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Crustal melting vs. fractionation of basaltic magmas: Part 2, Attempting to quantify mantle and crustal contributions in granitoids

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1. Introduction

“I believe that we can look forward to a general unifying thesis concerning the production of granitic rocks. The basis of such a thesis must be that magmas reflect differences in source and process in response to changing geological environment.” – Pitcher, 1987 (p. 68)

More than thirty years ago, W.S. Pitcher, reflecting on the then state of the-art on granite thinking, concluded that the long-standing granite controversy, that harked back to the famous Read vs. Bowen debate of the 1940s and beyond, stated that there are *“granites and yet more granites forty years on”*. He concluded that granites are diverse, and that there is little point in trying to explain them all with a single model (Pitcher, 1987). It is, perhaps, disheartening to realize that to this day, the controversy still stands and is still very much structured along the same lines: are granites the product of melting of older crust, or of fractionation of mantle-derived basalts? Although Pitcher (1987) presented a very good case for the existence of both possibilities, his holistic view has not been fully accepted by the community, which to this day remains split into two largely disconnected sub-communities, the *“(crustal) melting”* community and the *“(basaltic magma) fractionation”* community. The former is connected to the study of migmatites and high-grade metamorphic terrains, chiefly – but not only – in former continental collisions. The latter is rooted in volcanic-plutonic terranes of magmatic arcs above active subduction zones.

Perhaps the only place of interaction between these two views is in the realm of crustal growth and crustal evolution through time, and in particular of reading the zircon record – as zircons chiefly form in granitic igneous rocks. The melting paradigm leads to consider that zircons come from granites, themselves chiefly reflecting reworking of older crust. Thus, the age of zircons tells little on crustal extraction age, and one has to resort to model ages to get insights on this question. The fractionation paradigm considers that zircons come from granites, themselves mainly reflecting fractionation of mantle-derived magmas. Thus, the age of zircons should nearly equate the age of crust formation.

We have explored all these aspects in a companion paper (Moyen et al., 2021), detailing the evidence used by both schools of thought. We also discussed the mostly unspoken implications in terms of the nature of the crust and the mechanism and timing of crustal growth. We concluded that both paradigms are rooted in a strong body of evidence that is pointless to ignore, thus calling for a more balanced view. We acknowledged that both mechanisms (crustal melting and fractionation of mantle-derived melts) are viable processes to produce granitic magmas, yet operating in different proportions in individual geological/geodynamic settings. The aim, then, is to try to delineate the scope of application of either mechanism in order to derive a global model for granite formation in various parts of the Earth.

In this contribution, we start from the premises that both mantle and crust can contribute, to a variable degree, to the formation of granitoids. This simple assumption proves very fruitful and opens several

interesting lines of investigation:

- Do individual granites represent pure “melting” or “fractionation” end-members, or are they rather hybrids, incorporating material from both sources? In the latter case, how is hybridization achieved?
- At the scale of a geological province, what is the balance between the two sources? This balance can be achieved through different pathways – by juxtaposing, in certain proportions, purely crust- or purely mantle-derived plutons, or by forming a number of well-blended hybrid plutons.
- Assuming that the balance differs between provinces, what are the key factors that govern it regionally? Petrologists today would typically equate subduction with mantle fractionation, and collision with crustal melting. There are, however, examples (such as the Australian Lachlan Fold Belt) of subduction-related provinces with a strong crustal imprint, and conversely. This suggests that we need a better framework.
- Does the balance stay the same if it is integrated over time? Melting of a recently accreted crustal component (a young basaltic sequence for instance) is crustal reworking at the scale of the formation of a given pluton; but integrated over the whole cycle of basalt formation and remelting, it collectively defines crustal growth.

We address these issues by firstly describing the many petrological ways that lead to the formation of hybrids at all scales: hand specimens, plutons and, in particular, provinces. We explore conceptual possibilities to quantify the contribution of mantle and crustal components to granitoids formation, and offer a viable framework to assess the role of granitoids in crustal evolution. Finally, we apply these approaches to three key granitic provinces: Western North America, the Lachlan Fold Belt of Australia and the European Variscan Belt. This allows us to identify the parameters that control the crust/mantle balance at the scale of a geological province, hopefully paving the way for a better understanding of the role of granitoids in crustal evolution processes.

2. End-members and hybrids

Some (comparably rare) examples represent pure and unquestionable end-members, i.e. rocks that are generated either exclusively by crustal melting, or purely by fractionation of mantle-derived magmas. They provide a useful point to start the discussion.

A pure “crustal” end-member is represented by the granites clearly formed by melting of sediments (Hopkinson et al., 2017). There is, therefore, a consensus on the fact that strongly peraluminous leucogranites, most typically in Himalayas, were formed by muscovite breakdown in pelitic metasediments (e.g. Le Fort et al., 1987; Inger and Harris, 1993; Nabelek, 2020; Patiño-Douce and Harris, 1998; Searle et al., 2010; Weinberg, 2016). The cordierite-bearing strongly peraluminous granites also reflect melting of sediments, although at slightly higher temperatures and by biotite dehydration melting (Villaros et al., 2018). However, even those are often accompanied by mafic rocks, whose contribution (coincidental, heat only, or also matter?) is disputed,

and may not be absolutely pure end-members.

Pure “mantle” end-members are harder to find. A strong case can be made for granites generated in a setting far from any pre-existing continental crust, especially if they carry an isotopic signature clearly inconsistent with any involvement of a mature crustal material. Even those, however, are hardly “undisputed”. For instance, oceanic plagiogranites (e.g. Rollinson, 2009; Grimes et al., 2013) or granites from oceanic plateaux (Willbold et al., 2009) are now commonly explained by remelting of the base of the (hydrated) mafic crust. The same applies, in convergent systems, to oceanic arcs where the granitoids could be regarded either as pure mantle fractionates (Jagoutz, 2010; Müntener and Ulmer, 2018; Ulmer et al., 2008) or melts of a young mafic crust (Atherton and Petford, 1993; Collins et al., 2016, 2020a, b). While petrologically distinct, these alternative models are of little concern in terms of long-term crustal evolution, inasmuch as the crust that melts is young and itself recently extracted from the mantle. Thus, they still do represent new additions to the crust on a 50–100 Myr scale.

On the other hand, the vast majority of granitoids are either ambiguous (i.e., they can be explained by either paradigm) or hybrids (as they incorporate, in different proportions, material that was ultimately either crust- or mantle-derived). Consider for instance the case of metaluminous granitoids: often, they can justifiably be regarded either as the product of differentiation of mafic melts, or melting of older mafic rocks (Moyen et al., this issue). Likewise, the majority of granitoids at active continental margins occur in settings where there is both an important influx of mafic melts from the mantle, and large amounts of continental crust available for melting. Many of these granitoids are ambiguous in nearly all respects: their composition does not require a clear sedimentary origin and their isotopic properties can be reconciled with either scenario. In all these cases, the petrographic or geochemical argument would not allow us to conclude unambiguously.

In fact, for the vast majority of these ambiguous granites, most petrologists would probably be satisfied with the notion of hybrid granitoids, i.e. rocks whose origin involves hybridization (at different possible depths and through a range of mechanisms, as discussed below) between crustal and mantle components.

2.1. Physical processes for hybridization

Firstly, we briefly review the physical processes that permit hybridization, i.e. the formation of an igneous rock whose constitutive material was previously hosted partly in the crust, and partly in the mantle. For clarity, we describe these processes from the top (emplacement site) to the bottom (source regions).

2.1.1 Assimilation and magma mixing in upper-crustal plutons

Assimilation of country rocks was long proposed as a possible process during the emplacement of granitoids (Daly, 1933; DePaolo, 1981; Taylor, 1980), initially as a way to solve the “room problem” (Pitcher and Berger, 1972; Vernon and Paterson, 1993). In the process, crustal country rock is incorporated into the magma – that hence acquires a “mixed” parentage. It was soon realized however, that assimilation suffers from very strict thermal limitations owing to the need to heat and effectively melt the country rocks before they become part of the granite (Glazner, 2007; Roberts and Clemens, 1995; Taylor, 1980). One way to overcome the difficulty is not to melt the country rocks, but rather physically disperse them in the magma (Beard et al., 2005), such that the hybrid granitoids are made of melt (from the mantle) carrying xenocrysts (from the crust). Another

approach to the issue is the coupling of endothermic assimilation with exothermic fractionation into the so-called “AFC” (Assimilation and Fractional Crystallization) processes (O’Hara, 1977; DePaolo, 1981), the most advanced models of which explicitly balance the energy (Bohrson et al., 2014; Reiners et al., 1995; Spera and Bohrson, 2001).

The AFC models, although deeply rooted in the fractionation paradigm, often require large degrees of assimilation to reproduce the observed compositions, up to 20 or 50 % of the initial mass of magma (Bohrson and Spera, 2001). The resulting granitoids would be therefore hybrids, in the extreme as much crust- as mantle-derived by mass. However, an AFC model differs from crustal melting followed by mixing in that the only heat source in the system is the hot mafic melt, and there is therefore no (or very limited) crustal melting outside of the pluton. No regional melting occurs, no migmatites are observed, and there is little to no scope for extraction of pure crustal melts and formation of purely crust-derived granitic bodies. In this case the two components are intimately blended – pure end-member plutons, or even samples, are rare.

Magma mixing has been the focus of intense research activity for a long time (e.g. Bateman, 1995; Bunsen, 1851; Castro et al., 1991; Perugini and Poli, 2012). A typical magma mixing scenario is proposed to account for the existence, in the same pluton, of coeval mafic and felsic igneous rocks, possibly with contrasting isotopic signatures, and transitional rock types whose composition falls between the end-members (e.g. Collins et al., 2006; Janoušek et al., 2000; Kemp, 2004; Moyen et al., 2001; Slaby and Martin, 2008; Wiebe et al., 2002). Typically, the mafic component occurs as bodies ranging from a few centimetres (mafic microgranular enclaves, MME: Didier and Barbarin, 1991) to a few hundreds of meters across. The putative hybrids often contain textural evidence for chemical disequilibria (rapakivi textures, reverse zoning, ocelli...), thermal disequilibria/multistage crystallization and/or exchange of xenocrysts between both contrasting systems (Didier and Barbarin, 1991; Hibbard, 1995; Janoušek et al., 2004; Robinson and Miller, 1999; Wiebe, 2016). Pure end-members may be preserved, but most of the rocks in the pluton are regarded as more or less complete blends, with varying proportions of each component. It has thus been pointed out that the petrological evidence preserved provides a clear evidence of *mingling* – a physical process in which two distinct compositions can be still distinguished in field or under petrographic microscope – but not necessarily of *mixing* – the complete chemical, diffusion-driven homogenization of the components into a new rock. In fact, such a distinction may be meaningless – recent calculations and experiments document the chaotic nature of the hybridization processes, whereby both well-mixed and poorly homogenized regions could coexist on a scale of a single outcrop (Perugini and Poli 2000; Morgavi et al., 2013) or even within the same hand sample, depending on the considered element (Laurent et al., 2017a; Leshner, 1990). Still a rather heated debate is going on about the feasibility of achieving chemical mixing in granitoids (Laumonier et al., 2014; Morgavi et al., 2017; Petrelli et al., 2006; Reubi and Blundy, 2009).

2.1.2 Lower crustal melting, assimilation, storage and homogenization (MASH) zones

In the upper crust, hybrid models are difficult to balance thermally. The heat available for crustal melting (or for assimilation) is limited to the volume of mafic magmas, such as – unless vast amounts of mafic melts are

present, which is uncommon – this process cannot lead to significant melting. Country-rock melting and assimilation is much more efficient in the (hot) lower crust, as is magma mixing due to lower rheological contrasts between magmas of different compositions. It has been, therefore, proposed that the lower crust of, for instance, magmatic arcs forms MASH (= Melting, Assimilation, Storage, Homogenization) zones (Larsen and Cross, 1956; Larsen et al., 1936–1938; Hildreth and Moorbath, 1988; Walker Jr. et al., 2015). Here all these processes occur more or less concurrently and collectively homogenize the various components into a hybrid magma feeding the overlying granitoid intrusions, and volcanoes.

MASH zone processes are largely cryptic. Some field examples allowed to describe the complexity of petrological evolution in these domains (e.g. Otamendi et al., 2009; Sinigoi et al, 1991; Walker Jr. et al., 2015), but more commonly, plutons with a hybrid geochemical signature are inferred to have originated from an underlying (and unexposed) crustal level. The development of the MASH zones is probably unavoidable at the base of a thick, hot continental crust that was injected with mantle melts and as such, they may represent a globally relevant framework for hybridization within the crust – much more so than emplacement-level mixing or assimilation.

2.1.3 Metasomatism and contamination of the mantle by crust-derived material

There are common examples of rocks that are probably sourced in the mantle (typically because they are mafic) but at the same time have crust-like isotopic and elemental (e.g., LILE, Th and U enrichment, HFSE depletion) characteristics. In the absence of any intra-crustal process, this implies that the mantle source included domains with crust-like chemistry, and possibly physically made of crustal material mixed with the mantle (e.g., Hawkesworth and Vollmer, 1979).

In continental collision zones, the local lithospheric mantle may be directly contaminated by deeply subducted continental crustal material (or metasomatized by (supercritical) fluids derived therefrom: e.g., Hermann and Rubatto, 2009; McInnes et al., 2001; Zheng et al., 2011; Zheng, 2012) yielding, after unspecified, but often short (10–100 Myr), time interval, unusual (ultra-) potassic magmas of mixed mantle–crustal chemical and isotopic signature (Förster et al., 2019) that are associated with (U)HP metamorphic complexes, like in the European Variscides (Couzinié et al., 2016; Janoušek and Holub, 2007; Laurent et al., 2017a; Tabaud et al., 2015) or in the Dabie–Sulu orogenic belt in China (Dai et al., 2012; Zhao et al., 2013; Zheng et al., 2019).

In oceanic subduction zones, the hydrous fluids derived from oceanic slab, with potential contribution of oceanic sediments, are responsible for metasomatism of the overlying mantle wedge and generation of subduction-related magmas (Tatsumi and Eggins, 1995; Zheng, 2019). However, these metasomatized domains can be reactivated much later, after the subduction has ceased, yielding primary melts with subduction-like LILE over HFSE enrichments, as well as radiogenic Sr, Pb and Nd isotopic signatures (e.g., Davis et al., 1993; Hawkesworth et al., 1995).

Lastly, some domains of the mantle show long-term enrichments in incompatible elements that are “anorogenic”, i.e. caused by fluid/small-scale melts migrating in subcontinental lithospheric mantle (SCLM), especially under ancient cratons. The time-integrated, high Rb/Sr, U/Pb and Th/Pb as well as low Sm/Nd and

Lu/Hf ratios then lead, over time, to crustal-like radiogenic Sr, Pb and unradiogenic Nd, Hf isotopic compositions of these SCLM domains (e.g., Roden and Murthy, 1985; Förster et al., 2019; Tappe et al., 2018).

These scenarios highlight the terminological ambiguities around the use of terms such as “hybrid” and “juvenile”, as well as the scale and time issues. In all cases, the resulting rocks may be regarded as hybrids of some sort: part of their chemical budget was once hosted in the crust, cycled through the mantle, and carried into the resulting igneous rocks and derivative granitoids.

A first issue is related to the use of the term “juvenile” that may refer either to (i) material extracted from the mantle and added to the crust (irrespective of its isotopic signature), or (ii) material with a (depleted-)mantle-like isotopic signature. The hybrids envisioned here would be “juvenile” in sense (i) but not in sense (ii). In this text we refrain from using “juvenile” and rather use “new additions to the crust” (sense (i)) or “mantle-like isotopic ratios” (sense (ii)).

Timing causes another issue. If the whole process is short-lived, everything occurred in the same orogenic cycle and the contaminating crust can be related to local compositions (e.g. Laurent and Zeh, 2015), regarding the resulting rocks as hybrids is legitimate. If, on the other hand, the contamination and melting events are well separated in time, by duration exceeding the orogenic cycle during which the granitoids in question formed, the notion may be better approached in terms of long-term mantle heterogeneities.

2.2. Scale of hybridization

As we can see from the previous discussion, there are many ways to generate hybrids, i.e. granitoids ultimately coming partly from pre-existing crust, and partly from the mantle. Such a hybridization (s.l.) occurs at different scales and, at each level of scale, can be viewed as either a juxtaposition of the two, still identifiable end-members, or an already homogeneous blend thereof (Fig. 1). The chaotic (fractal) nature of hybridization has been well-documented in the case of the magma mixing (e.g. De Campos et al., 2011; De Rosa et al., 2002; Laurent et al., 2017a; Perugini et al., 2003). Evidence for hybridization may be visible and preserved at the scale of a single *crystal* – as it may contain overgrowths of contrasting composition or even heterogeneously nucleate at the surface of other mineral phases (Bruand et al., 2014; Hibbard, 1995; Laurent et al., 2017a), or of a *hand sample* – that could contain dispersed crustally-derived xenocrysts. The granitoids may be hybrid at the scale of a *pluton*, e.g. the composite Ploumanac’h Variscan pluton made of several well-identified intrusive phases, including cordierite (or muscovite) granites surrounded by amphibole-bearing high-K granites (Barrière, 1977), or of a single magmatic facies, but with individual hand samples characterized by distinct crust/mantle contributions. An entire *magmatic province* may be hybrid (Moyen et al., 2017), for instance made of coexisting purely crustal vs. purely mantle-derived granitoid plutons (Fig. 1b), or a collection of variously hybrid ones (Fig. 1c–d). Finally, of course, continental magmatism at the scale of the entire *Earth* is hybrid in nature, as a mixture of sites dominated by fractionation of mantle-derived melts and crustal melting.

Similar crust/mantle proportions can be obtained by distinct combinations of smaller scale hybridization. Fig. 1 (b–d) illustrates this point at the scale of a province: in all three examples, the regional balance between crust and mantle contributions is the same. However, in a coexistence scenario (Fig. 1b) this is achieved by

juxtaposing plutons of distinct origin, with no or nearly no pluton- or sample-scale hybrids. Fig. 1c is a situation where each pluton is well-blended (there is no sample-scale heterogeneity), but each pluton differs from its neighbour. In Fig. 1d, we depict the case where plutons are essentially all similar, and all formed by a range of rocks of mixed origins. The case depicted in Fig. 1b (and also, to a lesser extent, 1c) would make any quantitative attempt very difficult indeed, as no pluton is representative of the whole province: preservation issues, or simply non-exhaustive studies, would therefore hugely influence the final estimate.

2.3. Quantifying hybrids

In principle, hybrids at any scale can be described in terms of mass, whereby X % of the mass (of a sample, a pluton, a region) comes from the mantle, and $(100-X)$ % from the crust. This simple concept provides a general framework to discuss related issues, notably the contribution of a given magmatic system to the growth vs. reworking of continental crust. Practically, however, retrieving the value of X is anything but straightforward and relies on the careful consideration of several parameters.

- A precise determination of the end-member compositions is required, potentially a difficult task because these are not necessarily preserved anywhere in the system and may vary in space and time. For instance, the mantle-derived melts in accretionary orogens such as the Central Asian Orogenic Belt, CAOB (Kröner et al., 2014; Janoušek et al., 2018) are Depleted Mantle-like (producing low-K granitoids), in stark contrast with the primitive melts of metasomatized/crustally contaminated mantle domains, such as the (ultra-) potassic vaugnerite/durbachite suite of the European Variscides or comparable volcanic rocks in Tibet (Goussin et al. 2020; Maierová et al., 2016; von Raumer et al., 2014; Xu et al., 2017). The latter, K-rich rocks are “juvenile” in terms of being mantle-derived, but the mantle contained a considerable proportion of recycled crustal material, that shows up especially in isotopic signatures of mantle-incompatible elements (Couzinié et al., 2016; Janoušek et al., 2020). Likewise, recognition of crustal reworking can be problematic if the continental crust is geochemically primitive and young (in the CAOB, for instance: Kröner et al., 2014; Spencer et al., 2017).
- The proportions of individual elements in such a mixture may differ. As an illustration, consider assimilation of a continental crust (Hf = 5 ppm) by a basalt (Hf = 1 ppm). A 50:50 mixture contains 3 ppm Hf, 2.5 ppm of which (5/6 by weight) come from the crustal component and 0.5 ppm (1/6) from the basalt. Conversely, for Ni (basalt = 90 ppm, crust = 10 ppm) 90 % of Ni is of mantle and 10 % of crustal origin. The effect is thus most pronounced for elements whose concentrations strongly differ between the two end-members (e.g. Couzinié et al., 2016).
- The X value is only valid at a certain scale. Consider a fictional granitoid sample, containing 50 wt. % of “frozen” liquid resulting from basalt differentiation, and 50 wt. % of xenocrysts from the local crust. If one zooms in to a single crust-derived xenocryst in this sample, X will drop to 0 %. Likewise, if the magmatic phase of which this sample is representative makes only 10 % of the mass in a pluton, and the rest is mantle-derived, then X is 95 % at the pluton scale. Figure 1b–d also shows a graphical illustration of this effect at the province scale.
- The same composition may be reached by different pathways (Fig. 2), involving distinct proportions of each contributing reservoir. For instance, forming a hybrid signature in an enriched mantle requires

relatively small proportions of the crustal component, owing to the strong compositional contrast between the mantle and the contaminant. Such a signature will be carried on to the granitoid differentiates, at the cost of leaving behind large volumes of melt-depleted mantle source and mafic cumulates. A similar composition may be achieved much more efficiently by mixing a crustal granitoid and a mantle fractionate, with already relatively similar compositions: however, in this case the crust–mantle balance will be offset towards the crustal contribution.

