



## Editorial

## IGCP Project 510 “A-type Granites and Related Rocks through Time”: Project vita, results, and contribution to granite research

### 1. Introduction

The IGCP 510 project *Global Correlation of A-type Granites and Related Rocks, their Mineralization, and Significance in Lithospheric Evolution* (or, in short, *A-type Granites and Related Rocks through Time*) of the International Geoscience Programme was developed in the period of 2005 to 2010 with the sponsorship of the International Union of Geological Sciences (IUGS) and United Nations Educational, Scientific and Cultural Organization (UNESCO). The project assembled participants from forty-two countries. The general goals of the project focus on correlating the petrology, geochronology, geochemistry, and metallogeny of A-type granites found in various tectonic settings throughout geologic time and on a global scale. Specific themes that were investigated included:

- (1) Age distribution, petro-tectonic associations, and genetic models of A-type granites and related rocks;
- (2) Their significance in metallogeny;
- (3) Their bearing on granite typology and evaluation of hitherto proposed classifications; and
- (4) Their overall role in the evolution of the Earth's lithosphere.

It was evident at the end of the project that it produced many relevant contributions to the proposed themes and that significant advances were made in the characterization of different types of A-type granites and related rocks and in the understanding of their origin and metallogeny. However, not all issues were resolved. In particular, the definition and usage of the term “A-type granite” continue to cause some ambiguities (cf. [Section 2](#)). The current classification schemes of A-type granites can be confusing and so complex as to be difficult to apply. Nevertheless, it is also clear that the increasing number of publications on the classification and origin of granites serves to emphasize that A-type granites include a spectrum of rocks, both in terms of composition and origin. The studies resulting from this project serve to reinforce the classic words of Prof. Read: ‘*There are granites and granites*’ ([Pitcher and Berger, 1972](#)).

In the last meeting of the project at Helsinki in August 2010, it was decided to prepare a special issue of an international journal assembling the contributions presented at that gathering. The present issue of *Lithos* was co-edited by three of the leaders of the IGCP 510 project. It represents the final scientific contribution of the collaborative project.

The first paper of the present volume is an essay by the co-leaders of the IGCP 510 project that summarizes the main achievements of the project and discusses several relevant aspects of A-type granites. This synthesis reflects largely the scientific thinking of the authors

but attempts to summarize the major contributions to the central subject obtained during the project execution. We hope that this work will be useful to researchers on A-type granites and related rocks.

The original research papers of this special issue explore A-type granites or related rocks found in different continents and with ages varying from the Archean to the Phanerozoic. These papers discuss the role in the crustal evolution, petrology and metallogeny of A-type granites.

Heinonen et al. report on a manifestation of Mesoproterozoic intraplate magmatism in the northern Amazonian craton, which includes the only massif anorthosite identified in the craton to date. The ca. 1525 Ma Mucajaí complex is composed of rapakivi granite and subordinate monzonite, syenite, and anorthosite. This complex was emplaced into Proterozoic rocks over a short period (no more than 12 million years). The authors attribute the limited heterogeneity in isotopic compositions of the rocks of the complex to contamination of the parent magmas by the upper crust into which the magmas were emplaced.

Robert F. Martin delivers a follow-up of his recent ([Martin, 2006](#)) paper that introduced the “lower crust fertilization” model for the generation of A-type granites from a lower crustal source preconditioned by fluids emanated from degassing mantle in an extensional (post-delamination) tectonic setting. In this paper, Martin presents long-dormant experimental evidence (acquired under polybaric, high-T, H<sub>2</sub>O-saturated conditions induced upon a substantial thermal gradient) in favor of the model. He concludes that, in the presence of an excessive H<sub>2</sub>O–CO<sub>2</sub> fluid, incompatible elements derived from a degassing mantle in a lithospheric delamination regime metasomatize the lower crust into A-type granite composition, which in turn melts more or less completely to yield A-type melts and respective crystalline solids (A-type granite, quartz syenite) as the melts solidify at the level of emplacement. The model also has implications regarding the origin of high-Al basalt magmas, anorthositic cumulates, and cryptic contamination of associated mantle-derived melts. Martin's paper is a fresh contribution to the petrogenesis of A-type granites and related rocks and urges further studies on the physical relevance of H<sub>2</sub>O-enriched fluids and dynamics of high-fraction melting in the upper mantle–lower crust environment.

Andersen et al. present a description of the mineralogy and petrology of the Jurassic, anorogenic Mt Gibraltar microsyenite of New South Wales, Australia. This small intrusive body of hypersolvus microsyenite consists of intermediate alkali feldspar with minor titanomagnetite and interstitial pyroxene. It is crosscut by an

irregular system of late-magmatic veins consisting of homogeneous alkali feldspar ( $\approx \text{Ab}_{50}\text{Or}_{50}$ ), clinopyroxene evolving from sodic hedenbergite to zirconium-rich aegirine, arfvedsonite and siderite. The authors demonstrate that the veins crystallized at very low oxygen fugacity, at moderately elevated peralkalinity and intermediate silica activity. These conditions prevented crystallization of magmatic zircon or more exotic Zr silicates and made possible the formation of magmatic siderite, a unique occurrence in peralkaline, igneous rocks. Zirconium is camouflaged in pyroxene and amphibole because of an uncommon combination of high sodium silicate activity and very low oxygen fugacity.

Feio et al. describe one of the relatively rare Archean A-type granite suites. Their study presents petrographic, elemental geochemical, Nd isotope geochemical, and U–Pb zircon geochronological data on the Neoproterozoic, syntectonic Planalto igneous suite in Carajás, Amazonian craton (east-central Brazil). They show that the granites, charnockites, and a gabbroic rock of the suite all were emplaced within  $2730 \pm 10$  Ma. The Planalto granites are hydrated charnockites that have the geochemical characteristics of A-type granites but, according to the authors, are related to regional deformation—that is, transpression related to tectonic inversion. The authors suggest that upwelling of the asthenosphere during regional extension provided the heat that  $\sim 30$  m.y. later resulted in partial melting of a mafic-intermediate tholeiitic magma source in the lower crust.

Lauri et al. review Early Paleoproterozoic felsic and mafic magmatism in the Karelian province of the Fennoscandian shield. These authors relate the bimodal Kianta complex to an extensional event in the Archean Karelia craton. They propose that emplacement of the mafic layered intrusions in the crust caused heating and induced the partial melting of the Archean lower crust to form the A-type granite and subsidiary syenite of the complex. Although the Kianta complex has a different age, the authors suggest that its formation is analogous to that of the Bushveld complex, which is seen as a similar magmatic association.

Elburg et al. present a detailed study on Mesoproterozoic A-type granites intruded by 455 Ma granites in order to evaluate the role of Mesoproterozoic granites in the formation of Fe-oxide-U-REE ores during the Phanerozoic. The older rocks have geochemical affinities with A-type granites and compose part of the Mt Painter–Mt Babbage Inliers, in the Gawler craton, South Australia. The authors evaluate new Lu–Hf data on zircon, whole rock geochemistry, and Sm–Nd isotope data, together with previous field, metallogenetic and geochronological information, and conclude that the Mesoproterozoic granites are suitable sources for the Iron oxide–copper–gold (IOCG)-type mineralization. Their work demonstrates that zircon studies can be a successful approach for identifying the protolith of strongly metasomatised rocks.

Breiter reviews the nearly contemporaneous A- and S-type granites in the classical Erzgebirge tin province of central Europe. He highlights the geochemical and mineralogical contrasts between the strongly peraluminous P, F, Li, Rb, Cs, U, Sn-rich (S-type) granites and the slightly peraluminous F, Li, Rb, Cs, Sn, Zr, Y, HREE-rich and P-poor A-type granites. The author shows that both granite magmas were intruded in rapid succession over a period of about 10 Ma (about 330–320 Ma). The author proposes that the magma sources for the two types of granites were probably a mixture of fertile quartz-feldspathic rocks and micaceous metapelites enriched in LILE and Sn + W. Variation in the proportions of the source components, contrasts in pressure and temperature of melting and in the degree of metamorphic dehydration of the source may account for the differences between the S-type and A-type magmas. This paper points out the coexistence of A-type granites with dominant S-type granites in collisional tectonic settings, an environment for the formation of A-type granites that may deserve further examination and study.

Alirezai and Hassanzadeh describe the 288 Ma Hasarobat granite, which was emplaced into Neoproterozoic to Phanerozoic rocks of the

Sanandaj-Sirjan metamorphic–plutonic belt of west-central Iran. This small,  $\sim 20$  km<sup>2</sup> pluton has the high iron/magnesium ratio and other geochemical characteristics typical of A-type granites. It is intruded by mafic dikes. The authors link this bimodal association to extension and breakup of Gondwana, and interpret the Hasarobat granite as constraining the timing of the opening of the Neotethys Ocean in present-day Iran.

## 2. Results of IGCP-510: A-type granites and related rocks

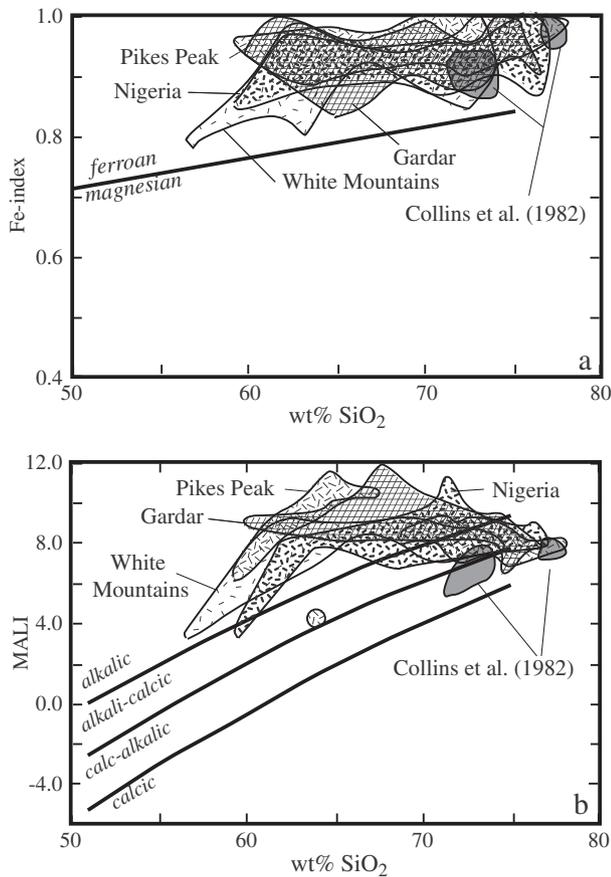
### 2.1. Characteristics of A-type granites

The term “A-type granite” was first defined by [Loiselle and Wones \(1979\)](#), who identified a previously unrecognized group of iron-enriched granitoids that occur in intra-continental environments (see also [Bonin, 2007](#); [Eby et al., 1992](#)). These authors defined A-type granitoids chemically as containing high Fe/(Fe + Mg), high K<sub>2</sub>O and K<sub>2</sub>O/Na<sub>2</sub>O, high incompatible trace element contents (including REE, Zr, Nb and Ta), and low concentrations of trace elements compatible in mafic silicates and feldspars. [Loiselle and Wones \(1979\)](#) identified as type examples granitoids from the Pikes Peak batholith of Colorado, USA, the White Mountain Magma Series of New Hampshire, USA, the Nigerian Younger Granites, and the Gardar Province, Greenland.

