MDPI

Review

A Tentative Model for the Origin of A-Type Granitoids

Åke Johansson

Department of Geosciences, Swedish Museum of Natural History, P.O. Box 50 007, SE-104 05 Stockholm, Sweden; ake.johansson@nrm.se

Abstract: A-type granites are typically formed in stable intra-plate, back-arc or postcollisional settings and are characterized by highly ferroan and potassic major element compositions, and by strong enrichment in incompatible trace elements. Unlike I-, S- and M-type granites, where the letters denote the dominant source material (igneous, sedimentary or mantle derived), there is no consensus on the source and processes giving rise to A-type magmas. In this contribution, a conceptual model for the origin of A-type granitoids, using the Bornholm A-type granitoid complex in southern Fennoscandia as an example, is presented. In this model, underplated mantle-derived basaltic magma may develop into intermediate and siliceous A-type magma, which is ferroan, potassic and highly enriched in incompatible trace elements, through a combination of fractional crystallization leading to cumulate formation, and partial melting and crustal assimilation, in a process akin to zone refining in metallurgy. The key factor is a relatively stable tectonic environment (postcollisional, anorogenic, or extensional), where there is little or no replenishment of more primitive basaltic magma to the system, allowing it to attain more evolved, enriched and extreme compositions. The A-type granitoids may then be viewed as a more evolved counterpart of subduction-related I-type granitoids.

1. Introduction

Ever since the introduction of the term A-type granites in an abstract by Loiselle and Wones [1]—never developed into a full paper—as an addition to the I- (igneous-derived) and S- (sedimentary-derived) granite types, the concept has been controversial (cf. [2], and the references therein). Do A-type granites really exist? If so, what does the "A" stand for? Anorogenic? Alkaline? Anhydrous? Aluminous? Ambiguous? (cf. [2]). Or should the term be dismissed in favor of ferroan granites [3]?

What is their tectonic setting? Originally perceived as anorogenic, having formed in stable continental within-plate settings far away from any active plate boundary as a result of mantle upwelling, plume activity and/or incipient rifting of a stationary supercontinent [4–8], this idea has become increasingly questioned. Maybe they rather formed in the aftermath of orogenic activity, in postcollisional or postorogenic settings [9]? Or maybe they had a distal relation to penecontemporaneous orogenic activity, as proposed by Åhäll et al. [10] for the central Fennoscandian rapakivi granites in relation to the Gothian orogeny in southwestern Fennoscandia, or for the extensive Mesoproterozoic granite-rhyolite terrain of the central United States (cf. [4]) in relation to orogenic activity along the southeastern margin of Laurentia [11–13]?

Why do A-type granites and associated AMCG (anorthosite-mangerite-charnockite-granite) complexes appear to have formed predominantly during the Mesoproterozoic (e.g., [14])? If related to mantle heating and upwelling beneath the Mesoproterozoic supercontinent Columbia (Nuna), was that supercontinent more long-lived and/or more stationary than subsequent supercontinents?

What about the origin of these highly evolved and enriched magmas? Since A-type granites are sometimes spatially associated with gabbroic and anorthositic rocks, or such rocks are inferred to exist at depth beneath them, does this mean that they formed from the same mantle-derived magmas by a high degree of fractionation, or by partial melting of underplated mafic rocks (e.g., [2,3,15–19]), perhaps with an additional component of crustal contamination (e.g., [20])? Or did they form by partial melting of lower crustal rocks (e.g., [21,22]), more specifically of a dehydrated granulitic or charnockitic residual source [23–27]. Or from a tonalitic-granodioritic source [3,5,13,28–31] under low pressure (≤4 kbar, [29]), with the basaltic mantle-derived magma only providing the heat source for the crustal melting? Possibly there was a mixture of mantle- and crustal-derived magmas involved in their petrogenesis (e.g., [9,32]). Could they be derived by melting of mantle or lower crustal rocks metasomatized by alkali-rich H_2O- or CO_2-rich fluids in a rift setting (e.g., [33,34])? Maybe different subtypes originate from different sources, so that there are both mantle-derived and crustal-derived A-type (or ferroan) granitoids occurring in separate environments [3,35,36].

Here, the A-type Bornholm granitoid complex in southern Fennoscandia is used as an example and inspiration for a tentative conceptual model for the origin of A-type granitoids in general, as well as a discussion about the relation between A-type and other types of granitoids. Naturally, it has to be borne in mind that there are different varieties and subtypes of A-type granitoids, and one model may not fit them all. On the other hand, considering that they have many traits in common, a common underlying general process for their petrogenesis would seem likely, with variations caused by different P-T conditions, source materials, fractionating mineral assemblages or tectonic settings.

The Bornholm complex is located on the Danish island of Bornholm in the southern Baltic Sea, and consists of pervasively deformed orthogneisses and less deformed or totally undeformed granitoids of intermediate and felsic composition (for location and detailed geology, see maps, descriptions and references in [37–39]). U-Pb zircon dating has yielded ages of 1.45–1.46 Ga for all of its rock types [37,38]. Subsequent geochemical investigations indicate that these rocks consist of a single intrusive suite, irrespective of degree of deformation, having quartz monzonitic to granitic compositions, ranging from 64 to 78 wt% SiO_2, with a possible gap at around 70 wt% SiO_2 [39]. All the rocks have traits considered typical for A-type granites (e.g., [3,36]): they are metaluminous to weakly peraluminous, alkali-calcic, potassic (shoshonitic), ferroan, and are highly enriched in many incompatible trace elements (REE, Rb, Ba, U, Zr, Hf, Y) with strong negative Eu anomalies [39]. They dominantly plot in the A-type fields of Whalen et al. [25] and the within-plate granite fields of Pearce et al. [40], and fall in the A_2 subgroup of Eby [35] and the oxidized magnetite-bearing subgroup of Dall'Agnol and Oliveira [41]. They have initial ε_{Nd} (WR) values of −2 to +1.5 at 1455 Ma (with one outlier at +3.8), and initial ε_{Hf} (zr) from −4 to +3, suggestive of a mixed mantle-crustal origin for the magmas [39].