For these reasons, it appears that the use of geochemical proxies based on observations at a single scale (such as e.g. the radiogenic isotopic composition of a suite of samples, or a batch of detrital zircons) can only yield at best incomplete, at worst completely erroneous information regarding the crust/mantle balance in igneous systems. Furthermore, the scale and degree of hybridization would be a function of fertility of the crust, longevity of the magmatic system and amount of energy (heat) available to drive processes such as magma convection, partial melting, melt mobilization, solid–liquid segregation, crystal resorption, and diffusional exchange. Integrating observations at various scales within a well-constrained geological setting is therefore the best chance to quantify crustal vs. mantle contributions in large-scale magmatic systems (plutons and magmatic provinces).

3. The crust/mantle balance of type geological provinces

Equipped with theoretical considerations on the crustal or mantle origin of granitoids, it becomes possible to explore geological examples and look for a way to discuss regional scale estimates, in an attempt to upscale to – eventually – the whole planet.

We start this discussion by briefly presenting three examples of granite-rich geological provinces, where the balance between crust and mantle contributions has been proposed to differ. These examples allow us to extract some important points and propose a generalized framework.

In the following text, for clarity, we use the granite classification proposed by Barbarin (1999), and in particular we refer to ACG (Amphibole Calc-Alkaline Granites), KCG (Potassic Calc-alkaline Granites), CPG and MPG (Cordierite- and Muscovite-bearing Peraluminous Granites)¹. Bonin et al. (2020) recently demonstrated that

¹ Without entering in a debate on the “best” classification of granitoids, to which was dedicated our previous work (Bonin et al., 2020), we choose not to use the I/S/M classification of granitoids chiefly because it is interpretative and ambiguous, rather than based on descriptive criteria. The main thrust of this paper is to demonstrate that for many granitoids, several interpretations are tenable: a genetic classification appears to be inappropriate. In fact, the situation is even worse in that I/S/M are employed both in the original sense (interpretative), but often also as purely descriptive terms (i.e. strongly peraluminous granites are nearly equivalent to S-types), such that it is not always clear in which sense (descriptive, or genetic) are these terms used. The problem becomes acute for the ACG granitoids, that can be interpreted both in the crustal (in which case they are I-types) or mantle view (making them M-types) (Moyen et al., 2021): thus two groups of workers may use different classification terms for the same rock, which is not desirable and mostly causes confusion. Therefore, although we try to show equivalences in Table 1, we find that the I/S/M terminology is not fit for

this scheme corresponds to objective petrographic observations as well as robust chemical features, and as such encompasses the majority of other classifications. Table 1 summarizes the key features of each type, and Fig. 3 shows the four diagrams we use each time that synthetically describe most of the geochemical variability of granitoids (see details in Bonin et al., 2020): (i) SiO₂ vs. K₂O (wt. %), to evidence both the degree of differentiation and the alkalinity (note that we use slightly different boundaries than Peccerillo and Taylor, 1976); (ii) SiO₂ vs MALI (Modified Alkali-Lime Index of Frost et al., 2001), showing the balance between CaO and the alkalis, Na₂O + K₂O; (iii) Shand's (1943) A/CNK–A/NK diagram, that – in addition to aluminosity and peralkalinity – also informs on the Ca/(Na + K) balance, here depicted as the α parameter of Bonin et al. (2020) (α = molar (Al – Na – K)/Ca, i.e., A/CNK = 1 corresponds to α = 2); (iv) Debon and Le Fort (1983)'s B–A (maficity vs. aluminosity) diagram (slightly modified, similar to the diagram used by Villaseca et al. 1998, to highlight the fact that most metaluminous series reach slightly peraluminous compositions in their most felsic members). We identify on every diagram the area of “near minimum compositions” (NMC), towards which all magmatic series converge; thus, a composition in this region is not discriminant as it may result from either process (crust melting or basalt differentiation). We filter the databases as described in Bonin et al. (2020), i.e., by removing obviously spurious analyses (bad totals) and retaining the basic and intermediate samples (SiO₂ < 62 wt. %), but plotting them with empty symbols. In addition, we identify “fractionated” compositions (Rb > 150 ppm, Ba < 250 ppm and Sr < 75 ppm, more often than not they also have SiO₂ > 75 %; Chappell, 1999) in Fig. 7 and 9 by using paler versions of the colours for the same group. The whole dataset is available as Electronic Supplementary Material 1, and the R script used to plot Figs 5, 7 and 9 is given as ESM 2.

3.1. The western north American Cordillera: a sediment-poor active continental margin

Western North America (Fig. 4) is a long-lived active continental margin, with subduction occurring throughout the Mesozoic and Cenozoic. Voluminous basaltic and andesitic volcanism attests to the role of mantle-derived magmas, but this area also hosts large volumes of granitoids, mostly Amphibole-bearing Calc-alkaline Granitoids (ACG sensu Barbarin, 1999) that can justifiably be understood either from a fractionation or melting perspective.

Omitting the (volumetrically minor) Eocene and younger high-K compositions, the majority of granitoids in this province are petrologically and chemically similar with only second-order differences (Fig. 5). They all are calc-alkaline to calcic, low- to medium-K, and although they range from metaluminous to moderately peraluminous (in particular for the most felsic compositions), all granitoids follow negative trends in B–A diagrams. All of these granitoids are associated with mafic and intermediate rocks ranging from gabbros to quartz-diorites and tonalites. In detail, a regionally significant boundary has long been established, based on the initial Sr isotopic ratios (⁸⁷Sr/⁸⁶Sr)_i, between the isotopically mantle-like granitoids outboard, and the more radiogenic granitoids inboard (the “706 line”: Kistler and Peterman, 1973; Fig. 5). The “outboard” granitoids are on average somewhat poorer in K than their inboard counterparts. Inboard, a portion of the granitoids (such as the Idaho Batholith) define a distinct group, identified by higher silica contents and more aluminous compositions (but

our purpose, and does not allow the discussion on end-members, hybrids etc. that we are trying to pursue.

nevertheless lacking the positive correlations in B–A diagram that typifies the CPG/MPG granitoids; Miller and Bradfish, 1980; Miller et al., 1990; Miller and Barton, 1990). The differences are, in any case, relatively minor between these types.

Several models are tenable to explain this range of compositions. From a *purely “crustal” view*, they represent melting of a range of sources from mafic to felsic metaigneous, and the mantle-like isotopes of the outboard granitoids attest to the reworking of recently underplated mafic rocks in the magmatic arc s.s. Again, we highlight the importance of timescale in the interpretation of crustal growth: melting of young mafic rocks is petrologically an intra-crustal process (thus, these granitoids represent crustal reworking on the timescales required for the evolution of magmas from source to emplacement, i.e. < 10 Myr; Annen et al., 2006; Harris et al., 2000; Petford et al., 2000). Still, their source was only recently extracted from the mantle and thus, on timescales of c. 50 Myr and longer, this material corresponds to new additions to the crust. From a *“mantle” view*, all granitoids are a product of AFC evolution of basaltic arc magmas. Isotopic (and minor chemical) differences would simply reflect the nature and amount of assimilated crust, with the more radiogenic cratonic basement contributing a higher $^{87}\text{Sr}/^{86}\text{Sr}_i$ material to the magmas, and/or a larger degree of assimilation inboard. Although in terms of processes, this model is firmly rooted in the fractionation paradigm, it nevertheless requires a sizable mass of crustal component (up to 30 %) incorporated in the granitoids. *Composite views* would envision different models for each group of rocks and propose spatially and/or temporally separated melting of both mantle and crust, followed by limited mixing, and the *coexistence* of a fractionation system outboard, coexisting with a melting system inboard. This last model perhaps offers the simplest explanation for both the mantle-like isotopic composition of outboard granitoids, and the aluminous and isotopically more evolved composition of inboard granitoids. In this model, although two distinct and spatially disconnected processes coexist, both form similar granitoids (e.g. Castro, 2020), a result of the thermodynamic constraints that govern the evolution of magmas².

Although these models are rooted in distinct paradigms, it is critical to note that on a time-scale of a few tens of Myr or more, they all involve both new crust extracted from the mantle (directly, or via transient storage in arc crust), as well as old continental material (directly, or by assimilation in differentiating magmas). The proportion of each component varies, with a lesser crustal component required outboard (Farmer and DePaolo, 1983; Miller and Barton, 1990).

3.2. The Lachlan Fold Belt (LFB), Australia: a sediment-rich active continental margin

The Lachlan Fold Belt (Figs 6–7) in southeastern Australia was a slightly older (Paleozoic) long-lived active continental margin. A key difference from North American Cordillera is the presence of thick sedimentary sequences (mostly deposited in inverted back-arc basins; e.g., Collins et al., 2020b) whose melting produced

² Thus, in the “crustal” view all these granites are I-types. In the “mantle” view they are all M-types, although they include a considerable proportion of crust; in fact the term of “M-type” is meaningless in the mantle view since *all* granites are inferred to be at least in part mantle-derived. In the “coexistence” model the outboard granitoids are M-types, and the inboard series are I-types.

undisputable examples of crustally derived granites, in the form of alkali-calcic to calc-alkaline and mostly high-K peraluminous granitoids with positive correlations on B-A diagram – the “S-type” granitoids, Cordierite-bearing Peraluminous Granites (CPG) and Muscovite-bearing Peraluminous Granites (MPG) of Barbarin (1999). The “I-type” granitoids offer a more interesting problem in the context of the present discussion. They are chemically very similar to North America’s ACG (calc-alkaline, low- to medium-K, metaluminous to weakly peraluminous with negative B–A correlations). Mafic rocks are a rather common occurrence, in the form of small plutons emplaced along linear arrays, or stocks to enclaves down to a few cm in size in I-type plutons. Again, “outboard” granitoids (e.g., the Moruya Batholith) are more mafic, have lower K and are isotopically mantle-like (even for $\text{SiO}_2 > 60\%$). The more aluminous variants of inboard ACG granitoids identified in North America are not found in the LFB.

Famously, the dominant model for the origin of LFB granitoids is *melting of the pre-existing crustal rocks*, metasediments for the CPG/MPG (hence “S-types”), and meta-igneous rocks for the ACG (“I-types”). The LFB is, in the crustal paradigm, the best example of source control on the chemistry of granitoids (Chappell and White, 1974, 2001; Chappell, 1984; Chappell et al., 1987). This view is also supported by the regional correlation of isotopic signatures (Fig. 9b), reflecting the composition of the pre-existing basement (Clemens, 2019; Clemens and Phillips, 2014). In this model, minor mafic rocks are regarded as independent, mantle-derived intrusions, largely unrelated in terms of their chemical contribution (Clemens et al., 2016, 2017; Elburg, 1996), although they may have supplied heat and fluids.

This is clearly expressed in the “three component mixing model” (Collins, 1996; Keay et al. 1997), proposing that LFB granitoids are the product of mixing between partial melts of Cambrian mafic rocks or Ordovician turbidites and coeval basalts with a depleted-mantle isotopic signature. In this model, the mantle-like isotopic composition of some of the I-type granites reflects their hybrid source dominated by young (ca. 100 Myr) mafic rocks with minor basalts (Collins, 1996). Since the metabasic rocks were relatively recent, their signature did not depart much from the mantle and only a modicum of fresh basaltic magma was required. The S-types are much closer to the metasedimentary component. A *purely mantle view* is of course not tenable at the scale of the whole LFB that includes a large fraction of CPG/MPG (S-type) granitoids, although it may be considered for the ACG (I-type³) plutons by analogy with North America.

The *composite models* that are proposed for the LFB do not call for the juxtaposition and coexistence of mantle- and crust-derived belts, as was the case in North America; but rather for *mixing* between various components at the pluton scale. For instance Kemp et al. (2008, 2009) proposed that all granites evolved from sources formed by mixing in the lower crust, in various proportions, of mantle-derived basalts with metasediment-derived melts. Thus, S-types are regarded as dominated by crustal end-members, whereas I-types are interpreted as more even mixtures of crustal and mantle components.

Compared to North America, the fact that the crustal source is largely made of sediments makes the interpretation easier: there is, indeed, no doubt about the dominantly crustal origin for most of the LFB granitoids, even if the origin of the rest may be discussed. The proportion of the mantle component, on different timescales, is less clear and would hugely depend on a model, specifically on the timescale

³ Which would then become M-types...

considered. Focussing on the Silurian evolution only, the I-types may be regarded as either mostly crustal or half mantle-derived. However, inasmuch as even the crustal model interprets them as formed by melting of recent (Cambrian) mafic rocks, they still reflect net crustal growth during the Early Paleozoic.

3.3. The Variscan Belt of Europe: a collisional orogen

The Variscan Belt of western–central Europe hosts a range of different granitoids, with successive associations corresponding to different evolutionary stages and geotectonic zones of the belt (Figs 8–9). Bonin (2004) proposed a useful framework to describe the successive stages, identifying (after the early oceanic subduction period) syn-collision, post-collision and post-orogenic stages. Remnants of Devonian to Early Carboniferous arc magmatism are preserved as small intrusions throughout the belt (Fig. 8; Janoušek et al., 2004; Pin and Paquette, 2002; Shaw et al., 1993). Similar to the other examples of such rocks, they are ACG: calc-alkaline, metaluminous and low- to medium-K. Products of syn- to post-collisional Carboniferous anatexis are dominant and feature different associations in the inner and outer parts of the belt, with variable peraluminous granites (muscovite- and/or cordierite-bearing, i.e. MPG or CPG, all alkali-calcic to calc-alkaline, high-K, strongly peraluminous with no or positive correlations in B–A diagram), reflecting evolving melting conditions and/or sources (Villaros et al., 2018). They occur either as discrete plutons, or in anatectic domes. In the outer zones (e.g. Iberian Massif), post-collisional peraluminous granites are associated with calc-alkaline, medium- to (rarely) high-K, metaluminous to weakly peraluminous granites (with negative correlations in B–A diagram) akin to the North American inboard ACG granites. In the inner zone, on the other hand (French Massif Central, Corsica, External western-central Alps and the Moldanubian Zone of Vosges, Black Forest and Bohemian Massif), the post-collisional peraluminous granites are accompanied by high-K to ultra-high K (mela)syenites–melagranites (Janoušek and Holub, 2007; Tabaud et al., 2015; von Raumer et al., 2014) and related granitoids (KCG, sensu Barbarin 1999). They collectively define a series of alkali-calcic and metaluminous to weakly peraluminous (and negatively correlated in B–A diagram) rocks. The timing between the two components, i.e. the anatectic and (ultra-) potassic plutons, varies from place to place, but generally, the two types occur within < 5–20 Myr of each other (e.g. Laurent et al., 2017b; Žák et al., 2014). Plutons from the inner zone may be dominated by either type, or may be composite with distinct phases of contrasting composition, or even feature hybrid compositions intermediate between the two end members.

Lastly, late Carboniferous to Permian, post-collisional to post-orogenic granites occur (Bonin 1990, 2004; Bonin et al., 1998, Casini et al., 2015; Schaltegger and Brack, 2007). They are medium-K, metaluminous and somewhat more ferroan than the older granitoids; they also include commonly very differentiated compositions, sharing some characteristics with A2 granites (Eby, 1992; also classified as KCG by Barbarin, 1999). Both the high/ultra-high K post-collisional granites and the post-orogenic granites do not fit well in the I/S classification, emphasizing its limitation in post-collisional provinces. For completeness, Permian anorogenic granitoids (Bonin, 1990), distinctly A1 (or PAG: Barbarin, 1999) in character (peralkaline, ferroan) are also found, most typically in Corsica.

Excluding the early arc magmatism, all Variscan granitoids have, broadly speaking, crust-like isotopic compositions (Fig. 8b), even in the associated mafic rocks that are, most likely, of enriched mantle origin (Couzinié et al., 2016; Janoušek et al., 2020; Tabaud et al., 2015). Composite and hybrid plutons are also rather

common. Variscan granitoids were mostly studied in a series of disconnected regional studies, and belt-wide syntheses remain rare (Finger et al., 1997), such that it is difficult to make general statements on Variscan plutonic activity. Concentrating on the dominant Carboniferous magmatism, several points are noteworthy: (a) There is little doubt that the CPG/MPG are purely or dominantly crustal melts, chiefly from metasediments; the coeval mafic rocks may be a minor contributor (the mafic rocks are probably hybrids, similar to the KCG-related mafics). (b) Modern thinking on the KCG granitoids and their associated mafic magmas regards them as hybrids, although opinions differ on the locus of hybridization: they are diversely interpreted as products of magma mixing at or near emplacement site, in lower crustal MASH zones, or as magmas evolving from a hybrid (metasomatized mantle) source (Couzinié et al., 2016; Janoušek and Holub, 2007; Janoušek et al., 2019; Scarrow et al. 2009; Tabaud et al., 2015; von Raumer et al., 2014). As we have seen (Fig. 2), this is particularly critical since, depending on the hybridization process, the same chemical signature can be achieved with varying proportions of each end-member. (c) The ACG granitoids are diversely interpreted as reflecting melting of an older, igneous crust (Fiannacca et al. 2015, 2017; Janoušek et al., 2004), or as products of fractionation of arc-like mafic melts (Castro, 2014, 2020). This is similar to all other ACG granitoids in the world – again, a critical point for global crustal evolution models.

At the scale of the whole Variscan belt, both crust and mantle contributions appear to be required. What remains unclear, however, is the bulk proportion of each component.

4. A global view of crust/mantle balance in Earth's granites

4.1. Possible province-scale models

Our three case studies demonstrate the range of province-scale models for granitoids and their implications for crustal growth. Broadly, the models range from purely (or mostly) mantle-derived to purely (or mostly) crustal.

1. **Purely mantle models** in which all the granitoids come from fractionation of basaltic magmas. These may only be appropriate to crust-free settings (oceanic plateaux, or perhaps young intra-oceanic arcs), i.e. none of the above described case studies. They can hardly account for any scenario featuring CPG/MPG or other isotopically evolved granitoids, which in contrast are present in the majority of settings.
2. **Modified mantle models** (enriched mantle source or assimilation of older crust, via various mechanisms). Although rooted in the fractionation view, in that the ultimate driver is the mantle-derived basaltic magmas, these models require subordinate, but significant amounts of pre-existing crust incorporated in the magmas.
3. **Coexistence models** postulating the coexistence of both purely (or nearly) crustal granitoids, and purely mantle-derived granitoids (Fig. 1b). Each type represents a near end-member composition, so in the end the balance depends on the proportion of the two granitoid types in the regional crust. This situation resembles what can be observed at many active margins (North America, as previously discussed, but also e.g. the Ordovician Famatinian arc/back-arc in Argentina, featuring a juxtaposition of melting-dominated (arc proper) and fractionation-dominated (back-arc) belts; Grosse et al., 2011; Otamendi et al., 2010; Pankhurst et al., 2000; Wolfram et al., 2017, 2019). The mantle-driven system occurs, at a given time, in a

rather narrow region: this reflects the tightly focussed nature of arc magmatism, linked with dehydration reactions above the slab (England and Katz, 2010; Peacock, 1990; Tatsumi and Eggins, 1995). Slab-migration processes and reconfiguration of subduction geometry, however, may cause the mantle-driven magmatism to eventually sweep large portions of the overriding plate. The crustal magmatism occurs mostly inland, further away from the subduction front, where the high conductive heat flux induced by mantle dynamics creates an environment particularly favourable for crustal melting, especially in fertile sedimentary sequences accumulated in back-arc basins or previously accreted in former accretionary wedges.

4. **Multi-component mixing models.** In this case, crustal melting and basaltic magma fractionation occur in the same geographic area, and probably via the whole range of mechanisms operating within the mantle (metasomatism and formation of a hybrid source) as well as in the crust (ascent and emplacement-site interactions), through lower crustal processes (MASH zones). Depending on efficiency of the hybridization processes involved, the bulk of the magmas forming a pluton can be homogeneous hybrids (Fig. 1c), or the pluton may be heterogeneous and made of recognizable components (Fig. 1d). These models seem applicable especially to the post-collisional evolution.
5. **Modified crustal models.** Evolving from the purely crustal paradigm, but prompted by igneous rocks with mantle-like isotopic properties, these models propose melting in the deep crust, notably of young, mafic crustal rocks. Some crustal growth is nonetheless involved on timescales longer than required by the process itself (more than a few tens of Myr). Such melting is triggered by the underplating of basaltic magmas, but these mostly supply heat and aqueous fluids released upon their crystallization. Only a very minor amount of silicic melts produced by fractional crystallization may mix with the dominant crustal melts, such that they represent an anecdotic fraction of the resulting volume of granitoids. Such models are popular in collisional zones or at active margins (Lachlan Fold Belt). They have also been proposed to be the key mechanism to generate Cordilleran, metaluminous low-K granitoids (ACG) (Atherton and Petford, 1993; Collins et al., 2016, 2020a).
6. **Purely crustal models** proposing that the bulk of the granitoids comes from crustal melting only (Fig. 1e). Such models are seldom proposed but they may apply to special cases such as the late Cenozoic High Himalayan leucogranites.

