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Original paper

Death of super-continents and birth of oceans heralded by discrete A-type granite igneous events: the case of the Variscan–Alpine Europe

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Granitoids occupy large areas of the Variscan–Alpine Europe. The specific group of A-type granites identifies post-collisional (post-orogenic) and anorogenic geodynamic settings. Post-orogenic igneous provinces are emplaced during the very last episodes of supercontinent amalgamation. Anorogenic igneous provinces accompany continental break-up and predate the development of new oceanic basins. Though not voluminous compared with the other granite types, A-type granites substantiate critical periods of the life of supercontinents.

Their ages of emplacement in the Variscan–Alpine Europe span the entire Cambrian–Triassic time interval. They are not random, however, and correspond to discrete episodes. Two major age groupings, both with a *c.* 60 My duration, are distinguished. The Early Cambrian–Early Ordovician period corresponds to Pannotia amalgamation, followed by its break-up and the development of the Rheic–Proto-Tethys Ocean. The Late Carboniferous–Early Triassic period corresponds to Rheic closure and Pangaea amalgamation, followed by its break-up and the development of the Neo-Tethys Ocean. Devonian–Early Carboniferous A-type igneous episodes, scarce in Europe but widespread in Central Asia, accompanied the development of the Palaeo-Tethys Ocean.

Keywords: A-type granite, geodynamic settings, Palaeozoic, Cadomian, Variscan, Triassic, Europe
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1. Introduction

Granitoids are extensively studied for the following reasons: (i) they are the most abundant rocks in the Earth's upper continental crust, (ii) like other igneous rocks, they represent probes into the deep planetary interiors, and (iii) they are closely connected with tectonics as well as geodynamics. Even now, the proportion of granitoids and associated volcanic rocks present on Earth is low, about 0.1 % of the Bulk Earth (Clarke 1996). Such a small proportion corresponds nevertheless to a total mass of at least 10^{22} kg and a volume of about 3.74×10^9 km^3 (Bonin et al. 2002). Roughly 86 vol. % of the upper continental crust is granitic in composition (Wedepohl 1991). Granite occurs also, albeit in smaller amounts, within lower continental crust, oceanic crust, upper mantle and meteorites (Bonin et al. 2002; Bonin and Bébien 2005, and references therein).

In this Special Issue devoted to 'Field, analytical and experimental approaches to silicic magmatism in collisional orogens', the aim of this paper is to provide an overview of the occurrences and geodynamic settings of Cambrian to Triassic A-type granites within the Variscan–Alpine Europe, i.e. the peri-Gondwanan terranes that collided with Baltica during the Palaeozoic era, before being collided by the rest of Gondwana during the Permian.

A-type granites were first named by Loiselle and Wones (1979). Further refinements (for a review, see Bonin 2007) led to a proposal of clear criteria that are commonly used to distinguish A-type granites from the other granite types worldwide (Tab. 1). They were ascribed for a long time (e.g., Billings 1945; Black et al. 1985) to the specific geodynamic settings, namely post-collisional to within-plate, which gives them the popular name of 'anorogenic'. Examples of tectonic settings of A-type igneous provinces occurring in Europe are listed in Tab. 2.

Three issues will be addressed. The first concerns the so-called "crustal signatures" yielded by radiogenic isotopes in otherwise mantle-derived rocks. The second is the problem of identifying undoubtedly A-type granites emplaced within polygenetic orogenic belts, after they suffered deformation and alteration and were converted into orthogneisses. The last one consists of a critical overview of A-type igneous provinces emplaced during the build-up of the Variscan–Alpine Europe.

2. What is A-type granite?

A-type granites constitute a well-defined type of silicic igneous rocks. The concept and usage of the term "A-type" follow closely the recommendations of the UNESCO-IGCP Project 510 "A-type granites and related

Tab.1 Major features of A-type granite igneous suites (Bonin 2007 and references therein)

A-type granites	Monzogranite – syenogranite – alkali feldspar granite		
Associated rock types IUGS nomenclature (Le Maitre, 2002)	Anorthosite – gabbro – diorite Monzogabbro – monzodiorite – monzonite Syenite – alkali feldspar syenite – nepheline syenite		
Rock-forming mineralogy	Felsic assemblage	Quartz	Purple to brown to black euhedral β-shaped crystals
		Feldspathoids in associated silica-undersaturated rocks	Anhedral crystals
		Feldspar hypersolvus type	Mesoperthite with two discrete alkali feldspar phases
		Feldspar subsolvus type	Discrete crystals of K-feldspar and plagioclase (An < 15)
		Feldspar transsolvus type	Mesoperthite cores with K-feldspar rims, K-feldspar and albite in discrete crystals
	Mafic assemblage	Liquidus assemblage	Fayalite + pyroxenes + iron oxides
		Late magmatic calcic amphibole trend	Hastingsite – ferro-edenite – ferrohornblende
		Near-solidus to subsolidus sodic-calcic – sodic – iron amphibole trend	Barroisite – winchite – richterite – arfvedsonite – riebeckite – grünerite
		Near-solidus to subsolidus mica associations	Annite – siderophyllite; Zinnwaldite – trilithionite, Montdorite; Celadonitic muscovite; Clay minerals
	Accessory mineralogy	Fe-Ti oxides	Ilmenite – ulvöspinel – magnetite
		Silicates	Zircon – thorite – elpidite – allanite – chevkinite – aenigmatite – topaz ± titanite ± tourmaline ± garnet
		Phosphates (low to very low abundances)	Apatite – monazite – xenotime
		High-tech metal ore minerals	Fergusonite – polycrase – chernovite – pyrochlore – genthelvite – ...
		Ore minerals	Cassiterite – molybdenite – wolframite – sphalerite – galena – pyrite ± pyrrhotite – chalcopyrite – mimetite – ...
		Other minerals	Fluorite – REE fluorides ± carbonates
Bulk-rock geochemistry	$FeO/(FeO + MgO) > 0.446 + 0.0046 \times$ wt. % SiO_2 $FeO^T/(FeO^T + MgO) > 0.486 + 0.0046 \times$ wt. % SiO_2		Ferroan A-type group
	For low Ga/Al and (Zr + Nb + Ce + Y): $FeO^T/MgO > 16$		A-type granites
	$4 < FeO^T/MgO < 16$		Fractionated felsic granites
	$FeO^T/MgO < 4$		Unfractionated granites
	ASI = A/CNK = molar $Al_2O_3/(CaO + Na_2O + K_2O) = Al/(2\,Ca + Na + K) > 1$		Peraluminous
	ASI < 1	NK/A = (Na + K)/Al < 1	Metaluminous
		NK/A > 1	Peralkaline
	For any ASI values	NK/A > 0.85 NK/A > 0.88	Alkaline or A-type suites
	Trace-element discrimination	Y + Nb > 50–55 ppm Yb + Ta > 6 ppm	Within-Plate Granite (WPG) and Oceanic Ridge Granite (ORG)
		10000 × Ga/Al > 2.6 Zr + Nb + Ce + Y > 350 ppm	A-type granite
		Y/Nb < 1.2	A1 subtype, intra-plate rifting
		Y/Nb > 1.2	A2 subtype, post-collisional
	REE contents and patterns	High contents in metaluminous and peralkaline types Low contents in evolved topaz-bearing peraluminous types	Gull-wing shape
		Non-mineralized types	Slightly fractionated $(La/Yb)_N < 30$ Varying Eu negative anomalies
		Mineralized types: pronounced tetrad effects	Unfractionated $(La/Yb)_N$ down to 0.3, negative Eu anomalies with Eu/Eu* down to 0.01
	Stable and radiogenic isotopes	A-type suites yield no specific values in Sr-Nd-Hf-Pb-O isotopic systems. Depleted mantle to crustal signatures are not obviously correlated with ages of emplacement and tectonic settings, thus suggesting either a mixture of various sources, complex differentiation processes, or both.	