2. A Tentative Petrogenetic Model for A-Type Granitoids

A tentative petrogenetic model for the origin of A-type granitoids, with the Bornholm complex as an example, is outlined in Figure 1. According to this model, the continental crust is underplated by a large amount of mantle-derived basaltic magma that ponds in a large magma chamber in the lower crust or at the crust–mantle boundary. Prior fertilization of the mantle by fluids enriched in alkalis and other incompatible elements, either in a subduction setting or in a rift setting (e.g., [33,34]), could be an important factor, but may not explain the highly ferroan nature of A-type granites. The generally accepted high melting temperatures and dry nature of A-type magmas would also preclude a very water-rich source, suggesting CO_2 as the main fluid (cf. [33]).
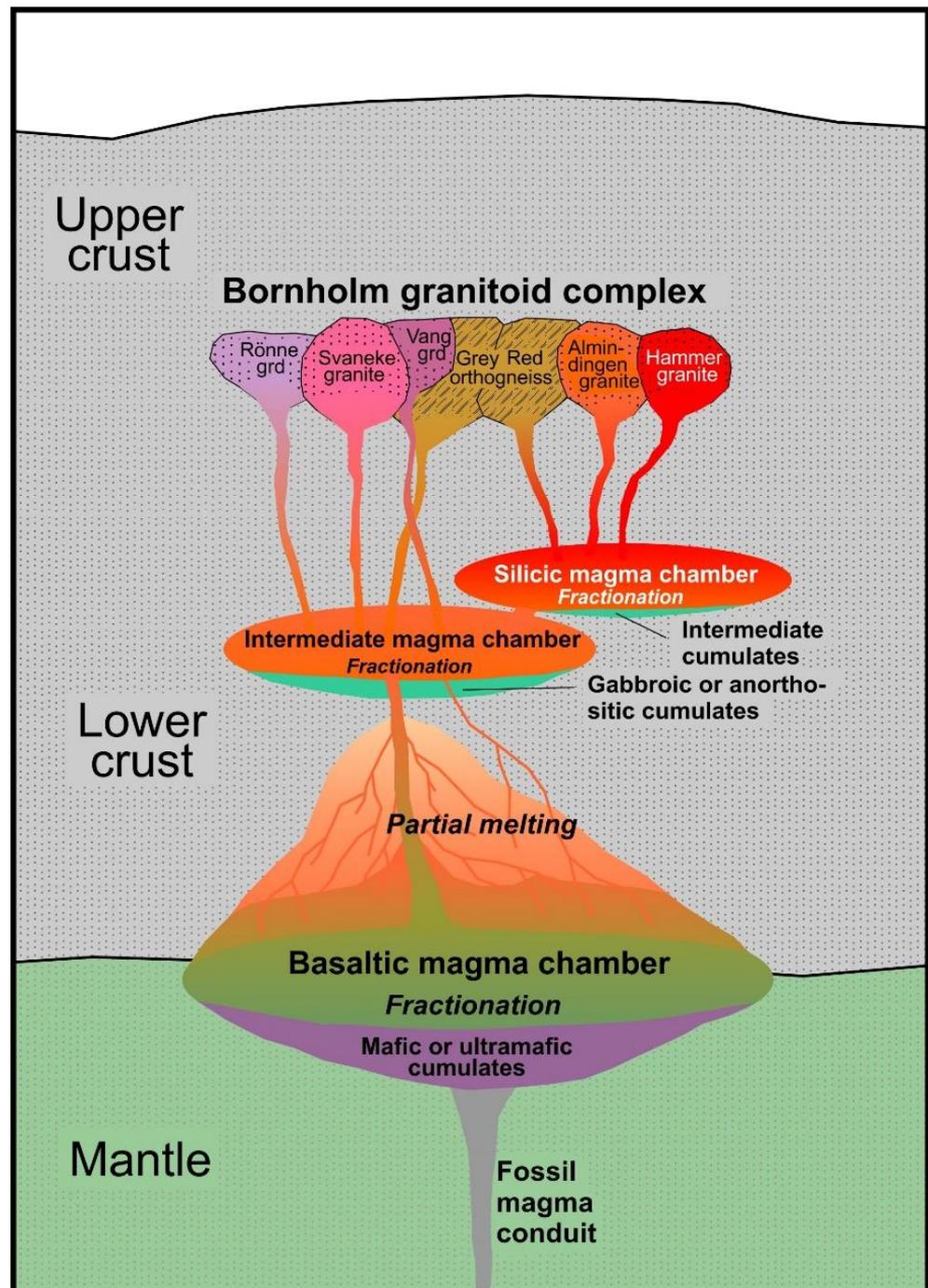
Figure 1. Highly schematic profile, not to scale, through the crust, illustrating the preferred conceptual model for A-type granitoid genesis, with the Bornholm granitoid complex as an example. See text for further discussion.

The basaltic magma remains stationary for a relatively long time, and as it slowly cools, there is abundant time for the crystallization of mafic minerals and formation of mafic or ultramafic cumulates at the bottom of the magma chamber, as well as plagioclase cumulates at its top. At the same time, heat from the magma, augmented by the latent heat released by the crystallizing mafic phases, leads to extensive partial melting in the overlying crust. The data for crystallization and fusion enthalpy in Bohrson and Spera [42] show that there should be more energy released by the crystallization of one kilogram of mafic rock than is needed for the melting of one kilogram of felsic rock, resulting in a surplus of heat

and hot magma that may percolate upwards. In that way, the basaltic magma is able to slowly melt itself upwards through the crust, while gradually shifting its composition from basaltic to intermediate and ultimately to siliceous, while still preserving a relatively big magma volume compared to that remaining if fractionation was the only process behind the formation of the granitic magma. Thus, rather than having a bimodal situation with two immiscible magmas, one mantle-derived basaltic and one crustal-derived granitic, there may be cases with one magma gradually shifting its composition from basaltic to granitic.

A key factor behind this shift would be that there is little or no replenishment with new batches of juvenile basaltic magma from below. Unlike in a supra-subduction environment, where there may be a more or less continuous supply of primitive magma from below, a relatively stable tectonic environment is envisaged, where a single huge batch of mantle-derived magma is underplated and left to fractionate and melt the overlying crust for a prolonged period of time with little or no further additions of more primitive magma. The prime example of such an environment would be above a mantle plume within the interior of a stable (super)continental plate, but an incipient rift zone, a continental back-arc region, or mantle delamination and asthenospheric upwelling in a postcollisional setting may also fulfil these requirements.