Although the definition of A-type was specific in this original abstract, referring to low H<sub>2</sub>O and low oxygen fugacity granitoids derived from an alkali basalt parental magma, the term has subsequently been applied to a much broader spectrum of granitic compositions. [Collins et al. \(1982\)](#) proposed that the Gabo, Mumbulla, Monga and Wangrah suites of southeastern Australia were A-type on the basis of their high (K<sub>2</sub>O + Na<sub>2</sub>O)/Al<sub>2</sub>O<sub>3</sub> ratios, but defined the group mainly on trace element characteristics including high Nb, Ga, Y and REE. High Ga/Al ratios were suggested to be diagnostic of A-type granitoids, a feature that [Whalen et al. \(1987\)](#) incorporated into discrimination diagrams involving Ga/Al and Zr, Nb, Ce and Y. Using the classification of [Frost et al. \(2001\)](#), it is clear that the Australian examples of A-type granitoids are distinct from the suites that were originally used to define the term ([Fig. 1](#)). The Australian examples are ferroan, like the examples cited by [Loiselle and Wones](#), but they are less strongly alkalic. Most of the [Collins et al. \(1982\)](#) A-type granitoids are calc-alkalic, not alkalic to alkali-calcic like those identified by [Loiselle and Wones](#). In addition, they tend to include peraluminous as well as metaluminous rocks.

[Eby \(1990, 1992\)](#) subdivided A-type granitoids into two groups on the basis of trace element abundances, particularly the Y/Nb ratio. The group with lower Y/Nb ratios (group A1, with Y/Nb < 1.2) includes felsic rocks from oceanic islands and continental rifts; these granitoids were suggested to form from an oceanic island basalt source in an intraplate or rift setting. The group with higher Y/Nb (group A2, with Y/Nb > 1.2) was proposed to form by a number of different mechanisms: from an island arc or continental margin basalt source, or from crustal sources such as tonalite or granodiorite, or by partial melting of crust from which a melt was previously extracted ([Eby, 1992](#)). In addition, crustal contamination of A1 group granitic magmas may increase Y/Nb such that they plot in the A2 field ([Eby, 1992](#)). A1 granitoids are ferroan and metaluminous, and are dominantly alkalic and alkali-calcic. Of [Loiselle and Wones'](#) examples, the White Mountain and Nigerian granites belong to the A1 group, as do the sodic series of Pikes Peak granites and some Gardar granites ([Eby, 1990](#); [Goodenough et al., 2000](#); [Smith et al., 1999](#)). A2 granitoids include a greater diversity of compositions, from metaluminous to peraluminous to peralkaline, and from alkalic to calc-alkalic. The potassic series of Pikes Peak granites and some Gardar granites belong to group A2 ([Marks et al., 2003](#); [Smith et al., 1999](#)).

[Anderson and Bender \(1989\)](#) noted that most of the A-type granitoids from the southwestern USA contained magnetite. [Dall'Agnol](#)



**Fig. 1.** Compositions of granites used to define A-type granite by Collins et al. (1982) and Loiselle and Wones (1979). a. Fe-index =  $(\text{FeO} + 0.9\text{Fe}_2\text{O}_3)/(\text{FeO} + 0.9\text{Fe}_2\text{O}_3 + \text{MgO})$  versus  $\text{SiO}_2$ ; boundary between ferrous and magnesian rocks from Frost and Frost (2008) b. MALI (modified alkali lime index;  $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ ) versus  $\text{SiO}_2$ , boundaries between calcic, calc-alkalic, alkali-calcic and alkalic granitoids from Frost et al. (2001).

and Oliveira (2007) called these and other similar magnetite-bearing granitoids “oxidized A-type” granitoids. These granitoids are less strongly ferroan, mainly calc-alkalic, and commonly peraluminous. The “oxidized A-type granites” are more magnesian than the strongly reduced A-type granitoids identified by Loiselle and Wones (1979), and hence crystallized at a higher oxygen fugacity. However, they are generally less oxidized than magnesian granitoids.

Some A-type granitoids exhibit a distinct rapakivi texture, in which rounded crystals of orthoclase are mantled with oligoclase. The classic rapakivi granite complexes are in Finland (Haapala and Rämö, 1992), but rapakivi granites has been recognized worldwide. The Finnish complexes are ferroan, alkali-calcic, and dominantly metaluminous (Rämö, 1991).

Because the common feature of all these A-type granitoids is their ferroan composition, Frost and Frost (2011) suggested that “ferroan” is a synonym for A-type granites.

## 2.2. Classification of A-type granites

Frost and Frost (2008) and Frost et al. (2001) showed that indices based upon major elements are surprisingly powerful in distinguishing groups of granitic rocks. They suggested that major element compositions may be the most appropriate basis for granitoid classifications, because unlike basalts, trace elements in granitic rocks commonly are not incompatible (Bea, 1996). Elements such as REEs, U, Th, and Zr reside in minor mineral phases such as apatite, zircon, titanite, allanite and monazite. Other trace elements, including Nb

and Y, are concentrated in oxides and amphiboles, among other minerals, and their abundances may reflect crystallization history and intensive parameters (oxygen and water fugacity) as much as the composition of the parental magma. Crustal contamination also commonly has a much larger influence on the trace element abundances of a granitic melt than on its major element compositions. Thus, reliance on trace element abundances and ratios as discriminators in granitoid rocks may not unambiguously identify magma source or tectonic setting.

Discrimination based upon four major element indices, including  $\text{Fe}^*$  (ferroan versus magnesian), MALI (modified alkali-lime index), ASI (aluminum saturation index), and AI (alkalinity index), (Frost and Frost, 2008; Frost et al., 2001) can be used to recognize eight types of A-type granitoids (Table 1). These include alkalic granitoids that may be metaluminous or peralkaline, alkali-calcic granitoids that may be metaluminous, peraluminous or peralkaline, calc-alkalic granitoids that may be metaluminous or peraluminous, and rare calcic ferroan granitoids.

## 2.3. Petrogenesis of A-type granites

Many origins have been proposed for A-type granitoids, which is not surprising in light of the varying geochemical composition of these ferroan rocks. Loiselle and Wones (1979) suggested that they form by fractionation of mantle-derived alkali basalt, with or without crustal interaction. They proposed that the crustal component may be granulite facies lower crust that had undergone a previous partial melting episode, an idea based on Barker et al.’s (1975) study of the Pikes Peak batholith in which such a contaminant was hypothesized. Collins et al. (1982) suggested that melting of this residual felsic granulite source alone may produce A-type granitoids. They proposed that high temperature, vapor-absent melting of such a source would generate a relatively anhydrous melt containing halides and large, high-charge cations such as Zr and REE that are abundant in A-type granitoids. However, this proposed origin is not possible for reasons presented by Creaser et al. (1991): previously partially melted crust will be depleted in silica, potassium and have lower Fe/Mg than its original protolith. Partial melts from such a source should show those major element geochemical characteristics, which are opposite to those observed in A-type granitoids. Alternatively, Anderson (1983) suggested that the major element compositions of A-type granitoids may be derived by partial melting of quartz diorite, tonalite, and granodiorite. Creaser et al. (1991) argued that 15% to

**Table 1**  
Varieties of A-type granitoids.

Alkali-lime index	Aluminum saturation	Example	Reference
Alkalic	Metaluminous	Bjerkreim-Sokndal, Norway	(1)
	Peralkaline	Lireui, Nigeria	(2)
Alkali-calcic	Metaluminous	Sherman granite, Wyoming USA	(3)
	Peraluminous	Lincoln granite, Wyoming USA	(3)
Calc-alkalic to alkali-calcic	Peralkaline	Brandberg, Namibia	(4)
	Metaluminous	Granophyres of Skaergaard, Greenland	(5)
	Metaluminous to mildly peraluminous	Mumbulla suite, Australia	(6)
Calcic	Metaluminous	Carajás, Brazil Red Hill granophyres, Australia	(7)

References: (1) Duchesne and Wilmart (1997), (2) Jacobson et al. (1958); Orjaka (1986), (3) Frost et al. (1999), (4) Schmitt et al. (2000), (5) Wager and Brown (1967), (6) Collins et al. (1982); Dall’Agnol and Oliveira (2007), (7) McDougall (1962).

40% melting of such a source could produce the appropriate water contents and geochemical characteristics of many A-type granitoids.

Taken together, these studies suggest three main petrogenetic processes produce ferroan granitic compositions:

- Partial melting of quartzofeldspathic crustal rocks,
- Differentiation of tholeiitic or alkali basaltic magmas,
- A combination of the first two models, in which differentiating basaltic magmas assimilate crustal rocks.

These processes may account for the full range of A-type granitoid compositions: extreme differentiation of basaltic melts results in ferroan granitoids that are either peralkaline alkalic and alkali-calcic, or metaluminous alkalic, alkali-calcic, and calc-alkalic. The pressure of differentiation can be an important control on alkalinity, which increases with increasing pressure. Partial melting of tonalitic to granodioritic crust produces alkali-calcic to calc-alkalic granitoids that are metaluminous at low pressures and peraluminous at high pressures (Frost and Frost, 2011). The oxygen fugacity and water content of the crustal melts also influence the composition of the resulting granitoids (Dall'Agnol and Oliveira, 2007). It is likely that most ferroan granitoids formed by a combination of these two processes. Below we describe the varieties of A-type granitoids, their geologic context, and their likely petrogenesis.

### 2.3.1. Alkalic metaluminous granitoids

Many alkalic, metaluminous ferroan granitoids are associated with massif anorthosites and layered mafic intrusions and may be referred to as rapakivi granites because rapakivi texture is a common feature (Rämö and Haapala, 1995, 2005). The rocks associated with this group of granitoids, which are sometimes called AMCG suites for the association of anorthosite, mangerite, charnockite and granite (Emslie, 1991), cover a wide range of silica contents. The most silica-poor portions of this suite are ferrodiorite and monzodiorite. These grade into monzonites and syenites, which at higher silica contents may contain minor amounts of free quartz. True granites, some of which may be alkali-calcic, comprise only a small proportion of rock types in these suites.