rocks through time" discussed in its first meeting in 2005 (Bonin 2007). Clear criteria, involving specific petrological–mineralogical features and geochemical compositions (e.g., Pearce et al. 1984; Whalen et al. 1987; Eby 1990) commonly used to identify A-type granites, are listed in Tab. 1. In addition, A-type granites are not emplaced randomly in continental areas, as their tectonic settings involve always some amounts of extension (Tab. 2). Last, in agreement with their original definition (Loiselle and Wones 1979), they are associated with coeval mafic to intermediate rocks within compositionally expanded igneous suites (e.g., Bonin et al. 2008).

2.1. A-type granites and A-type granites?

No radiogenic and stable isotopic criteria (e.g., Sr, Nd, Hf, Pb, O) can define A-type granites unambiguously, thus raising the question whether we are dealing with a too vague concept. Most popular textbooks on igneous petrology usually consider granites as a specific entity genetically unrelated to other igneous, plutonic and volcanic, suites. Because they yield variable isotopic signatures, granites are also frequently regarded as entirely of crustal derivation, with or without hybridization by varying amounts of mantle-derived mafic magmas. This is, in particular, the basic scheme of the S – I – M alphabetical classification. However, A-type granites differ from the other granite types in that, though crustal sources seem to be evidenced in many cases by the isotopic record, no migmatitic terranes on Earth have yielded any leucosomes of A-type compositions, nor had experimental petrology succeeded in producing unambiguous A-type liquids from crustal materials (for a discussion, see Bonin 2007 and references therein). On the contrary, occurrences of A-type granites within oceanic islands and even on the Moon indicate they are likely to form through mineral fractionation, not partial melting, of mafic magmas, even in the absence of significant amounts of H_2O (Bonin et al. 2002).

2.2. The crustal issue

The isotopic "crustal signature" constitutes an important issue to address. Geoscientists involved in upper mantle studies are well aware of enriched compositions that can mimic crustal values. In the lack of evidence for preserved primitive mantle reservoirs, occurrences of various enriched mantle end-members are explained by subduction-induced incorporation of crustal (oceanic and continental) materials into depleted upper mantle of the overriding lithospheric plate.

Consider a depleted mantle of harzburgitic composition and add either continental upper crustal materials, or TTG-like silicic liquids produced from oceanic crust. Abundances of incompatible elements within harzburgite are exceedingly low. Addition of small volumes of products rich in incompatible elements results in harzburgite converted into re-fertilized lherzolite and/or websterite, with an overall signature strongly influenced by crustal materials. Isotopic initial ratios and Nd depleted-mantle model ages yielded by magmas originating from such a [depleted mantle + crust] mixture stand, therefore, closer to the crustal than to the depleted mantle end-member.

There is, therefore, no need for a key role played by continental wall rocks, which A-type magmas pass through, or are emplaced in. As baffling as this idea can appear at a first glance, crustal signatures have little to do with the exposed crust. They have to be searched at deeper levels within the lithospheric keels of continental plates. Evolved low-P specialized granites can be strongly contaminated by exogenous elements carried by reactive Cl- and F-rich hydrothermal fluids. Their high initial $^{87}Sr/^{86}Sr$ ratios and low $\varepsilon_{Nd}(t)$ values, totally unrelated to magma sources, constitute apparent exceptions that should be mentioned (e.g., Zinnwald–Cínovec granite).

2.3. A unified view

In the following pages, A-type granites will not be considered as a discrete entity unrelated to other coeval igneous rocks. The concept of A-type igneous suite involves not only A-type granites, but also mafic and intermediate, volcanic and plutonic, igneous rocks. Such suites include bimodal associations derived from tholeiitic and mildly alkaline basaltic magmas (Frost and Frost 2008). Though following apparently different evolutionary paths, their real unity was recognized for a long time within plu-

Tab. 2 Selected Phanerozoic A-type igneous suites in Europe (adapted from Bonin 2007)

Orogenic stages	Tectonic settings	Examples	Ages
Post-collision	Transcurrent shear zones	Assynt Igneous Province, Scotland Western Mediterranean Province Comendite, San Pietro Island, Italy	440–425 Ma 280–235 Ma 15 Ma
Rifts	Extensional regime	Midland Valley, Scotland Oslo Rift, Norway Pantellerite, Pantelleria Island, Italy	*c.* 345 Ma 280–250 Ma 0.33–0.003 Ma
Passive margins	Extensional regime	Peralkaline gneisses, Galicia, Spain Rheinisches Schiefergebirge, Germany British Tertiary Igneous Province	500–480 Ma 390–380 Ma *c.* 50 Ma

tonic–volcanic provinces, but it is still underestimated in granite studies. Keeping this idea in mind, it is not surprising that A-type granites do not have to be of only crustal derivation.

3. The A-type orthogneiss conundrum

A-type igneous suites are fairly easy to discriminate and have specific ferroan alkali-calcic to alkaline bulk-rock compositions. However, aluminous subsolvus granites do not have to yield specific features of A-type granite. In the case of post-orogenic igneous suites, in which they are abundant, it is not always straightforward to define whether they are A-type, or not. Field criteria are helpful, such as textures including euhedral shape of purple–brown–black quartz crystals and anhedral shape of biotite flakes.

3.1. Interpretation of metamorphic textures and compositions

Evidence for A-type granites highly deformed and involved within orogenic fold belts is generally not easy to decipher, because they lost partly their petrological and geochemical characteristics through mineral breakdown, leaching and/or re-crystallization. A-type orthogneisses usually carry a subsolvus feldspar assemblage, with K-feldspar only slightly to non-perthitic (Floor 1974). Alkali loss and silicification result into bulk rocks having non-igneous compositions, with less than 8 wt. % of Na_2O + K_2O and more than 78 wt. % SiO_2. A-type metagranites, with primary (igneous) peraluminous and metaluminous compositions, can yield metamorphically-induced, strongly peraluminous compositions that apparently resemble evolved S-type rocks. In orthogneisses issued from strongly peralkaline granites, though (Na + K)/Al ratios can remain higher than 1.0, alkali loss is reflected by occurrence of newly formed bipyramidal zircon crystals and metamorphic riebeckite, a sodic amphibole with empty A-site, replacing igneous arfvedsonite, characterised by full occupancy of the A-site (Floor 1974). The HFSE contents can decrease through leaching by hydrothermal F-bearing fluids. In most cases, immobile elements can help, such as, e.g., fairly low (< 14–15 wt. %) Al_2O_3 contents, low MgO/FeO_T ratios and gull-wing shapes of REE patterns, diagnostic of A-type granite compositions.

