Al_2O_3–SiO_2–H_2O$ (CNKFMASH). J. Metamorph. Geol. 19, 139–153.

Wickham, S.M., 1987. The segregation and emplacement of granitic magmas. J. Geol. Soc. 144, 281–297.

Williams, I.S., 2001. Response of detrital zircon and monazite, and their U–Pb isotopic systems, to regional metamorphism and host-rock partial melting, Cooma Complex, southeastern Australia. Aust. J. Earth Sci. 48, 557–580.

Wolf, M.B., Wyllie, P.J., 1994. Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time. Contrib. Mineral. Petrol. 115, 369–383.

Wolf, M.B., Romer, R.L., Glodny, J., 2019. Isotope disequilibrium during partial melting of metasedimentary rocks. Geochim. Cosmochim. Acta 257, 163–183.

Yakymchuk, C., Brown, M., 2014. Behaviour of zircon and monazite during crustal melting. J. Geol. Soc. 171, 465–479.

Yanagida, Y., Nakamura, M., Yasuda, A., Kuritani, T., Nakagawa, M., Yoshida, T., 2018. Differentiation of a hydrous arc magma recorded in melt inclusions in deep crustal cumulate xenoliths from Ichinomegata Maar, NE Japan. Geochem. Geophys. Geosyst. 19, 838–864.

Zandt, G., Gilbert, H., Owens, T.J., Ducea, M., Saleeby, J., Jones, C.H., 2004. Active foundering of a continental arc root beneath the southern Sierra Nevada in California. Nature 431, 41–46.

Závada, P., Schulmann, K., Racek, M., Hasalová, P., Jeřábek, P., Weinberg, R.F., Štípská, P., Roberts, A., 2018. Role of strain localization and melt flow on exhumation of deeply subducted continental crust. Lithosphere 10, 217–238.

Zeck, H.P., Williams, I.S., 2002. Inherited and magmatic zircon from Neogene Hoyazo cordierite dacite, SE Spain – anatectic source rock provenance and magmatic evolution. J. Petrol. 43, 1089–1104.

Zeh, A., Gerdes, A., Barton Jr., J.M., 2009. Archean accretion and crustal evolution of the Kalahari Craton – the zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. J. Petrol. 50, 933–966.

Zen, E., 1986. Aluminium enrichment in silicate melts by fractional crystallization: some mineralogic and petrographic constraints. J. Petrol. 27, 1095–1117.

Zhao, Z.F., Zheng, Y.F., Wei, C.S., Wu, Y.B., 2007. Post-collisional granitoids from the Dabie Orogen in China: zircon U–Pb age, element and O isotope evidence for recycling of subducted continental crust. Lithos 93, 248–272.

Zheng, Y.F., 2021. Convergent plate boundaries and accretionary wedges. In: Alderton, D., Elias, S.A. (Eds.), Encyclopedia of Geology, 2nd edition. Academic Press, Oxford, pp. 770–787.

Zheng, Y.F., Zhao, Z.F., 2017. Introduction to the structures and processes of subduction zones. J. Asian Earth Sci. 145, 1–15.