Alkalic ferroan granitoids are metaluminous, presumably because assimilation of aluminous crust to make them peraluminous would also drive the granitoid compositions toward calc-alkalic. In fact assimilation of felsic crust may be responsible for the trend from alkalic to alkali-calcic compositions for some granitic bodies at high silica: the highest silica members of the Sybille and Red Mountain intrusions exhibit Nd and Sr isotopic compositions indicative of assimilation of felsic Archean crust (Anderson et al., 2003; Scoates et al., 1996).

The ferroan alkalic granitoids have been interpreted as forming by fractional crystallization of a ferrobasalt parent magma at moderately high pressure and with minor crustal contamination (Duchesne and Wilmart, 1997; Frost et al., 1999), which is consistent with their geochemical similarities to the higher pressure volcanic suites such as the lavas of the Snake River Plain (Frost and Frost, 2011).

### 2.3.2. Alkalic and alkali-calcic peralkaline granitoids

Peralkaline granitoids tend to be strongly ferroan and may be either alkalic or alkali-calcic. Some suites, such as Puklen, Kiuqi, and the Saudia Arabian granitoids, have both alkalic and alkali-calcic components. In addition, some batholiths containing peralkaline granitoids, such as Puklen and Brandberg, also include monzonitic and syenitic components and, hence have silica contents as low as 60%. Most plutons containing peralkaline granitoids also have components that are either metaluminous or peraluminous. Some of the Nigerian and Saudi Arabian granitoids, for example, are concentrically zoned and single plutons may contain metaluminous, peraluminous, and peralkaline components (Bowden and Kinnaird, 1984; Stuckless et al., 1982). The calc-alkalic Saudi Arabian granitoid samples are

peraluminous, not peralkaline (Stoeser and Frost, 2006; Stuckless et al., 1982).

It is likely that the peralkaline granitoids formed largely by differentiation of transitional or alkali basalt because peralkaline volcanic suites, such as Boina, Nyambeni, and Suswa (Barberi et al., 1975; Brotzu et al., 1983; Nash et al., 1969) have been shown to have formed by fractional crystallization of a transitional basalt (Frost and Frost, 2008). This is a manifestation of the plagioclase effect (Bowen, 1945), whereby crystallization of Ca-rich plagioclase extracts Al over Na in the melt, decreasing the alkalinity index of the magma and producing peralkaline compositions.

It is likely that the peraluminous portions of the plutons that contain peralkaline granitoids are the products of crustal melting (Frost and Frost, 2011).

### 2.3.3. Alkali-calcic metaluminous and peraluminous granitoids

As with the alkalic suites, alkali-calcic batholiths display a range of silica contents. Examples of alkali-calcic ferroan granitoids include the Mesoproterozoic San Isabel and Sherman batholiths of the southwestern USA (Cullers et al., 1992; Frost et al., 1999) and the Suomenniemi batholith of the Finnish rapakivi granite association (Rämö, 1991). The Sherman and San Isabel batholiths do have a monzonitic component (Frost et al., 1999), but most of the silica variation in the Sherman and the San Isabel is caused by a large variation in the abundance of ferromagnesian minerals in the granitoids themselves. Cullers et al. (1992) and Frost et al. (1999) argue that some of this variation is caused by incomplete mixing of basaltic magma with granitic magma. Unlike the alkalic ferroan granitoids, some of the alkali-calcic ferroan granitoids have peraluminous components. These peraluminous alkali-calcic granitoids appear to have assimilated a greater amount of felsic crust than metaluminous alkali granitoids. For example, in the Laramie Mountains of southeastern Wyoming, the alkalic Red Mountain and Sybille plutons were intruded into refractory Archean crust and only the most siliceous rocks assimilated more than 10–15% crust (Anderson et al., 2003; Scoates et al., 1996) but the alkali-calcic Sherman batholith intruded Proterozoic crust and assimilated a greater amount (Frost et al., 1999, 2002). Metaluminous alkali-calcic ferroan granitoids commonly are associated with high-silica, peraluminous granites. In the Sherman batholith, the metaluminous alkali-calcic Sherman granite is intruded by fine-grained, more siliceous, peraluminous Lincoln granite. The Lincoln granite has more radiogenic initial  $^{87}\text{Sr}/^{86}\text{Sr}$  and more negative initial  $\epsilon_{\text{Nd}}$ , indicating that it assimilated a greater proportion of older continental crust than did the Sherman granite. This is consistent with its higher silica content and more strongly peraluminous nature (Frost et al., 1999).

### 2.3.4. Calc-alkalic metaluminous and peraluminous granitoids

Unlike the other groups of ferroan granitoids, batholiths containing the calc-alkalic ferroan granitoids tend to lack low-silica members. Most calc-alkalic ferroan granitoids have high silica contents (>70%  $\text{SiO}_2$ ) and are generally characterized by lower  $\text{Al}_2\text{O}_3$  contents (12 to 13.5 wt.%  $\text{Al}_2\text{O}_3$ ) when compared with typical I-type magnesian calc-alkalic granitoid series (>14 wt.% of  $\text{Al}_2\text{O}_3$ ). They span the metaluminous/peraluminous boundary. Examples include granites from Carajas, Brazil (Dall'Agnol and Oliveira, 2007; Oliveira et al., 2009), which were interpreted to form by melting of quartzofeldspathic crust under relatively oxidizing conditions. Other examples from Australia have been attributed to partial melting of felsic granulite (Collins et al., 1982; King et al., 2001). These ferroan, calc-alkalic granitoids have compositions similar to the partial melts made experimentally by dehydration melting of granodiorite and tonalite (Patiño Douce, 1997; Skjerlie and Johnston, 1993). For example, the Carajas granite was attributed by Dall'Agnol and Oliveira (2007) to partial melting of quartzofeldspathic igneous sources. An

origin by partial melting also may explain the scarcity of intermediate and mafic members of the ferroan calc-alkalic granitoid suites.

Calc-alkalic metaluminous granitoids may also form through low-pressure differentiation of tholeiitic magmas, as in the granophyres associated with the Skaergaard intrusion. These granitoids are distinct from the metaluminous calc-alkalic granitoids produced by crustal melting in that they are likely to have extremely high Fe\*, are clearly associated with mafic intrusions and are part of a suite of rocks that extends down to low silica contents.

### 2.3.5. Calcic ferroan granitoids

Metaluminous calcic granitoids are uncommon. One example is the Red Hill dolerites, which contain granitoids that overlap from the calc-alkalic into the calcic field (McDougall, 1962). As discussed above, these calc-alkalic to calcic metaluminous granitoids form as the result of low-pressure fractionation of basalt.

## 2.4. Metallogeny of A-type granites

### 2.4.1. Introduction

The high metallogenetic potential of A-type granites was first identified in the studies on the Mesozoic Younger Granites of Nigeria (Bowden et al., 1987; Jacobson et al., 1958; Kinnaird, 1985). The fluorine-enriched peralkaline and peraluminous granites of that classic province are mineralized, in niobium and tin, respectively. The mineralizations of the Rondonian tin province in the southwestern Amazonian craton are also related to A-type granites. That province was initially considered similar to the Nigerian province (Kloosterman, 1966), but it is considerably older, having formed during the Mesoproterozoic and beginning of the Neoproterozoic, and is more akin to the rapakivi granites and AMCG assemblages of Laurentia and Fennoscandia (Bettencourt et al., 1999; Emslie, 1991; Rämö and Haapala, 1995). Large tin deposits genetically related to A-type granites have been exploited in the Rondonian province during the last forty years (Bettencourt and Dall'Agnol, 1995; Bettencourt et al., 1999, 2005). In the Amazonian craton, tin deposits associated with A-type topaz granites have been also found in the Xingu region (Dall'Agnol et al., 1993; Teixeira et al., 2002) and in the Pitinga province (Borges et al., 2009; Costi et al., 2000; Horbe et al., 1991; Lenharo et al., 2002). Similar granites, some of them with associated Sn-In mineralization, have been described in Central Brazil (Goiás tin province; Botelho and Moura, 1998; Lenharo et al., 2002; Moura and Botelho, 2000). The relationship of topaz granites to polymetallic mineralization dominated by tin was also emphasized in studies of the most evolved phases of mid-Proterozoic rapakivi granites (Haapala, 1977, 1995; Haapala and Lukkari, 2005). In summary, it is now clear that large polymetallic tin deposits are not only related to S-type granites, most generally of the high-P granite type (Bea et al., 1992; Taylor and Fallick, 1997), such as those found in the Southeast Asian Tin Belt (Cobbing et al., 1986; Schwartz et al., 1995), and Erzgebirge (Breiter, 2012-this issue; Breiter et al., 2005), but also to low-P, A-type granites, mostly of Precambrian age.

In the Brazilian Pitinga tin province, the occurrence of the Madeira peralkaline subsolvus alkali-feldspar granite with primary, world class deposits of tin and associated Nb, Ta, Zr, and fluorine (mostly concentrated in cryolite) is also noteworthy (Bastos Neto et al., 2009; Costi et al., 2000, 2009; Lenharo et al., 2002). Peralkaline A-type granites can also be the carriers of HFSE mineralization (mostly Zr, Nb, Y, and REE; Salvi and Williams-Jones, 2006 and the references therein).

Iron oxide-copper-gold (IOCG)-type deposits also can be spatially and temporally related to A-type granites (Groves et al., 2010), as exemplified by the Fe-Cu deposits in southeastern Missouri (Kisvarsanyi and Kisvarsanyi, 1990), and the Olympic Dam and Conclurry Cu-Au-(REE-U) deposits of Australia (Pollard, 2006; Pollard et al., 1998).

However, the A-type granite magmas do not appear to be the carriers of the mineralizing metals (Groves et al., 2010; Williams et al., 2005). Instead, ultrabasic to basic deep, volatile-rich, mantle-derived magmas are the likely primary energy- and fluid-driving force of the IOCG ore systems (Groves et al., 2010). A case in point is the Fe-oxide-U-REE ores found in the Mt Painter Inlier (South Australia). Mesoproterozoic A-type granites of that domain were affected by intense metasomatism and elemental remobilization during the Phanerozoic; deposition generated the associated mineralization (Elburg et al., 2012-this issue).

Finally, Bi et al. (2000) argued that there is a direct relationship between the A-type granites of the Machanguing pluton and porphyry copper mineralization and they concluded that water-bearing A-type granites could host porphyry copper deposits under specific geological conditions.