Models (1) and (6) are difficult to hold at the scale of a whole province except in very specific settings. They require discarding, or ad-hoc explanations, for too many observations. The other models all imply that granitoids represent, in different proportions (and at variable timescales), reworking of old crust as well as net additions from the mantle, and are thus amenable to a quantitative treatment to assess the importance of each contribution. Despite some attempts (e.g. DePaolo et al., 1992; Paterson et al., 2011; Paterson and Ducea, 2015; Trubač et al., 2020), this remains a difficult task and region-wide attempts are likely to suffer, to various degrees, from some shortcomings that we can group under several headings:

- Geometric considerations and erosion. One can observe only practically planar, and often tilted, sections through the given orogen/magmatic province, proposing that the areal addition rates can be used as a proxy of true magma addition rates. Hence, it has to be assumed that the average shapes of all intrusions studied were essentially the same, while they are likely to differ depending on the depth

where they have been cut by erosion vs. the geometry of the magma system (see fig. 3 in Paterson et al., 2011). Thus, some plutons may vanish without trace, while others may be just preserved as insignificant remnants or leave behind merely a cross-section of their feeding system. In any case, the geometries of the magmatic systems are not very well constrained and likely to vary much for various geodynamic settings during a single orogenic cycle;

- Focussing/migration of the igneous activity. Some regions record evolving settings (from subduction, to collision), each with its own package of igneous suites. The older suites may then be penetrated and ‘cannibalised’ by the younger ones, leading to underrepresentation of the early granitic suites. In contrast, at current or former active continental margins like in western North America or in eastern Australia, magmatism may have migrated both out- or inboard, sweeping large regions of continental crust. In this case, the estimate of magmatic production has to be inevitably higher, and the chance for survival of the early magmatic products comparably high;
- Preservation potential in different geotectonic settings. Even for a single magmatic suite of comparable geodynamic setting, the earlier plutons or those emplaced at higher structural levels will be more prone to removal by erosion. On a global scale, it is well-known that different tectonic sites do not have equal preservation potential in the geological record. In particular, (post-)collisional systems that generate a very stable crust (and even lithosphere) structure are over-represented compared to e.g. oceanic arcs (Stern and Scholl, 2010). Thus, our long-term view may well be skewed towards certain settings, where the proportion of basaltic magma fractionates to crustal melts may not be representative of the bulk Earth.

Keeping this in mind, we can nonetheless try crude surface-based estimates for our three case studies (Tab. 2). Granitoids with mantle-like isotopic properties, thus representing long-term additions to the crust irrespective of their actual petrogenesis (basaltic magma fractionation or melting of young mafic rocks), correspond to 40 % of the exposed granitoids in western North America (outboard) vs. < 1 % in the LFB and the Variscan Belt. Granitoids of unambiguous, pure crustal origin (CPG/MPG) are not identified in North America (although the inboard, peraluminous granites are very probably crustal; they represent 12 % of the total surface: Miller and Bradfish, 1980), while they amount to 53 % in the LFB and 63 % in the Variscan Belt. The balance – up to 60 % in North America, 47 % in the LFB and 37 % in the Variscan Belt – is made of granites which, at face value, could reflect either crustal reworking, new crust generation, or variable proportions thereof.

Importantly, none of the three cases discussed in our simplistic example appears as representing a site of either pure crustal growth or of pure crustal reworking. Even continental-arc granitoids of western North America are likely to include significant proportions of recycled pre-existing crust and post-collisional domains can be a place with significant new crustal additions. Moreover, although the western North American Cordillera and LFB both represent two long-lived active continental margins, the corresponding granitoids seem to incorporate quite different proportions of newly formed crust (at least 40 %, and up to 100 % in North America; not more than 50 % in the LFB).

4.2. A conceptual framework accounting for the crust/mantle balance in different settings

The previous analysis shows that both active continental margins and collisional zones can comprise regions dominated, at different places and evolutionary stages, by granitoids formed by either fractionation of mantle-derived magmas, melting of crustal metagneous and/or metasedimentary protoliths, or both. Thus, we need a new framework to discuss which parameters control the dominant petrogenetic style in individual settings. We propose that these parameters are the nature and composition of any pre-existing crust, and the tectono-thermal state of the crust–mantle system at any given time of the geodynamic evolution.

Here we try to integrate the previous considerations in a unified framework. On the regional scale, the balance between crustal melting, fractionation of mantle-derived melts, as well as the total volume of granites generated, depends on several factors (Fig. 10).

- The amount and H₂O content of mantle-derived melts (basaltic to andesitic) underplated or intruded in the crust. Higher fluxes, of course, result in more granites produced both directly by fractionation of the mafic melts, and indirectly by induced melting of the crust. However, higher basaltic fluxes would also tilt the balance towards fractionation-related granitoids, so the net effect is both more granitoids, and a higher proportion of mantle-derived rocks (Annen et al., 2006; Moyen, 2020).
- The amount of heat that is not tied to basalts, regardless of its origin: internally generated (by radioactive decay in the crust, shear heating, etc.), or conducted through the Moho (without basalt advection). Exhumation of the deep crust (and the resultant melting) is not explicitly described in our framework, but would also promote decompression crustal melting. More heat, of course, increases the overall amount of granitoids formed, and since this is basalt-free heat, this yields to an increased share of crustal sources in the production of granitoids. Thus, extension (post-collision collapse, or “rifting orogens” sensu Zheng 2021; Zheng and Gao, 2021) favour the production of crustal granites.
- The fertility of the crust, depending on quartz–feldspar balance and, critically, on the amount of water stored in hydrous minerals of the protolith as well as of the potentially dehydrating metamorphic complexes at depth. This reflects the nature of lithologies present, as sediments are wetter than igneous rocks and felsic rocks have generally lower solidus temperatures than mafic ones. Important is also the prehistory of the region: units having undergone previous melting are more refractory. Clearly, a fertile crust favours crustal granite production.

Combining these factors allows us to abstract them in a summary diagram (Fig. 10). We simplify the three-dimensional array of factors by splitting the fertility into two cases (“fertile” and “less-fertile” crust) and portray the amount of granites, and the proportion of crust- vs mantle-sourced granites in an internal heat vs. basaltic magma flux diagram.

4.3. Granitoids of convergent margins

In Fig. 11, we apply the analysis of the previous Section to several examples of tectonic settings associated with plate convergence. Because sketches can only depict a snapshot image of evolving systems, and can obviously not cover every subtlety encountered in real tectonic settings, it was purposely chosen to represent idealized

settings, which still cover a large range of possible situations.

4.3.1 Subduction

Periods of oceanic subduction are dominated by mantle-wedge melting (Fig. 11a–c), and it is of course no surprise that differentiation of basaltic or basaltic andesite magmas is the main driver of granitic magmatism in magmatic arcs (Fig. 10). In detail, oceanic arcs (Fig. 11a) are thin and dominated by mafic rocks. Their internal heat production is low and they are only moderately fertile. Granites generated are overwhelmingly of mantle parentage.

Active continental margins (Fig. 11b–c), in addition to mantle-wedge melting, the continental crust, being both thicker and more fertile, has more potential to melt, especially if it includes thick sedimentary sequences such as those deposited in back-arc or fore-arc basins or previously accreted. In this context, an important factor may be the dynamics of subduction: if retreating, asthenosphere upwelling in the back-arc domain would promote both thinning of the overriding plate, and higher basaltic magma injection rate, collectively leading to granite-richer environments than advancing systems. Yet, it is not clear in which direction the *balance* will be tilted: more melting, or more fractionation?

In petrological terms, the fractionation-related granitoids of active continental margins are dominated by various types of metaluminous, generally low- to medium-K series (ACG granitoids). The anatectic members can be diverse, and include peraluminous potassic granites (CPG/MPG, the Australian “S-types”), but also peraluminous varieties of ACG, possibly undistinguishable in petrological terms from some mantle-derived components (Castro, 2020).

4.3.2 Continental collision

Long-lived subduction may eventually be terminated by closure of the subducting ocean and continent–continent collision and the formation of a thick orogenic wedge. Part of the continental crust can be even dragged deep into the former subduction zone, subjected to UHP metamorphism and contaminate the local lithospheric mantle (e.g., Zheng, 2012). In such collisional environments, the presence of very fertile material (metasedimentary rocks) and the increased internal heat production by radioactive decay (see Section 4.2) favour crustal melting (Fig. 11d–e). Following the framework by Bonin (2004), we discuss the successive magmatic stages in such a collisional system:

- (1) Pre-collisional **subduction** stage – in general, collision follows subduction, so oceanic subduction-related granitoids (ACG) are often preserved in the upper plate of continental collision zones (e.g. Late Devonian gabbros, quartz diorites and tonalites of the Variscan Belt, Trans-Himalayan batholith, etc.).
- (2) **Collision** proper (i.e. syn-collisional stage; Fig. 11d) is not very favourable to the formation of granitoids, as it corresponds to the underthrusting of cold continental material below the overriding plate, with resulting low geothermal gradients (e.g. England and Thompson, 1984). If melting occurs, it is spatially associated to main thrusts and related inverse metamorphic gradients with hot rocks overlying wet, cooler sediments (Le Fort et al., 1987; Searle et al., 2010), and results in purely crustal, leucocratic and strongly peraluminous granites (MPG) of undisputable crustal origin (e.g. the High

Himalayan leucogranites: Everest, Manaslu, etc.).

- (3) **Post-collisional stage** (Fig. 11e) corresponds chiefly to the maturation and collapse of a thickened orogenic crust (Vanderhaeghe and Teyssier, 2001), as exemplified by the Carboniferous evolution of the Variscan Belt. This situation permits massive granitoid generation, but also significant hybridization. Crustal thinning, affecting a still fertile, hot crust (England and Thompson, 1984) results in extensive melting of all the lithologies from the orogenic wedge. At the same time, the mantle lithosphere, fertilized by the addition of crustal material in the form of slab-derived fluids/melts released during previous oceanic ± continental subduction, is thinned as well and perhaps further heated by slab breakoff and/or delamination events, triggering important mantle melting (Couzinié et al. 2016). This environment is also amenable to hybridization at all scales. The enriched mantle itself is a hybrid source, and as the mantle-derived melts emplace in an already partially molten crust of the still hot orogen, they have ample potential to interact with crustal melts. A very large range of granitoids form in such sites; the importance of hybridization is such, however, that pure mantle components are rare or at least hard to identify. Pure (or near pure) crustal end-members are represented by peraluminous, potassic granitoids (CPG and MPG). They are accompanied by large volumes of weakly peraluminous to metaluminous, medium- to ultra-high K granitoids (KCG) of less clear (but at least partially mantle-derived) origin. Some ACG granitoids may represent either melting of non-sedimentary crustal components, or differentiation of (low-K to medium-K) basalts.
- (4) **Post-orogenic stage** (Fig. 11f) records the final collapse of a collisional orogen and the last tectonic activity, generally along strike-slip shear zones, that reflect lithospheric extension and further thinning. Granitoids are less voluminous. Few come from the crust, partly because it already largely cooled down and also because it underwent massive melting already, and is therefore less fertile. Most granitic activity is dominated by the fractionation of mantle melts (e.g. Ivrea Zone), and the resulting rocks are typically metaluminous, medium- to high-K, and tend to become more ferroan (A2 granitoids; Eby et al., 1992, also KCG in terminology of Barbarin, 1999).
- (5) **Anorogenic** granitoids, finally, are outside the scope of this study – they would be peralkaline, rift-related “A1” granitoids (Eby et al., 1992; Bonin, 2007) (PAG in Barbarin, 1999).

4.3.3 Tectonic tracing of granitoids

A first-order correlation between geodynamic settings and the type of granitoids formed has long been established (e.g. Pitcher, 1987, 1997; Bonin, 1990; Barbarin, 1999), and granitoids are thus often taken as tracers for past tectonic environments (Pearce et al., 1984). Tectonic tracing thus associates a given type of granitoid with a unique tectonic setting, which may be over-simplistic. Our work leads indeed to reconsider this view. Different types of granites may form in the same geodynamic setting, and conversely, similar granites may be generated in different geodynamic settings, therefore hampering a direct connection between plate tectonics and granite petrology/chemistry.

Most of the time, the geochemical features of a given granitoid do not point directly to a tectonic environment, but rather to its petrologic type, reflecting source and/or mode of formation. Of course, the main driver in forming distinct granitoid types is the possibility to tap contrasting reservoirs (in the crust and/or in the

mantle), and it is true that certain combinations are more likely than others in a given geodynamic setting. However, this leaves space for many ambiguities, as recently stressed by Collins et al. (2020b). Melting of mature sediments, for instance, would generate peraluminous, potassic granitoids (CPG, also known as S-types, with a COLG trace-element signature in Pearce et al., 1984 nomenclature) irrespective of where and when they form. In this view, rather than the presence of individual granitic types, their spatial association and temporal sequence are more discriminant (Table 2). For instance, the post-collisional settings can be distinguished from collision proper by the greater volume of magmas produced, but also by the association of CPG/MPG granitoids with high- to ultra-high K series, even though none of these types is restricted to this geodynamic setting. Lastly, we emphasize that common discriminant diagrams do not consider all key granite-forming sites. A conventional view focuses mostly on arc-related and syn-collisional granitoids. They almost never include any other convergent setting and largely ignore two of the most efficient sites of granitoid production: back-arc regions of accretionary orogens, formed during periods of slab retreat along active continental margins (Collins and Richards, 2008; Collins et al., 2020b) and post-collisional collapse settings (Pitcher, 1987; Pearce, 1996). Blind application of the geotectonic diagrams leads to shoehorning many granitoids from such environments into an over-simplified “Wilsonian” framework. Yet, the back-arc and post-collisional settings are probably very important net contributors to granite magmatism globally, and as such should feature more prominently in our thinking on granitoids and crustal growth.

4.4. Scaling up – towards a global view?

Building a solid case and petrogenetic model on the basis of available petrological and geochemical evidence is difficult to expand to a large region or to the whole planet. It is of course impossible to study every pluton on Earth in detail, and in any case preservation issues would render this exercise futile when trying to extrapolate back in time. There is a need, therefore, to find reliable proxies that can easily be scaled up.

A very influential tool in recent years have been Hf–O isotopes in zircons. However, as mentioned above, the isotopic composition of single zircon crystals only represents one level of scale in a potentially complex and chaotic hybrid system. As these are most often considered out of context (as commonly done with analysing detrital zircons or statistically processing global databases; e.g. Belousova et al., 2010; Dhuime et al., 2012; Korenaga, 2018), the isotopic information cannot be linked to the other scales (the hand sample, the pluton, the magmatic province). This leads to the classically described biases in the interpretation of zircon isotopic data (Payne et al., 2016; Roberts and Spencer, 2015; Vervoort and Kemp, 2016). For instance, zircons crystallized from magmas derived from melting of enriched, crustally contaminated lithospheric mantle sources generally show crust-like Hf isotopic signatures because these isotopic ratios are controlled by the crustal component (Couzinié et al., 2016). Although representing a new addition to the crust at their emplacement age, these magmas are then incorrectly assigned to ancient crust recycling using Hf model ages.

Correctly interpreting such ambiguous signatures would require upscaling (from crystal to bulk sample, pluton or province) and using different geochemical tracers (from various isotopic systems, including those of major elements). Thus, although accessory minerals, and in particular those recovered from detrital rocks, provide vital clues to the past of the Earth, we still miss a crucial piece of information to fully unlock their potential: how to link them to petrological evolution? We suggest that this is an important avenue to follow to further

our understanding of crustal growth.

5. Conclusions

Many (or maybe most) of the features do not allow to decide between fractionation of mantle-derived basaltic magmas and crustal anatexis (as we detailed in Moyen et al., this issue). Of course, some examples are unambiguous or very close to either end-member. On the other hand, a large number of granitoids from diverse tectonic settings can equally be explained under either the “crustal” or the “mantle” model.

Furthermore, many, and maybe most granitoids or granite-bearing provinces should be interpreted as hybrids at various scales: a range of mechanisms can yield granites that are mixtures, in different proportions, of both a crustal and a mantle components. Collectively, the hybrid systems seem to represent a sizable proportion of the terrestrial granitic magmatism.

Quantifying these interactions remains a first-order challenge for the Earth sciences. Only when resolved can we expect to unravel important issues such as global elemental fluxes between the mantle and crust (and vice versa) and the timing and processes of the formation/stabilization of the continental crust. The ‘great debate’ on granite petrogenesis, perhaps viewed by many geoscientists as a rather odd and old-fashioned dispute within an isolated community, is in fact of prime importance as it is shaping the current view of geodynamic evolution of our planet. Detailed studies of granite genesis, at scales from minerals, through individual magma pulses, plutons to whole magmatic provinces, provide important clues on timing and mechanisms of Earth’s differentiation, elemental fluxes, crustal formation, stabilization and reworking, that should not be overlooked in any tectonic and geodynamic models to come.

Acknowledgements

Most of what we wrote in the first part of this work (Moyen et al., 2021) could be repeated here. We particularly thank the Editor, Y.F. Zheng, for his patience with this paper. Reviews by C. Miller and B. Collins were invaluable in fixing some misinterpretations and errors in our original manuscript, and sharpening our thinking. They probably still disagree with some of our conclusions, but they helped a lot in improving the paper.

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Captions

Figure 1. A schematic representation of the nature of hybrid systems at the scale of granitic provinces. In all diagrams, the horizontal axis illustrates the actual proportion (in %) of the mass/volume of a given granite

pluton derived from the crust. Note that no geochemical indicator allows to simply trace this value (see Section 2.3). Individual frequency curves (thin lines, filled) depict the range of compositions found within one given pluton (or identifiable unit), whereas the thick curves show the range of compositions in a province as a whole. To the right, the pie-charts offer a graphical representation of the resulting amount of crust- and mantle-derived material in the province. (a) and (e) depict the “pure” fractionation (mantle-derived) or melting (crust-derived) views: the bulk of observed compositions is ascribed to one process, with rare and volumetrically insignificant exceptions. In (b) is depicted a system in which each pluton is made of pure, or nearly pure end-member composition. Collectively, the province may be hybrid, in that it corresponds perhaps equally to crustal growth from the mantle, and reworking of older crust. (c) In this case, each pluton is itself a hybrid but spans only a restricted range of compositions, and differs largely from its neighbour: collectively, the province encompasses a large range of compositions. Again, the whole province is partly formed from crust, and partly from the mantle. In (d) is shown a system in which, in contrast, each pluton features a broadly similar range of compositions, itself rather wide: at the scale of the province, the resulting distribution of compositions is similar. Once again, the province is a mixture of crustal and mantle components. Although (b) to (d) have the same meaning in terms of global mass balance and crustal growth budget, they correspond to strongly different situations in the field and, for cases (c) and (d), possibly different hybridization mechanisms and/or loci.

Figure 2. Conceptual sketch showing how similar compositions (grey box) can be reached by distinct processes, in this case (a) melting of depleted mantle followed by AFC of continental crust by the primitive melt; (b) contamination of the mantle by deeply subducted continental crust, followed by melting of the contaminated mantle and fractionation of the resulting melt; (c) mixing between a depleted-mantle derived melt (or its fractionation products), and an anatectic, crust-derived melt. However, although the compositions obtained are broadly similar, and although all scenarios correspond to crust–mantle hybridization, the proportions of the crust (red) vs. mantle (blue) components are not the same in all three scenarios. Moreover, the proportions of atoms (or mass) coming from the crust or the mantle differ for individual elements: in general, incompatible elements originate mostly from the crust while compatible ones are mostly mantle-derived. As a conclusion, a granite of a given composition may represent, in these examples, almost pure crustal growth (addition of new material, formerly in the mantle) or > 50 % crustal recycling.

