Geodynamic significance of S-type granites in circum-Pacific orogens

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ABSTRACT

In Phanerozoic circum-Pacific orogenic belts, most "post-collisional" S-type granites and associated high-temperature, low-pressure metamorphic complexes formed during early arc extension. The granites are part of a tripartite association consisting of (1) inboard S-type granite, (2) outboard oceanic arc, and (3) intervening, turbidite-filled backarc basin. S-type granites herald the formation of new outboard oceanic arc and extensional backarc systems, but thickening of a preexisting, sediment-dominated backarc basin is a prerequisite for their generation. In these environments, S-type plutonism is triggered by renewal of arc magmatism following thickening, when hot basaltic magmas are intruded into the thickened backarc crust once slab retreat is reestablished. With ongoing extension during retreat, the crust becomes progressively thinned, the sedimentary contribution is diminished, and the granites lose their S-type character. Such tripartite associations involving S-type granite are probably diagnostic of repeated slab-retreat episodes, and the Jurassic U.S. cordillera might be an example.

Keywords: S-type granite, subduction retreat, postcollisional, extension, backarc, Tasmanides.

INTRODUCTION

Since S-type granites were first recognized as strongly peraluminous magmas derived (dominantly) from metasedimentary rocks, their tectonic setting has been debated. Circum-Pacific S-type granites usually contain biotite-cordierite, or garnet-muscovite, as the dominant aluminous minerals, the difference largely reflecting lower water fugacity and higher magmatic temperatures of the former (Clemens and Wall, 1988). S-type granites typically contain abundant inherited zircon (e.g., Williams, 1998), and the complex age spectra of the zircon population allows the metasedimentary source to be distinguished from other potential components.

Nonetheless, S-type granites are an end member of a compositional spectrum. They form if the proportion of metasedimentary to other melt components (from metaigneous lower crust and/or basaltic magma) is sufficiently high to produce strongly peraluminous compositions (e.g., Ague and Brimhall, 1987; Collins, 1996). Otherwise, granitic magmas of typically metaluminous (I-type, hornblende bearing) or transitional I-S character, form. Many S-type granites also contain mafic microgranitoid enclaves, a record of putative mantle input in their genesis. Variable mixing of common source components during granite generation explains why S- and I-type granites overlap on the MALI index of Frost et al. (2001).

A key factor in S-type granite generation is to have a metasedimentary source buried in the deep crust before anatexis, and many workers have preferred continent-continent collision to achieve this (Barbarin, 1998, and references therein). The common "postcollisional," or rather postkinematic, timing has reinforced this model. However, S-type granites occur sporadically in all the Phanerozoic circum-Pacific orogens, few if any of which have undergone any form of continental collision. Rather, in these accretionary orogens, it seems that most S-type granites formed under specific geodynamic conditions associated with backarc extension, as discussed below.

The type area of S-type granites is the eastern Lachlan orogen within the Tasmanide orogenic system of eastern Australia (Fig. 1), part of the active margin of eastern Gondwana during the Paleozoic. The Tasmanide orogenic system is dominated by extensive turbidite-filled, backarc basin sequences, separated by subordinate, coeval oceanic arc remnants that become successively younger outboard (e.g., Foster and Gray, 2000; Collins, 2002a, 2002b; Glen, 2005). Also, a complex array of short-lived deformation zones and plutonic belts generally youngs outboard, forming narrow fold-thrust belts, usually ~20–60 m.y. after turbidite deposition. Thus, the Tasmanide orogenic system comprises a series of outboard-younging, turbidite-granite orogens composing the inboard Delamerian (530–500 Ma), the medial Lachlan (490–350 Ma), and the outboard New England (350–240 Ma) orogens. S-type granites compose as much as 50% of the plutonic rocks (White and Chappell, 1988), but were generated within short-lived intervals and occur in discrete belts. Most are associated with high-temperature–low-pressure (HTLP) metamorphic complexes (Fig. 1), at least locally.

S-type plutonism has been associated with backarc extension in the New England orogen (Little et al., 1992), but here we show it to be a repeated process throughout Tasmanide orogenic system evolution. The presence of rare S-type granites in other circum-Pacific orogens suggests that repeated subduction retreat events leading to formation of oceanic arc during backarc extension were uncommon, but probably occurred during the Jurassic in the North American Cordillera.