### 2.4.2. Granite classification and metallogenetic potential

Some granite classifications establish clear links between the general characteristics of each series and its respective potential for associated mineralization. One of the most prominent classifications distinguished magnetite-series and ilmenite-series granites based on studies of the island arc granites of Japan (Ishihara, 1977, 1981). That classification relies strongly on the oxygen fugacity prevailing during magma origin and crystallization. The magnetite-series granites are more oxidized compared to the ilmenite-series ones and there is clear evidence that the nature of the granite magma is generally crucial for the type of associated mineralization. In the tectonic setting where Ishihara's classification was originally defined, there is a total dominance of I-type and S-type granites. However, Ishihara proposed that his classification could be applied also to anorogenic granites (Ishihara, 1981). This has been done for the Mesoproterozoic A-type granites of central and southwestern USA (Anderson and Bender, 1989; Anderson and Morrison, 2005; Anderson and Smith, 1995) and for similar Paleoproterozoic granites of the eastern Amazonian craton (Dall'Agnol and Oliveira, 2007; Dall'Agnol et al., 1997, 1999a,b, 2005). In general, the ilmenite series correspond to ferroan granites and the magnetite series granites are ferroan to magnesian granites in the classification of Frost et al. (2001). It is noteworthy that magnetite-bearing granitoids formed at the FMQ buffer conditions are not true oxidized granites (Anderson and Morrison, 2005; Dall'Agnol and Oliveira, 2007).

A tentative correlation between I-type and S-type granites formed at different oxygen fugacity conditions and associated mineralization was originally done for Australian granites and associated deposits (Blevin and Chappell, 1995; Blevin et al., 1996). In the case of A-type granites, the relationship between oxidation state and mineralization may be illustrated by three Paleoproterozoic anorogenic granite suites in the Carajás province of the eastern Amazonian craton (Dall'Agnol et al., 2005). These are the oxidized Jamon suite, the moderately reduced Serra dos Carajás suite and the reduced Velho Guilherme suite. The latter has associated polymetallic tin deposits (Teixeira et al., 2002). The Jamon suite is poorly mineralized and only small tungsten deposits are associated with it (Dall'Agnol et al., 2005; Oliveira et al., 2009). Finally, the Serra dos Carajás suite has associated mineralization that resulted from original IOCG deposits of Archean age, modified and remobilized by Paleoproterozoic fluids related to the A-type granites (Botelho et al., 2005; Monteiro et al., 2008; Xavier et al., 2010). Although additional studies are essential in order to develop a clear understanding of the metallogeny of these Paleoproterozoic A-type granites, it appears that tectonic setting, magma sources, and the oxygen fugacity prevailing during the crystallization of the magmas influence mineralization. Thus, an important subject for future research will be to establish more definitively the relationship between the classification and origin of A-type granites and their metallogeny. Below we describe some examples of evolved fluorine-rich A-type granites commonly with associated polymetallic tin mineralization.

#### 2.4.3. The A-type topaz granites and similar topaz rhyolites

During the IGCP 510 project, special attention was given to the A-type topaz granites and similar rhyolites and related mineralization (Bettencourt et al., 2005; Borges et al., 2009; Christiansen et al., 2007; Haapala and Lukkari, 2005; Haapala et al., 2007; Lukkari and Holtz, 2007; Lukkari et al., 2009). These papers have contributed to clarifying the geochemical characteristics and petrogenesis of these granites that occur in different continents and periods of Earth history, from Precambrian (Bettencourt et al., 2005; Haapala and Lukkari, 2005) to Phanerozoic (Haapala et al., 2007). These authors discussed also the nature of the fluids involved in the mineralization (Bettencourt et al., 2005; Borges et al., 2009; Lukkari et al., 2009) and demonstrate their strong similarities with the Cenozoic topaz rhyolites of the western USA (Christiansen et al., 2007).

Lukkari and Holtz (2007) investigated experimentally, at 100–500 MPa as a function of water activity and F content, the phase relations of the Kymi topaz granite, a representative of the evolved topaz granites associated with the Wiborg batholith rapakivi granites. They concluded that, for peraluminous systems, topaz and fluorite can be present on the liquidus if the F melt content exceeds 2.5–3.0 wt.%. Moreover, the mean F content of natural biotite of the Kymi granite (3.92 wt.%) suggested that the late-stage crystallization of biotite occurred in melts containing about 3 wt.% F. Finally, their experimental results indicated also that crystallization pressure may have been lower than 200 MPa for the Kymi granite.

A complementary melt inclusion study of the Kymi granite and associated pegmatite indicated the presence, in both varieties of rocks, of two coexisting types of melt inclusion differentiated on the basis of high-F and low F content (Lukkari et al., 2009). It was concluded that the topaz granites and the stockscheider pegmatite of the Kymi stock crystallized from very F- and H<sub>2</sub>O-rich melts, and that Li and B were present in the granitic melt at high concentrations. The melt inclusions in quartz and topaz grains from the granites and pegmatite contain indirect indications of melt separation and formation of a minor peralkaline melt fraction in addition to the prevailing peraluminous melt at the final stages of the crystallization (Lukkari et al., 2009). The estimated high-B content in the fluid phase of these granites is unexpected because B-bearing phases, e.g., tourmaline, are not common in A-type granites (cf. Dall'Agnol et al., 2005; Jacobson et al., 1958; Kinnaird, 1985; Rämö and Haapala, 1995).

The A-type topaz granites with associated tin-polymetallic greisen-type deposits are geochemically akin to the low-P leucogranites (Bettencourt et al., 2005; Taylor and Fallick, 1997). Mineralization is commonly associated with greisens, veins and stockworks containing cassiterite as the main ore. The deposits contain generally a similar rare-metal suite that includes Sn ( $\pm$ W,  $\pm$ Ta,  $\pm$ Nb,  $\pm$ Be), and, more rarely, a base-metal suite (Zn–Cu–Pb) (Bettencourt et al., 2005; Borges et al., 2009; Haapala, 1995; Haapala and Lukkari, 2005). The proposed model for the formation of the Pitinga greisens associated with A-type granites considers the circulation of two independent fluids that interacted mutually and with the host granites in space and time (Borges et al., 2009). The evidence indicates that, in the first stages, a magmatic-hydrothermal relatively high-temperature (~400 °C) fluid that may have originated from the porphyritic topaz granite of the Água Boa pluton was involved in the evolution of the greisens. The second fluid was more probably a surface-derived fluid, on account of its very low-salinity and low trapping temperatures (200–150 °C; Borges et al., 2009).

#### 2.4.4. The Madeira subsolvus, peralkaline cryolite-bearing alkali feldspar granite of the Pitinga tin province

The 1818 Ma Madeira albite-rich granite is a subsolvus magmatic rock formed by the crystallization of a residual melt, strongly enriched in F, Na, Rb, HFSE, Li, Sn, and rare metals (Bastos Neto et al., 2009; Costi et al., 2000, 2009). The albite-rich granite is composed of a dominant, peralkaline and cryolite-bearing core facies and a

peraluminous to metaluminous, oxidized, and fluorite-bearing border facies. The two facies were considered as consanguineous and the border albite-rich granite facies was interpreted as the product of late hydrothermal oxidizing processes that affected the core facies (Costi et al., 2000, 2009). The crystallization of the core albite-rich granite liquid started at a low temperature ( $\leq$ 700 °C), with quartz as the liquidus phase. The high concentrations of F caused a strong depression of the solidus temperatures with intersection of the solvus. The eutectic temperature was probably at ca. 500 °C allowing the crystallization of albite and K-feldspar as independent magmatic phases (Costi et al., 2009). Precipitation of ore minerals occurred contemporaneously with crystallization of the albite granite and led to a magmatic disseminated mineralization (Lenharo et al., 2002). The presence of magmatic cassiterite and pyrochlore, the high modal contents of zircon, and the presence of thorite are remarkable in this granite. As pointed out by Costi et al. (2009), the Madeira albite granite is a rare example of world-class economic primary deposit of Sn, Nb, Ta, U, Zr, and Th hosted by a peralkaline A-type granite.

The main process responsible for the magmatic evolution of the Madeira peralkaline albite granite and the origin of associated mineralization remain controversial. Costi et al. (2009) suggested that the melt that formed the granite was probably produced by a phase-separation process, or immiscibility, similar to that proposed for the tin granites of the Erzgebirge (Thomas et al., 2006). According to that hypothesis, the peralkaline melt had separated from a parental melt, most probably slightly peralkaline to metaluminous and similar in composition to the porphyritic hypersolvus alkali feldspar granite of the Madeira pluton. The massive cryolite and pegmatitic rocks found in the center of the stock were derived from the residual melt of the Madeira peralkaline granite (Costi et al., 2009). On the other hand, Bastos Neto et al. (2009) stated that there is no evidence for silicate–fluoride liquid immiscibility, nor for a continuous transition from volatile-rich silicate melt to solute-rich fluids. They inferred the existence of an abrupt magmatic–hydrothermal transition marked by albitization accompanied by the crystallization of hydrothermal cryolite in the rock matrix, conversion of pyrochlore to a columbite-group mineral, and formation of the massive cryolite deposit, made up of crystals of twinned cryolite (87%) plus quartz, feldspar, and zircon. They also concluded that the cryolite deposits of Pitinga are distinct and could not be explained by the models invoked for Ivigtut, in Greenland. Bastos Neto et al. (2006) proposed that the open-system fenitization model proposed by Martin (2006) could explain the main aspects of the Madeira peralkaline granite origin.

#### 2.4.5. The relationship between evolved tin-mineralized S-type and A-type granites

The Krušné hory/Erzgebirge Mountain province is a classical reference for tin-mineralized granites. There is increasing evidence that two different kinds of magmas were responsible for mineralization in that Variscan province (cf. Breiter, 2012–this issue, and the references therein): (1) Strongly peraluminous P, F, Li, Rb, Cs, U, Sn-rich and Zr, Th, Y, HREE-poor S-type magmas were intruded at about 330–320 Ma, and (2) slightly peraluminous F, Li, Rb, Cs, Sn, Zr, Y, HREE-rich and P-poor magmas were intruded in several events at ca 325–295 Ma. The first type corresponds to the P-rich granites and the second one to the P-poor granites. In the Altenberg-Treplce Caldera, S-type rhyolites and dacites and A-type rhyolites were erupted in close succession. This is strong evidence that the S-type and A-type magmas are closely related in time and space (Breiter, 2012–this issue). According to Breiter, the late-Variscan granites of the Krušné hory/Erzgebirge were derived from a mixture of different proportions of crustal fertile quartz–feldspathic rocks and metapelites enriched in LILE and Sn + W.

The close association between A-type and S-type magmas merits special attention. In the past there were attempts to compare

A-type and I-type granites because of their close similarities (Chappell and White, 2001; Creaser et al., 1991; King et al., 1997, 2001), whereas A-type and S-type granites were generally seen as two entirely distinct groups. The results for the Erzgebirge demonstrate that careful mineralogical, geochemical and metallogenic studies are necessary for the correct classification of associated S-type and A-type granites and to decipher the origin of related mineralization.