Figure 3. Presentation of the diagrams used in Figs 5, 7 and 9. (a) SiO_2 vs. K_2O (wt. %). For granites from convergent domains, the boundaries drawn in solid lines are more appropriate to separate magmatic series than the original boundaries by Peccerillo and Taylor (1976), dashed. (b) SiO_2 vs. MALI diagram (Frost et al., 2001), where MALI (Modified Alkali–Lime Index) = $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ in wt. %. This diagram permits the identification of calcic, calco-alkalic (*not* calc-alkaline – see discussion in Bonin et al., 2020), alkali-calcic and alkalic (*not* alkaline!) series. (c) A/CNK vs. A/NK diagram (Shand, 1943), where $\text{A/CNK} = \text{Al}/(2\text{Ca} + \text{Na} + \text{K})$ and $\text{A/NK} = \text{Al}/(\text{Na} + \text{K})$, expressed in atomic proportions (or millications). A/CNK is therefore closely related to Debon and Le Fort’s A parameter. The curves correspond to the parameter α , defined such that $\text{Al} = \alpha \text{Ca} + \text{Na} + \text{K}$ (i.e. $\text{A/CNK} = 1$ corresponds to $\alpha = 2$). Curves of constant α mimic the evolution of individual magmatic series,

and reflect the relative balance of Ca vs. Na and K. NMC: near-minimum melt compositions. (d) B vs. A diagram (Debon and Le Fort, 1983), where $B = Fe + Mg + Ti$ and $A = Al - (K + Na + 2Ca)$, expressed as millifications. Since this projection uses an additive combination of elements (and not ratios) it is possible to plot the compositions of minerals and use it as a phase diagram. Key minerals (clinopyroxene, amphibole, biotite, cordierite and muscovite) plot well outside of the field of view, but the original lines in Debon and Le Fort (1983) diagram lead to them (see fig 5a in Bonin et al., 2020). Therefore, the individual fields can be read as corresponding to distinct characteristic mineral assemblages. Note that the muscovite + biotite association can only occur in cordierite-free assemblages, and can be chemically equivalent to either cordierite + muscovite or biotite + cordierite associations. A key difference occurs between the series that show positive correlations (strongly peraluminous or felsic peraluminous, see Villaseca et al., 1998), and those that show negative correlations, even when part of the series extends to the peraluminous domain (high-Al negatively correlated; see Miller, 1985).

Figure 4. The 706 line in western USA. (a) Geological map of Western North America (modified from <https://www.usgs.gov/media/images/geologic-map-north-america>; geographic background made with Natural Earth, free vector and raster map data from *naturalearthdata.com*). Mesozoic and Cenozoic granites are in pink. Individual samples (from *earthref.org*) have symbols corresponding to their type as in (b) and colours corresponding to their $^{87}Sr/^{86}Sr_i$ value. The purple line shows the 706 line inferred from these data, i.e. slightly different from Miller and Barton (1990). (b) Longitude vs. $^{87}Sr/^{86}Sr_i$ for the same dataset. Caption on the basis of literature attribution and chemical properties (Fig. 5).

Figure 5. Chemical properties of Western North America granitoids, using projections discussed previously (Fig. 3). (a–d) Isotopically primitive granitoids, outboard. (e–h) isotopically evolved granitoids, inboard. (i–l) “Aluminous” granitoids interpreted by Miller et al. (1990) as being crustal. (m–p) Tertiary high-K to shoshonitic granitoids. Data from *earthref.org*. Full database in Electronic Appendix 1. gr (full symbols): granitoids, $SiO_2 > 62$ wt. %; m/i (open symbols): mafic and intermediate compositions, $SiO_2 < 62$ wt. %.

Figure 6. (a) Geological map of the Lachlan Fold Belt of south-eastern Australia. Base map from Natural Earth, geology from Geoscience Australia (1:1 million scale Surface Geology of Australia; <https://www.ga.gov.au/about/projects/resources/continental-geology>) with further information from Chappell et al. (1991). (b) $^{87}Sr/^{86}Sr_i$ vs $\epsilon Nd(T)$ diagram for samples from the LFB. Data from Chappell et al. (1991), Clemens et al. (2017b), Collins et al. (2006), Keay et al. (1997), Kemp et al. (2009), King et al. (1997) and McCulloch and Chappell (1982).

Figure 7. Chemical features of LFB granitoids. Data compiled from OzChem database (Champion et al., 2007) with additions from Clemens et al. (2017b), Collins et al. (2006), Griffin et al. (1978), Keay et al. (1997), Kemp et al. (2009), King et al. (1997), Maas et al. (1997) and McCulloch and Chappell (1982). (a–d): I-type, isotopically primitive granitoids from the Moruya Batholith; (e–h) I-type, isotopically evolved granitoids; (i–l) A-type granitoids; (m–p) S-type granitoids. Full database in Electronic Appendix 1. gr (full symbols): granitoids, $SiO_2 >$

62 wt. %; m/i (open symbols): mafic and intermediate compositions, SiO₂ < 62 wt. %.; frc (pale symbols): fractionated compositions (Chappell, 1999), identified as having Rb > 150 ppm, Ba < 250 ppm and Sr < 75 ppm.

Figure 8. (a) Geological map of the Variscan Belt in Western Europe. Zoneography adapted from Ballèvre et al. (2014). Granites outlines from the 1 : 5 Million International Geological Map of Europe and Adjacent Areas (https://www.bgr.bund.de/EN/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/International/Europa/IGME5000/IGME_Project/IGME_Projectinfo.html), and basemap from Natural Earth. Granite typology is by the current authors and compiled geochemistry, see Fig. 11. (b) ⁸⁷Sr/⁸⁶Sr_i vs εNd(T) diagram for samples from Variscan granitoids. Data after Agranier (2001), Janoušek et al. (1995), Pin and Duthou (1990), Pinarelli and Rottura (1995), Shaw et al. (1993), Turpin et al. (1988, 1990), Williamson et al. (1992, 1996).

Figure 9. Chemical features of Variscan granitoids. Data compiled from the authors' personal data and compilations. Full database (and references) in Electronic Appendix 1. (a–d). Geochemically rather primitive, subduction-related Devonian to Early Carboniferous metaluminous granitoids (from Bohemian Massif and French Massif Central). (e–h): Isotopically evolved, weakly peraluminous, medium-K granitoids, either syn- (mostly in Iberia and Calabria, different colours) or post-collisional (in Alps and Bohemian Massif, light green). (i–l). High- to ultra-high K granitoids and associated mafic rocks from the internal zones (Moldanubian) in Bohemian Massif, French Massif Central and Vosges. (m–p). Peraluminous granitoids throughout the belt. gr (full symbols): granitoids, SiO₂ > 62 wt. %; m/i (open symbols): mafic and intermediate compositions, SiO₂ < 62 wt. %.; frc (pale symbols): fractionated compositions.

Figure 10. Conceptual view of the differences in granite production at different geodynamic sites. The two main drivers are the influx (and differentiation) of mafic magmas from the mantle, and the heat available in the crust unrelated to basalt influx, i.e. either generated *in situ* by radioactive decay etc. or conducted through the Moho. An additional factor is the fertility of the crust: more heat is required to generate the same amount of granites from a less fertile crust than from a more fertile one. Each cartoon is contoured for the bulk amount of granitoids formed (grey shading, and dashed contours) and the balance between crustal and mantle contributions (colour lines).

Figure 11. Generation of mantle- and crust-derived granites at distinct geodynamic sites. Compare with fig. 1 in Moyen et al. (2021), adapted from Pitcher (1987). Over 30 years after Pitcher (1987, 1997), we still agree that contrasting types of granitoids dominate individual geodynamic settings (for instance, mantle-derived calc-alkaline granites in advancing subductions = Andinotype association of Pitcher; peraluminous granites in collisional/post-collisional setting = Hercynotype association; K-rich, hybrid calc-alkaline granites in post-collisional to post-orogenic settings = Caledonian-type association), but emphasize the fact that individual sites are characterized by coexistence, in variable proportions, of several granitic types more than by a unique type. Moreover, the actual balance can vary greatly within one family (subduction or collision), as a result of the factors shown in Fig. 10. Since 1997, there is also a better understanding of accretionary systems and of the

collisional, through post-collisional, to post-orogenic evolution of the collisional systems. Comments in text.

Table 1. Chemical properties of the granitic types identified in this work.

Table 2. Surface-based estimates of the proportion of granitic types in the three case studies used in this paper.

Electronic appendices

EA1: Whole-rock compositions of granitoids from Western North America, the Lachlan Fold Belt and the Variscan Belt.

EA2: R-language script used for plotting of Figs 5, 7 and 9.

References

- Agranier, A., 2001. Un exemple de magmatisme ultrapotassique syn-orogénique: les lamprophyres du Massif Central Français. Approche géochimique et géochronologique. D.E.A. (Master thesis), Université B. Pascal, Clermont-Ferrand, France.
- Annen, C., Blundy, J.D., Sparks, R.S.J., 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. *Journal of Petrology* 47, 505-539.
- Atherton, M., Petford, N., 1993. Generation of sodium-rich magmas from newly underplated basaltic crust. *Nature* 362, 144-146.
- Ballèvre, M., Martínez Catalán, J.R., López-Carmona, A., Pitra, P., Abati, J., Fernández, R.D., Ducassou, C., Arenas, R., Bosse, V., Castiñeiras, P., Fernández-Suárez, J., Gómez Barreiro, J., Paquette, J.-L., Peucat J.-J., Poujol, M., Ruffet, G., Sánchez, S. Martínez, 2014. Correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: a joint French–Spanish project. In: Schulmann, K., Martínez Catalán, J.R., Lardeaux, J.-M., Janoušek, V., Oggiano, G. (eds) *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust*. Geological Society, London, Special Publications 405, pp. 77-113.
- Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. *Lithos* 46, 605-626.
- Barrière, M., 1977. Le complexe de Ploumanac’h (Massif Armoricaïn), essai sur la mise en place et l’évolution pétrologique d’une association plutonique subalcaline tardi-orogénique. PhD thesis, Université de Rennes-I.

- Bateman, R., 1995. The interplay between crystallization, replenishment and hybridization in large felsic magma chambers. *Earth-Science Reviews* 39, 91-106.
- Beard, J.S., Ragland, P.C., Crawford, M.L., 2005. Reactive bulk assimilation: a model for crust–mantle mixing in silicic magmas. *Geology* 33, 681-684.
- 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.
- Bohrson, W.A., Spera, F.J., 2001. Energy constrained open-system magmatic processes II: application of Energy Constrained Assimilation–Fractional Crystallization (EC-AFC) model to magmatic systems. *Journal of Petrology* 42, 1019-1041.
- Bohrson, W.A., Spera, F.J., Ghiorso, M.S., Brown, G.A., Creamer, J.B., Mayfield, A., 2014. Thermodynamic model for energy-constrained open-system evolution of crustal magma bodies undergoing simultaneous recharge, assimilation and crystallization: the Magma Chamber Simulator. *Journal of Petrology* 55, 1685-1717.
- Bonin, B., 1990. From orogenic to anorogenic settings: evolution of granitoid suites after a major orogenesis. *Geological Journal* 25, 261-270.
- Bonin, B., 2004. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review. *Lithos* 78, 1-24.
- Bonin, B., 2007. A-type granites and related rocks: evolution of a concept, problems and prospects. *Lithos* 97, 1-29.
- Bonin, B., Azzouni-Sekkal, A., Bussy, F., Ferrag, S., 1998. Alkali-calcic and alkaline post-orogenic (PO) granite magmatism: petrologic constraints and geodynamic settings. *Lithos* 45, 45-70.
- 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.
- Bruand, E., Storey, C., Fowler, M., 2014. Accessory mineral chemistry of high Ba–Sr granites from northern Scotland: constraints on petrogenesis and records of whole-rock signature. *Journal of Petrology* 55, 1619-1651.
- Bunsen, R., 1851. Ueber die Prozesse der vulkanischen Gesteinsbildungen Islands. *Annalen der Physik* 159, 197-272.
- 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. *Geoscience Frontiers* 5, 63-75.

- Castro, A., 2020. The dual origin of I-type granites: the contribution from experiments. 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. 101-145.
- 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-Science Reviews* 31, 237-253.
- Champion, D.C., Budd, A.R., Hazell, M.S., Sedgmen, A., 2007. OZCHEM National Whole Rock Geochemistry Dataset. Geoscience Australia, Canberra, <http://pid.geoscience.gov.au/dataset/ga/65464>, <https://researchdata.edu.au/ozchem-national-rock-geochemistry-dataset>
- 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. *Pacific Geology* 8, 173-174.
- Chappell, B.W., White, A.J.R., 2001. Two contrasting granite types: 25 years later. *Australian Journal of Earth Sciences* 48, 489-499.
- Chappell, B.W., Simpson, P.R., Moorbath, S.E., Thompson, R.N., Oxburgh, E.R., 1984. Source rocks of I- and S-type granites in the Lachlan Fold Belt, southeastern Australia. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* 310, 693–707.
- Chappell, B.W., White, A.J.R., Wyborn, D., 1987. The importance of residual source material (restite) in granite petrogenesis. *Journal of Petrology* 28, 1111-1138.
- Chappell, B.W., English, P.M., King, P.L., White, A.J.R., Wyborn, D., 1991. Granites and related rocks of the Lachlan Fold Belt. Geological map at the scale 1/250 000. Bureau of Mineral Resources, Geology and Geophysics, Canberra.
- Clemens, J.D., 2019. The You Yangs Batholith in Southeastern Australia, the sources of its magmas and inferences for local crustal architecture. *Australian Journal of Earth Sciences* 66, 247-264.
- Clemens, J.D., Phillips, G.N., 2014. Inferring a deep-crustal source terrane from a high-level granitic pluton: the Strathbogie Batholith, Australia. *Contributions to Mineralogy and Petrology* 168, 1070.
- Clemens, J., Regmi, K., Nicholls, I., Weinberg, R., Maas, R., 2016. The Tynong pluton, its mafic synplutonic sheets and igneous microgranular enclaves: the nature of the mantle connection in I-type granitic magmas. *Contributions to Mineralogy and Petrology* 171, 35.
- Clemens, J.D., Elburg, M.A., Harris, C., 2017. Origins of igneous microgranular enclaves in granites: the example of Central Victoria, Australia. *Contributions to Mineralogy and Petrology* 172, 88.
- Collins, W.J., 1996. Lachlan Fold Belt granitoids: products of three-component mixing. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 87, 171-181.

- Collins, W.J., Richards, S.W., 2008. Geodynamic significance of S-type granites in circum-Pacific orogens. *Geology* 36, 559-562.
- Collins, W.J., Wiebe, R.A., Healy, B., Richards, S.W., 2006. Replenishment, crystal accumulation and floor aggradation in the megacrystic Kamberuka Suite, Australia. *Journal of Petrology* 47, 2073-2104.
- Collins, W.J., Huang, H.-Q., Jiang, X., 2016. Water-fluxed crustal melting produces Cordilleran batholiths. *Geology* 44, 143-146.
- Collins, W.J., Murphy, J.B., Johnson, T.E., Huang, H.Q., 2020a. Critical role of water in the formation of continental crust. *Nature Geoscience* 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.
- 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 and Planetary Science Letters* 456, 182-195.
- Dai, L.Q., Zhao, Z.F., Zheng, Y.F., Zhang, J., 2012. The nature of orogenic lithospheric mantle: geochemical constraints from postcollisional mafic-ultramafic rocks in the Dabie Orogen. *Chemical Geology* 334, 99-121.
- Daly, R.A., 1933. *Igneous Rocks and the Depths of the Earth*. McGraw Hill, New York.
- Davis, J.M., Elston, W.E., Hawkesworth, C.J., 1993. Basic and intermediate volcanism of the Mogollon-Datil volcanic field: implications for mid-Tertiary tectonic transitions in southwestern New Mexico, USA. In: Prichard, H. M., Alabaster, T., Harris, N. B. W. & Neary, C. R. (eds) *Magmatic Processes and Plate Tectonics*. Geological Society, London, Special Publications 76, pp. 469-488.
- De Campos, C.P., Perugini, D., Ertel-Ingrisch, W., Dingwell, D.B., Poli, G., 2011. Enhancement of magma mixing efficiency by chaotic dynamics: an experimental study. *Contributions to Mineralogy and Petrology* 161, 863-881.
- De Rosa, R., Donato, P., Ventura, G., 2002. Fractal analysis of mingled/mixed magmas: an example from the Upper Pollara eruption (Salina Island, southern Tyrrhenian Sea, Italy). *Lithos* 65, 299-311.
- Debon, F., Le Fort, P., 1983. A chemical–mineralogical classification of common plutonic rocks and associations. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 73, 135-149.
- DePaolo, D.J., 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth and Planetary Science Letters* 53, 189-202.
- DePaolo, D.J., Perry, F.V., Baldrige, W.S., 1992. Crustal versus mantle sources in granitic magmas: a two-

- parameters model based on Nd isotope studies. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 83, 439-446.
- 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.
- Didier, J., Barbarin, B., (eds) 1991. *Enclaves and Granite Petrology*. Elsevier, Amsterdam.
- Eby, G.N., 1992. Chemical subdivision of the A-type granitoids – petrogenetic and tectonic implications. *Geology* 20, 641-644.
- 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., Katz, R.F., 2010. Melting above the anhydrous solidus controls the location of volcanic arcs. *Nature* 467, 700-703.
- 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. *Journal of Petrology* 25, 894-928.
- Farmer, G.L., DePaolo, D.J., 1983. Origin of Mesozoic and Tertiary granite in the western United States and implications for Pre-Mesozoic crustal structure: 1. Nd and Sr isotopic studies in the geocline of the Northern Great Basin. *Journal of Geophysical Research: Solid Earth* 88, 3379-3401.
- 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, pp.302-314.
- Finger, F., Roberts, M.P., Haunschmid, B., Schermaier, A., Steyrer, H.P., 1997. Variscan granitoids of central Europe: their typology, potential sources and tectonothermal relations. *Mineralogy and Petrology* 61, 67–96.
- Förster, M.W., Prelević, D., Buhre, S., Mertz-Kraus, R., Foley, S.F., 2019. An experimental study of the role of partial melts of sediments versus mantle melts in the sources of potassic magmatism. *Journal of Asian Earth Sciences* 177, 76-88.
- 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. *Journal of Petrology* 42, 2033-2048.
- Glazner, A.F., 2007. Thermal limitations on incorporation of wall rock into magma. *Geology* 35, 319-322.
- Goussin, F., Riel, N., Cordier, C., Guillot, S., Boulvais, P., Roperch, P., Replumaz, A., Schulmann, K., Dupont-Nivet, G., Rosas, F., Guo, Z., 2020. Carbonated inheritance in the eastern Tibetan lithospheric mantle:

- petrological evidences and geodynamic implications. *Geochemistry, Geophysics, Geosystems* 21, e2019GC008495.
- Griffin, T.J., White, A.J.R., Chappell, B.W., 1978. The Moruya Batholith and geochemical contrasts between the Moruya and Jindabyne suites. *Journal of the Geological Society of Australia* 25, 235-247.
- Grimes, C.B., Ushikubo, T., Kozdon, R., Valley, J.W., 2013. Perspectives on the origin of plagiogranite in ophiolites from oxygen isotopes in zircon. *Lithos* 179, 48-66.
- Grosse, P., Bellos, L.I., Camilo, R., Larrovere, M.A., Rossi, J.N., Toselli, A.J., 2011. Across-arc variation of the Famatinian magmatic arc (NW Argentina) exemplified by I-, S- and transitional I/S-type Early Ordovician granitoids of the Sierra de Velasco. *Journal of South American Earth Sciences* 32, 110-126.
- Harris, N., Vance, D., Ayres, M., 2000. From sediment to granite: timescales of anatexis in the upper crust. *Chemical Geology* 162, 155-167.
- Hawkesworth, C.J., Vollmer, R., 1979. Crustal contamination versus enriched mantle: $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ evidence from the Italian volcanics. *Contributions to Mineralogy and Petrology* 69, 151-165.
- Hawkesworth, C., Turner, S., Gallagher, K., Hunter, A., Bradshaw, T., Rogers, N., 1995. Calc-alkaline magmatism, lithospheric thinning and extension in the Basin and Range. *Journal of Geophysical Research: Solid Earth* 100, 10271-10286.
- Hermann, J., Rubatto, D., 2009. Accessory phase control on the trace element signature of sediment melts in subduction zones. *Chemical Geology* 265, 512-526.
- Hibbard, M.J., 1995. Mixed magma rocks. In: *Petrography to Petrogenesis*. Prentice Hall, New Jersey, pp. 242-260.
- Hildreth, W., Moorbath, S., 1988. Crustal contributions to arc magmatism in the Andes of central Chile. *Contributions to Mineralogy and Petrology* 98, 455-489.
- Hopkinson, T.N., Harris, N.B., Warren, C.J., Spencer, C.J., Roberts, N.M., Horstwood, M.S., Parrish, R.R., 2017. The identification and significance of pure sediment-derived granites. *Earth and Planetary Science Letters* 467, 57-63.
- Inger, S., Harris, N.B.W. 1993. Geochemical constraints on leucogranite magmatism in the Langtang Valley, Nepal Himalayas. *Journal of Petrology* 34, 345-368.
- Jagoutz, O.E., 2010. Construction of the granitoid crust of an island arc. Part II: a quantitative petrogenetic model. *Contributions to Mineralogy and Petrology* 160, 359-381.
- Janoušek, V., Holub, F.V., 2007. The causal link between HP–HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif. *Proceedings of the Geologists' Association* 118, 75--86.
- Janoušek, V., Moyen, J.F., 2020. Whole-rock geochemical modelling of granite genesis: the current state of the

- play. In: V. Janoušek, B. Bonin, W.J. Collins, F. Farina, and P. Bowden (eds) *Post-Archean Granitic Rocks: Contrasting Petrogenetic Processes and Tectonic Environments*. Geological Society, London, Special Publications 491, pp. 267-291.
- Janoušek, V., Rogers, G., Bowes, D.R., 1995. Sr–Nd isotopic constraints on the petrogenesis of the Central Bohemian Pluton, Czech Republic. *Geologische Rundschau* 84, 520-534.
- Janoušek, V., Bowes, D.R., Braithwaite, C.J.R., Rogers, G., 2000. Microstructural and mineralogical evidence for limited involvement of magma mixing in the petrogenesis of a Hercynian high-K calc-alkaline intrusion: the Kozárovec granodiorite, Central Bohemian Pluton, Czech Republic. *Transactions of the Royal Society Edinburgh – Earth Sciences* 91, 15-26.
- Janoušek, V., Braithwaite, C.J.R., Bowes, D.R., Gerdes, A., 2004. Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sázava intrusion, Central Bohemian Pluton, Czech Republic. *Lithos* 78, 67-99.
- Janoušek, V., Jiang, Y.D., Buriánek, D., Schulmann, K., Hanžl, P., Soejono, I., Kröner, A., Altanbaatar, B., Erban, V., Lexa, O., Ganchuluun, T., Košler, J., 2018. Cambrian–Ordovician magmatism of the Ikh-Mongol Arc System exemplified by the Khantaishir Magmatic Complex (Lake Zone, south–central Mongolia). *Gondwana Research* 54, 122-149.
- Janoušek, V., Holub, F.V., Verner, K., Čopjaková, R., Gerdes, A., Hora, J.M., Košler, J., Tyrrell, S., 2019. Two-pyroxene syenitoids from the Moldanubian Zone of the Bohemian Massif: peculiar magmas derived from a strongly enriched lithospheric mantle source. *Lithos* 342–343, 239–262.
- 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. *International Journal of Earth Sciences* 109, 1767-1810.
- 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.
- Kemp, A.I.S., 2004. Petrology of high-Mg, low-Ti igneous rocks of the Glenelg River Complex (SE Australia) and the nature of their interaction with crustal melts. *Lithos* 78, 119-156.
- Kemp, A.I.S., Hawkesworth, C.J., Paterson, B.A., Foster, G.L., Kinny, P.D., Whitehouse, M.J., Maas, R., 2008. Exploring the plutonic–volcanic link: a zircon U–Pb, Lu–Hf and O isotope study of paired volcanic and granitic units from southeastern Australia. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh – Earth Sciences* 97, 337-355.
- Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M., Blevin, P.L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: the Tasmanides, eastern Australia. *Earth and Planetary Science Letters* 284, 455-466.