An argument against such a scenario would be that according to Petford and Gallagher [43], multiple injections of thinner sheets of basaltic magma are more efficient in heating and melting the overlying mafic lower crust than one single large magma body. On the other hand, if the underplated basaltic magma body is very large and occurred in an area of unusually high heat flow related to asthenospheric upwelling, the heat from the magma nevertheless may be able to sustain partial melting in the overlying crust for a substantial time, especially if the latent heat released by the crystallization of mafic cumulate phases is also factored in.

Through such combined assimilation and fractional crystallization (AFC) processes, a magma may undergo rather drastic compositional changes, both in its major element composition and its trace element concentrations, while still retaining an isotopic memory of its mantle origins. If the magma originated from asthenospheric upwelling, its original chemical and isotopic composition may, in fact, have been similar to the asthenospheric rather than the lithospheric mantle, but the compositional changes caused by AFC processes both in the upper mantle and the lower crust would have obliterated most signs of its asthenospheric prehistory, making it appear like a mixture of lithospheric mantle and crustal components.

Magma evolution trends for some different types of elements are outlined in Figure 2, with the solid part of the trends (from intermediate to silicic magma) being based on the compositions of the actual Bornholm rocks (circles and squares), and the dashed parts (from basaltic to intermediate) being more speculative. Elements that are compatible in mafic minerals, and occur in relatively limited amounts in crustal partial melts, such as magnesium, iron and titanium, will quickly become depleted in the magma, as outlined in Figure 2A. The same behavior applies to trace elements such as Sc and V, and may also apply to calcium, which is incorporated into clinopyroxene and anorthitic plagioclase. At the same time, as MgO is preferentially incorporated into the ferromagnesian minerals (olivines, pyroxenes or spinel at the early stages of fractionation, amphibole in the later stages) compared to FeO, a prolonged period of fractionation with little or no magma replenishment from below will lead to high FeO/MgO ratios in the residual magma, and the highly ferran compositions typical for A-type granites.
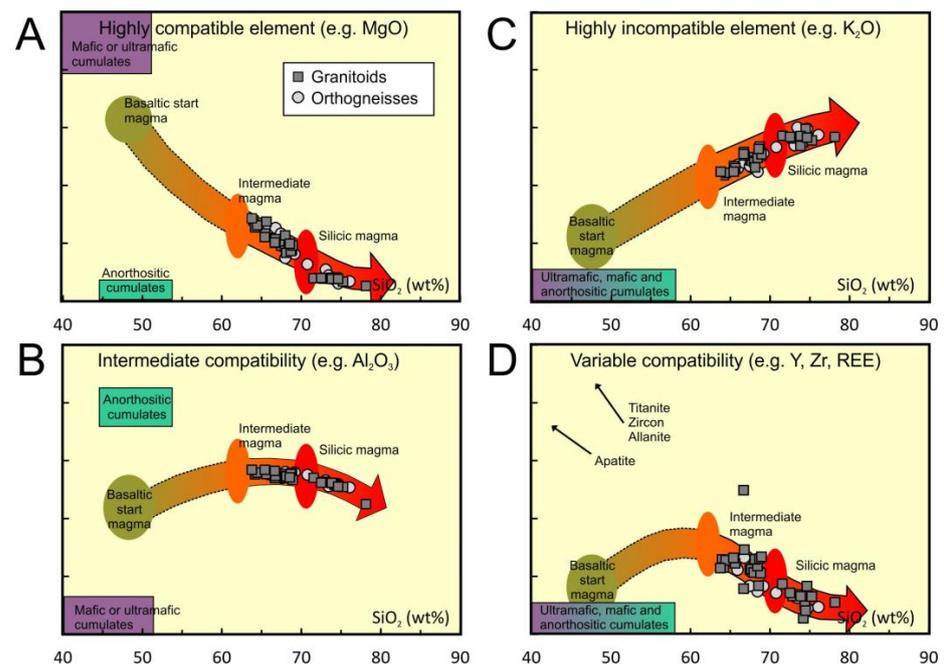
Figure 2. Schematic fractionation trends for an assumed basaltic start magma, through an intermediate magma, to a silicic magma, for different types of elements. The data points show the actual compositions of the Bornholm A-type granitoids and orthogneisses [39], with the intermediate to silicic part of each trend inferred from them, while the preceding basaltic to intermediate part of each trend (dashed) is more speculative. (**A**) Highly compatible element that is concentrated in mafic and ultramafic cumulate phases, with MgO used as example. (**B**) Element of intermediate and somewhat variable compatibility, with Al_2O_3 that is concentrated in feldspars, e.g., in anorthositic cumulates, as an example. (**C**) Highly incompatible element, with K_2O that is concentrated in the liquid and in late-stage biotite and K-feldspar, as an example. (**D**) Elements of variable compatibility (first incompatible, then compatible in the solid phases), with Zr as an example.

Elements of somewhat intermediate compatibility that are common in crustal rocks and melts, such as aluminum, may show an initial increase caused by partial melting of the overlying crust, in combination with olivine and pyroxene crystallization, which will, however gradually, give way to a decrease in the residual magma, as Al_2O_3 is used up by the crystallization of plagioclase in gabbroic or anorthositic cumulates, and later on by plagioclase and alkali feldspar crystallizing in intermediate rocks (Figure 2B). Highly incompatible elements, such as potassium, that are also common in crustal rocks and melts, will show a strong and steady increase in the magma, and become incorporated into biotite and K-feldspar in the granitic rocks (Figure 2C). Again, the prolonged fractionation and crustal assimilation process will account for the highly potassic trends seen in A-type granitoids, whereas sodium, to some extent, becomes incorporated into plagioclase at an earlier stage and instead shows a weakly decreasing trend.