## 2.5. Relation of A-type granites to lithospheric evolution

### 2.5.1. Introduction

A-type granites are rather enigmatic not only as regards their tectonics and petrogenesis but also in terms of their tectonic setting and overall significance in the evolution of the Earth's lithosphere. One of the connotations of the label "A" is "anorogenic". This implies emplacement of these granites (and the mafic and intermediate rocks associated with them) in non-compressional settings, including such regimes as oceanic islands near spreading ridges, apparently stable cratons, and intraplate extensional continental rifts which, in many cases, imply a principal role of mantle processes in the initiation of the magmatism (cf. Bonin, 2007, and the references therein). Post-collisional or post-orogenic settings have, however, also been invoked and "anorogenic" A-type complexes have also been associated with concurrent subduction processes in distant craton margins (e.g., Åhäll et al., 2000; Karlstrom and Humphreys, 1998). A further issue of controversy, tied to the role of A-type granites and related rocks in lithospheric evolution, is whether they represent crustal reworking (melting of pre-existing lithologic domains in the lower and middle crust) or contribute to net crustal growth (via mafic underplating and resultant emplacement of juvenile mantle-derived magmas into the lower crust) (e.g., Anderson, 1983; Frost and Frost, 2011). IGCP-510 gathered together a versatile group of geoscientists that focus their research on these issues and has produced new, important data and concepts that help in pursuit of a deeper comprehension of the role of A-type granites in the Earth's evolution through time. We will here focus on the pertinent results of IGCP-510 and discuss the significance of A-type granites as a time-associated proxy of lithospheric processes in the light of the new data collected since 2005.

### 2.5.2. A-type associations examined and their temporal context

A-type granite associations were examined from all continents, including Antarctica, and their locations and ages are shown on a global map in Fig. 2. The emplacement ages of the felsic and associated mafic and intermediate rocks range in age from Neoproterozoic (~2.7 Ga) through Proterozoic to Phanerozoic (~10 Ma, and younger).

Overall, the currently known Archean A-type granite associations are quite rare (cf. Bonin, 2007; Dall'Agnol and Rämö, 2009; Zozulya et al., 2005). Voluminous Archean A-type granites have been reported from the Kapvaal craton in southern Africa (the ~2.78 Ga Gaborone rapakivi granite–anorthosite–rhyolite complex; Moore et al., 1993). Barros et al. (2009) and Feio et al. (2012–this issue) described Neoproterozoic granitoids with A-type geochemical traits from the Carajás province, southeastern Amazonia, Brazil (Fig. 2). The ~2.75 Ga granites in the Itacaiúnas supergroup (Carajás basin) are interpreted as A-type (Barros et al., 2009), whereas the 2730 Ma granites south of the Carajás basin are considered as hydrated charnockitic-series granitoids, not A-type granites per se (Feio et al., 2012–this issue).

Early- and mid-Paleoproterozoic A-type granites are rare as well. Relatively small granitic and syenitic plutons are found in the Archean Karelian craton of the Fennoscandian shield (Fig. 2). The oldest of these (2.45–2.44 Ga) are related to the early Paleoproterozoic layered mafic intrusions of north-central Finland and adjacent Russia (Lauri et al., 2006). Further to the south, scattered A-type intrusions dated at 2.43–2.39 Ga are found (Mikkola et al., 2010). These early Paleoproterozoic granites are small (<100 km<sup>2</sup>), discordant plutons

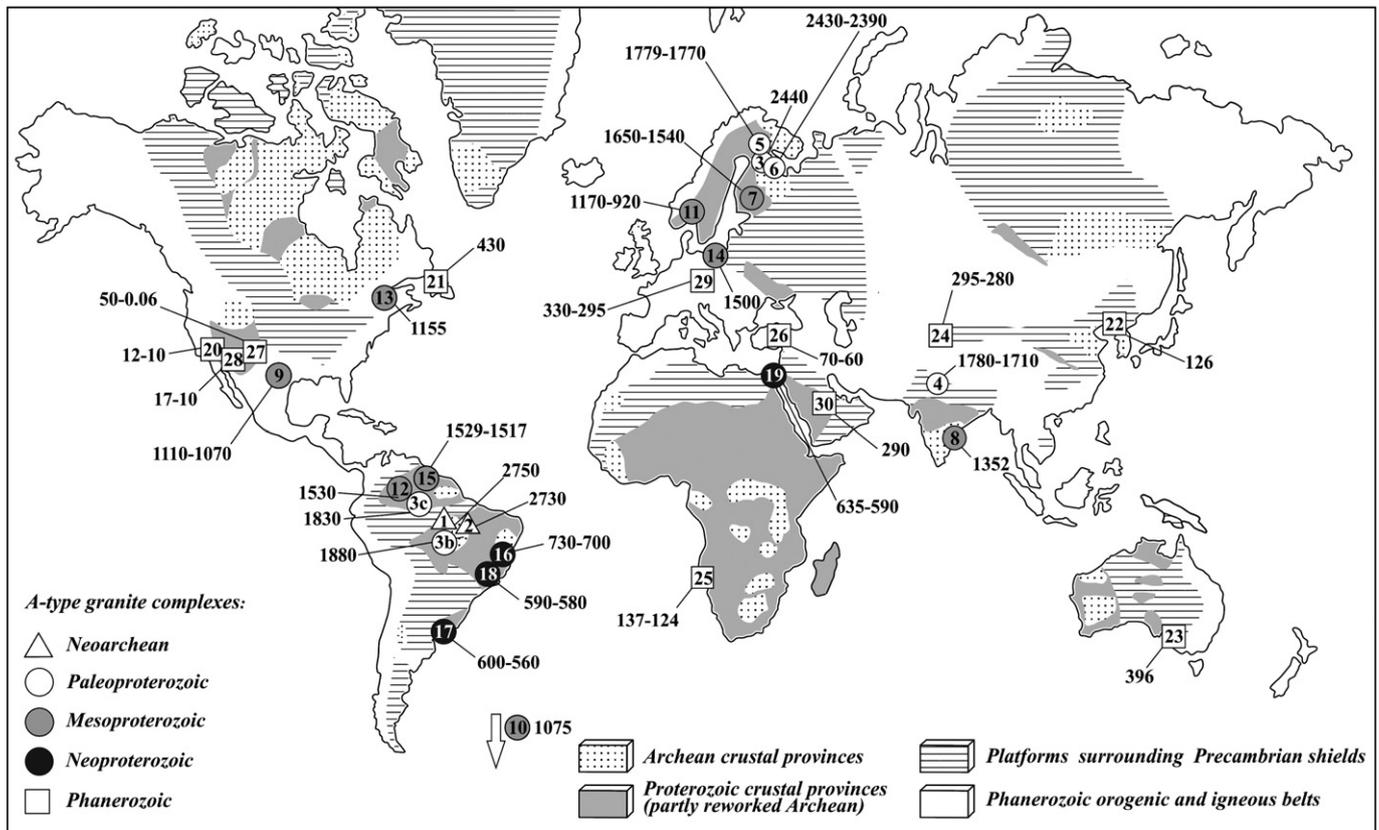
and they were emplaced into a Mesoarchean TTG-dominated crust (see Lauri et al., 2012–this issue, for a review).

Late Paleoproterozoic (1.88–1.82 Ga) A-type granites are widespread in the Amazonian craton (Fig. 2). In the Carajás province, in the southeastern Amazonian region, three distinct suites of 1.88 to 1.86 Ga A-type granites crosscut the Archean basement (Dall'Agnol and Oliveira, 2007; Dall'Agnol et al., 2005; Oliveira et al., 2008, 2009). In the Tapajós province, in the southern-central domain of the Amazonian craton (Lamarão et al., 2002), and in the southern part of the Guiana shield, near the border between Amazonas and Roraima states of Brazil (Almeida et al., 2008; Ferron et al., 2010; Valério et al., 2009), ca. 1.88–1.87 Ga A-type granites and coeval felsic volcanic rocks are also common. Finally, the Madeira suite granites of the Pitinga tin province are 1.83–1.82 Ga old (Costi et al., 2000).

Somewhat younger (1.8–1.7 Ga) late Paleoproterozoic A-type granites are described from the Archean bedrock of Finnish Lapland and western Kola Peninsula, Russia (the 1.79–1.77 Ga Nattanen, Vainospää, Juvoivi, and Litsa-Araguba granites; Heilimo et al., 2009a,b) as well as from the Khetri Copper Belt in Rajasthan, north-western India (~1.77–1.71 Ga plutons in the Aravalli Mountains; Kaur et al., 2006).

Mesoproterozoic A-type granite associations are much more abundant than those emplaced in the Archean and Paleoproterozoic. Mesoproterozoic A-type complexes include, for example, A-type granites commonly associated with massif anorthosites that peak between 1.8 Ga and 1.0 Ga (e.g., Ashwal, 1993, 2010; Bettencourt et al., 1999; Emslie, 1978; Haapala and Rämö, 1999). These suites comprise large, batholith-size plutons of considerable lateral extent and generally include substantial volumes of leucogabbro and anorthosite (massif-type), granitoid, and intermediate rock types. The A-type granites associated with anorthosite that were studied during the course of IGCP-510 include complexes in southern Finland (1.65–1.54 Ga; Christiansen et al., 2007; Elliott et al., 2005), Roraima, Brazil (~1525 Ma; Fraga et al., 2009; Heinonen et al., 2012–this issue), subsurface northeastern Poland (~1.50 Ga; Duchesne et al., 2010), eastern Ghats Belt, eastern India (1352 Ma; Kumar et al., 2007), and eastern North America (1155 Ma; McLelland et al., 2010) (Fig. 2). These occurrences are enclosed by Paleoproterozoic to Mesoproterozoic crust. The A-type magmatism in the eastern Ghats Belt is remarkable for a Proterozoic A-type suite in displaying both over and undersaturated magmatic lineages. Grenville-age (mid-late Mesoproterozoic) A-type granite suites, not associated with substantial bodies of massif-type anorthosite, are described from the subsurface of far west Texas and adjacent New Mexico (1110–1070 Ma silica and basic magmatism; Li et al., 2007), western Dronning Maud Land, Antarctica (1084–1073 Ma rapakivi granites of Mannefallknäusane; Rämö et al., 2007), and southern Norway (1170–920 Ma ferroan, high-K granites that postdate ductile deformation of the mid-Mesoproterozoic Sveconorwegian orogeny; Andersen et al., 2009) (Fig. 2).