The Randa orthogneiss (Thélin 1987) offers a pertinent example: this Permian (269 ± 2 Ma, Roadian, Bussy et al. 1996) A-type granite underwent Alpine tectonic episodes under greenschist-facies conditions. The slightly deformed core of the massif yields its original ferroan alkali-calcic composition, with low Fe_2O_3/FeO ratio, 40–50 ppm Y and 15–30 ppm Nb, corresponding to the Within-Plate Granite (WPG) field of Pearce et al. (1984). The still ferroan sheared margins are highly silicic, with up to 81.5 wt. % SiO_2, and calc-alkaline, due to decreasing alkali contents. They yield high Fe_2O_3/FeO ratios, low TiO_2 contents, fairly constant (20–40 ppm) Y contents and low (< 10 ppm) to very low (below detection limit by the XRF method) Nb contents. They plot no longer in the WPG, but in the Volcanic-Arc Granite (VAG) field. Positive Y–Zr correlations indicate that zircon is the main carrier of Y and that this element remains stable during the metamorphic overprint. Positive Nb–TiO_2 and negative Nb–Fe_2O_3 correlations suggest breakdown of Nb-bearing Fe–Ti oxides and Nb mobility through oxidizing fluids.

3.2. The problem of age determination of A-type orthogneiss protoliths

High LILE mobility favours partial to complete resetting of Rb-Sr isotopic systems; even Sm-Nd systems can be disturbed in the presence of F-bearing fluids. The isochron method is, therefore, unable to provide reliable emplacement ages for the igneous protoliths. In the most favourable cases of complete resetting during major metamorphic events, it can provide ages of those events. Like the Rb-Sr isotopic system, the U-Th-Pb isotopic system is also susceptible to variable amounts of resetting through Pb loss during hydrothermally mediated events. Zircon is currently in systematic use for age determination purposes, as well as other U-Th-bearing minerals, such as monazite and titanite. Abundant in non-peralkaline A-type granites, zircon precipitates either as early euhedral prismatic (100) crystals in fluid-deficient conditions, or as late euhedral to anhedral bipyramidal crystals in fluid-rich environments (Pupin et al. 1978). Early prismatic crystals are limpid, while late bipyramidal crystals are often metamict. Zircon usually cannot crystallize in Zr-rich peralkaline A-type granites, because of its high solubility in the magma, and is replaced by elpidite, a hydrous alkali zirconosilicate (Tab. 1).

Though stable under a wide range of conditions, zircon can re-crystallize during a metamorphic event forming new crystals and/or rims around igneous cores. In meta-igneous peralkaline rocks, secondary bipyramidal crystals result from alkali loss. Associated xenotime is frequent (Pan 1997). There is a range of textures between two zircon end-members. One end-member is a pristine generation of igneous crystals and/or cores, characterized by well-developed growth zoning evidenced by cathodoluminescence imaging, and the other end-member is a package of newly formed porous to skeletal metamorphic crystals and/or rims intergrown with secondary mineral inclusions, reflecting dissolution–re-precipitation processes (Tomaschek et al. 2003; Bendaoud et al. 2008).

Thus, the crystal rims are likely to yield U-Pb ages differing from the crystal cores.

The ID-TIMS technique using populations of zircon crystals is unable to provide concordant isotopic dates in the case of rocks that have undergone multiple episodes of crystallization. Zircon crystals in A-type granites are generally devoid of inherited cores. Single crystals subjected to a removal of re-crystallized and/or metamict rims by the air abrasion technique can give concordant dates that are likely to indicate the emplacement age of the protolith. If re-crystallized metamorphic rims remain, results plot along a discordia line. In the most favourable cases, the upper intercept with the concordia curve yields the age of the protolith and the lower intercept the age of the metamorphic overprint. In the more difficult cases of aluminous A-type granites containing inherited cores, multiple discordia chords can be computed and should be interpreted. The seemingly promising evaporation technique precludes direct investigations on the parts of the crystal that are removed during incremental heating steps and the results are less precise than those obtained by the ID-TIMS technique.

With modern techniques using *in situ* isotopic measurements, these difficulties could be addressed. As igneous zircon incorporates U and Th, according to zircon/liquid distribution coefficients for the two elements, Th/U ratios measured in the crystals are higher than 0.2 and frequently higher than 0.5. In the case of re-crystallization in the presence of coexisting solid phases, such as xenotime, Th/U ratios in metamorphic zircon decrease considerably, down to less than 0.05 (Williams and Claesson 1987). In zoned crystals, igneous crystals and cores, with Th/U ratios higher than 0.2, can be distinguished from low Th/U metamorphic crystals and rims, though igneous-like Th/U ratios can be preserved in some metamorphic crystals (Tomaschek et al. 2003).

3.3. Ordovician events within parts of the Iberian Peninsula

The Early to Middle Ordovician igneous episodes in the Palaeozoic orogenic belt of Western Iberia afford a pertinent example. The Ossa-Morena Zone is bordered to the north by the autochthonous units of Central Iberia and Galicia–Trás-os-Montes and the Malpica–Tuy allochthon. The terrane assemblage, deformed and amalgamated during the Variscan orogenic event, corresponds to a volcanic passive margin developed since the Ediacaran–Early Cambrian transition (Simancas et al. 2004; Etxebarria et al. 2006). A-type orthogneisses are exposed within all units and their zircon crystals have been analysed for U-Pb dating (e.g., Lancelot et al. 1985; Santo Zalduegui et al. 1995; Valverde-Vaquero et al. 2005; Bea et al. 2006; Cordani et al. 2006; Montero et al. 2008).

Ion microprobe and LA-ICPMS techniques allowed to obtain trace-element and isotopic data on zircon crystals of orthogneisses from Portalegre and Alcóçavas, Ossa-Morena Zone (Cordani et al. 2006), Galiñeiro, Galicia (Montero et al. 2008), and Miranda do Douro, Central Iberian Zone (Bea et al. 2006). The evolution of Th/U ratios with time (Fig. 1) constitutes a good marker of the origin of zircon crystals. The 370–340 Ma (Variscan) crystals and rims yield consistently low Th contents and Th/U ratios, from 0.12 to 0.03, substantiating metamorphic crystallization.

In the Portalegre orthogneiss, a single population of crystals yields a concordant age of 497 ± 10 Ma, with no obvious inherited cores (Fig. 1). Igneous crystals yield 109 to 363 ppm U and igneous Th/U ratios from 0.15 to 1.43, suggesting that they crystallized at various stages from liquidus to solidus. One non-igneous U-rich (682 ppm), low-Th/U (0.09), yet concordant crystal is likely to have precipitated in subsolidus conditions from late-stage fluids.

In the Alcóçavas orthogneiss, two populations of crystals yield concordant ages of 539 ± 20 Ma and 464 ± 14 Ma, with one 2.5 Ga inherited core and one 620 Ma highly discordant crystal. The Th/U ratios are higher than 0.22 in the 464 Ma crystals and 0.18 in the 539 Ma crystals, implying that both populations grew from magmas (Fig. 1). Rounded shapes displayed by some crystals suggest that all 539 Ma crystals are inherited from Early Cambrian igneous formations. The emplacement age of the protolith to the Alcóçavas orthogneiss is, therefore, Middle Ordovician.