Trace elements that are normally considered incompatible both in mafic rocks and minerals and in plagioclase cumulates, such as Y, Zr, Hf, Nb and REE, would show more complex behaviors, as outlined in Figure 2D. While some of them, such as Nb, show an almost flat trend in the Bornholm rocks, most of them show a more or less marked decrease. This was, however, probably preceded by a strong increase, as outlined in Figure 2D, as the initial basaltic magma became enriched in these elements through fractional crystallization of mafic minerals, and partial melting of crustal rocks rich in incompatible elements (cf. [19]). The very strong enrichment in incompatible trace elements, typical for the Bornholm granitoids and other A-type rocks and magmas, would be akin to the process of zone refining in metallurgy [44], as the magma picks up and concentrates more and more of these elements as it melts its way up through the crust. With time, however, the magma

becomes saturated and starts to crystallize trace-element-rich minerals such as allanite, apatite and zircon, leading instead to a decline of the trace elements contained in these minerals in the residual magma (Figure 2D).

As crustal rocks normally contain much more of such incompatible trace elements than mantle rocks, the trace element budget and hence the isotopic composition of elements such as Nd and Hf will be much more controlled by the crustal sources than the original mantle source, even for a magma consisting of a significant mantle component. Thus, the mantle contribution could easily be underestimated, or even overlooked. Nevertheless, it should be possible to discern a mantle component in the isotope systematics, if the isotopic differences between local crust and mantle at the time of intrusion were large enough, so that melts of mixed origin can be distinguished from pure crustal or mantle melts.

With the magma gradually becoming more silicic in composition, and presumably also more volatile rich, it will become less dense and more buoyant and eventually start to force its way up through the crust mechanically, and not only by melting. One may envisage several intermediate magma chambers at different crustal levels, as in Figure 1 here, and as in Figures 6 and 8 in Bonin [2], with continued fractional crystallization, cumulation, and assimilation of crustal material, albeit on a smaller scale as the magma cools down. In order to explain the "bimodal" SiO_2 distribution in the Bornholm granitoids, with an apparent gap in SiO_2 content around 70 wt%, two additional magma chambers en route to the final emplacement level, one containing intermediate magma, and one containing silicic magma, have been drawn (Figure 1). In the case of Bornholm, the quartz monzonitic rocks should be derived directly from the intermediate magma chamber, and the granitic ones (with SiO_2 > 70 wt%) from the silicic one. However, as the magmas share the same origin, they belong to the same igneous suite, as shown by the continuity of geochemical trends from the intermediate to the felsic granitoids in the various diagrams (Figure 2, and figures in [39]), and their identical isotope characteristics ([39]; Figure 3A,B). Final emplacement and solidification of the different granitoids then occurred at a relatively shallow crustal level, as shown in Figure 1. A subvolcanic to volcanic caldera complex on top of the crust, as depicted by Bonin [2] in his Figure 8 could also be envisaged here, although it has not been drawn in Figure 1. If such a complex existed at the surface above the Bornholm granitoids, it has long been eroded away.

When it comes to the time scales involved, Hawkesworth et al. [45] summarized evidence that magma differentiation in large, deep-seated basaltic magma chambers may go on for tens or hundreds of thousands of years, whereas differentiation from intermediate to silicic compositions in small, shallow magma chambers may be very rapid, perhaps only tens to hundreds of years. They did not discuss any relation to tectonic setting, but it would seem feasible that differentiation and assimilation processes may proceed uninterrupted for longer periods of time in more stable intraplate or postcollisional settings than in subduction- or collision-related settings, leading to the attainment of more evolved compositions. Detailed U-Pb zircon geochronology, with the separation of zircon in early megacryst phases and groundmass zircon (cf. [46]), may shed more light on the timescales involved.

For the Bornholm granitoids, there is no systematic change in initial ε_{Nd} or ε_{Hf} with increasing SiO_2, but the isotopic values remain relatively stable at -2 to $+1$ (with a couple of outliers) for ε_{Nd} and -1 to $+2$ for average ε_{Hf} in each sample (Figure 3A,B). This suggests that crustal melting and mixing of mantle and crustal material took place during the early stages of magma evolution in the lower crust, but not during late-stage differentiation in the shallower magma chambers. Furthermore, the Bornholm magmas had already attained their A-type ferroan and potassic characteristics during early magma development, and during the subsequent differentiation from intermediate to felsic compositions, their evolution paralleled the division lines between ferroan and magnesian rocks, and between shoshonitic and high-K calc-alkaline, although their $FeO_T/(FeO_T + MgO)$ ratios and K_2O contents continued to increase (Figure 3C,D). In fact, with continued differentiation, they became less "A-typical" in the Whalen et al. [25] diagrams (Figure 3E,F), reflecting the