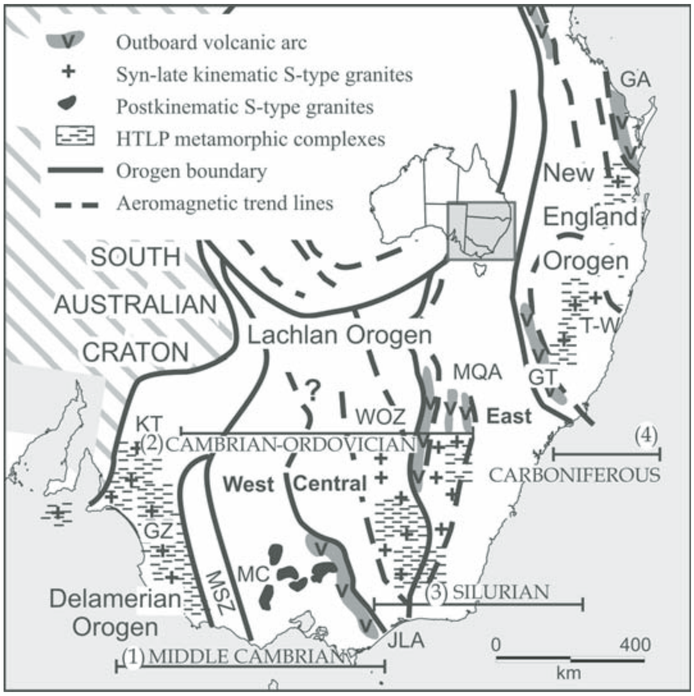

Figure 1. Map of Tasman orogenic system highlighting the four tripartite associations consisting of inboard high-temperature–low-pressure (HTLP) metamorphic complexes and S-type granites, slightly younger outboard oceanic arc systems, and intervening regions dominated by coeval backarc basin turbidite fill. The associations overlap, which establishes the link between inboard and younger outboard orogenic systems. See text for details. GA—Gympie arc; GT—arc in Gamilaroi terrane; JLA—Jamieson-Licola arc; KT—Kanmantoo Trough; MC—Moornambool metamorphic complex; MQA—Macquarie arc; MSZ—Mount Stavely zone; T-W—Tia-Wongwibinda complexes; WOZ—Wagga-Omeo zone (backarc basin).

S-TYPE MAGMATISM IN THE WESTERN PACIFIC

Most oceanic island arcs form by outboard retreat of old, dense, subducting plate, which sinks faster than it converges. This causes the trench and arc to migrate outboard, generating a system of extensional oceanic backarcs that may be separated by remnant arcs or highly extended continental ribbons. The numerous Cenozoic oceanic arc and widespread backarc systems of the western Pacific formed in this way (e.g., Taylor, 1995). Some arcs are built on extended continental ribbons, such as Japan and New Zealand.

Both New Zealand and Japan contain S-type granites that formed after a crustal thickening phase, during the initial stages of subsequent outboard arc retreat. The vast backarc system of the present-day southwest Pacific began ca. 100 Ma, following the Rangitata orogeny ca. 120 Ma in New Zealand and generation of 110 Ma, synextensional S/I-type granites in the extensional Paparoa metamorphic core complex (e.g., Spell et al., 2000). Similarly, the 19 Ma S-type, garnet-orthopyroxene tonalites and associated HTLP (granulite facies) metamorphism in the Hidaka belt of Japan were coeval with backarc basin opening and formation of the Japan Sea following collision with the Kurile arc ca. 37 Ma (Kemp et al., 2007).

In the west Pacific examples described above, S-type granites and associated HTLP metamorphic complexes were associated with reinitiation of arc magmatism following crustal thickening. In each case, a tripartite association was established, consisting of (1) inboard S-type granites and HTLP metamorphic complexes with (2) newly developed outboard arc systems, each separated by (3) slightly younger backarc basins that may persist for tens of millions of years. This provides a framework for establishing if outboard oceanic terranes and active continental margins were linked by common geodynamic processes. As described below, this tripartite association occurred at least four times in the Tasmanide orogenic system.

TASMANIDE OROGENIC SYSTEM

Middle Cambrian

Initiation of the Tasmanide orogenic system is generally attributed to rapid subsidence of a shelf sequence and deposition of Kanmantoo trough turbidites, beginning at 525 Ma, in an extensional setting (Foden et al., 2006). The first tripartite association did not develop until ~10 m.y. later, probably following a poorly recognized thickening event.

The oldest tripartite association in the Tasmanide orogenic system consists of (1) ca. 515–510 Ma transitional S/I-type granites and metamorphosed Kanmantoo turbidites (e.g., Foden et al., 2006); (2) an outboard Middle-Late Cambrian Jamieson-Licola arc at the eastern edge of the western Lachlan orogen (Fig. 1), which evolved from mafic to felsic by 500 Ma; and (3) an intervening oceanic backarc, the western Lachlan orogen, which has a Botomian (517–513 Ma) greenstone basement overlain by Cambrian-Ordovician deep-water turbidites (VandenBerg et al., 2000). The onset of Kanmantoo HTLP metamorphism at 515 Ma (Foden et al., 2006) was associated with subhorizontal fabrics and emplacement of tholeiitic basalt dikes, which are hallmark extensional features (Oliver and Zakowski, 1995).