In the Galiñeiro peralkaline orthogneiss, abundant zircon crystals are brown, turbid, totally or partially metamict, thus apparently not suitable for U-Pb dating. However, SIMS analyses yield a mean common Pb-corrected age of 482 ± 2 Ma, considered as the age of emplacement. U and Th contents, 265–5827 ppm and 30–641 ppm, respectively, and Th/U ratios ranging from 0.64–0.17 (igneous, 50 % spots) to 0.14–0.01 (secondary) show that zircon crystallized under magmatic to subsolidus conditions and that late-stage fluids were coeval to the emplacement of the peralkaline protolith (Fig. 1).

Like other metavolcanic and metagranitic rocks of the Ollo de Sapo Formation of the Central Iberian Zone (Parga-Pondal et al. 1964; Montero et al. 2007), the magnesian calc-alkaline Miranda do Douro orthogneiss does not display A-type characteristics. Its age of emplacement is currently a matter of controversy. Based on upper intercept in U-Pb concordia diagram, a 618 ± 9 Ma age was reported by Lancelot et al. (1985), while Bea et al. (2006) claimed that the dominant population of 483 ± 3 Ma crystals reveals the true age of a granitoid produced by melting of Panafrican source. Using the U-Th data of Bea et al. (2006), it appears that the 483 ± 3 Ma concor-

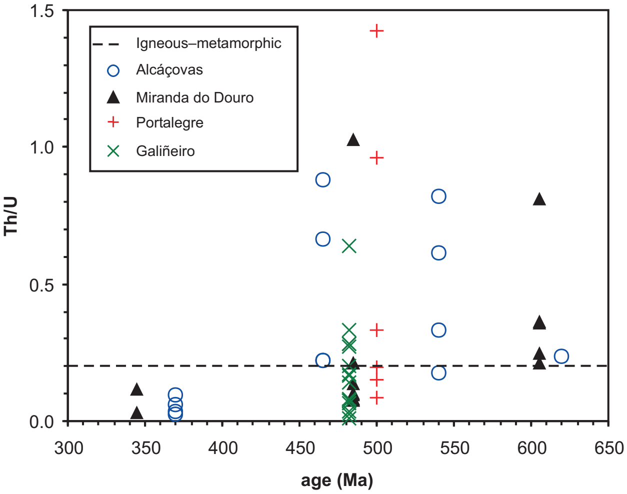

Fig. 1. Th/U ratios vs. radiometric ages in Iberian orthogneisses. Dashed line: boundary line separating disturbed metamorphic compositions (Th/U < 0.2) from undisturbed igneous compositions (Th/U > 0.2). Zircon crystals of Portalegre and Galiñeiro orthogneisses, though yielding varying Th/U ratios, give the same ages, implying that ages of emplacement and of hydrothermal disturbance are identical within analytical uncertainties. Zircon crystals of Alcóçavas and Miranda do Douro orthogneisses yield igneous compositions and ages of emplacement that differ largely from disturbed compositions and ages of metamorphic overprint. In addition, the distribution of igneous ages in the Alcóçavas orthogneiss reveals an occurrence of older inherited cores.

dant crystals yield non-igneous Th/U ratios lower than 0.21 (down to 0.07), with only one crystal having high U and Th contents (808 ppm and 828 ppm, respectively) and Th/U ratio as high as 1.02. On the contrary, the 605 ± 13 Ma concordant crystals yield igneous Th/U ratios consistently higher than 0.21 (Fig. 1). It is suggested here that the Miranda do Douro orthogneiss was derived from an Ediacaran protolith, which underwent hydrothermal alteration by fluids issued from Early Ordovician A-type dykes and sills that are known throughout the Ollo de Sapo domain and are related to the Galiñeiro igneous episode (Floor 1974; Lancelot et al. 1985).

3.4. Relevance of A-type orthogneisses in geodynamic reconstructions

A-type igneous suites can be recognized fairly well, if, after their emplacement and cooling, they were not subsequently deformed and metamorphosed. The A-type orthogneiss issue is critical for two reasons: (i) the original bulk-rock and mineral compositions can be obscured by hydrothermal alteration promoted by fluids percolating within the shear zones, (ii) the exact age of igneous emplacement can be erased within the isotopic clocks.

The geological record can provide some help. Within-plate settings can be recognized from sedimentary formations evidencing rifting or passive margin regimes during their deposition. Associated orthogneisses are ascribed to A-type igneous episodes, even if their compositions do not fulfil the required criteria. Accurate radiometric age determinations are necessary, as both inheritance and isotopic resetting may result in dates that are difficult to interpret correctly.

Granitoids and orthogneisses occupy large areas of the basement of the Variscan–Alpine Europe. Careful examination of chemical and isotopic data on undeformed granitoids as well as on orthogneisses provides an evidence of discrete A-type igneous events. Though pieces of older A-type igneous provinces can be preserved, major igneous events took place frequently since the Neoproterozoic and are still going on in the Mediterranean area (Tab. 1).

4. Periodic A-type granite events within the Variscan–Alpine Europe: an overview

Though not voluminous compared with the other granite types, A-type granites substantiate post-collisional (post-orogenic) and anorogenic geodynamic settings. Their emplacement ages span a large time interval, from Neoproterozoic (*c.* 600 Ma) to Triassic (*c.* 230 Ma). The intrusive ages are not randomly distributed, however, and correspond to discrete critical episodes. This will be illustrated by a roughly N–S geotraverse. The occurrences described hereafter are listed in Tab. 3.

4.1. The Central Europe geotraverse

The Variscan–Alpine Europe is essentially made up of slices of continental and oceanic terranes that were squeezed between the big old continents of Laurentia, Baltica and Gondwana during the Palaeozoic. The terminology used hereafter is extracted from Stampfli and Borel (2004)[1]. The geotraverse considered here comprises the southern margin of Laurentia, the Eastern Avalonia Superterrane and the Hunic Superterrane, which includes the Armorican Terrane Assemblage (ATA). Names of stages, epochs and periods follow hereafter the very last definitions of the IUGS International Commission of Stratigraphy (Ogg et al. 2008).

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[1] Constantly updated versions of paleogeographic maps are available at:
http://www.unil.ch/igp/page22636.html
Other useful world-scale maps can be consulted at:
http://www.scotese.com/earth.htm and *http://jan.ucc.nau.edu/rcb7/RCB.html*

4.2. The Laurentian margin

The southern margin of Laurentia in Scotland is composed of a Lewisian foreland, or Hebridean Terrane, bordered by a collage of narrow (*c.* 50 km wide) terranes (Oliver et al. 2008 and references therein). The Northern Highland and Grampian terranes, delimited by the Moine Thrust, the Great Glen Fault and the Highland Boundary Fault, yield Proterozoic basements. The Midland Valley and Southern Upland terranes, bordered by the Highland Boundary Fault, the Southern Upland Fault and the Iapetus Suture, represent Early Palaeozoic island arcs and accretionary prisms including remnants of oceanic crust (Ballantrae ophiolite). Ediacaran, Ordovician and Silurian A-type granites occur within the northern continental terranes (Oliver et al. 2008). Early Carboniferous A-type basalt–rhyolite–trachyte igneous suites are mostly exposed within the southern island arc terranes.