decreasing trends in the trace elements used in these diagrams. Continued fractionation of plagioclase is, however, seen in the increase in the negative Eu anomaly with increasing SiO_2 (Figure 3G). Roughly linear relations between Ba and the magnitude of Eu anomaly (Figure 3H) as well as Sr and Rb versus $(Eu/Eu^*)_N$ (not shown) also point to the dominance of feldspar fractionation (cf. [15]).
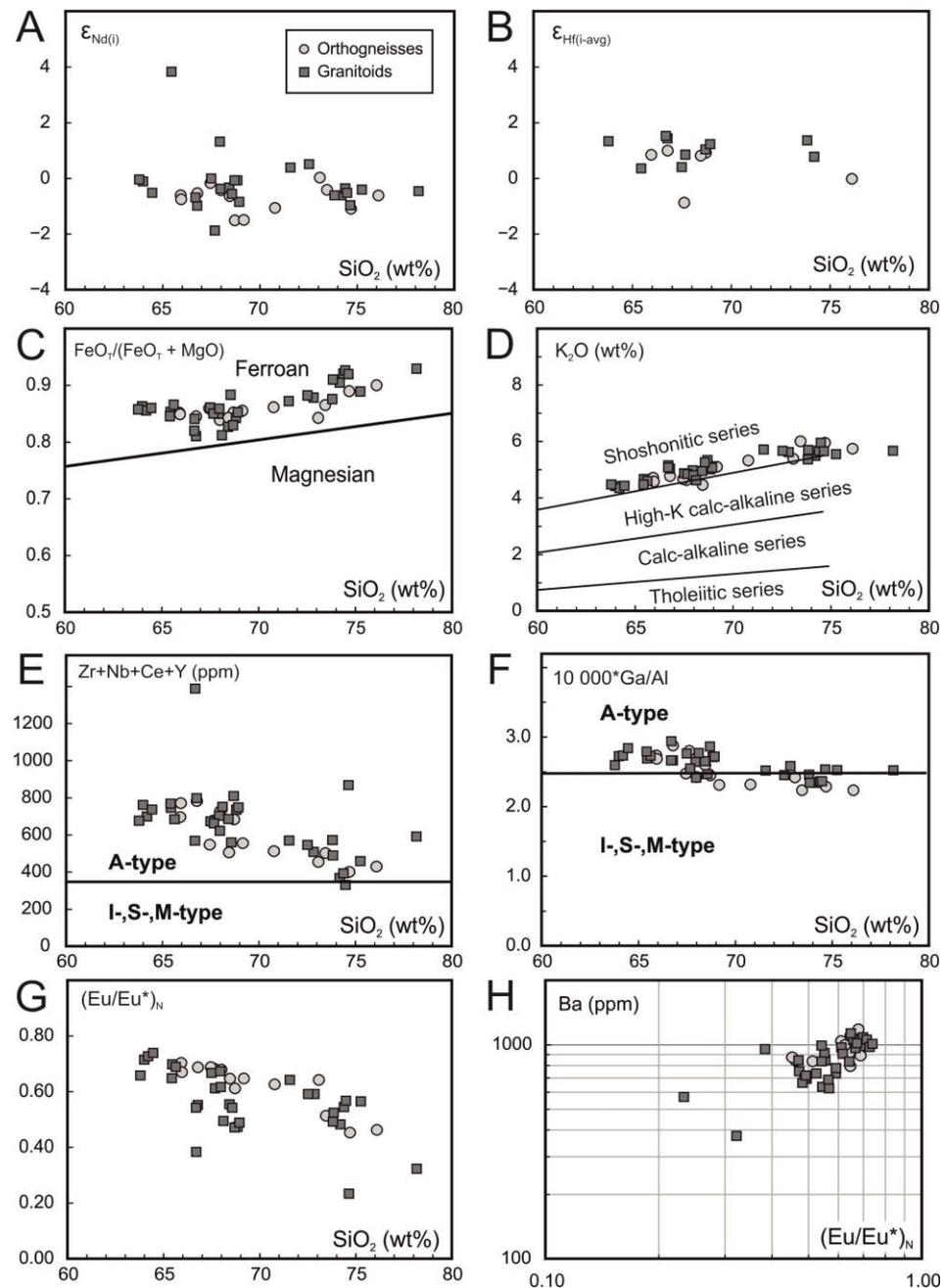

Figure 3. Fractionation trends for the Bornholm A-type granitoids and gneisses, with data from Johansson et al. [39]. (**A**) Initial ε_{Nd} versus SiO_2. (**B**) Average initial ε_{Hf} for analyzed zircons in each sample versus SiO_2 (not all samples analyzed for ε_{Hf}). (**C**) $FeO_{tot}/(FeO_{tot} + MgO)$ versus SiO_2. Division line between magnesian and ferroan granites from Frost et al. [47]. (**D**) K_2O versus SiO_2, with division lines from Rickwood [48]. (**E**) Zr + Nb + Ce + Y (ppm) versus SiO_2, with division line of A-type granites from Whalen et al. [25]. (**F**) 10,000 * Ga/Al versus SiO_2, with division line of A-type granites from Whalen et al. [25]. (**G**) $(Eu/Eu^*)_N$ versus SiO_2. (**H**) Ba vs. $(Eu/Eu^*)_N$ diagram from Eby et al. [15].

3. Alphabet Systematics

The A-type concept differs from the earlier established I-type (igneous-derived) and S-type (sediment-derived) concepts [49], as well as the rare M-type (mantle-derived, or derived from subducted oceanic crust; [50]), in that the A does not refer to a separately distinguishable source, making the A-type the odd one out, and the A-type concept more questionable. A way of integrating the A-type granitoids with the other three "alphabet types", and showing their mutual interrelationships, is depicted in Figure 4.
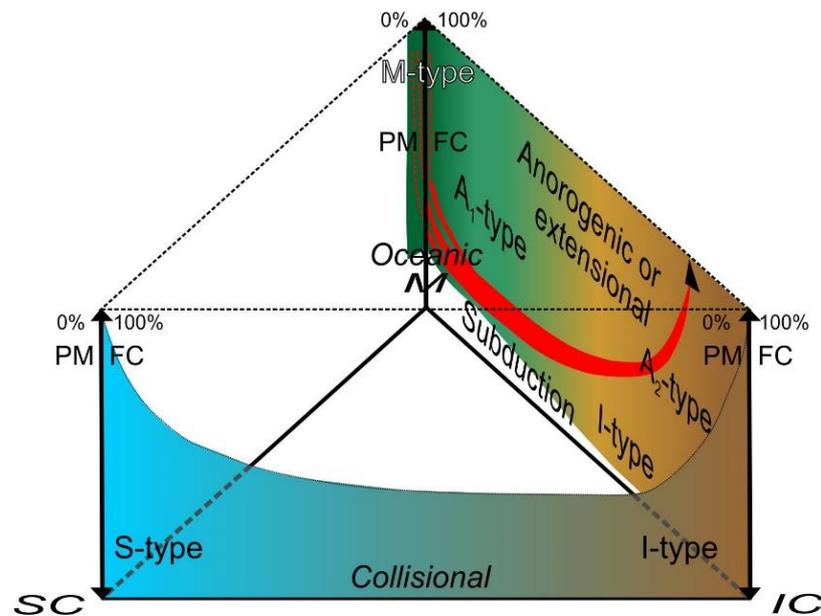

Figure 4. Three-dimensional diagram with the triangular base showing the source of the magma (M = mantle; SC = sedimentary continental crust; IC = igneous continental crust), and the vertical dimension showing the degree of partial melting (PM, from 0 to 100% melt when going downwards), or fractional crystallization (FC, from 0 to 100% solids when going upwards). Along the vertical sides of the diagram, approximate areas of generation of S-, I-, A- and M-type granitoids are shown, and associated tectonic environment (collisional, subduction, anorogenic or extensional, and oceanic) in italics. The red arrow along the M–IC side depicts the approximate inferred magma evolution trend for mantle-generated basaltic magmas ultimately achieving an A-type granitoid composition, with the width of the arrow illustrating magma volume. The front of the diagram (SC–IC side) has been partly left blank for visibility reasons, although low-degree melts could exist all along this join. For clarity, no melts containing mixtures between mantle material and sedimentary crust, or tri-component M–IC–SC mixtures, have been drawn in the diagram, although magmas of such nature may certainly also be envisaged, especially in a subduction environment.