- King, P., White, A., Chappell, B., Allen, C., 1997. Characterization and origin of aluminous A-type granites from the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* 38, 371-391.
- Kistler, R.W., Peterman, Z.E., 1973. Variations in Sr, Rb, K, Na, and initial $^{87}\text{Sr}/^{86}\text{Sr}$ in Mesozoic granitic rocks and intruded wall rocks in central California. *Geological Society of America Bulletin* 84, 3489-3512.
- Korenaga, J., 2018. Crustal evolution and mantle dynamics through Earth history. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376, 20170408.
- Kröner, A., Kovach, V., Belousova, E., Hegner, E., Armstrong, R., Dolgoplova, A., Seltmann, R., Alexeiev, D.V., Hoffmann, J.E., Wong, J., Sun, M., Cai, K., Wang, T., Tong, Y., Wilde, S.A., Degtyarev, K.E., Rytsk, E., 2014. Reassessment of continental growth during the accretionary history of the Central Asian Orogenic Belt. *Gondwana Research* 25, 103-125.
- Larsen, E.S., Irving, J., Gonyer, F.A., Larsen, E.S.J., 1936–1938. Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region, Colorado. *American Mineralogist* 21, 666-701; 22, 880-905; 23, 417-429.
- Larsen, E.S.J., Cross, W., 1956. *Geology and Petrology of the San Juan Region, Southwestern Colorado*. US Geological Survey Professional Papers 258, pp 1-303
- Laumonier, M., Scaillet, B., Pichavant, M., Champallier, R., Andujar, J., Arbaret, L., 2014. On the conditions of magma mixing and its bearing on andesite production in the crust. *Nature Communications* 5, 5607.
- 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 and Planetary Science Letters* 430, 326-338.
- Laurent, O., Zeh, A., Gerdes, A., Villaros, A., Gros, K., Słaby, E., 2017a. How do granitoid magmas mix with each other? Insights from textures, trace element and Sr–Nd isotopic composition of apatite and titanite from the Matok Pluton (South Africa). *Contributions to Mineralogy and Petrology* 172, 80.
- Laurent, O., Couzinié, S., Zeh, A., Vanderhaeghe, O., Moyen, J.F., Villaros, A., Gardien, V., Chelle-Michou, C., 2017b. Protracted, coeval crust- and mantle melting during Variscan late-orogenic evolution: zircon U–Pb dating in the eastern French Massif Central. *International Journal of Earth Sciences* 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.
- Leshner, C. E., 1990. Decoupling of chemical and isotopic exchange during magma mixing. *Nature* 344, 235-237.
- Maas, R., Nicholls, I.A., Legg, C., 1997. Igneous and metamorphic enclaves in the S-type Deddick Granodiorite, Lachlan Fold Belt, SE Australia: petrographic, geochemical and Nd–Sr isotopic evidence for crustal melting and magma mixing. *Journal of Petrology* 38, 815-841.
- Maierová, P., Schulmann, K., Lexa, O., Guillot, S., Štípská, P., Janoušek, V., Čadek, O., 2016. European Variscan orogenic evolution as an analogue of Tibetan–Himalayan Orogen: insights from petrology and numerical

- modeling. *Tectonics* 35, 1760-1780.
- McCulloch, M.T., Chappell, B.W., 1982. Nd isotopic characteristics of S- and I-type granites. *Earth and Planetary Science Letters* 58, 51-64.
- McInnes, B.I., Gregoire, M., Binns, R.A., Herzig, P.M., Hannington, M.D., 2001. Hydrous metasomatism of oceanic sub-arc mantle, Lihir, Papua New Guinea: petrology and geochemistry of fluid-metasomatised mantle wedge xenoliths. *Earth and Planetary Science Letters* 188, 169-183.
- Miller, C.F., Barton, M.D., 1990. Phanerozoic plutonism in the Cordilleran interior, USA. In: Kay, S.M, Rapela, C.W. (eds) *Plutonism from Antarctica to Alaska*. Geological Society of America Special Papers 241, pp. 213-231.
- Miller, C.F., Bradfish, L.J., 1980. An inner Cordilleran belt of muscovite-bearing plutons. *Geology* 8, 412-416.
- Miller, C.F., Wooden, J.L., Bennett, V.C., Wright, J.E., Solomon, G.C., Hurst, R.W., 1990. Petrogenesis of the composite peraluminous–metaluminous Old Woman–Piute Range Batholith, southeastern California; Isotopic constraints. In: Anderson, J.L. (ed.) *The Nature and Origin of Cordilleran Magmatism*. Geological Society of America Memoirs 174, pp. 99-110.
- Morgavi, D., Perugini, D., De Campos, C.P., Ertel-Ingrisch, W., Lavallée, Y., Morgan, L., Dingwell, D.B., 2013. Interactions between rhyolitic and basaltic melts unraveled by chaotic mixing experiments. *Chemical Geology* 346, 199-212.
- Morgavi, D., Arienzo, I., Montagna, C., Perugini, D., Dingwell, D.B., 2017. Magma mixing: history and dynamics of an eruption trigger. In: Gottesmann, J., Neuberg, J., Scheu, B. (eds) *Volcanic Unrest. From Science to Society*. Springer, Berlin, pp. 123-137.
- 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., Martin, H., Jayananda, M., 2001. Multi-element geochemical modelling of crust–mantle interactions during late-Archaean crustal growth: the Closepet granite (South India). *Precambrian Research* 112, 87-105.
- 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
- Moyen, J.F., Jacob, J.B., Janoušek, V., Laurent, O., Bachmann, O., Farina, F., Fiannacca, P., Villaros, A., 2021. Crustal melting vs. fractionation of basaltic magmas: Part 1, the bipolar disorder of granites. *Lithos* xx, this volume
- Müntener, O., Ulmer, P., 2018. Arc crust formation and differentiation constrained by experimental petrology. *American Journal of Science* 318, 64-89.

- 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 491 491, pp. 179-207.
- O'Hara, M.J., 1977. Geochemical evolution during fractional crystallisation of a periodically refilled magma chamber. *Nature* 266, 503-507.
- Otamendi, J.E., Ducea, M.N., Tibaldi, A.M., Bergantz, G.W., de la Rosa, J.D., Vujovich, G.I., 2009. Generation of tonalitic and dioritic magmas by coupled partial melting of gabbroic and metasedimentary rocks within the deep crust of the Famatinian magmatic arc, Argentina. *Journal of Petrology* 50, 841-873.
- Otamendi, J., Pinotti, L., Basei, M., Tibaldi, A., 2010. Evaluation of petrogenetic models for intermediate and silicic plutonic rocks from the Sierra de Valle Fértil–La Huerta, Argentina: petrologic constraints on the origin of igneous rocks in the Ordovician Famatinian–Puna paleoarc. *Journal of South American Earth Sciences* 30, 29-45.
- Pankhurst, R., Rapela, C.W., Fanning, C.M., 2000. Age and origin of coeval TTG, I- and S-type granites in the Famatinian belt of NW Argentina. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 91, 151-168.
- Paterson, S.R., Ducea, M.N., 2015. Arc magmatic tempos: gathering the evidence. *Elements* 11, 91–98.
- Paterson, S.R., Okaya, D., Memeti, V., Economos, R., Miller, R.B., 2011. Magma addition and flux calculations of incrementally constructed magma chambers in continental margin arcs: combined field, geochronologic, and thermal modeling studies. *Geosphere* 7, 1439-1468.
- Patiño-Douce, A.E. Harris, N., 1998. Experimental constraints on Himalayan anatexis. *Journal of Petrology* 39, 689-710.
- 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.
- Peacock, S.M., 1990. Fluid processes in subduction zones. *Science* 248, 329-337.
- Pearce, J.A., 1996. Sources and settings of granitic rocks. *Episodes* 19, 120-125.
- Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* 25, 956-983.
- Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, Northern Turkey. *Contributions to Mineralogy and Petrology* 58, 63-81.
- Perugini, D., Poli, G., 2000. Chaotic dynamics and fractals in magmatic interaction processes: a different approach to the interpretation of mafic microgranular enclaves. *Earth and Planetary Science Letters* 175, 93-103.
- Perugini, D., Poli, G., 2012. The mixing of magmas in plutonic and volcanic environments: analogies and

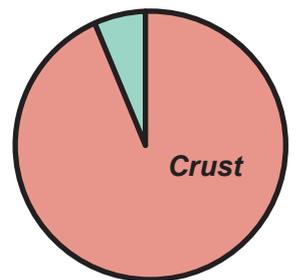
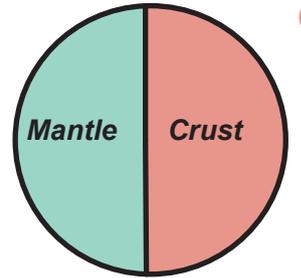
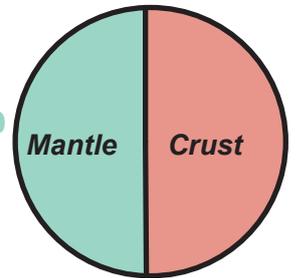
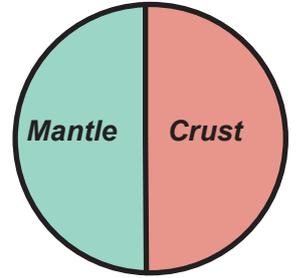
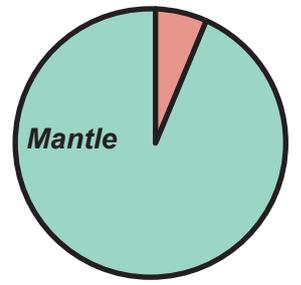
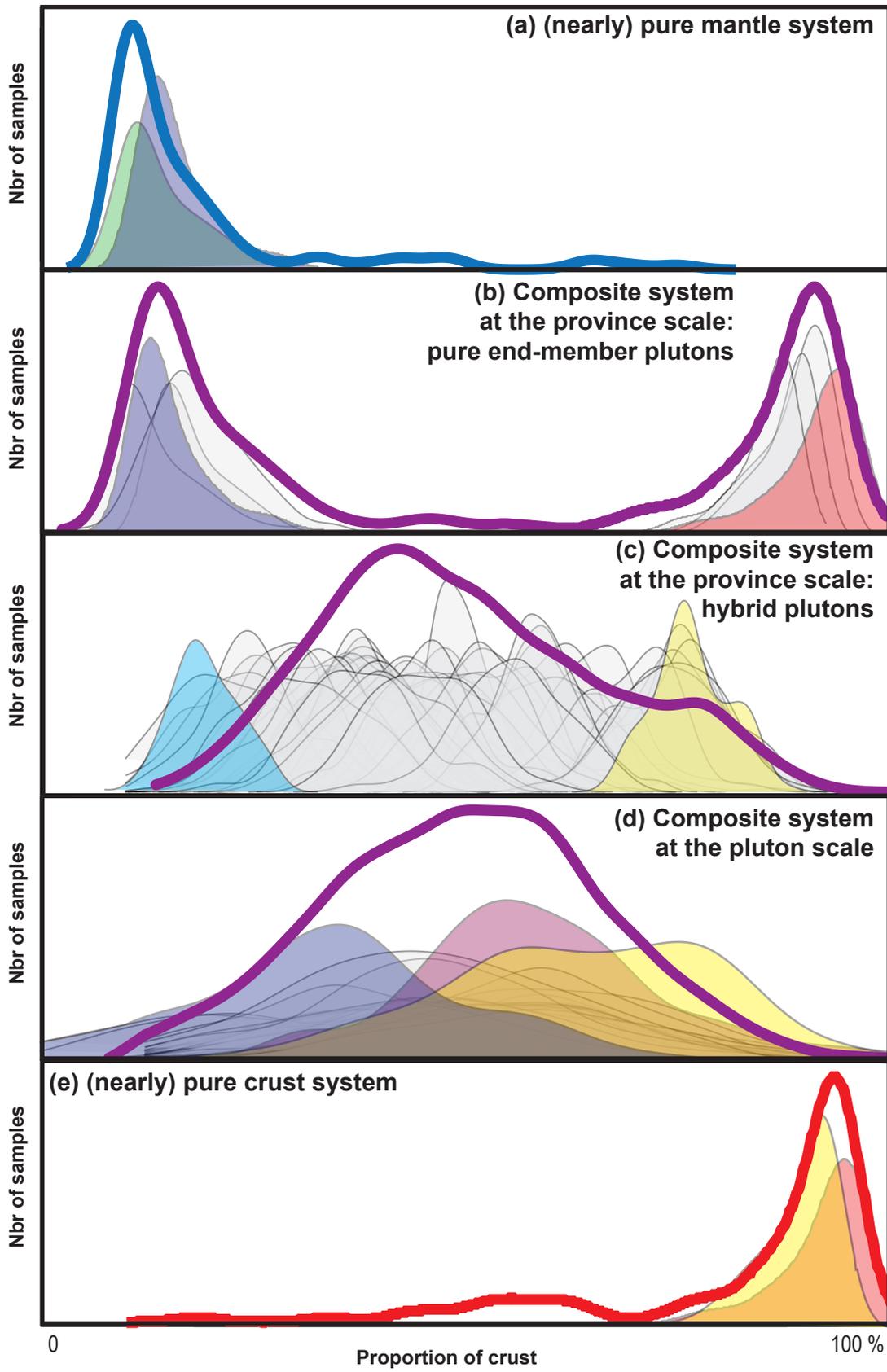
- differences. *Lithos* 153, 261-277.
- Perugini, D., Poli, G., Christofides, G., Eleftheriadis, G., 2003. Magma mixing in the Sithonia Plutonic Complex, Greece: evidence from mafic microgranular enclaves. *Mineralogy and Petrology* 78, 173-200.
- Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.L., 2000. Granite magma formation, transport and emplacement in the Earth's crust. *Nature* 408, 669-673.
- Petrelli, M., Perugini, D., Poli, G., 2006. Time-scales of hybridisation of magmatic enclaves in regular and chaotic flow fields: petrologic and volcanologic implications. *Bulletin of Volcanology* 68, 285-293.
- Pin, C., Duthou, J.L., 1990. Sources of Hercynian granitoids from the French Massif Central: inferences from Nd isotopes and consequences for crustal evolution. *Chemical Geology* 83, 281-296.
- Pin, C., Paquette, J.-L., 2002. Le magmatisme basique calcoalcalin d'âge dévono-dinantien du nord du Massif Central, témoin d'une marge active hercynienne: arguments géochimiques et isotopiques Sr/Nd. *Geodinamica Acta* 15, 63-77.
- Pinarelli, L., Rottura, A., 1995. Sr and Nd isotopic study and Rb-Sr geochronology of the Bejar granites, Iberian Massif, Spain. *European Journal of Mineralogy* 7, 577-589.
- Pitcher, W.S., 1987. Granites and yet more granites forty years on. *Geologische Rundschau* 76, 51-79.
- Pitcher, W. S., 1997. *The Nature and Origin of Granite*. Springer Science & Business Media, Dodrecht.
- Pitcher, W.S., Berger, A.R., 1972. *The Geology of Donegal: a Study of Granite Emplacement and Unroofing*. Wiley-Interscience, New York.
- Reiners, P.W., Nelson, B.K., Ghiorso, M.S., 1995. Assimilation of felsic crust and its partial melt by basaltic magma: thermal limits and extents of crustal contamination. *Geology* 23, 563-566.
- 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. *Contributions of Mineralogy and Petrology* 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.
- Robinson, D.M., Miller, C.F., 1999. Record of magma chamber processes preserved in accessory mineral assemblages, Aztec Wash Pluton, Nevada. *American Mineralogist* 84, 1346-1353.
- Roden, M.F., Murthy, V.R., 1985. Mantle metasomatism. *Annual Review of Earth and Planetary Sciences* 13, 269-296.
- Rollinson, H. 2009. New models for the genesis of plagiogranites in the Oman ophiolite. *Lithos*, 112, 603-614.