The Ediacaran massifs (Older Granites, according to the terminology of Barrow 1893) yield U-Pb zircon ages ranging from 601 ± 4 Ma to 588 ± 8 Ma, substantiating a fairly short-lived event. Metagranite augen gneisses include riebeckite-bearing peralkaline types and constitute, with coeval 601 ± 4 Ma metabasalt–keratophyre formations, a bimodal igneous suite. Isotopic ratios (summary in Steinhoefel et al. 2008) are variable, with $\varepsilon_{Nd}(t)$ ranging from -6.3 to -4.3 in A-type metagranite and to +4 in metavolcanic rocks, precluding a single homogeneous source, $\delta^{18}O$ of 8–9 ‰ and high initial $^{87}Sr/^{86}Sr$ (> 0.710), due to Rb-Sr disturbance during metamorphism and deformation. The 601–588 Ma old bimodal rift-related igneous suite was classically assigned to Rodinia break-up (Soper 1994). This interpretation is at odds with the recent synthesis issued from IGCP 440 (Li et al. 2008), in which the Rodinia supercontinent was subjected to discrete rifting events, prior to the onset of continental disruption at 740 Ma. From the 600 Ma period of time onwards, Rodinia was already broken-up, whereas Scottish Laurentia was bordered by a passive margin created by Iapetus Ocean drifting (see Fig. 9j in Li et al. 2008).

The Ediacaran A-type massifs were metamorphosed and deformed during two discrete episodes forming the Caledonian orogeny, namely the *c.* 470 Ma Grampian and the *c.* 430 Ma Scandian events (Oliver 2001). The Grampian event is related to 'hard' collision (Oliver et al. 2008) of Laurentia with the southern island arc terranes and its age is bracketed between the Floian (Mid Arenig), based on 473 ± 2 Ma emplacement age of a S-type Newer Granite, and the Darriwilian (Late Arenig), based on 466 ± 3 Ma cooling ages. No A-type granites are known from that period of time.

Between the Grampian and Scandian events, after a 12 My pause, S-type granites were emplaced between 457 ± 1 Ma and 451 ± 4 Ma in the Grampian Terrane, under extensional regime inducing crustal thinning and erosion rate of about 1.4 $mm.a^{-1}$. In the Northern Highland Terrane, only one alkaline igneous event is displayed by the 456 ± 5 Ma (Sandbian-Katian boundary) Glen Dessary syenite (van Breemen et al. 1979). Isotopic characteristics ($\varepsilon_{Nd}(t)$ varying from +1 to +4, $^{87}Sr/^{86}Sr_i = 0.7041 \pm 0.0001$, $\delta^{18}O$ of 5.5–7.5 ‰), fractionated concave-upward REE patterns and Nb–Ti troughs require an amphibole-bearing upper mantle source of probable lithospheric origin (Halliday et al. 1987).

After a 20 My gap, the Scandian event corresponds to flat thrusting of the Northern Highland Terrane onto the Hebridean Terrane to the north and 'soft' collision of the extended Laurentian margin, comprising the Grampian to Southern Upland terranes, with Avalonia to the south (Oliver et al. 2008). It is marked by the emplacement of numerous and voluminous Newer Granite massifs from the Middle Silurian to the Middle Devonian. A-type igneous suites were emplaced coevally with the Newer Granites in the continental terranes.

Within the Northern Highland Terrane, syenite complexes aligned along the Moine Thrust Zone yield emplacement ages from 439 ± 4 Ma (Loch Ailsh) to 426 ± 9 Ma (Loch Loyal), indicating a Llandovery–Wenlock short-lived magmatic episode (Halliday et al. 1987). Their ages constrain the timing of the ductile to brittle transition along the Moine Thrust Zone. Independently acquired phengite-feldspar Rb-Sr data indicate a long-lasting episode of brittle deformation from 437 ± 5 Ma to 408 ± 6 Ma, covering the Silurian and the Early Devonian (Freeman et al. 1998). Syenites are either slightly older than, or roughly coeval with, the famous high-Ba-Sr ("HiBaSr") alkali-calcic granites. The igneous suite comprises mafic rocks, silica-saturated to undersaturated syenites and felsic peralkaline (grorudite) dykes. Isotopic data, i.e. $\varepsilon_{Nd}(t)$ varying from 0 to -8, $^{87}Sr/^{86}Sr_i$ of 0.7045–0.7065 and $\delta^{18}O$ of 8.1–10.0 ‰, plot along the Caledonian Parental Magma Array (CPMA) defined by two, depleted and enriched, mantle end-members (Fowler et al. 2008 and references therein).

Within the Grampian Terrane, scarce A-type granite massifs and dykes include biotite ± amphibole-bearing subsolvus and hypersolvus types. Published ages (Oliver et al. 2008) ranging from 408 ± 5 Ma to 406 ± 5 Ma indicate a short-lived Early Devonian episode. They are younger than the 415 ± 3 Ma (Lochkovian) ultimate stage displayed by the Etive dyke swarm within the famous Glen Coe Complex (Morris et al. 2005). Geochemical features (Steinhoefel et al. 2008) include high LILE and HFSE contents, low Ba, Sr and Eu contents, poorly fractionated REE patterns, with unfractionated patterns showing the tetrad effect. The $\varepsilon_{Nd}(t)$ vary from -2.1 to -6.9, in the same range as the Caledonian array defined in the Northern Highland Terrane.

No Ordovician–Silurian A-type igneous suites are exposed in the southern Midland Valley and Southern Upland island arc terranes that are located close to the Iapetus Suture. By contrast, they occur as large lava sheets erupted during the Early Carboniferous and filling the Midland Valley (Francis 1983). The greatest volume, up to 6000 km^3, was produced during the Tournaisian–Visean in the form of lava flows, of which *c.* 85 % were mildly silica-undersaturated basalts. The other formations consist of silica-undersaturated and saturated trachytic and rhyolitic differentiates, which were mostly erupted at *c.* 345 Ma (Tournaisian–Visean boundary). After the Visean, only basalts and basanites were emitted with no felsic differentiates.

4.3. Eastern Avalonia

Avalonian terranes constitute a long ribbon extending from eastern North America to southeastern Europe. They are commonly subdivided into Western Avalonia, located now in the North American continent, and Eastern Avalonia, covering in Europe a large area from Ireland–England to north-central Europe to Eastern Carpathians–Moesia. The Proterozoic continental basement crops out in Poland and Czech Republic, whereas the Early to Middle Palaeozoic sedimentary cover is developed in Belgium and Germany.