The bottom of the figure is a standard triangular diagram, with each apex representing a potential source: sedimentary continental crust (SC), igneous continental crust (IC), and mantle (M), and with each of the three corresponding granite types occurring within the triangle close to their respective corners. Certain sides or corners of the triangle, and certain granite types, are also associated with certain tectonic environments, as outlined in italics. The rare M-type granites form by extreme differentiation of mantle-derived basaltic melts in oceanic environments, such as hotspot-related oceanic islands, or by melting of subducted oceanic crust and overlying mantle in primitive island arcs, with little or no chance for continental involvement. Along the tie line between mantle and igneous crust sources, I-type granitoids form above subduction zones from a mixture of mantle-derived and crustal-derived melts, the latter predominantly originating from rocks of igneous origin. One may envisage a progression from primitive oceanic island arcs to more evolved island arcs or continental magmatic arcs going towards the IC corner. Along the SC–IC tie line,

crustal anatectic granites form from a mixture of sedimentary and igneous sources, typically during crustal thickening due to continental collision, with the pure I- and S-types being end-members of this suite, the latter one at the low-temperature end. For simplicity of drawing, no melts consisting of mixtures between mantle material and sedimentary crust, or tri-component M–IC–SC mixtures, have been drawn in the diagram, although magmas of such a nature may certainly also be envisaged, especially in a subduction environment.

The vertical dimension of this diagram consists of an axis depicting percent of fractional crystallization proceeding upwards (from 0 to 100% solid fraction) or partial melting proceeding downwards (from 0 to 100% melt). The different granite types are thus depicted on two of the three vertical surfaces of this three-dimensional triangle, the SC–IC surface and the M–IC surface. M-type granites are the result of a high degree of fractional crystallization of mantle-derived partial melts, whereas S- and I-type granites result from small to moderate degrees of fractional crystallization of partial melts of crustal origin (or, in the case of I-type, sometimes of mixed mantle-crustal origin). In this diagram, the A-type granites would occur along the M–IC surface above the I-type granites, representing a higher degree of fractionation (or lower degree of partial melting) of magmas of mixed mantle and crustal origin, in a tectonic environment that is typically relatively stable (anorogenic intra-plate or postcollisional) or extensional (rift or back-arc). When it comes to the A_1–A_2 subdivision of Eby [35], the A_1 granites, characterized by relatively high Nb/Y ratios and supposed to be dominantly mantle-derived, should plot towards the M-corner, and the Nb-depleted A_2 granites towards the IC corner, since these are interpreted to contain a large fraction of crustally derived material originally generated by subduction [35].

However, the critical factor determining the highly evolved and enriched character of A-type granites would not be the source proportions (mantle or crust), or the specific tectonic setting, but the degree to which the AFC process may proceed uninterrupted for a protracted period of time in a large magma chamber (or a series of interconnected magma chambers at different crustal levels, cf. [2]) with little or no replenishment of primitive basaltic magma from below. This will typically not happen in a supra-subduction environment, where a semi-continuous supply of mantle-derived melt will prevent the development of more highly fractionated and extreme compositions, but could occur in more stable tectonic settings where A-type granites are typically found. Yellowstone may serve as a modern analogue, with its infrequent but large eruptions, thereby giving some hints on the timescales involved. The arrival of a mantle plume head to the base of the crust, with associated mantle melting, basaltic underplating, and/or outpouring of basalt in a large igneous province (LIP), is considered to be an event of relatively short duration, perhaps only 1–5 million years [51,52]. If the basaltic magma ponds at the base of the crust, instead of directly erupting through it, this would be a favorable location for the formation of A-type granites. Nevertheless, it should come as no surprise that there exists a conti-nuum from less evolved I-type to more evolved A-type granites, with many magmatic complexes showing mixed characteristics, and with the A-type characteristics presumably developing through time as the supply of more primitive magma dwindles. Furthermore, towards the M-corner, predominantly mantle-derived A-type granites may grade into M-granites.

The arrow along the M–IC side of Figure 4 depicts the approximate inferred evolution path for a mantle-generated magma ultimately producing an A-type granite. The magma originates by partial melting of mantle rocks, perhaps in several separate mantle domains, with the ensuing basaltic magma gradually merging into a single, large magma chamber at the crust–mantle boundary. The degree of partial melting may gradually increase as melting proceeds into shallower mantle levels where pressure decreases. Nevertheless, the increase in total magma volume (symbolized by the thickening of the arrow in Figure 4) mainly reflects the increasing volume of mantle rocks undergoing partial melting, rather than the increasing degree of partial melting within the same rock volume. As the magma reaches and pools at the crust–mantle boundary, and then starts melting the overlying crust, it starts changing its composition from basaltic to intermediate, gradually acquiring

more and more of a crustal and A-type geochemistry. As partial melting of the overlying crust is largely balanced by fractional crystallization and cumulation of mafic minerals at the bottom of the magma chamber, the magma volume remains approximately the same, but the composition changes towards more ferroan, potassic, and increasingly enriched in incompatible trace elements. Eventually, fractional crystallization takes the upper hand and magma volume starts to decrease, and without any replenishment of more primitive magma, the ensuing magma volume moves into the A-type granite field, becoming highly "A-typical" in composition. As stated already above, the strong enrichment of potassium, iron over magnesium, and various incompatible trace elements in the melt is similar to the process of zone refining in metallurgy, in which a batch of melt is passed along a metal rod and picks up trace pollutants along its way, leaving a highly purified metal rod behind, usable for semiconductors or high precision Re filaments in thermal ionization mass spectrometry [44]. The decrease in magma density due to the change from basaltic through intermediate to siliceous composition, possibly enhanced by increased volatile content, will increase its buoyancy and allow it to erupt to shallow crustal levels or even to the surface.