Since the end of the Mesoproterozoic, A-type granites appear to have been emplaced rather regularly through time, yet in modest volumes relative to the mid-Proterozoic A-type granites and related magmatism. Neoproterozoic–Cenozoic A-type granite plutons are relatively small, often bimodal, and their mafic magmatic associations seem to lack significant anorthositic units (cf. Ashwal, 2010). Neoproterozoic A-type suites were reported from three locations in northeastern, southeastern and southern Brazil (Fig. 2): the 730–700 Ma syenites in the Southern Bahia Alkaline Province of the São Francisco craton (Rosa et al., 2007); the 600–560 Ma A-type plutons in the Brasiliano orogen in southernmost Brazil (Nardi and Bitencourt, 2009); and the 590–580 Ma, rapakivi-textured intrusions of the Itu Granite Province, southeastern Brazil (Janasi et al., 2009). Be'eri Shlevin et al. (2011) reported a further late Neoproterozoic (Pan-African) A-type magmatic suite from east-central Sinai Peninsula



**Fig. 2.** Global map showing location of A-type granite complexes studied in the framework of IGCP-510 for their lithospheric context and relation to crustal evolution. Key to the occurrences examined (emplacement ages are given in Ma): Neoproterozoic: 1—Barros et al. (2009), 2—Feio et al. (2012-this issue); Paleoproterozoic: 3—Lauri et al. (2006), 3b—Oliveira et al. (2008, 2010), 3c—Costi et al. (2009) and the references therein, 4—Kaur et al. (2006), 5—Heilimo et al. (2009a), 6—Mikkola et al. (2010); Mesoproterozoic: 7—Elliott et al. (2005), 8—Kumar et al. (2007), 9—Li et al. (2007), 10—Rämö et al. (2007), 11—Andersen et al. (2009), 12—Fraga et al. (2009), 13—McLelland et al. (2010), 14—Duchesne et al. (2010), 15—Heinonen et al. (2012-this issue); Neoproterozoic: 16—Rosa et al. (2007), 17—Nardi and Bitencourt (2009), 18—Janasi et al. (2009), 19—Be’eri Shlevin et al. (2011); Phanerozoic: 20—Calzia and Rämö (2005), 21—Whalen et al. (2006), 22—Yang et al. (2006), 23—Hergt et al. (2007), 24—Konopelko et al. (2007), 25—Haapala et al. (2007), 26—Boztuğ et al. (2007), 27—Christiansen et al. (2007), 28—Calzia et al. (2008), 29—Breiter (2012-this issue), 30—Alirezai and Hassanzadeh (2012-this issue). Figure modified from Haapala and Rämö (1999).

in the northern Arabian–Nubian shield (Fig. 2). The A-type magmatism in Sinai was preceded by calc-alkaline (adakitic) granitoid magmatism.

A-type granite associations are found throughout the Phanerozoic and they comprise granites (often shallow-level) and volcanic members of the (quite often bimodal) magmatic systems. Paleozoic A-type granites are reported from North America, Australia, central Europe, and Asia (Fig. 2). Whalen et al. (2006) described a Silurian (~430 Ma) bimodal magmatic suite in the Newfoundland Appalachians. This suite marks intermittent transitions from calc-alkaline (arc-type) to alkaline (A-type). Hergt et al. (2007) reported a lower Devonian (396 Ma) A-type granite–rhyolite suite in the Cambrian basement of the western Lachlan Fold Belt in southeastern Australia. Breiter (2012-this issue) described a Carboniferous (330–295 Ma) granite association, which includes both S-type and A-type granites, from the Krušné hory/Erzgebirge Mountains along the border of Germany and Czech Republic. Konopelko et al. (2007) reported on a Permian (295–280 Ma), bimodal A-type granite suite in the Mesoproterozoic basement of the southern Tien Shan Mountains, Kyrgyzstan. Alirezai and Hassanzadeh (2012-this issue) also examined a Permian (290 Ma) A-type granite suite, in the Sanandaj–Sirjan metamorphic–plutonic belt in west-central Iran.

Mesozoic examples of A-type granites were reported from South Africa and southeastern Europe (Fig. 2). Haapala et al. (2007) examined the Jurassic–Cretaceous, highly fractionated, topaz-bearing A-type granite stocks (Gross Pitzkoppe and Klein Spitzkoppe) from the Neoproterozoic Damara orogenic belt in Namibia. The stocks were emplaced at 137–124 Ma and belong to the Paraná–Etendeka

Large Igneous Province (White and McKenzie, 1989). Yang et al. (2006) examined a Cretaceous subaluminous A-type granite assemblage (the 126 Ma Qianshan granite) in the eastern part of the North China (or Sino-Korean) craton in northeastern China. The Qianshan granite is commingled with mafic magmas and was emplaced into Archean–Proterozoic basement rocks. Cretaceous–Paleogene (70–60 Ma) A-type monzonites and syenites and associated mafic rocks (gabbro, diorite) were reported from the Divriği–Sivas region in central Turkey (Boztuğ et al., 2007). This A-type suite was emplaced within a Paleozoic basement of low-grade metasedimentary rocks and ophiolitic mélanges.

Cenozoic examples of A-type granite associations are found in the southwestern United States in the Colorado River extensional corridor area in southernmost Nevada (e.g., Calzia et al., 2008) and in the Death Valley region in southeastern California (Calzia and Rämö, 2005). In both regions, mid-Miocene (17–10 Ma) A-type granites have been exposed owing to the Basin and Range extension. The mid-Miocene A-type granite plutons in Nevada and California are relatively small and high-level, show a bimodal magmatic association, and are rapakivi-textured in places. Christiansen et al. (2007) presented a review of the Paleogene to Quaternary (50–0.06 Ma) topaz rhyolites of the western United States. These rhyolites show the geochemical traits of A-type granites, including the *locus classicus* rapakivi granites of southern Finland, and are confined to the extended crustal terranes of the Basin and Range Province and the Rio Grande Rift.

### 2.5.3. Crustal growth vs. reworking

The magmatic association of the A-type granites is characteristically bimodal, comprising (1) metaluminous to marginally peraluminous granites, alkali-feldspar granites, and syenites and (2) tholeiitic mafic rocks. Alkaline rocks (peralkaline granites, foid-bearing silicic rocks, basanites) are found but are less significant in terms of total volume. A-type granite associations thus make a strong case for at least two principal sources: mantle (for the tholeiitic mafic lineage and alkaline rocks) and crust (for the oversaturated silicic rocks), as discussed in Section 2.3. The relative importance of these two principal sources is debatable, however, and the question of the source of A-type granites thus extends to what the A-type granites actually contribute to net crustal growth. Alkaline undersaturated assemblages reflect mantle-derived lineages with little interaction with the continental crust. Examples include the Mesoproterozoic Uppalapadu nepheline syenites of southeastern India (Fig. 2) that were derived from a basanitic precursor (Kumar et al., 2007), and the Neoproterozoic sodalite syenites of the Southern Bahia Alkaline Province (Fig. 2; Rosa et al., 2007). These mantle-derived assemblages are volumetrically quite small (stocks and small batholiths) and also much smaller than the associated subalkaline A-type lithologic units (if present; cf. Kumar et al., 2007), and thus mark very modest additions of mantle-derived material to the continental crust.

The subalkaline/tholeiitic members of the A-type granite associations are clearly more voluminous than the alkaline ones and, hence, probably more important in terms of mantle–crust differentiation. The relative roles of mantle and crust as source components of A-type granite complexes should thus be assessed. Kumar et al. (2007) favored a mantle-derived (high-Al tholeiitic) magma as the parent for the tholeiitic magmatism of the Mesoproterozoic Eastern Ghats Belt of southeastern India. Likewise, Lauri et al. (2006) considered the A-type Kynsijärvi syenite (Fig. 2) as a differentiate (via combined assimilation-fractional crystallization processes, AFC) of the mantle-derived magmas from which the 2.44 Ga layered mafic intrusions in north-central Finland were crystallized. The Grenville-age A-type magmatism along the southern margin of Laurentia (west Texas, New Mexico; Fig. 2) was inferred by Li et al. (2007) to manifest a significant addition of juvenile material to the continental crust (via underplated and intraplated mafic rocks and their differentiates). In their study on the Neoproterozoic A-type granitic rocks of southern Brazil (Fig. 2), Nardi and Bitencourt (2009) proposed a substantial role for the mantle (including both OIB and EM1 domains) as a source component with varying (in some cases nil) contribution from crustal sources.

The issue of the continental crust as a major source component, beyond that of a varying, minor contaminant of primitive mantle-derived magmas undergoing assimilation (AFC) processes in transit through the lithosphere, reflects directly on the significance of A-type granites in crustal growth. The larger the crustal (anatectic) component, the smaller is the net transfer of juvenile (mantle) material to the crust. Overall, this process may be dwarfed by accretionary processes that have, since the advent of modern-style plate tectonics (perhaps from ~3.6 Ga, probably from ~2.7 Ga on; Condie and Kröner, 2008; Kröner, 2010) governed the growth of the continents by adding juvenile material along convergent margins. However, the relative importance of continental addition by underplating (as opposed to lateral accretion of juvenile material along continental margins) was probably greatest during the mid-Proterozoic, when A-type granite magmatism was most voluminous.

A role for the (lower and middle) continental crust as a major source component for the A-type granites is endorsed by the majority of the contributions to IGCP-510, save for the studies cited above that stress the significance of the (subcontinental) mantle as the source. Duchesne et al. (2010) concluded that a Paleoproterozoic (~2.2–2.0 Ga) crust was the sole source for the mafic and silicic members

of the Mazury AMGC complex (Fig. 2), and thus no crustal growth was involved. All other are in favor of thermal perturbations and decompression melting in the subcontinental mantle having generated mafic melts (mafic underplate) that intrude the crust, partially melt it, and mix with the resultant anatectic melts in varying proportions (cf. Section 2.3). The remelted crust varies in these models from juvenile, mafic, in some cases hybrid lower crust (Calzia et al., 2008; Christiansen et al., 2007; see also Martin, 2012-this issue) to pre-existing continental crust formed in a preceding orogeny. The latter case is documented, for example, in Carajás (~3 Ga source for ~2.7 Ga granites; Barros et al., 2009), Roraima (~1.94 Ga source for ~1.53 Ga granites; Fraga et al., 2009; Heinonen et al., 2012-this issue), Fennoscandia (~2.8 Ga source for ~2.4 Ga granites; Mikkola et al., 2009), Victoria (~500 Ma sources for ~400 Ma granites; Hergt et al., 2007), and eastern North China craton (Archean/Proterozoic source for a Cretaceous granite; Yang et al., 2006). Some of the studies further revealed several different crustal source components that contributed to the formation of A-type granite magmas (Andersen et al., 2009; Haapala et al., 2007).