The Proterozoic continental basement is exposed in Poland and Czech Republic or known from boreholes (Jelínek and Dudek 1993). Despite a great complexity due to numerous boundary faults, terranes of Avalonian affinities, i.e. made up of Neoproterozoic high-grade metamorphic rocks unconformably overlain by a Devonian–Carboniferous envelope, can be recognized (Oliver et al. 1993). Among them, the Brunovistulian Terrane, including its Moravo–Silesian metamorphic counterparts (Kalvoda et al. 2008 and references therein) occupies the eastern Bohemian Massif and the Eastern Sudetes. The timing of collage of these terranes onto Baltica is still debated (for contrasting views, see Mazur et al. 2006; Nawrocki and Poprawa 2006). Orthogneisses interleaved with paragneisses and amphibolites yield Ediacaran to Cambrian ages (Oliver et al. 1993). Non-A-type Strzelin–Nowolesie orthogneisses, SW Poland, have zircon crystals with older inherited cores, igneous rims at 600 ± 7 Ma and metamorphic overgrowths at 568 ± 7 Ma (Oberc-Dziedzic et al. 2003). The latter age is reminiscent of the 567 ± 5 Ma igneous age of A-type metagranite exposed as small massifs within the *c.* 600–580 Ma Thaya Batholith, Austria (Friedl et al. 2004). These Ediacaran ages correspond to post-orogenic processes occurring after the Cadomian orogeny. A-type Gosciecice and Stachów–Henryków orthogneisses, SW Poland, yield, respectively, igneous ages of 504 ± 1 Ma and 500 ± 5 Ma (Drumian–Guzhangian) (Oberc-Dziedzic et al. 2005), coeval to the beginning of Rheic Ocean drifting. A-type metagranites, carrying both hypersolvus (Rudná-type) and subsolvus (Polanka-type) alkali feldspar assemblages, occur as yet undated small masses within the Desná Unit, Czech Republic. A Carboniferous age was assumed on the basis of too low $^{87}Sr/^{86}Sr$ ratios corrected to Ediacaran times (Hanžl et al. 2007), but this is questionable for low-grade cataclastic rocks (see above). In any case, high Nd isotopic ratios indicate juvenile magmas.

Early Paleozoic rocks are rare, only one basalt vein was dated by K-Ar at 438 ±16 Ma (Llandovery), substantiating Silurian igneous activity. Cooling ages of 487–420 Ma recorded by detrital white mica and monazite occurring within Devonian–Carboniferous sedimentary formations document, however, an important igneous and/or thermal activity in the source area during the Ordovician–Silurian period (Kalvoda et al. 2008). The Devonian Moravo–Silesian Basin is filled up with Emsian–Famennian shallow marine sedimentary formations and submarine to subaerial volcanic formations. Two discrete belts are distinguished (Janoušek et al. 2006). The western belt is characterised by abundant metasediments accompanied by submarine basic–intermediate calc-alkaline volcanites, with subordinate felsic types, suggesting a volcanic-arc setting above a subduction zone. The eastern belt displays abundant, partly subaerial, alkali basalt–A-type rhyolite volcanic suite, with a high proportion of Frasnian felsic products and dykes (rhyolite–comendite–pantellerite) crosscutting the Proterozoic basement. Late tholeiitic dolerite dykes and sills complete the igneous association. The within-plate settings indicate a continental passive margin subjected to extensional regime, perhaps under the influence of a nearby subduction zone (Patočka and Valenta 1996). As the Devonian basins within the Brunovistulian Terrane seem to have rotated *c.* 90° clockwise at the Devonian–Carboniferous boundary, the original orientation of the volcanic belts and the sedimentary basins should have been E–W, but their exact configuration remains unclear.

In Germany, Eastern Avalonia consists of inliers covered by the Mesozoic–Cenozoic sedimentary cover. It comprises the Rheno-Hercynian Zone (Kossmat 1927) and exotic terranes, including the Harz Mountains. From contradictory statements in etymological dictionaries, it appears that the classical term “Hercynian” could either come from, or be the origin for, the name of Harz, which formed a part of the larger Hercynian Forest described in the Antiquity. The Rheno-Hercynian Zone in Belgium and Germany is characterized by plateaux dissected by river valleys, among which the “Rheinisches Schiefergebirge” exposes autochthonous folded–faulted Palaeozoic sedimentary series, overthrusted by Giessen–Harz Nappe and other allochthonous slices. Autochthonous units represent the sedimentary cover of the former southern passive margin of Avalonia facing the Rheic Ocean, whereas allochthonous units are composed of dismembered oceanic flysch basins formed during the progressive Rheic oceanic closure (Huckriede et al. 2004).

No basement formations older than Devonian are exposed within the "Rheinisches Schiefergebirge". The autochthonous sedimentary series comprises Devonian deltaic, shallow and deep marine sequences, with local development of reefs, and Lower Carboniferous turbidites. Within-plate igneous activity is documented by Devonian (Flick et al. 2008) and Carboniferous (Salamon et al. 2008) volcanic events. The first Givetian–Frasnian event consists of 389–384 Ma episodes dated by conodont zones. It involved submarine eruptions of basanite–alkali basalt–trachyandesite pillow lavas and hyaloclastites forming large seamounts. Emerged islands display additional trachyte and A-type rhyolite lava flows, pyroclastites and domes. Subsequent events erupted only submarine mafic products, i.e. Famennian primitive basanites–alkali basalts, Tournaisian–Visean tholeiitic picrites–basalts and, ultimately, Visean primitive alkali basalts crowded with xenoliths of possible upper mantle origin, and no felsic differentiates.

Numerous boreholes through the Mesozoic–Cenozoic Northeast German Basin have reached or even perforated a *c.* 2000 m-thick Late Carboniferous–Early Permian volcanic succession (Benek et al. 1996). Based largely on lithostratigraphic correlations, five episodes, yet undated by radiometric techniques, are documented from the Ghzelian, i.e. slightly before the Carboniferous–Permian boundary, to the Sakmarian–Artinskian boundary. They accompanied extensional settings within the Pangaea super-continent. East Brandenburg yields an enigmatic, presumably Asselian, (trachy-) andesite–(trachy-) dacite magnesian suite that straddles the alkaline–subalkaline boundary in the total alkali–silica diagram (Rickwood 1989 and references therein). Ghzelian–Sakmarian tholeiitic dolerites–basalts, with depleted to enriched MORB-like compositions, are coeval to basalt–trachyandesite–trachyte–A-type rhyolite ferroan alkaline suites and were postdated by Late Sakmarian basanites–trachybasalts. A-type rhyolites, forming up to 70 % of the *c.* 48 000 km^3 volume of the Northeast German Basin volcanics, occur as ignimbrites (Benek et al. 1996) or lava domes (Paulick and Breitkreuz 2005). The U-Pb zircon igneous ages, bracketed between 300 and 297 ± 3 Ma, substantiate a very short-lived episode close to the Carboniferous–Permian boundary, though dated samples do not cover the entire range of volcanic activity in the Northeast German Basin. The mean extrusion rate was estimated at about 0.01 km^3.a^{-1}, corresponding to a magma production rate in the order of 0.1 km^3.a^{-1} (Breikreutz and Kennedy 1999). Thermal subsidence in the Northeast German Basin, slow during the Permian, increased abruptly at the Permian–Triassic boundary. The complete absence of post-Permian igneous activity was related to cooling and thickening of the continental lithosphere (Benek et al. 1996).