References

1. Loiselle, M.C.; Wones, D.R. Characteristics and origin of anorogenic granites. In Proceedings of the Annual Meetings of the Geological Society of America and Associated Societies, San Diego, CA, USA, 5–8 November 1979; Volume 11, p. 468.
2. Bonin, B. A-type granites and related rocks: Evolution of a concept, problems and prospects. *Lithos* **2007**, *97*, 1–29. [CrossRef]
3. Frost, C.D.; Frost, B.R. On ferroan (A-type) granitoids: Their compositional variability and modes of origin. *J. Petrol.* **2011**, *52*, 39–53. [CrossRef]
4. Anderson, J.L. Proterozoic anorogenic granite plutonism of North America. *Geol. Soc. Am. Mem.* **1983**, *161*, 133–154.
5. Anderson, J.L.; Bender, E.E. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States. *Lithos* **1989**, *23*, 19–52. [CrossRef]
6. Hoffman, P.F. Speculations on Laurentia's first gigayear (2.0 to 1.0 Ga). *Geology* **1989**, *17*, 135–138. [CrossRef]
7. Windley, B.F. Proterozoic anorogenic magmatism and its orogenic connections. *J. Geol. Soc.* **1993**, *150*, 39–50. [CrossRef]
8. Anderson, J.L.; Morrison, J. Ilmenite, magnetite, and peraluminous Mesoproterozoic anorogenic granites of Laurentia and Baltica. *Lithos* **2005**, *80*, 45–60. [CrossRef]
9. Bonin, B. Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting mantle and custal sources? A review. *Lithos* **2004**, *78*, 1–24. [CrossRef]
10. Åhäll, K.-I.; Connelly, J.N.; Brewer, T.S. Episodic rapakivi magmatism due to distal orogenesis?: Correlation of 1.69–1.50 Ga orogenic and inboard, "anorogenic" events in the Baltic Shield. *Geology* **2000**, *28*, 823–826. [CrossRef]
11. Nyman, M.W.; Karlstrom, K.E.; Kirby, E.; Graubard, C.M. Mesoproterozoic contractional orogeny in western North America: Evidence from 1.4 Ga plutons. *Geology* **1994**, *22*, 901–904. [CrossRef]
12. Nyman, M.W.; Karlstrom, K.E. Pluton emplacement processes and tectonic setting of the 1.42 Ga Signal batholith, SW USA: Important role of crustal anisotropy during regional shortening. *Precambrian Res.* **1997**, *82*, 237–263. [CrossRef]
13. Bickford, M.E.; Van Schmus, W.R.; Karlstrom, K.E.; Mueller, P.A.; Kamenov, G.D. Mesoproterozoic trans-Laurentian magmatism: A synthesis of continent-wide age distributions, new SIMS U-Pb ages, zircon saturation temperatures, and Hf and Nd isotopic compositions. *Precambrian Res.* **2015**, *265*, 286–312. [CrossRef]
14. Stern, R.J. The Mesoproterozoic single-lid tectonic episode: Prelude to modern plate tectonics. *GSA Today* **2020**, *30*, 4–10. [CrossRef]

15. Eby, G.N.; Krueger, H.W.; Creasy, J.W. Geology, geochronology, and geochemistry of the White Mountain batholith, New Hampshire. In *Mesozoic Magmatism in Eastern North America*; Puffer, J.H., Ragland, P., Eds.; Geological Society of America Special Paper; Geological Society of America: Boulder, CO, USA, 1992; Volume 268, pp. 379–397.

16. Turner, S.P.; Foden, J.D.; Morrison, R.S. Derivation of some A-type magmas by fractionation of basaltic magma: An example from the Padthaway Ridge, South Australia. *Lithos* **1992**, *28*, 151–179. [CrossRef]

17. Frost, C.D.; Frost, B.R. Reduced rapakivi-type granites: The tholeiite connection. *Geology* **1997**, *25*, 647–650. [CrossRef]

18. Frost, C.D.; Frost, B.R.; Chamberlain, K.R.; Edwards, B.R. Petrogenesis of the 1.43 Ga Sherman batholith, SE Wyoming: A reduced Rapakivi-type anorogenic granite. *J. Petrol.* **1999**, *40*, 1771–1802. [CrossRef]

19. Vander Auwera, J.; Bogaerts, M.; Liégeois, J.P.; Demaiffe, D.; Wilmart, E.; Bolle, O.; Duchesne, J.C. Derivation of the 1.0–0.9 Ga ferro-potassic A-type granitoids of southern Norway by extreme differentiation from basic magmas. *Precambrian Res.* **2003**, *124*, 107–148. [CrossRef]

20. Anderson, I.C.; Frost, C.D.; Frost, B.R. Petrogenesis of the Red Mountain pluton, Laramie anorthosite complex, Wyoming: Implications for the origin of A-type granite. *Precambrian Res.* **2003**, *124*, 243–267. [CrossRef]

21. King, P.L.; White, A.J.R.; Chappell, B.W.; Allen, C.M. Characterization and origin of aluminous A-type granites from the Lachlan Fold Belt, Southeastern Australia. *J. Petrol.* **1997**, *38*, 371–391. [CrossRef]

22. Goodge, J.W.; Vervoort, J.D. Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence. *Earth Planet. Sci. Lett.* **2006**, *243*, 711–731. [CrossRef]

23. Collins, W.J.; Beams, S.D.; White, A.J.R.; Chappell, B.W. Nature and origin of A-type granites with particular reference to southeastern Australia. *Contrib. Mineral. Petrol.* **1982**, *80*, 189–200. [CrossRef]

24. Clemens, J.D.; Holloway, J.R.; White, A.J.R. Origin of an A-type granite: Experimental constraints. *Am. Mineral.* **1986**, *71*, 317–324.