- Scarrow, J., Molina, J., Bea, F., Montero, P., 2009. Within-plate calc-alkaline rocks: insights from alkaline mafic magma–peraluminous crustal melt hybrid appinites of the Central Iberian Variscan continental collision. *Lithos* 110, 50-64.
- Schaltegger, U., Brack, P., 2007. Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. *International Journal of Earth Sciences* 96, 1131-1151.
- Searle, M., Cottle, J., Streule, M., Waters, D., 2010. Crustal melt granites and migmatites along the Himalaya: melt source, segregation, transport and granite emplacement mechanisms. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh – Earth Sciences* 100, 219-233.
- Shand, S.J., 1943. *Eruptive Rocks. Their Genesis, Composition, Classification, and Their Relation to Ore-Deposits with a Chapter on Meteorite.* John Wiley, Sons, New-York.
- Shaw, A., Downes, H., Thirlwall, M., 1993. The quartz-diorites of Limousin: elemental and isotopic evidence for Devonian–Carboniferous subduction in the Hercynian belt of the French Massif Central. *Chemical Geology* 107, 1-18.
- Sinigoi, S., Antonini, P., Demarchi, G., Longinelli, A., Mazzucchelli, M., Negrini, L., Rivalenti, G., 1991. Interactions of mantle and crustal magmas in the southern part of the Ivrea Zone (Italy). *Contributions to Mineralogy and Petrology* 108, 385-395.
- Slaby, E., Martin, H., 2008. Mafic and felsic magma interaction in granites: the Hercynian Karkonosze Pluton (Sudetes, Bohemian Massif). *Journal of Petrology* 49, 353-391.
- Spencer, C., Roberts, N., Santosh, M., 2017. Growth, destruction, and preservation of Earth's continental crust. *Earth-Science Reviews* 172, 87-106.
- Spera, F.J., Bohron, W.A., 2001. Energy constrained open-system magmatic processes I: general model and Energy-Constrained Assimilation and Fractional Crystallization (EC-AFC) formulation. *Journal of Petrology* 42, 999-1018.
- Stern, R.J., Scholl, D.W., 2010. Yin and yang of continental crust creation and destruction by plate tectonic processes. *International Geology Review* 52, 1-31
- Tabaud, A.S., Janoušek, V., Skrzypek, E., Schulmann, K., Rossi, P., Whitechurch, H., Guerrot, C., Paquette, J.L., 2015. Chronology, petrogenesis and heat sources for successive Carboniferous magmatic events in the southern-central Variscan Vosges Mts. (NE France). *Journal of the Geological Society* 172, 87-102.
- Tappe, S., Smart, K., Torsvik, T., Massuyeau, M., de Wit, M., 2018. Geodynamics of kimberlites on a cooling Earth: clues to plate tectonic evolution and deep volatile cycles. *Earth and Planetary Science Letters* 484, 1-14.
- Tatsumi, Y., Eggins, S., 1995. *Subduction Zone Magmatism.* Blackwell, Oxford.
- Taylor, H.P., 1980. The effects of assimilation of country rocks on $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ systematics in igneous

- rocks. *Earth and Planetary Science Letters* 47, 243-254.
- Trubač, J., Žák, J., Kondrová, L., 2020. Magmatic tempos in large hot orogens in comparison with continental margin arcs. *Journal of Geology* 128, 465-475.
- Turpin, L., Velde, D., Pinte, G., 1988. Geochemical comparison between minettes and kersantites from the Western European Hercynian Orogen – trace-element and Pb–Sr–Nd isotope constraints on their origin. *Earth and Planetary Science Letters* 87, 73-86.
- Turpin, L., Cuney, M., Friedrich, M., Bouchez, J.L., Aubertin, M., 1990. Meta-igneous origin of Hercynian peraluminous granites in NW French Massif Central – implications for crustal history reconstructions. *Contributions to Mineralogy and Petrology* 104, 163-172.
- 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. *Geochimica et Cosmochimica Acta* 72, A966.
- Vanderhaeghe, O., Teyssier, C., 2001. Partial melting and the flow of orogens. *Tectonophysics* 342, 451-472.
- Vernon, R.H., Paterson, S.R., 1993. The Ardara Pluton, Ireland – deflating an expanded intrusion. *Lithos* 31, 17-32.
- Vervoort, J.D., Kemp, A.I., 2016. Clarifying the zircon Hf isotope record of crust–mantle evolution. *Chemical Geology* 425, 65-75.
- Villaros, A., Laurent, O., Couzinié, S., Moyen, J.F., Mintrone, M., 2018. Plutons and domes: the consequences of anatexis magma extraction – example from the south-eastern French Massif Central. *International Journal of Earth Sciences* 107, 2819-2842.
- Villaseca, C., Barbero, L., Herreros, V., 1998. A re-examination of the typology of peraluminous granite types in intracontinental orogenic belts. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 89, 113-119.
- von Raumer, J.F., Finger, F., Veselá, P., Stampfli, G.M., 2014. Durbachites–Vaugnerites – a geodynamic marker in the central European Variscan Orogen. *Terra Nova* 26, 85-95.
- 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. *Journal of Petrology* 56, 1863-1896.
- Weinberg, R.F. 2016. Himalayan leucogranites and migmatites: nature, timing and duration of anatexis. *Journal of Metamorphic Geology*, 34, 821-843.
- Wiebe, R.A., 2016. Mafic replenishments into floored silicic magma chambers. *American Mineralogist* 101, 297-310.
- Wiebe, R.A., Blair, K.D., Hawkins, D.P., Sabine, C.P., 2002. Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California. *Geological Society of America Bulletin* 114, 909-

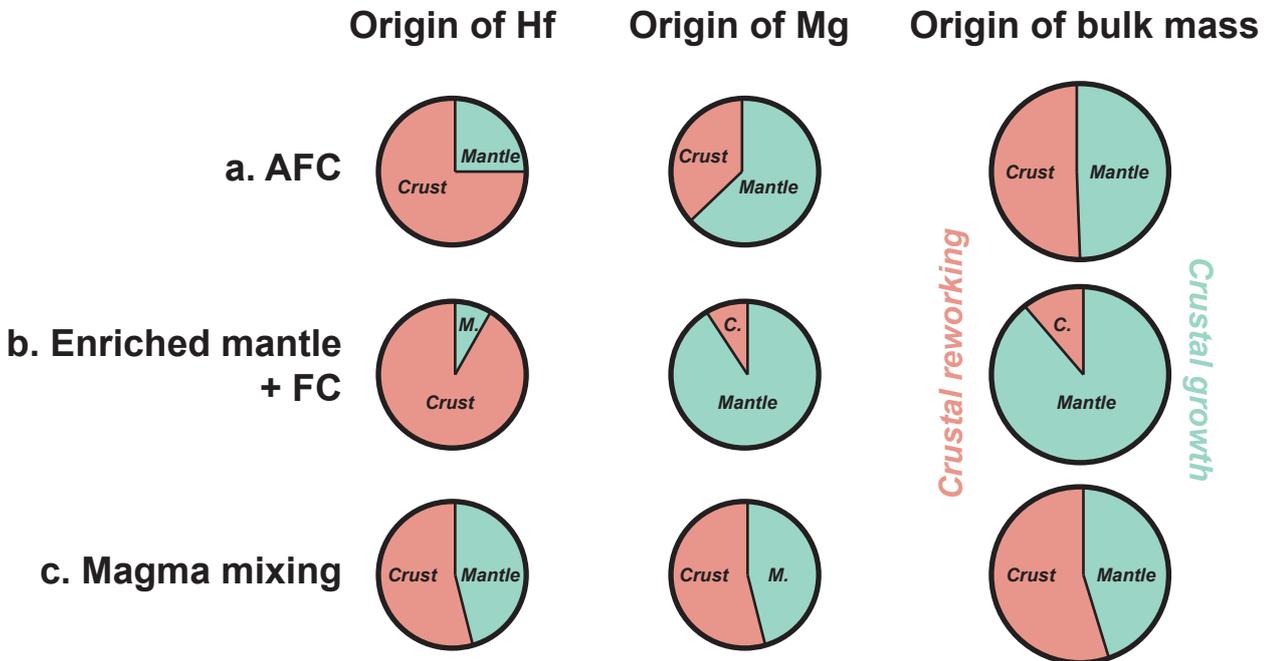
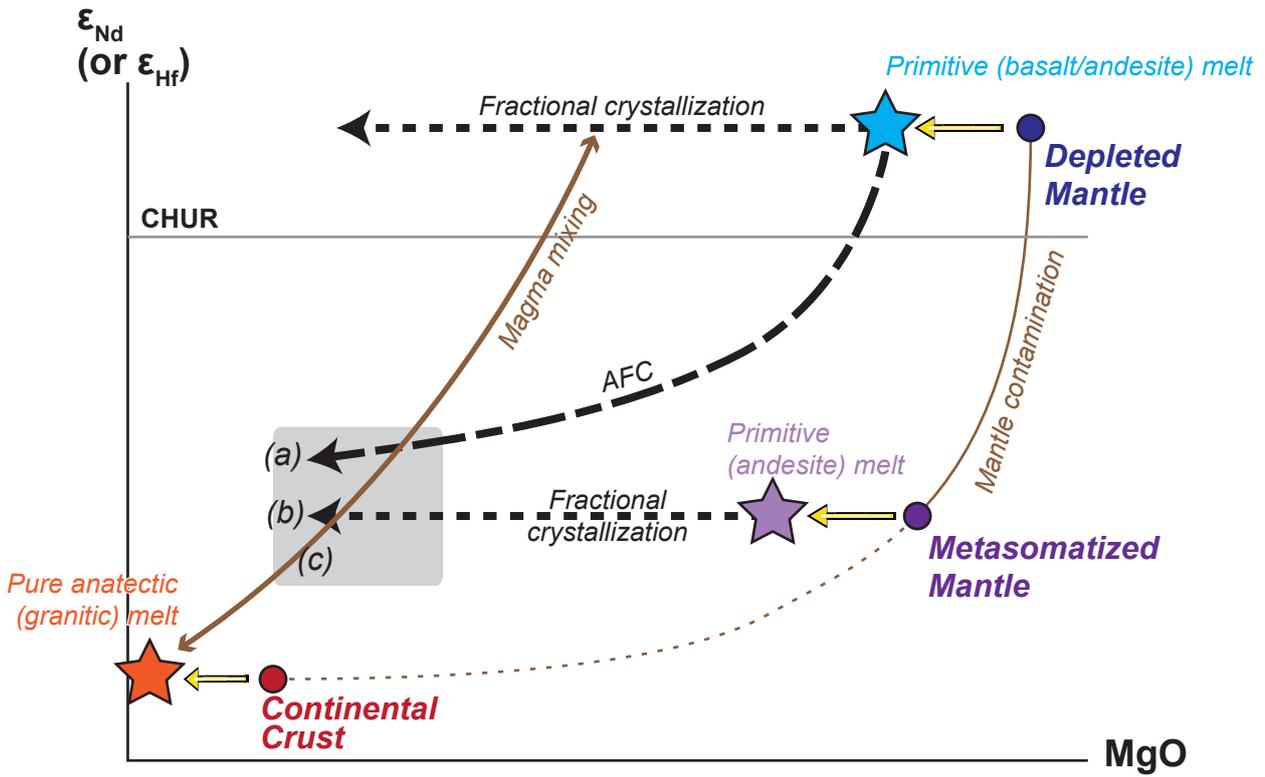
- Willbold, M., Hegner, E., Stracke, A., Rocholl, A., 2009. Continental geochemical signatures in dacites from Iceland and implications for models of early Archaean crust formation. *Earth and Planetary Science Letters* 279, 44-52.
- Williamson, B.J., Downes, H., Thirlwall, M.F., 1992. The relationship between crustal magmatic underplating and granite genesis – an example from the Velay Granite Complex, Massif Central, France. *Transactions of the Royal Society of Edinburgh – Earth Sciences* 83, 235-245.
- Williamson, B., Shaw, A., Downes, H., Thirlwall, M., 1996. Geochemical constraints on the genesis of Hercynian two-mica leucogranites from the Massif Central, France. *Chemical Geology* 127, 25-42.
- Wolfram, L., Weinberg, R.F., Hasalová, P., Becchio, R., 2017. How melt segregation affects granite chemistry: migmatites from the Sierra de Quilmes, NW Argentina. *Journal of Petrology* 58, 2339-2364.
- Wolfram, L.C., Weinberg, R.F., Nebel, O., Hamza, K., Hasalová, P., Míková, J., Becchio, R., 2019. A 60-Myr record of continental back-arc differentiation through cyclic melting. *Nature Geoscience* 12, 215-219.
- Xu, B., Griffin, W.L., Xiong, Q., Hou, Z.-Q., O'Reilly, S.Y., Guo, Z., Pearson, N.J., Gréau, Y., Yang, Z.M., Zheng, Y.C., 2017. Ultrapotassic rocks and xenoliths from South Tibet: contrasting styles of interaction between lithospheric mantle and asthenosphere during continental collision. *Geology* 45, 51-54.
- Žák, J., Verner, K., Janoušek, V., Holub, F. V., Kachlík, V., Finger, F., Hajná, J., Tomek, F., Vondrovic, L., Trubač, J., (2014). A plate-kinematic model for the assembly of the Bohemian Massif constrained by structural relationships around granitoid plutons. In: Schulmann, K., Martínez Catalán, J. R., Lardeaux, J. M., Janoušek, V. & Oggiano, G. (eds) *The Variscan Orogeny: Extent, Timescale and the Formation of the European Crust*. Geological Society, London, Special Publications 405, 169–196.
- Zhao, Z.F., Dai, L.Q., Zheng, Y.F., 2013. Postcollisional mafic igneous rocks record crust–mantle interaction during continental deep subduction. *Scientific Reports* 3, 3413, doi: 10.1038/srep03413.
- Zheng, Y.F., 2012. Metamorphic chemical geodynamics in continental subduction zones. *Chemical Geology* 328, 5-48.
- Zheng, Y.F., 2019. Subduction zone geochemistry. *Geoscience Frontiers* 10, 1223-1254.
- Zheng, Y.F., 2021. Convergent plate boundaries and accretionary wedges. In: *Encyclopedia of Geology*, 2nd edition. Elsevier, Amsterdam, pp. 770-787.
- Zheng, Y.-F., Gao, P., 2021. The production of granitic magmas through crustal anatexis at convergent plate boundaries. *Lithos*, 106232.
- Zheng, Y.F., Xia, Q.X., Chen, R.X., Gao, X.Y., 2011. Partial melting, fluid supercriticality and element mobility in ultrahigh-pressure metamorphic rocks during continental collision. *Earth-Science Reviews* 107, 342-374.
- Zheng, Y.F., Zhao, Z.F., Chen, R.X., 2019. Ultrahigh-pressure metamorphic rocks in the Dabie-Sulu orogenic belt:

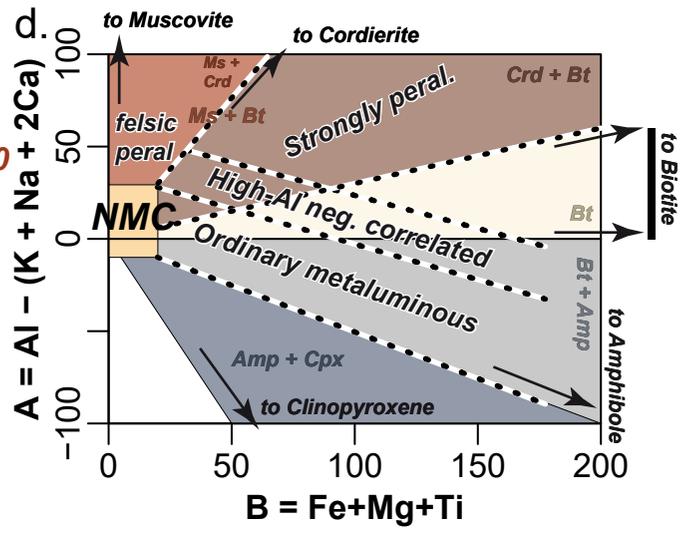
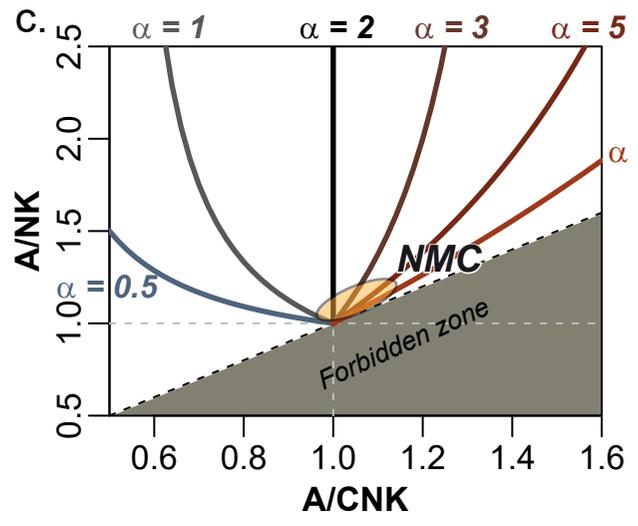
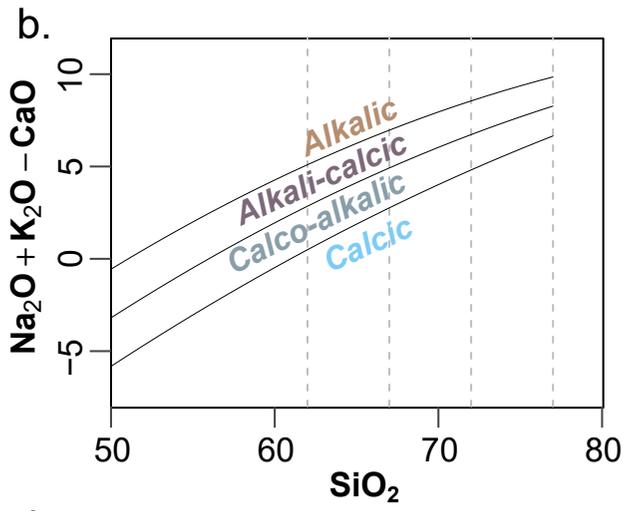
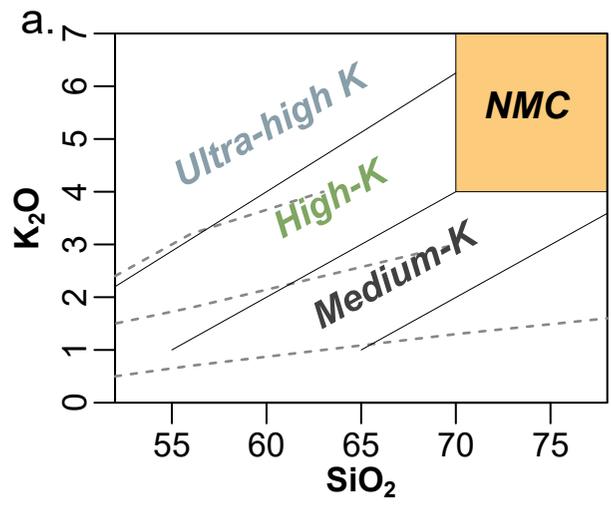
compositional inheritance and metamorphic modification. In: Zhang, L.F., Zhang, Z., Schertl, H.P., Wei, C. (eds) HP–UHP Metamorphism and Tectonic Evolution of Orogenic Belts. Geological Society, London, Special Publications 474, pp. 89-132.

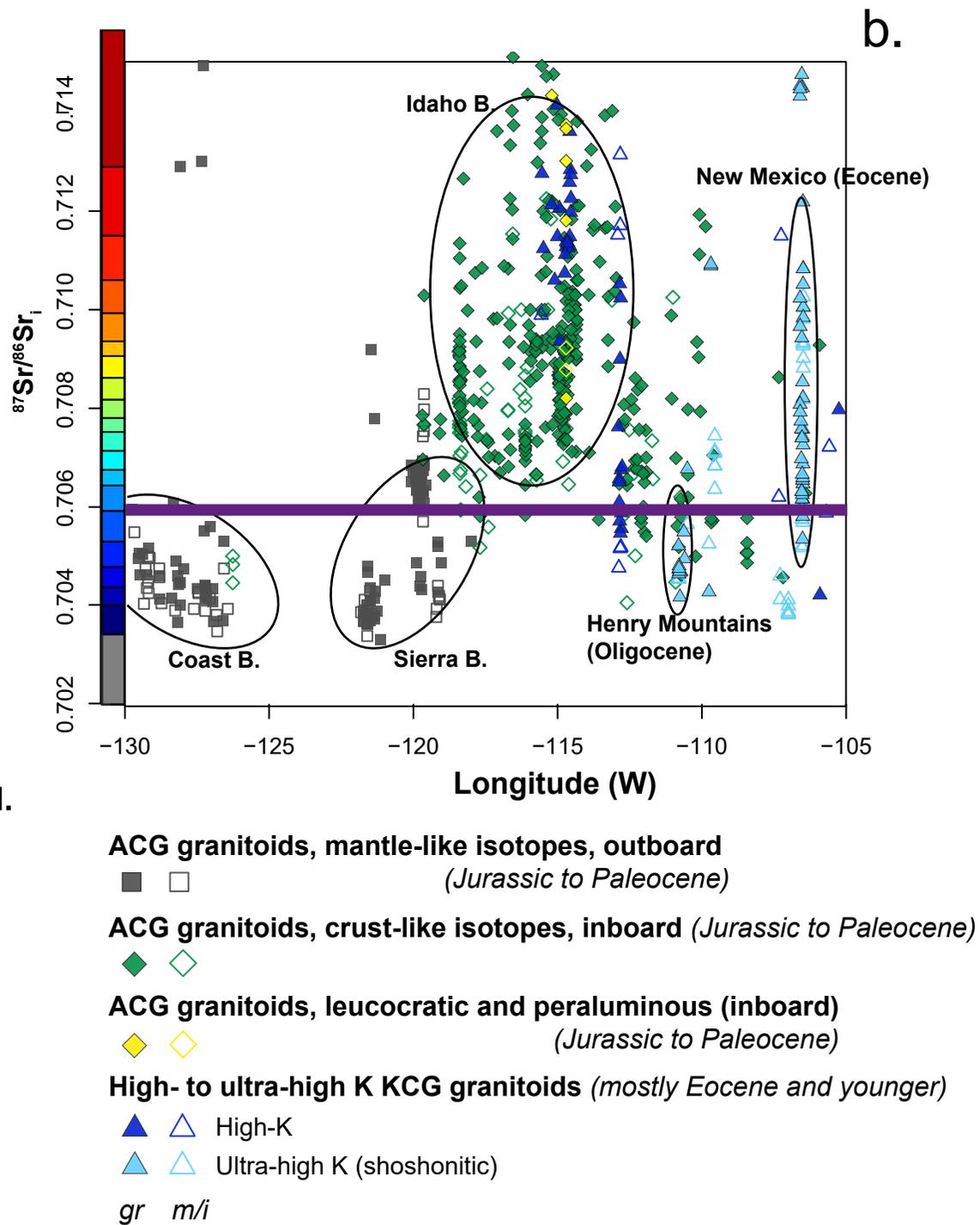
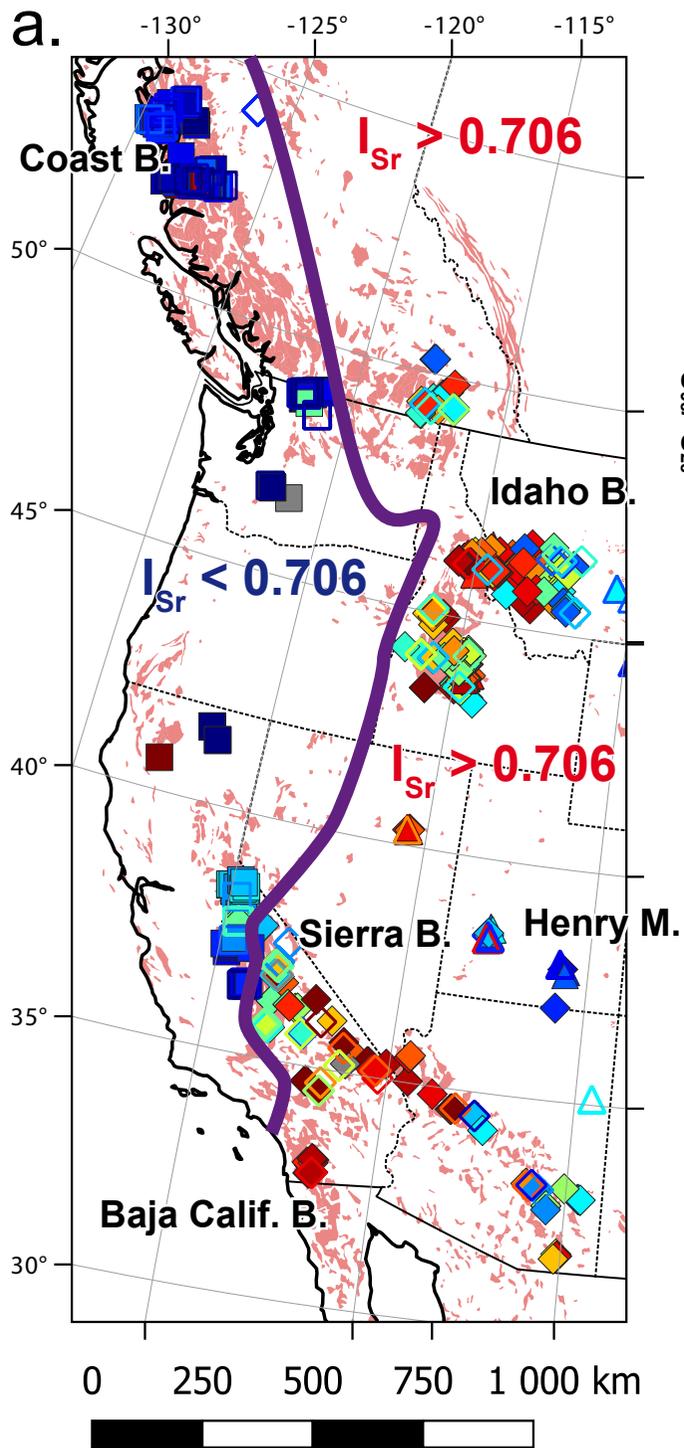