Allochthonous units display neither Proterozoic nor Early Paleozoic basements. They are essentially made up of metamorphosed Devonian–Carboniferous sedimentary units, with very few occurrences of metabasalts. Detrital zircon grains yield dominant Precambrian and rare Silurian–Early Devonian igneous, not metamorphic ages, implying that the sedimentation never took place before 410 ± 10 Ma (Geisler et al. 2005). Pelagic sediments are associated with turbidites, like the non-metamorphosed successions observed in autochthonous units. The Giessen–Harz Nappe contains N-MORB tectonic slices overlain by extremely condensed Devonian radiolarian cherts and pelagic shales, implying an oceanic provenance (Huckriede et al. 2004). A-type granite complexes and the coeval Harzburg layered igneous body, which the term "harzburgite" comes from, are exposed in the Harz Mountains, or were drilled near Flechtingen (Baumann et al. 1991, Förster and Tischendorf 1996). In the Flechtingen inlier, a bimodal trachyandesite–rhyolite igneous suite was emplaced as sills and ignimbritic sheets (Breitkreuz and Kennedy 1999). The U-Pb zircon igneous ages of 302 ± 3 Ma (ignimbrite), 295 ± 1 Ma (Oker granite), 294 ± 1 Ma (Harzburg gabbronorite) and 293 ± 3 Ma (Brocken granite) with K-Ar biotite cooling ages of 298 ± 5 Ma (Flechtingen granite) and 296 ± 10 Ma (Ramberg granite) document again a short-lived episode close to the Carboniferous–Permian boundary, in agreement with the U-Pb zircon 296 ± 1 Ma and titanite 295 ± 1 Ma cooling ages recorded in hornfels aureoles. Major- and trace-element compositions indicate A-type post-orogenic settings (for a review, see Förster and Tischendorf 1996).

4.4. The Armorican Terrane Assemblage

The Armorican Terrane Assemblage (ATA) is a part of the Hunic Superterrane (Stampfli et al. 2004). It occupies a nearly 1000 km-wide area throughout central and southern Europe and is bordered to the south by tectonic units (Rif, Kabylies) overthrusted onto the North African Gondwana shelf during Neogene times (Jolivet and Faccenna 2000). The current configuration differs strongly from the original setting, because the Armorican Terrane Assemblage was dismembered and recomposed by wrench and transcurrent shear zones.

A-type igneous suites exposed in Alpine-related realms have been reviewed elsewhere (Bonin et al. 1998 and references therein). The most voluminous suites were emplaced well after Pangaea welding and predate continental break-up and Neo-Tethys Ocean development during the Mesozoic. Corsica provides a unique example yielding two discrete igneous episodes separated by a period of quiescence. The first was Permian at 275 ± 10 Ma (Artinskian–Wordian) and the second Triassic at 245 ± 10 Ma (Induan–Anisian), followed ultimately by a thermal event at *c.* 200 Ma (Triassic–Liassic boundary) (Bonin et al. 2008, and references therein). Silica-oversaturated to undersaturated complexes, e.g., Monzoni–Predazzo and Karavanken in Southern Alps, Ditrău in Eastern Carpathians, yield Ladinian (*c.* 237–232 Ma) ages.

Such a sequence is unknown in the ATA that was unaffected by Alpine tectonics. The Mid-German Crystalline Zone and the Saxo-Thuringian Zone will be reviewed hereafter. The Mid-German Crystalline Zone (MGCZ) constitutes a SW–NE trending belt of crystalline rocks that are exposed in various inliers in Pfalz and form the massifs of Odenwald, Spessart, Ruhla and Kyffhäuser. The MGCZ was penetrated by drill holes in the Saar–Nahe Basin and other sedimentary troughs to the NE and could extend southwestwards to Cornwall (Dörr et al. 1999) and even Spain. It is currently considered as a part of the Rheic suture zone between the Eastern Avalonia and the Saxo-Thuringian Zone, which belongs to the ATA.

Post-Cambrian metasedimentary units yield both Gondwana and Baltica affinities (Gerdes and Zeh 2006). Intercalated metabasalts are mainly calc-alkaline with an island-arc signature, whereas MORB signatures are scarce. Such features suggest that the composite terrane could correspond to an accretionary prism close to the suture zone. Early Devonian orthogneisses intercalated with IAB-like metabasalts yield volcanic arc signatures, such as the 413 ± 5 and 398 ± 3 Ma members of the Central Gneiss Unit, Ruhla (Brätz 2000). From the Devonian–Carboniferous boundary onward, all orthogneissic and metasedimentary formations followed a clockwise P-T-t metamorphic evolution associated to ductile deformation before and during emplacement of post-collisional 360–325 Ma (Tournaisian–Serpukhovian) high-K calc-alkaline suites (Reischmann and Anthes 1996; Altherr et al. 1999; Zeh et al. 2005).

A-type igneous suites span the entire Cambrian–Permian range of time. The 489 ± 1 Ma (Cambrian–Ordovician boundary) Volkach syenite, revealed by drilling east of Spessart, yields the oldest age (Anthes and Reischmann 2001) and a Bulk Silicate Earth (BSE) isotopic signature (Anthes 1998); it was coeval to Rheic Ocean development. Late Silurian alkali-calcic orthogneisses of A-type affinities include the 426 ± 4 Ma Silbergrund gneiss and the 423 ± 6 Ma Erbstrom gneiss, Ruhla (Brätz 2000), the 418 ± 18 Ma Rotgneiss (Okrusch and Richter 1986) and the 410 ± 18 Ma Haibach gneiss, Spessart (Dombrowski et al. 1995). Early Devonian alkali-calcic A-type orthogneisses comprise the 405 ± 3 Ma Böllstein orthogneiss, Odenwald (Reischmann et al. 2001), and the 400 ± 4 Ma Steinbach augen gneiss, Ruhla (Brätz 2000). All igneous suites were emplaced in a continental area experiencing tensional regimes and located far from the active margin of the ATA. The *c.* 344 Ma (Visean) Darmstadt albite granite, Odenwald, is unique during the Early Carboniferous, with its A-type composition and a BSE isotopic signature (Anthes 1998).

A short-lived within-plate igneous episode at the Carboniferous–Permian boundary is documented by trachybasalt–trachydacite–A-type rhyolite igneous suites of the Halle Volcanic Complex (Romer et al. 2001) and the Saar–Nahe Basin as well as by the plutonic suite of the Ruhla inlier (Zeh and Brätz 2002). A-type rhyolite occurs as laccolith units (Breitkreuz and Mock 2004) emplaced in discrete pulses from the Middle Pennsylvanian to the Sakmarian at 307 ± 3 Ma, 301–298 ± 3 Ma and 294 ± 3 Ma (Breitkreuz and Kennedy 1999). Intense volcanic activity, with magmas ranging from basalt to trachyte and A-type rhyolite, took place in the Saar–Nahe Basin during the 296–293 Ma (Asselian–Sakmarian) period of time. Intrusions, extrusions, diatremes, lava flows and ignimbrites are exposed in a half-graben bounded to the north by a detachment fault parallel to the Avalonia–Armorica plate boundary (for a review, see Lorenz and Haneke 2004). As shown by major- and trace-element whole-rock chemical data (Brätz 2000), the Ruhla plutonic suite, emplaced under a transcurrent ductile–brittle shear regime, includes a monzonite–syenite feldspar cumulate body (the so-called Trusetal granite), monzodiorite (Brotterode diorite), A-type granites (Ruhla and Eselsprung granites) and granite porphyry dykes. Intrusive episodes yield mean ages of *c.* 305 Ma (Eselsprung granite, Brätz 2000), 301 ± 5 Ma (Trusetal granite), 295 ± 5 Ma (Ruhla granite and granite porphyry dykes), 289 ± 5 Ma (Brotterode diorite) and 285 ± 5 Ma to 277 ± 7 Ma (late granite porphyry dykes), in agreement with field evidence and Ar-Ar cooling ages in the metamorphic country rocks (Zeh et al. 2000).