Overall, it appears that A-type granite associations, being almost unequivocally bimodal (with mantle and crust as salient source components), do contribute to crustal growth as these magmatic complexes are emplaced (cf. Eby, 2011). Mantle-derived magmas are emplaced within the continental crust and they are mixed with crust-derived magmas, and thus form primary and “cryptic” juvenile additions to the crust that is undergoing A-type granite magmatism. Net crustal growth caused by A-type granite magmatism varies in concert with the overall volumes of the evolving magmatic system and has been substantial for example during the emplacement of the mid-Proterozoic AMGC complexes. Extensional zones undergoing craton-scale A-type magmatism are, should the process abort, left with extended, thinned, and domed terranes with new juvenile material in the form of mafic rocks and a (varying) crustal component in the associated A-type granites. This also has a bearing on the stabilization of the crust with dense, mafic rocks forming a substantial fraction of the lower continental crust in A-type granite terrains. An example of this comes from the Finnish Svecofennian (e.g., Elliott et al., 2005) where relatively extensive ~1.88 Ga and ~1.6 Ga alkaline granite assemblages mark the last major tectonomagmatic events in the crustal terranes of western and southern Finland, respectively.

A-type granites appear to be an almost exclusively post-Archean phenomenon (cf. Bonin, 2007; Section 2.5.2; Fig. 2) and there may be a causal relationship with the evolution of the continents. In the Proterozoic and Phanerozoic, the Earth records emplacement of A-type granites on a global scale, possibly because there was ample amount of (newly formed) crustal domains capable of being remelted as a source component to A-type granite assemblages. It is probably also safe to say that mantle melting is a pre-requisite for A-type granites to form and the combination of substantial melting in the subcontinental mantle and the overlying continental crust may only have been possible since the end of the Archean with the establishment of large supercontinents (cf. Hoffman, 1989).

### 2.5.4. Regional extension vs. contraction

The bimodal magmatic association of A-type granites and related rocks may be considered as fundamental evidence for an overall non-compressional tectonic setting. Igneous suites in magmatic arcs that undergo regional contraction for several tens of m.y. are of overall intermediate composition (e.g., Ward, 1995). For the Archean, these are well manifested by the TTG (Tonalite–Trondhjemite–Granodiorite) associations (Martin, 1994) that show a secular compositional change toward more primitive compositions owing to increased importance of the reaction of slab melts with mantle-wedge peridotite (Martin and Moyen, 2002), as the rigidity of the lithospheric plates increased with time. A-type granites are rare at this time and are only present in Neoproterozoic terranes well past their crust-forming

stage (cf. Barros et al., 2009). These A-type (or A-type like; cf. Feio et al., 2012-this issue) granites are synkinematic (emplaced during active regional stress) and are, in this respect, atypical.

Tectonic settings that do not promote profound mixing of mantle- and crust-derived melts and crystallize bimodal magmatic associations should thus have an overall extensional (non-compressional) character. This requires a plate tectonic system with rigid, relatively weak plates that may break under regional extensional stress or in regional contractional systems characterized by transcurrent tectonics (transpression/transension) (e.g., Silva and Pereira, 2004; Sleep, 2005). Regional extension occurs when continental lithosphere breaks in response to long-lived mantle perturbations when hot mantle rises and erodes continental lithosphere, leading to full-scale (or, in some instances, aborted) rifting along divergent plate boundaries (e.g., Santosh et al., 2010). Extensional domains in regimes of regional contraction form as a result of oblique collision of continental lithosphere plates. If this process is associated with lithospheric delamination and/or slab breakoff (e.g., Bird, 1978, 1979; Nelson, 1992; von Blanckenburg and Davies, 1995), the hot asthenosphere rises, undergoes decompression melting, and induces melting in the overlying continental crust. Both regional extensional and contractional regimes have been proposed as likely tectonic regimes for A-type granites and related rocks (cf. Frost and Rämö, 2007).

A causal relation of A-type granite formation and orogeny (formation of continent-scale orogenic belts along convergent margins) continues to be an actively debated issue, and this clearly shows also in the contributions to IGCP-510. Proponents of regional extension relate the examined A-type granites to concurrent rupture events of the Karelian craton in Fennoscandia (also marked by emplacement of ~2.4 Ga layered mafic intrusions; Lauri et al., 2006), rifting of the Paleoproterozoic Bhilwara aulacogen in northeastern India (Kaur et al., 2006), aborted rifting in the late-Paleoproterozoic in the Carajás province (Oliveira et al., 2008, 2010) and in the Mesoproterozoic, in the Guyana shield (Fraga et al., 2009), Neoproterozoic rifting in the eastern part of the São Francisco craton (Rosa et al., 2007), lower Permian breakup of Gondwana in the Arabian–Nubian shield (Alirezai and Hassanzadeh, 2012-this issue), lower Cretaceous extension in the North China craton (Yang et al., 2006), and deep mantle plume-related rupturing and rifting (in the advent of the opening of the South Atlantic) in southeastern Africa (Haapala et al., 2007). These examples show that bimodal A-type granite associations are a typical phenomenon at the outset of the Wilson cycle and record continental rifting events (successful or failed) from the early Paleoproterozoic to the Phanerozoic.

A salient part of the A-type associations examined is, however, temporally related to convergent tectonics. A-type magmatism is expected to result from the fast rise of asthenosphere as a result of foundering of lithospheric mantle (delamination) or as subcontinental lithosphere becomes detached from the surface slab following continental collision (e.g., Davies and von Blanckenburg, 1995). This leads to extension caused by traction along delamination faults and above ductily necking lithosphere (Sacks and Secor, 1990), and may result in pervasive bimodal magmatism. The 1.79–1.77 Ga A-type granites of northern Finland and vicinity (Heilimo et al., 2009a) are considered post-orogenic relative 1.9–1.8 Ga contractional events related to the amalgamation of the Fennoscandian shield, yet they are claimed to have formed in an extensional regime. Lithospheric delamination and resultant rise of the asthenosphere are considered as the causes of the 1.5 Ga AMGC magmatism of northeastern Poland (Duchesne et al., 2010). Likewise, McLelland et al. (2010) favored delamination of tectonically thickened lithosphere and resultant lithosphere-scale transcurrent zones as a prerequisite for the generation and emplacement of the Grenville-age AMGC complexes of eastern North America.

Post-collisional processes involving slab breakoff/delamination are favored for most of the Phanerozoic A-type associations studied

in the framework of IGCP-510 (Fig. 2). According to Be'eri Shlevin et al. (2011), in the northern part of the Arabian–Nubian shield, post-collisional delamination culminated at 610 Ma and subsequent rise of asthenosphere caused a shift from calc-alkaline to alkaline (A-type) magmatism at ~600–590 Ma. In southern Brazil, 600–560 Ma A-type associations were emplaced in post-collisional transcurrent regimes governed by lithospheric foundering (Janasi et al., 2009; Nardi and Bitencourt, 2009), as was the 430 Ma A-type granite association of Newfoundland Appalachians (Whalen et al., 2006). The latter also marks a shift from calc-alkaline to alkaline magmatism, which seems to be a magmatic hallmark of slab breakoff regimes. A transpressional regime is further favored for the 290–280 Ma A-type suites in Tien Shan (Konopelko et al., 2007), and a slab breakoff model was applied to explain the origin of the 70–60 Ma A-type granites of central Anatolia (Boztuğ et al., 2007).

The mid-Miocene A-type granites and associated mafic rocks (e.g., Calzia and Rämö, 2005; Calzia et al., 2008) as well as the Cenozoic topaz rhyolites (Christiansen et al., 2007) of the western and southwestern United States were emplaced in the extended terranes of the Basin and Range Province and the Rio Grande Rift, those in southern Nevada and southeastern California in lithospheric segments with in excess of 100% of post-subduction extension. The 17–10 Ma A-type granites of southernmost Nevada and adjacent California make an interesting case as their tectonic setting is unequivocally known. The end of the Cordilleran subduction at this latitude may have been followed by slab rollback (e.g., Best and Christiansen, 1991) and resultant upwelling of hot asthenosphere, lithospheric thinning, marked crustal extension, and bimodal (A-type) magmatism.

### 3. Concluding remarks

The six years of IGCP-510 marked active, global-scale collaboration among scientist from universities and research institutes representing 42 nationalities. Significant progress was made in the four main topical fields of IGCP-510, yet unresolved issues prevail and continue to deserve the attention of the Earth science community in the years to come. Regarding the petrogenesis of A-type granites and related rocks, both mantle and crustal sources are obviously required. The relative importance of these sources, however, varies considerably. Five groups of A-type granites (alkalic metaluminous; alkalic and alkali-calcic peralkaline; alkali-calcic metaluminous and peraluminous; calc-alkalic metaluminous and peraluminous; calcic ferroan) can be distinguished based on their geochemical composition, which reflects the interplay of varying source components. Regarding metallogenic significance, A-type granites are recognized as important carriers of Sn ( $\pm$ W,  $\pm$ Ta,  $\pm$ Nb,  $\pm$ Be), as well as F, Zr, Y, and the REE. Rare porphyry-copper and base-metal occurrences are also related to A-type granites. A-type granites are spatially associated with important Fe–Cu and Cu–Au (REE-U) deposits, but whether there is a petrogenetic relationship involved is unclear. Regarding granite typology, A-type granites continue to pose a challenge, not least because of the wide compositional spectrum involved. A-type granites may obviously form from several different sources and hence the source–granite connection is not at all straightforward (unlike for the I-type and S-type granites). The composition-based concept of “ferroan granites” could be considered a worthy synonym for “A-type granite”. Regarding the role of A-type granites in lithospheric evolution, it appears that the formation of the A-type granites is related to the secular evolution of the Earth. A-type granites are very rare in the Archean and early-mid Paleoproterozoic and abundant since the late Paleoproterozoic. This probably reflects the overall evolution (growth, stabilization, and reorganization) of the Earth's continents and associated (modern-style) plate tectonic phenomena. In general, A-type granite associations are related to extensional regimes. These may develop both in domains of regional extension

Table 2

Activities of IGCP Project 510 "A-type Granites and Related Rocks through Time" (2005–2010; R. Dall'Agnol, C.F. Frost, O.T. Rämö, L.J. Robb, co-leaders).