25. Whalen, J.B.; Currie, K.L.; Chappell, B.W. A-type granites: Chemical characteristics, discrimination and petrogenesis. *Contrib. Mineral. Petrol.* **1987**, *95*, 407–419. [CrossRef]

26. Landenberger, B.; Collins, W.J. Derivation of A-type granites from a dehydrated charnockitic lower crust: Evidence from the Chaelundi complex, eastern Australia. *J. Petrol.* **1996**, *37*, 145–170. [CrossRef]

27. Zhao, X.F.; Zhou, M.F.; Li, J.W.; Wu, F.Y. Association of Neoproterozoic A- and I-type granites in South China: Implications for generation of A-type granites in a subduction-related environment. *Chem. Geol.* **2008**, *257*, 1–15. [CrossRef]

28. Creaser, R.A.; Price, R.C.; Wormald, R.J. A-type granites revisited: Assessment of a residual-source model. *Geology* **1991**, *19*, 163–166. [CrossRef]

29. Patiño Douce, A.E. Generation of metaluminous A-type granites by low-pressure melting of calc-alkaline granitoids. *Geology* **1997**, *25*, 743–746. [CrossRef]

30. Smith, D.R.; Noblett, J.; Wobus, R.A.; Unruh, D.; Douglass, J.; Beane, R.; Davis, C.; Goldman, S.; Kay, G.; Gustavson, B.; et al. Petrology and geochemistry of late-stage intrusions of the A-type, mid-Proterozoic Pikes Peak batholith (Central Colorado, USA): Implications for petrogenetic models. *Precambrian Res.* **1999**, *98*, 271–305. [CrossRef]

31. Dall'Agnol, R.; Teixeira, N.P.; Rämö, O.T.; Moura, C.A.V.; Macambira, M.J.B.; de Oliveira, D.C. Petrogenesis of the Paleoproterozoic rapakivi A-type granites of the Archean Carajas metallogenic province, Brazil. *Lithos* **2005**, *80*, 101–129. [CrossRef]

32. Trumbull, R.B.; Harris, C.; Frindt, S.; Wigand, M. Oxygen and neodymium isotope evidence for source diversity in Cretaceous anorogenic granites from Namibia and implications for A-type granite genesis. *Lithos* **2004**, *73*, 21–40. [CrossRef]

33. Martin, R.F. A-type granites of crustal origin ultimately result from open-system fenitization-type reactions in an extensional environment. *Lithos* **2006**, *91*, 125–136. [CrossRef]

34. Montero, P.; Bea, F.; Corretgé, L.G.; Floor, P.; Whitehouse, M.J. U-Pb ion microprobe dating and Sr and Nd isotope geology of the Galiñeiro Igneous Complex: A model for the peraluminous/peralkaline duality of the Cambro-Ordovician magmatism of Iberia. *Lithos* **2009**, *107*, 227–238. [CrossRef]

35. Eby, G.N. Chemical subdivision of the A-type granitoids: Petrogenetic and tectonic implications. *Geology* **1992**, *20*, 641–644. [CrossRef]

36. Frost, C.D.; Frost, B.R. Proterozoic ferroan feldspathic magmatism. *Precambrian Res.* **2013**, *228*, 151–163. [CrossRef]

37. Zariņš, K.; Johansson, Å. U-Pb geochronology of gneisses and granitoids from the Danish island of Bornholm: New evidence for 1.47–1.45 Ga magmatism at the southwestern margin of the East European Craton. *Int. J. Earth Sci. (Geol. Rundsch.)* **2009**, *98*, 1561–1580. [CrossRef]

38. Waight, T.E.; Frei, D.; Storey, M. Geochronological constraints on granitic magmatism, deformation, cooling and uplift on Bornholm, Denmark. *Bull. Geol. Soc. Den.* **2012**, *60*, 23–46.

39. Johansson, Å.; Waight, T.; Andersen, T.; Simonsen, S.L. Geochemistry and petrogenesis of Mesoproterozoic A-type granitoids from the Danish island of Bornholm, southern Fennoscandia. *Lithos* **2016**, *244*, 94–108. [CrossRef]

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

41. Dall'Agnol, R.; de Oliveira, D.C. Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: Implications for classification and petrogenesis of A-type granites. *Lithos* **2007**, *93*, 215–233. [CrossRef]

42. Bohrson, W.A.; Spera, F.J. Energy-constrained open-system magmatic processes II: Application of energy-constrained assimilation-fractional crystallization (EC-AFC) model to magmatic systems. *J. Petrol.* **2001**, *42*, 1019–1041. [CrossRef]

43. Petford, N.; Gallagher, K. Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. *Earth Planet. Sci. Lett.* **2001**, *193*, 483–499. [CrossRef]
44. Pfann, W.G. *Zone Melting*, 2nd ed.; John Wiley & Sons: New York, NY, USA, 1966; 310p.
45. Hawkesworth, C.J.; Blake, S.; Evans, P.; Hughes, R.; Macdonald, R.; Thomas, L.E.; Turner, S.P.; Zellmer, G. Time scales of crystal fractionation in magma chambers—Integrating physical, isotopic and geochemical perspectives. *J. Petrol.* **2000**, *41*, 991–1006. [CrossRef]
46. Heinonen, A.; Mänttäri, I.; Rämö, O.T.; Andersen, T.; Larjamo, K. A priori evidence for zircon antecryst entrainment in megacrystic Proterozoic granites. *Geology* **2016**, *44*, 227–230. [CrossRef]
47. Frost, B.R.; Barnes, C.G.; Collins, W.J.; Arculus, R.J.; Ellis, D.J.; Frost, C.D. A geochemical classification for granitic rocks. *J. Petrol.* **2001**, *42*, 2033–2048. [CrossRef]
48. Rickwood, P.C. Boundary lines within petrological diagrams which use oxides of major and minor elements. *Lithos* **1989**, *22*, 247–263. [CrossRef]
49. Chappell, B.W.; White, A.J.R. Two contrasting granite types. *Pac. Geol.* **1974**, *8*, 173–174.
50. White, A.R.J. Sources of granitic magmas. In Proceedings of the Annual Meetings of the Geological Society of America and Associated Societies, San Diego, CA, USA, 5–8 November 1979; Volume 11, p. 539.
51. Campbell, I.H. Large igneous provinces and the mantle plume hypothesis. *Elements* **2005**, *1*, 265–269. [CrossRef]
52. Ernst, R.E.; Buchan, K.L.; Campbell, I.H. Frontiers in Large Igneous Province research. *Lithos* **2005**, *79*, 271–297. [CrossRef]