The Saxo-Thuringian Zone represents a continental part of the ATA. In Saxony and Thuringia, each of them representing a *locus typicus* defining the Saxo-Thuringian Zone, A-type granite suites are fairly well represented during the Paleozoic. In the external domain, the Vesser MOR-related complex comprises a basalt (508 ± 2 Ma) – dacite (497 ± 2 Ma) – rhyolite volcanic suite, associated with a 502 ± 2 Ma tholeiitic gabbro–dolerite. The nearby Ediacaran sedimentary assemblages were intruded by a *c.* 490 Ma (Furongian) granite (Linnemann et al. 2007). In the internal domain, they are cut by 490 ± 3 Ma (Furongian) to 485 ± 6 Ma (Tremadocian) granites and covered unconformably by two episodes of 487 ± 5 Ma (Cambrian–Ordovician boundary) rhyolitic pyroclastic units and 479 ± 5 Ma (Tremadocian–Floian) porphyroid (Linnemann et al. 2007). During the Carboniferous, contrasting igneous suites emplaced under shear stress regimes that changed abruptly from the 340–330 Ma (Visean) high-K Meissen granite association, related to dextral strike-slip movement of the Elbe Fault Zone, to the 327 ± 4 Ma (Visean–Serpukhovian boundary) Markersbach A-type granite, showing no strike-slip influence (Hofmann et al. 2008). This A-type Li-mica-bearing granite (Förster and Tischendorf 1996; Förster 2001) shares the same A-type affinities with the Sudetic 319–314 ± 4 Ma Karkonosze and 309 ± 2 Ma Strzegom-Sobotka granite massifs, as well as bimodal trachybasalt–trachyandesite–trachydacite–rhyolite volcanic suite (Mazur et al. 2007). Younger volcanic activity took place at the Carboniferous–Permian boundary, as shown by the 308 ± 1 Ma Teplice–Altenberg rhyolitic caldera (Förster et al. 1995), the younger, yet undated, Zinnwald–Cínovec zinnwaldite-albite granite and the 297 ± 8 Ma rhyolite dykes within the Eibenstock Pluton (Kempe et al. 2004). Later on, two eruptive episodes are documented in the Lower Rotliegend molasse of the Saxonian Sub-Erzgebirge Basin. A pyroxene quartz porphyry yielded an age of 296 ± 2 Ma (Förster and Tischendorf 1996), and ”lower series“ rhyolites 278 ± 5 Ma (Nasdala et al. 1998), substantiating diachronous activity throughout the large intermontane basin.

5. Summary and conclusions

A-type granite igneous complexes are fairly abundant within the Variscan–Alpine Europe (Tab. 3). However, discrete ages of emplacement document geodynamic settings varying from post-orogenic, through intra-continental rifting to passive margin tectonic regimes. They thus illustrate a repeated history of continental breakup and oceanic basin development followed by oceanic closure and post-collisional transcurrent displacement.

At the end of the Neoproterozoic, Laurentia developed a passive margin toward the Iapetus Ocean, whereas the Cadomian–Pan-African orogenic episode had its climax within Gondwana at about 600 Ma (Ediacaran). Ediacaran to Early Cambrian A-type granites, occupying pieces of consolidated Gondwana basement, display early anorogenic features associated with the birth of the Rheic Ocean.

The incipient drifting of the Rheic Ocean was followed within the Armorican Terrane Assemblage by a major 485 Ma (Tremadocian) rifting and igneous event characterized by A-type suites now converted into orthogneisses (metagranites), amphibolites (metabasalts) and leptynites (metatrachytes–metarhyolites) in the internal parts of the Variscan belt. The further development of the Rheic

Tab. 3 Representative A-type igneous episodes within the Variscan–Alpine Europe

Period	Stage	Age (Ma)	Laurentian margin		Eastern Avalonia		Armorican Terrane Assemblage	
Triassic	Induan–Anisian	250–230					Corsica Monzoni–Predazzo Ditrău, Romania	Intra-continental rift
Permian	Artinskian–Wordian	285–265					Saar–Nahe Basin, W Mediterranean Province	Intra-continental rift
	Asselian–Sakmarian	302–293			NE German Basin, Harz	Intra-continental rift	Halle, Saar–Nahe basins, Ruhla	Intra-continental rift
	Serpukhovian–Moscovian	327–309					Saxo-Thuringian	Intra-continental rift
Carboniferous	Tournaisian	345	Midland Valley	Intra-continental rift				
Devonian	Givetian–Frasnian	389–384			Rheinisches Schiefergebirge	Rheic Ocean passive margin		
	Pragian	408–400	Grampian	Post-Scandian episode			Mid-German Crystalline Rise	Intra-continental rift
Silurian	Telychian–Lochkovian	426–410					Mid-German Crystalline Rise	Intra-continental rift
	Llandovery–Wenlock	440–426	Moine Thrust	Scandian episode				
Ordovician	Sandbian–Katian	456	Northern Highland	Post-Grampian episode				
	Furongian–Tremadocian	490–480					Mid-German Crystalline Rise, Saxo-Thuringian	Rheic Ocean passive margin
Cambrian	Epoch 3	508–497			SW Poland	Rheic Ocean drifting	Saxo -Thuringian	Rheic Ocean drifting
Neoproterozoic	Ediacaran	570–560			Thaya, Austria	Post-Cadomian episode		
		601–588	Older Granites	Iapetus passive margin				

Ocean led to Avalonia–Laurentia collision postdated by A-type igneous episodes in Scotland. In addition, the Late Ordovician to Early Carboniferous period was marked by alkaline igneous episodes at the passive margin of Avalonia, whereas the active margin of the Armorican Terrane Assemblage was devoid of any A-type igneous events.

The Variscan collision was followed in the Armorican Terrane Assemblage by discrete post-orogenic episodes, namely 350–340 Ma (Tournaisian), 320 Ma (Serpukhovian) and 300 Ma (Ghzelian) igneous events. The 300 Ma event, widespread throughout the Variscan–Alpine Europe, constituted a climactic igneous event affecting both Avalonia and Armorican Terrane Assemblage.

Early to Middle Permian (280–260 Ma) and Late Permian to Early Triassic (250–230 Ma) A-type provinces were emplaced in the southernmost parts of the Variscan–Alpine Europe. They accompanied incipient Pangaea breakup and heralded the future birth of the Neo-Tethys Ocean, which started by the 200 Ma Central Atlantic Large Igneous Province.

A-type granite events provide space and time clues to discrete Ediacaran to Triassic episodes, during which Pannotia broke up, Gondwanan terranes were amalgamated onto Baltica and, ultimately, Pangaea broke up. They identify waning orogenic stages, corresponding to orogenic belt collapse, transcurrent movements along transform fault zones and subsequent peneplanation, as well as pre- to early oceanic stages, corresponding to extensional reactivation of shear zones, incipient rifting and passive margin development. Their occurrences are, therefore, especially helpful for recognition of terrane boundaries and palinspatic reconstructions.

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