Activity	Date	Venue	Conveners	P <sup>a</sup>	N <sup>b</sup>	Papers <sup>c</sup>	Conference publications	Proceedings volumes, conference reports
<i>The year 2005</i>								
"A-type Granites and Related Rocks through Time" Symposium (15th V.M. Goldschmidt Conference)	5/20–25	Moscow, Idaho	C.D. Frost, R. Dall'Agnol, O.T. Rämö	32	11	22	Podosek (2005)	Frost and Rämö (2007)
"Extrusive A-type Magmatism of the Yellowstone Hot Spot Track" Field trip (volcanic terrains of the Snake River Plain and Yellowstone area)	5/26–30	Idaho, Montana	C.D. Frost, M. McCurry, R. Christiansen, K. Putirka, M. Kuntz	27	9		Frost et al. (2005)	
"Eurogranites 2005 Field Conference" Field trip (southern and central Finland)	9/11–17	Finnish Svecofennian	O.T. Rämö, J. Halla, M. Nironen, L.S. Lauri, M.I. Kurhila, A. Käpyaho, P. Sorjonen-Ward, O. Äikäs	47	15		Rämö et al. (2005)	
<i>The year 2006</i>								
"Pitinga Mine" Field trip [Pitinga granites (~60°00'W, 0°50'S), northern Brazil]	8/2–5	Amazonas, Brazil	H.T. Costi, J.M.T.M. Ferron, M. Prado	13	5		Costi et al. (2006)	
"A-type Granites and Related Rocks through Time" Symposium (in conjunction with Symposium on Magmatism, Crustal Evolution, and Metallogensis of the Amazonian Craton)	8/6–9	Belém, Brazil	R. Dall'Agnol, C.M. Ferreira de Freitas	50	6	46	Dall'Agnol et al. (2006a)	Dall'Agnol and Rämö (2009)
"Archean and Paleoproterozoic Granitoids of Carajás Metallogenic Province, Eastern Amazonian Craton" Field trip (Marabá-Xinguara-Redenção-Xinguara-Canaã dos Carajás-Parauapebas-Carajás-Marabá)	8/10–15	Serra dos Carajás, Pará, Brazil	R. Dall'Agnol, M.A. de Oliveira, J. de Arimatéia Costa de Almeida, F.J. Althoff, A.A. da Silva Leite D.C. de Oliveira, C.E. de Mesquita Barros	23	6		Dall'Agnol et al. (2006b)	
<i>The year 2007</i>								
"A-type Granites and Related Rocks through Time" Symposium (Sixth International Hutton Symposium)	7/2–6	Stellenbosch, South Africa	J.D. Clemens, A.F.M. Kisters, J.A. Miller	20	13	18	Miller and Kisters (2007)	Clemens et al. (2010)
"Bushveld Granites and Associated Mineralization" Field trip (Johannesburg-Bronkhorstspuit-Marble Hall-Zaaipiaats-Vergenoeg-Johannesburg)	7/7–10	Bushveld Igneous Province, South Africa	J. Kinnaird, L.J. Robb	14	11		Kinnaird and Robb (2007)	
"Coeval Miocene Magmatism and Crustal Extension in the Colorado River and Death Valley Extensional Terrains" Field trip (Las Vegas-Laughlin-Searchlight-Primm-Shoshone-Pahrump-Las Vegas)	11/1–4	Nevada, California	J.P. Calzia, S. Luddington, C.F. Miller, O.T. Rämö	19	6		Calzia et al. (2008)	
<i>The year 2008</i>								
"Anorthosites to Rapakivi Granites: a Tribute to the Career of Ronald F. Emslie" Symposium (GAC-MAC-SEG-SGA Joint Annual Meeting)	5/26–28	Québec, Canada	M.A. Hamilton, J.S. Scoates, O.T. Rämö	40	9	31	GAC-MAC-SEG-SGA (2008)	Hamilton and Scoates (2010)
"Alkaline Rocks of the Oslo Rift, SE Norway" Field trip (Oslo-Asker-Finnemarka-Drammen-Mykle-Gjone-Ula-Oslo)	8/1–5	Oslo rift, southern Norway	T. Andersen	27	8		Andersen et al. (2008)	
"Granite Classification—a Never-ending Problem" Symposium (33rd International Geological Congress)	8/7–8	Lilleström, Norway	B. Bonin, O.T. Rämö, T. Andersen	40	9	14	33IGC (2008)	
"The Permian–Triassic A-type Volcanic–plutonic Igneous Suite of Corsica" Field trip (Ajaccio-Monte Peloso-Cauro-Porto-Scandola-Evisa-Ajaccio)	9/1–7	Corsica, France	B. Bonin	37	16		Bonin et al. (2008)	
<i>The year 2009</i>								
"Eurogranites ARCTIC 2009" Field conference (Rovaniemi-Saariselkä-Murmansk-Apatity-Kirovsk-Apatity-Salla-Rovaniemi)	8/14–22	Finnish Lapland, Kola Peninsula, Russia	O.T. Rämö, J. Halla, Yu. Voytekhovskiy	24	14	4	Heilimo et al. (2009b)	Rämö and Voytekhovskiy (2010)
"Geological Field Trip to the Cappadocian Volcanic Province" Field trip (Ankara-Urgup-Elazig-Tunceli)	9/26–29	Cappadocia, Turkey	V. Toprak	12	8		IGCP-510 Turkey group (2009a)	
"5th Annual Meeting of IGCP-510: A-type Granites and Related Mineralization in the Tethyan Belt" Symposium	9/29–30	Tunceli, Turkey	D. Boztug, C.D. Frost	26	9	14	IGCP-510 Turkey group (2009b)	
"A-type Magmatic Associations and Related Mineralizations at Eastern-central Anatolia" Field trip (Tunceli-Kangal-Malatya-Ankara)	10/1–3	Anatolia, Turkey	I. Kuscü, D. Boztug, G. Kuscü	16	8		IGCP-510 Turkey group (2009c)	
<i>The year 2010</i>								
"A-type Granites and Related Rocks through Time Field Trip, Southeastern Finland" Field trip (Helsinki-Kotka-Mäntyharju-Lappeenranta-Hamina-Kymi-Helsinki)	8/14–18	Southeastern Finland	O.T. Rämö, S. Lukkari, A.P. Heinonen	23	12		Heinonen et al. (2010)	
"International Conference on A-type Granites and Related Rocks through Time" Symposium	8/18–20	Helsinki, Finland	O.T. Rämö, S. Lukkari, A.P. Heinonen	40	15	35	Rämö et al. (2010)	Dall'Agnol et al. (2012)

<sup>a</sup> Number of participants, in total 530.<sup>b</sup> Number of nationalities involved, in total 42.<sup>c</sup> Oral and poster presentations given at technical sessions, in total 184.

(divergent plate boundaries) and regional contraction (oblique collisions; slab breakoff, foundering) that demote mixing of mantle- and crust-derived magmas and allow them to develop along discrete liquid lines of descent.

### Acknowledgments

We would like to sincerely thank all colleagues who participated in the activities of IGCP-510, shared the responsibility to organize symposia and field trips, and contributed to the scientific advancements made in the course of the project. Dr. Robert Missotten (Secretary, International Geoscience Program; Chief, Earth Observation Section) is acknowledged for excellent collaboration in administrative matters. We are much obliged to Professor G. Nelson Eby (Editor-in-Chief, *Lithos*) who not only participated in IGCP-510 as a prominent expert but also endorsed our plans to publish the final proceedings of IGCP-510 as a special issue of *Lithos*. The world map was drafted by Kirsi Larjamo. RD thanks the INCT program (CNPq/MCT/FAPESP—Proc. 573733/2008-2).

### Appendix A. Vita of IGCP-510

IGCP-510 was co-led by Roberto Dall'Agnol (Federal University of Pará, Belém, Brazil), Carol D. Frost (University of Wyoming, Laramie, U.S.A.), O. Tapani Rämö (University of Helsinki, Finland), and Laurence J. Robb (University of the Witwatersrand, Johannesburg, South Africa). The project website <http://www.igcp-510.org/IGCP-510.htm> was (and continues to be) mastered by Brent A. Elliott (State of Alaska Department of Natural Resources, Fairbanks, U.S.A.).

During its six years of existence (2005–2010) the project arranged seven meetings with technical scientific sessions (Moscow, Idaho, USA; Belém, Pará, Brazil; Stellenbosch, South Africa; Québec City, Québec, Canada; Oslo, Norway; Tunceli, Turkey; Helsinki, Finland) and twelve field trips/field conferences (Yellowstone-Snake River Plain, U.S.A.; Paleoproterozoic granite terrains of southern and central Finland; tin-granites of Pitinga, Amazonas, Brazil; Archean and Proterozoic granitoids of Serra dos Carajás, Pará, Brazil; Bushveld igneous province, South Africa; Miocene magmatic provinces in southern Nevada and southeastern California, U.S.A.; Oslo Rift, southeastern Norway; Corsica igneous suite, France; granites and alkaline rocks in Finnish Lapland and the Kola Peninsula, Russia; Cappadocian volcanic province, Turkey; Keban and Hasancelebi granite provinces, Turkey; Wiborg batholith, southeastern Finland) (Table 2). The overall attendance at the formal activities of the project was 530 and the number of scientific papers delivered was 184.

In total, five proceedings volumes were published:

2005 Annual Meeting (Moscow, Idaho): *Lithos*, Vol. 97, 1–2 (2007)

2006 Annual Meeting (Belém, Brazil): *The Canadian Mineralogist*, Vol. 47, Part 6 (2009)

2007 Annual Meeting (Stellenbosch, South Africa): *Geological Society of America Special Paper No. 472* (2010)

2008 R.F. Emslie Symposium (Québec, Canada): *The Canadian Mineralogist*, Vol. 48, Part 4 (2010)

2010 Annual Meeting (Helsinki, Finland): *Lithos* (this volume)

Conference publications (abstract volumes, field trip guides) were published for each activity (Table 2). The overall publication list of IGCP-510 comprises more than 100 items, most of them original, peer-reviewed research papers. The (still building) publication list may be accessed via the project website at [http://www.igcp-510.org/IGCP-510\\_results\\_publications.htm](http://www.igcp-510.org/IGCP-510_results_publications.htm).

Overall, IGCP-510 has established an active international consortium of researchers working in the field of A-type granites and related

rocks, with close ties to the society, e.g., local mining companies. Countries involved in the project are Argentina, Australia, Austria, Belgium, Brazil, Cameroon, Canada, Colombia, Czech Republic, Egypt, Estonia, Finland, France, Germany, India, Iran, Ireland, Israel, Italy, Japan, Namibia, the Netherlands, Norway, People's Republic of China, Poland, Portugal, Republic of Korea, Romania, Russia, Slovakia, South Africa, Spain, Sweden, Switzerland, Taiwan, Turkey, Ukraine, the United Kingdom, the United States of America, Uruguay, Venezuela, Yugoslavia. The mailing list of IGCP-510 includes more than 400 individuals worldwide. Doctoral and post-doctoral students from several participating countries were actively involved in the project, thus promoting the educational aspect of the project to recruit students especially from the less developed countries. Annual funds allocated to IGCP-510 via UNESCO and IUGS (in total, \$US 23,500) were used to support 24 individuals from the less developed countries to participate in the activities of the project.

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