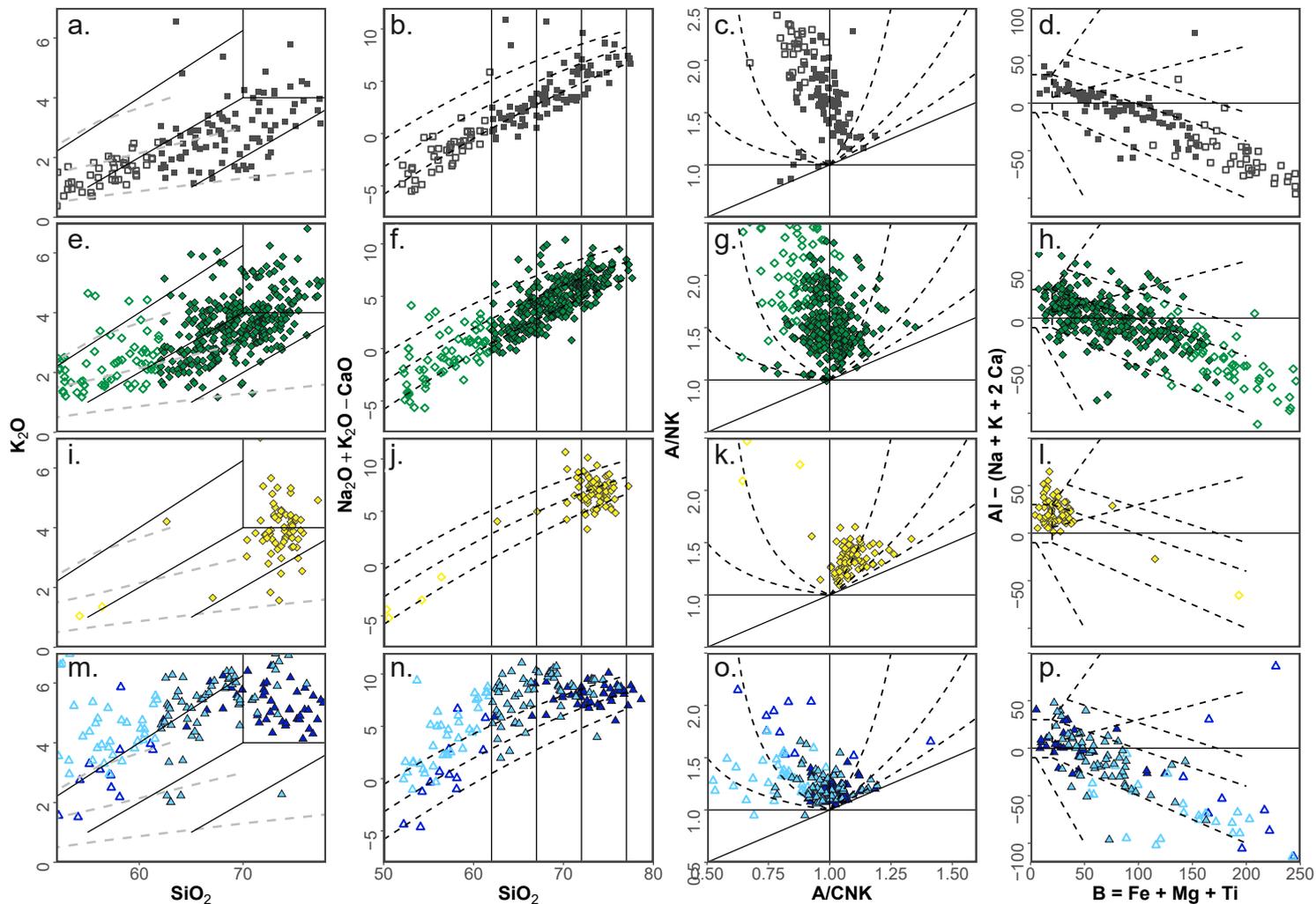
Crustal growth

Crustal reworking









ACG granitoids, mantle-like isotopes, outboard

■ □ *(Jurassic to Paleocene)*

ACG granitoids, crust-like isotopes, inboard *(Jurassic to Paleocene)*

◆ ◇

ACG granitoids, leucocratic and peraluminous (inboard)

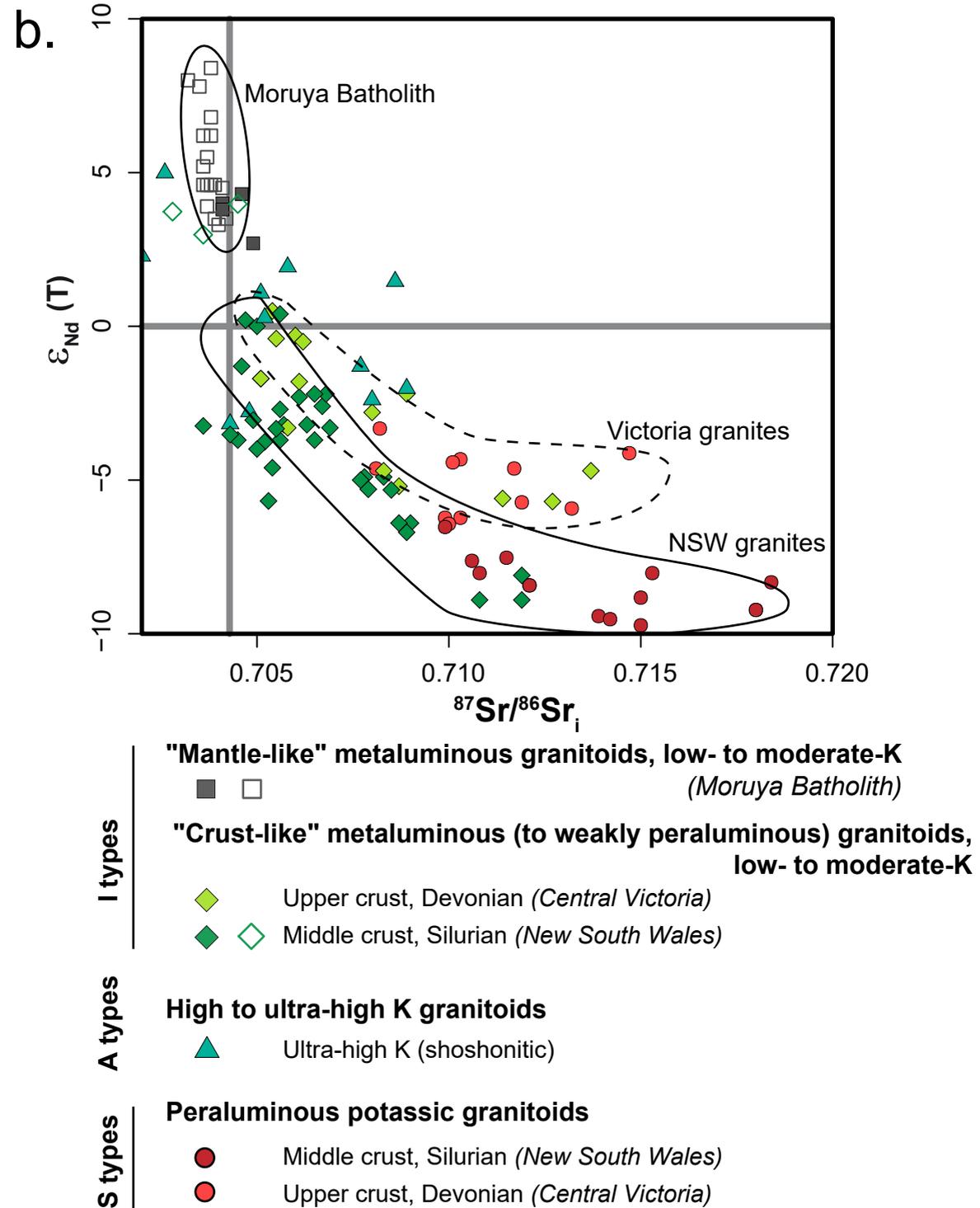
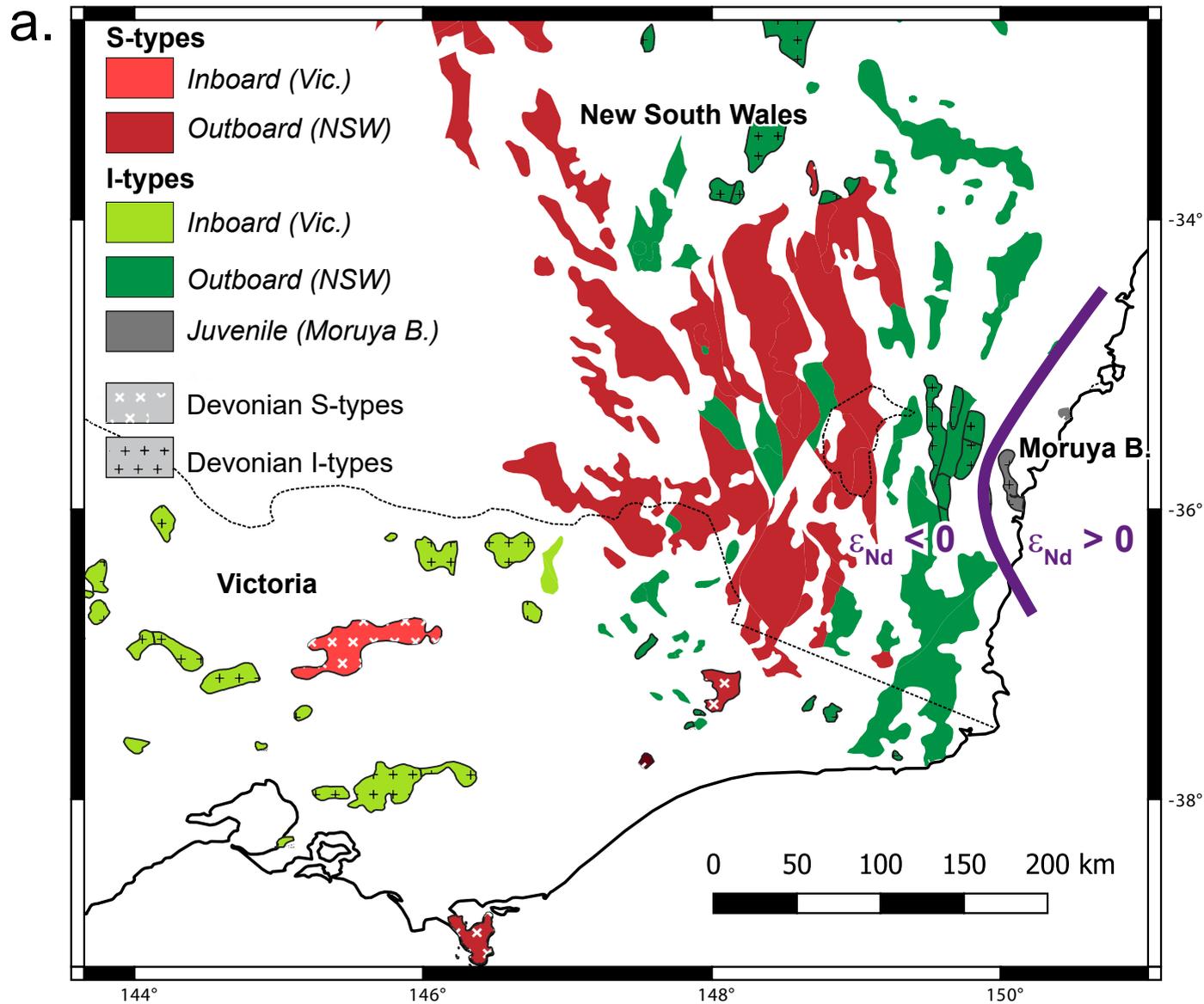
◆ ◇ *(Jurassic to Paleocene)*

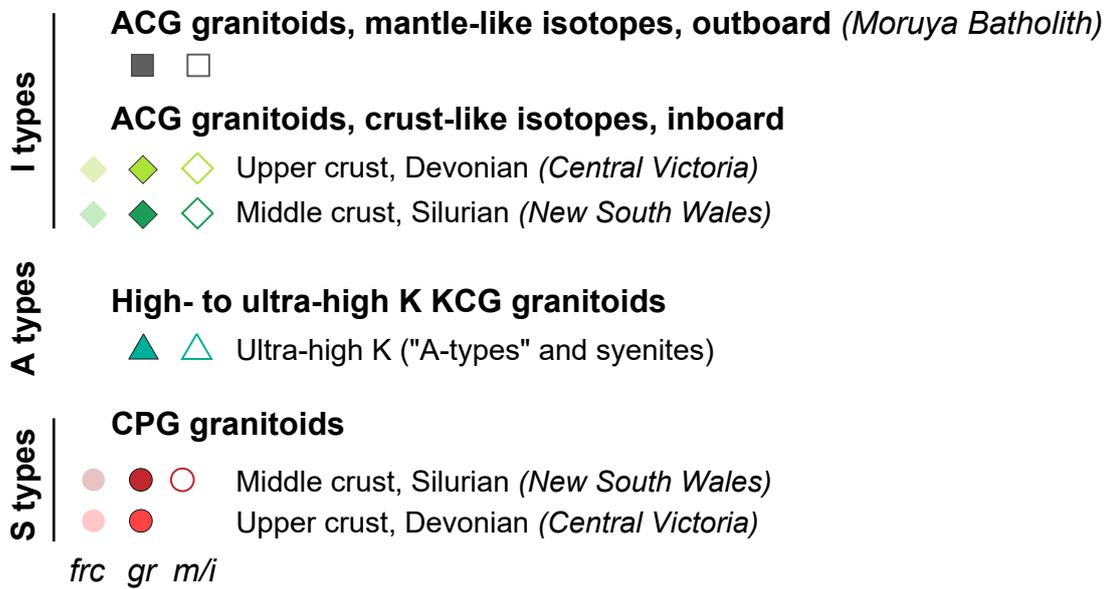
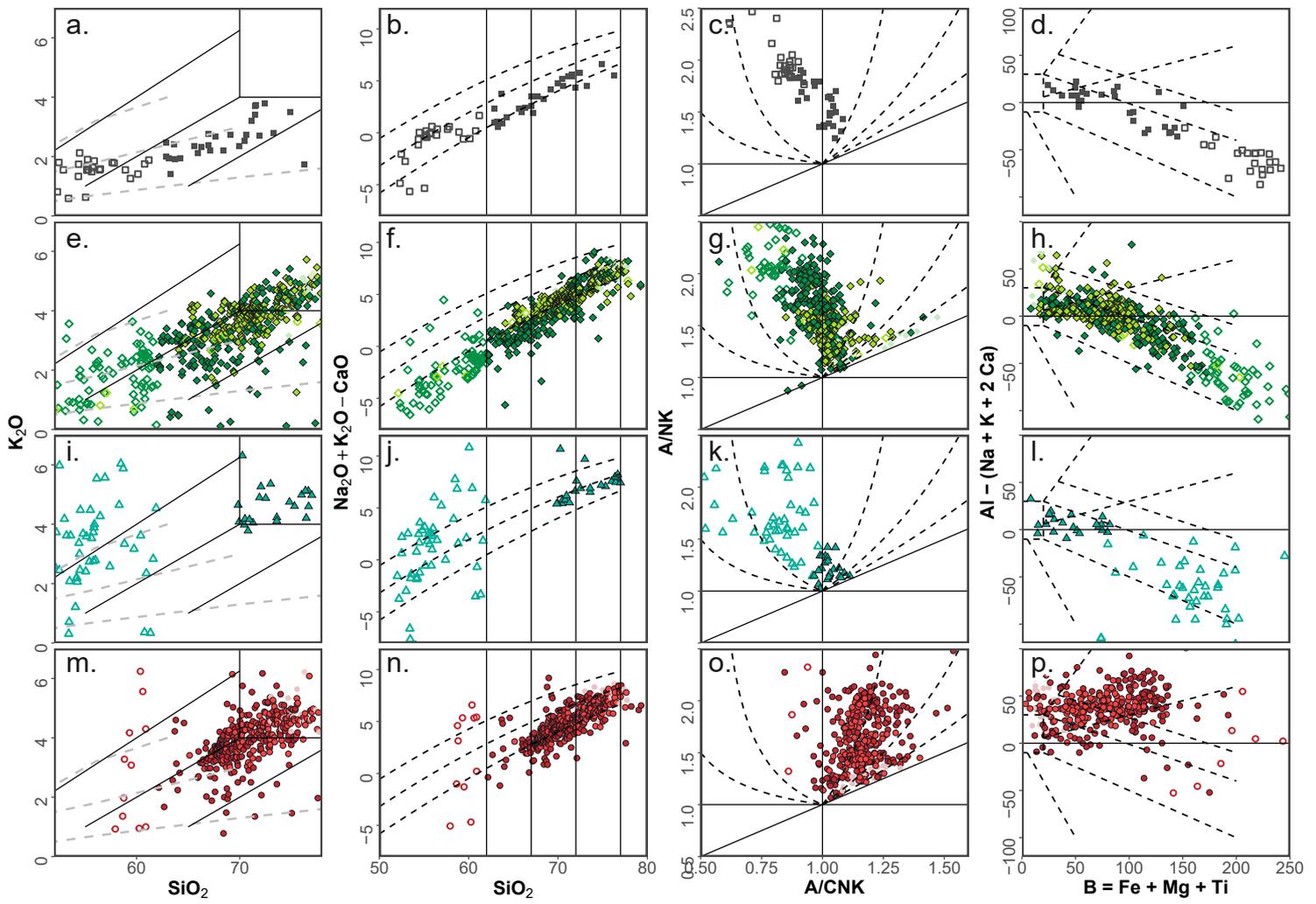
High- to ultra-high K KCG granitoids *(mostly Eocene and younger)*

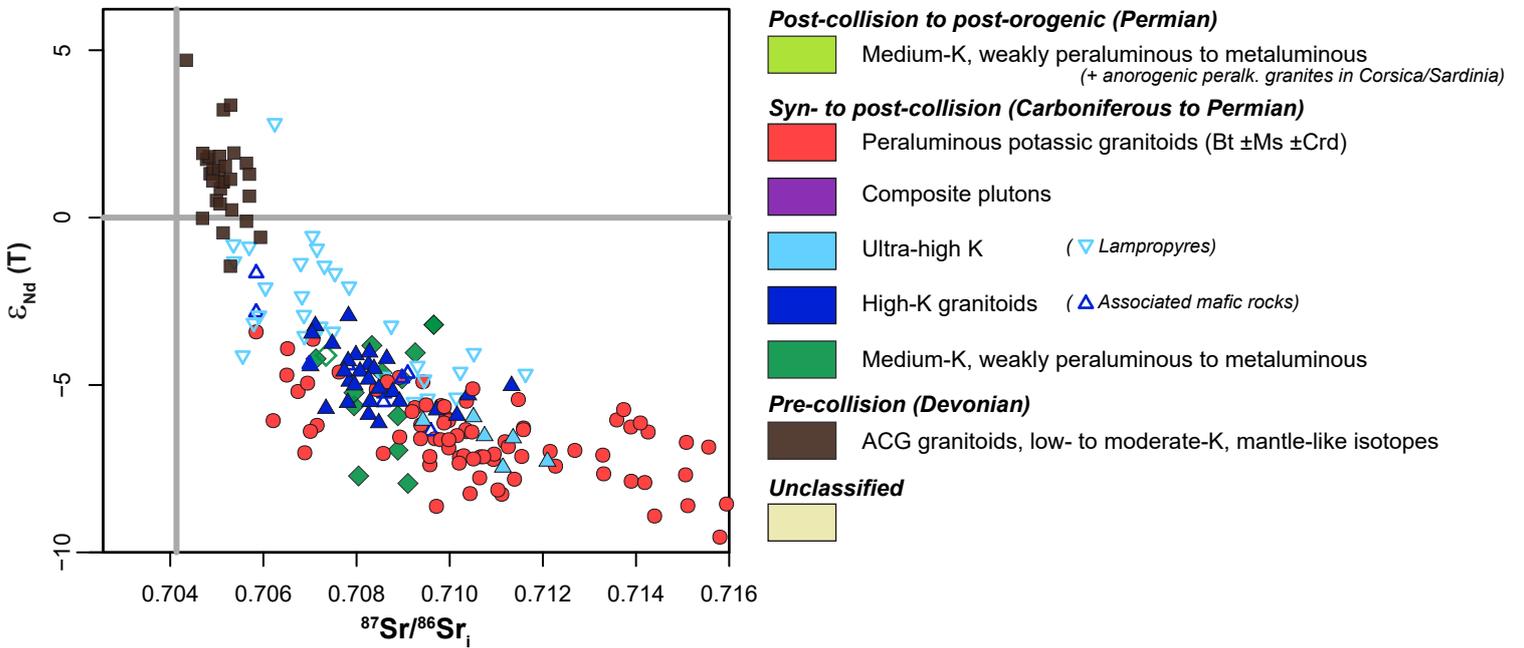
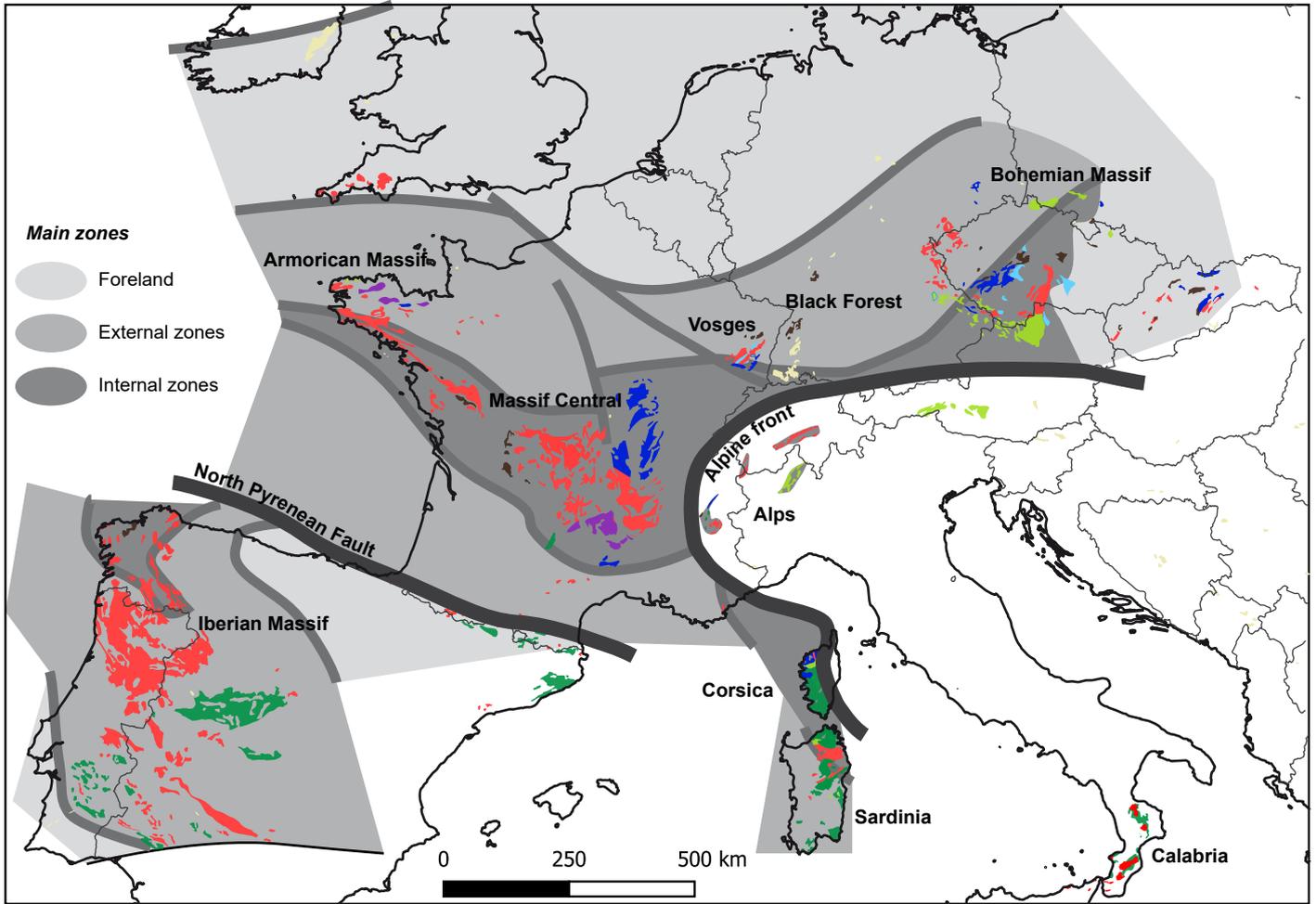
▲ △ High-K

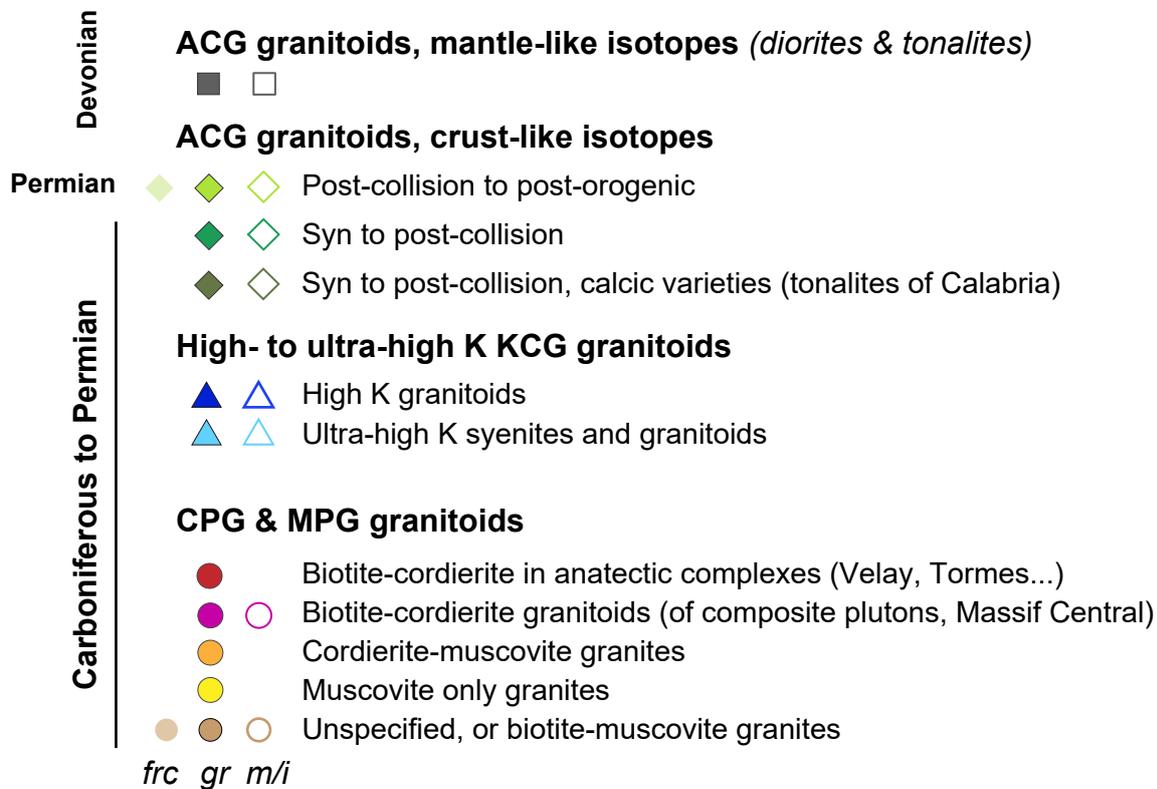
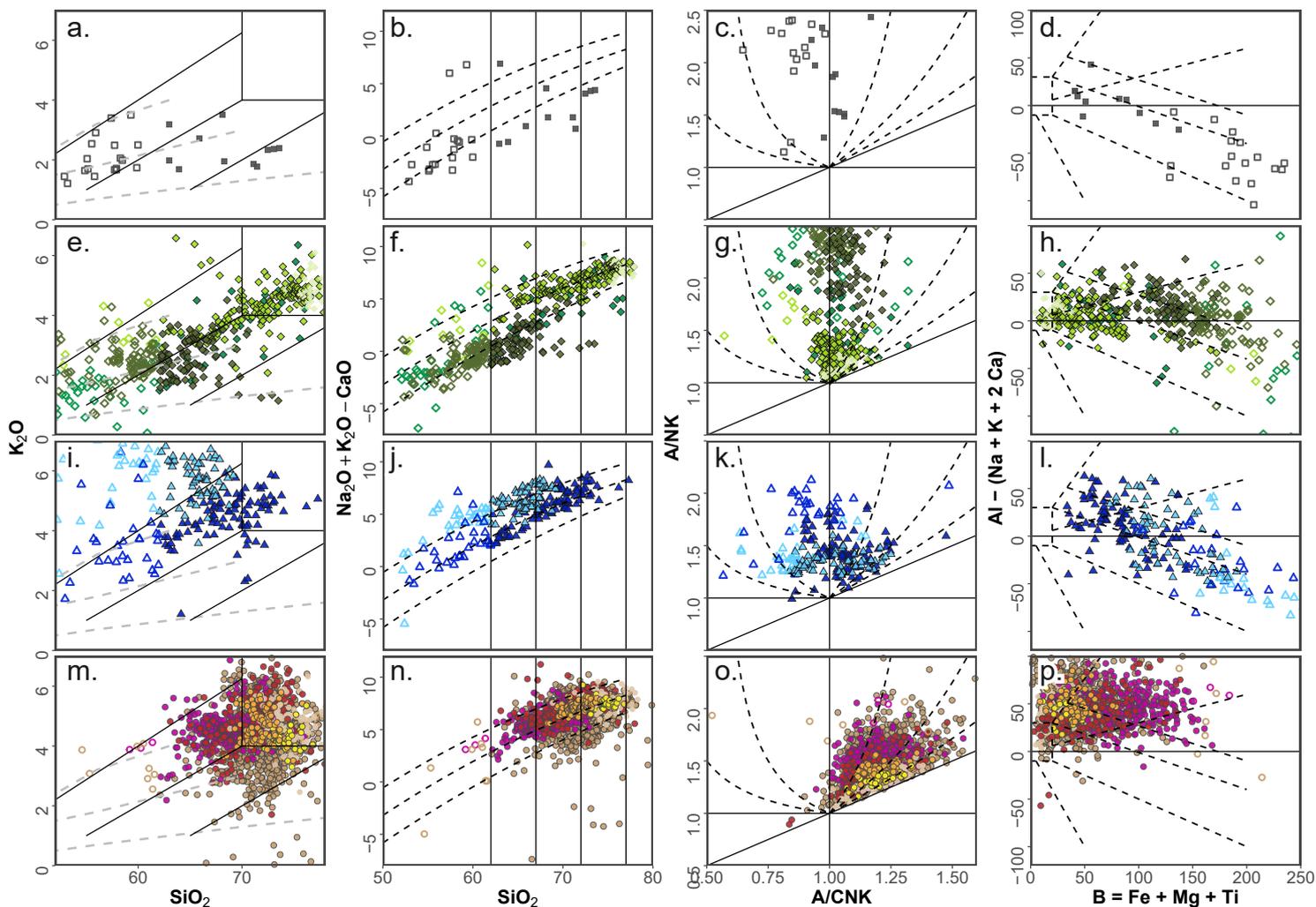
▲ △ Ultra-high K (shoshonitic)

gr m/i

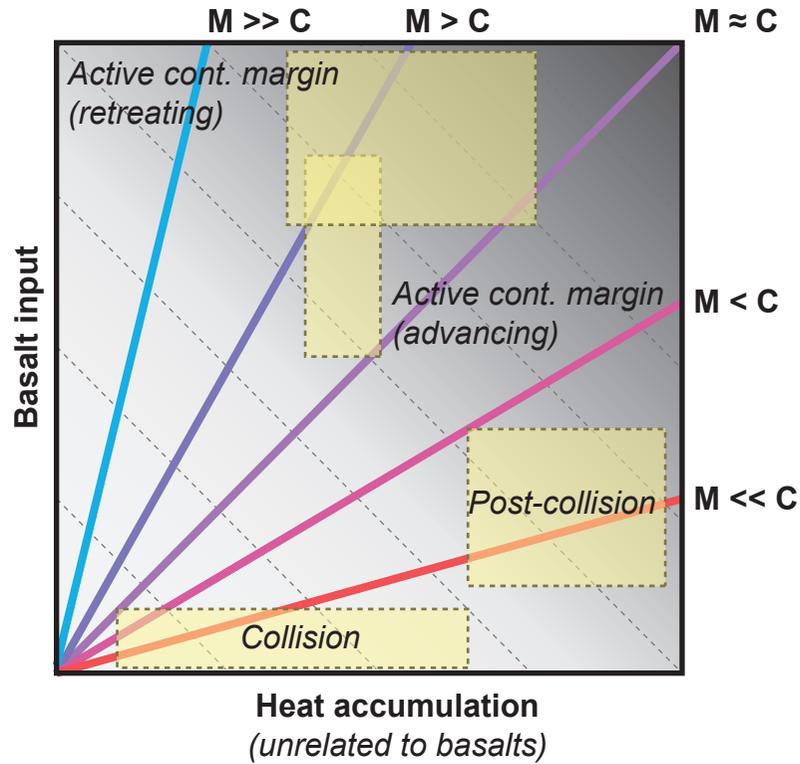








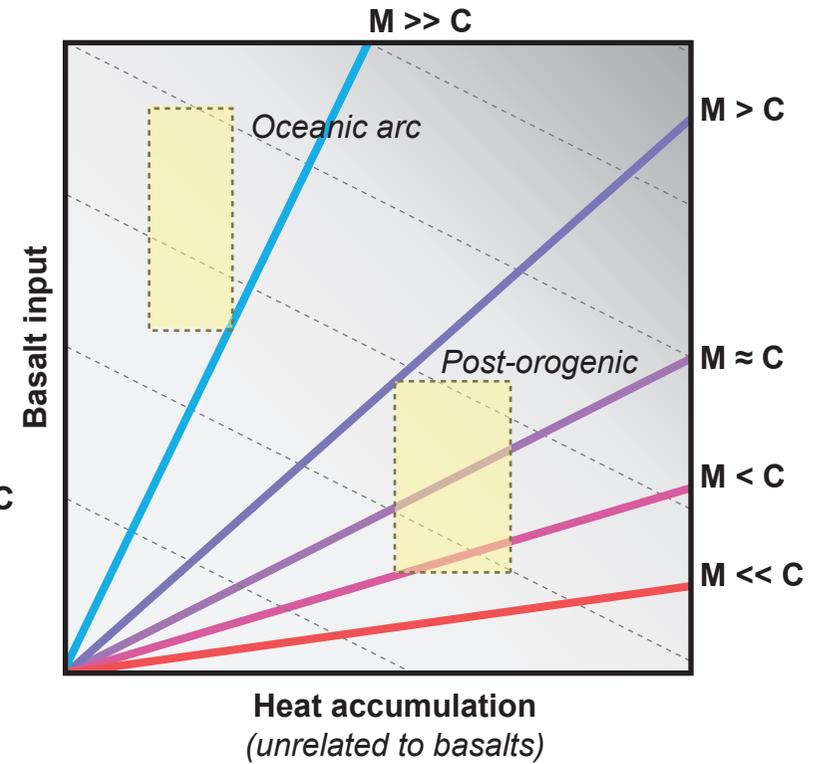
a. Fertile crust



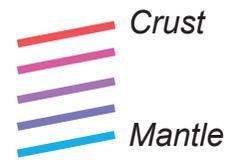
Amount of granites generated



b. Non-fertile crust



Origin of granites



Barbarin (1999)	Chappell & White	This work	Symbols in diagrams (Fig. 5, 7, 9)	Chemical characteristics					
				Radiogenic isotopes	Compositional range	Alumina balance	Alkalinity	K ₂ O	Fe/Mg
ACG and ATG	(I types, M types)	ACG "mantle like"		mantle-like	gabbro to tonalite, occasionally granite	ordinary metaluminous	calcic to calc-alkalic	medium-K	mostly magnesian, occasionally ferroan
ACG	(I types)	ACG "ordinary"	 	crust-like	gabbro to granite	ordinary metaluminous, sometimes high Al neg. B-A corr.	variable, mostly calc-alkalic	medium to high-K	mostly magnesian
ACG	(I types)	ACG "leucocratic peraluminous"		crust-like	granite and leucogranite	felsic peraluminous	calc-alkalic, alkali-calcic	medium-K	mostly magnesian
KCG	(I types)	KCG and ultrapotassic (UK)	  	crust-like	diorite or syenite to granite	ordinary metaluminous, sometimes high Al neg. B-A corr.	alkali-calcic to alkalic	high- to ultra-high K	vary from ferroan (A2) to magnesian (UK)
CPG, MPG	(S types)	CPG & MPG	     	crust-like	granodiorite, granite, leucogranite	felsic peraluminous, strongly peraluminous	alkali-calcic to calc-alkalic	medium- to high-K	magnesian

				Subduction			Collision				Origin				New crustal addition ?	
				Advancing (Andean type)	Oceanic arcs	Retreating ([inverted] back-arc basin)	Pre-collisional stage (subduction)	Collision stage	Post-collision collapse	Post-orogenic extension	Crustal paradigm		Mantle paradigm		Instantaneous	On ca. 50 Myr timescale
				<i>Western America (Andes, Western USA)</i>	<i>Western Pacific (Japan)</i>	<i>Lachlan Fold Belt</i>	<i>Early Variscan, Kohistan</i>	<i>Himalaya, Variscan</i>	<i>Variscan</i>	<i>Caledonian</i>	process	balance	process	balance		
Barbarin (1999)	Chappell & White	This work	Symbols in diagrams (Fig. 5, 7, 9)													
ACG and ATG	(I types, M types)	ACG "mantle like"	■	(outboard granites, W of 706 line) [40 %]	(dominant, M- to I-types)	(some I-types) [< 1 %]	(early quartz diorites and tonalites)				Melting of young metamafics	C to C > M	Fractionation of arc basalts	M	model-dependent	yes
ACG	(I types)	ACG "ordinary"	◆◆	(inboard granites, E of 706 line) [48 %]		(I-types) [47 %]				(Variscan external zones) [14 %]	Melting of older igneous lithologies	C to C > M	Fractionation of arc basalts + assimilation (AFC)	M > C	model-dependent	
ACG	(I types)	ACG "leucocratic peraluminous"	◆	(peraluminous granites, inboard) [12 %]							Melting of crustal lithologies	C	Fractionation of arc basalts + intense assimilation (AFC) (or crustal model)	C to C = M	no	possible (if reworking young crust)
KCG	(I types)	KCG and UK	▲▲▲	rare						(Variscan internal zones) [13 %]	Melting of potassic igneous rocks	C	Fractionation of potassic igneous rocks, metasomatized	M >> C	model-dependent	
CPG, MPG	(S types)	CPG & MPG	●●●●●●	rare		(S-types) [53 %]	(MCT leucogranites, early Variscan leucogranites)			(Variscan Crd/Bt/Ms granites) [67 %]	Melting of metasediments	C	Melting of sediments	C	no	possible (if reworking young metasediments)

Granite production and mantle crust balance: controlling parameters

a. Fertile crust

b. Non-fertile crust