Cambrian-Ordovician

Following a major contractional event (Delamerian), which folded the Kanmantoo metasediments into upright folds ca. 500 Ma (Kemp, 2003; Foden et al., 2006), the second tripartite association developed (Fig. 1). It consisted of (1) inboard 500–490 Ma S-type granites and migmatites of the Glenelg zone; (2) the 490–440 Ma outboard, oceanic, Macquarie arc of the eastern Lachlan orogen (e.g., Glen et al., 2007); and (3) the intervening Wagga-Omeo zone of the central Lachlan orogen, which filled with Early to Late Ordovician turbidites. Evidence for post-Delamerian rifting in the western Lachlan orogen (Fig. 1) during outboard arc migration includes the 500 Ma graben structures of the Mount Stavely zone and 500 Ma subhorizontal fabrics associated with deep crustal exhumation in the adjacent, outboard Moornambool metamorphic complex (Miller et al., 2005).

Silurian

The third tripartite association formed in the eastern Lachlan orogen (Fig. 1) after a widespread contractional deformation phase (Benambran) ca. 440 Ma, when the widespread Wagga-Omeo backarc basin sediments were buried to mid-crustal depths (e.g., Collins and Hobbs, 2001). The association consists of (1) the S-type granites (e.g., White and Chappell, 1988), which formed a new magmatic belt on the old Macquarie arc in the Early Silurian; (2) the Gamilaroi arc terrane of the outboard New England orogen, consisting of Late Silurian and Early Devonian basalts and basaltic andesites (e.g., Offler and Gamble, 2002); and (3) intervening Early Silurian–Early Devonian turbidite-filled grabens of the eastern Lachlan orogen, including the Tumut, Tantangara, Cowra, and Hill End troughs.

Early Silurian anatectic HTLP metamorphic complexes formed regional-scale aureoles partly around (or below) some of the S-type batholiths (e.g., Richards and Collins, 2002). Rare mafic rocks, coeval with S-type magmatism, are either low-K, arc tholeiite, or mid-oceanic ridge basalt–like, backarc basin tholeiitic basalts (Collins, 2002a, their Fig. 3), suggesting eruption though thin, extending crust.

Ongoing Silurian-Early Devonian extension in the eastern Lachlan orogen was associated with a change from S-type to I-type magmatism. Most plutonic belts and associated rift zones migrated outboard (Collins 2002b; Fig. 2), and the major batholiths became exclusively I-type in character. Late Silurian–Early Devonian metamorphic complexes formed the base of the rifts, or formed local extensional migmatite zones beneath large I-type plutonic complexes, such as the Bega Batholith (Richards and Collins, 2004).

Late Carboniferous

Following Late Devonian accretion of the Gamilaroi arc terrane to the Lachlan, a prolonged period of continental arc volcanism ensued and the outboard accretionary prism rapidly expanded to form the substrate of the New England orogen. Renewed late Carboniferous extension associated with core complex formation (Little et al., 1992) produced the fourth tripartite association of the Tasmanide orogenic system (Fig. 1). It consists of (1) 300 Ma, synextensional S-type granites, associated HTLP metamorphic complexes, and rare coeval tholeiitic gabbro complexes (e.g., Jenkins et al., 2002); (2) the primitive, outboard Early Permian Gympie arc; and (3) intervening, but now highly disrupted Early Permian basins (Leitch, 1988).

NONEXTENSIONAL(?) LACHLAN S-TYPE GRANITES

A contrasting, inboard belt of Middle-Late Devonian S-type granites formed after final closure of the western Lachlan backarc as the entire Lachlan orogen finally amalgamated (e.g., Foster and Gray, 2000). The result was generation of postkinematic S-type granites (Fig. 1) that intruded after adjacent I-type plutons and are not associated with exposed HTLP metamorphic complexes. Whether these S-type granites reflect Devonian intracontinental rifting (Collins, 2002a, 2002b), termination of divergent double subduction (Soesoo et al., 1997), or slab breakoff following amalgamation, is yet to be resolved.

DISCUSSION

The tripartite association of inboard S-type granites and associated HTLP metamorphic complexes, outboard oceanic arc, and intervening turbidite-filled, backarc basin, occurred four times in the Tasmanide orogenic system. It can be explained by repeated, long-term subduction retreat separated by short-lived contraction (subduction advance) events, described as tectonic switching by Collins (2002b). Like the modern western Pacific, slab rollback induces arc retreat and produces an oceanic

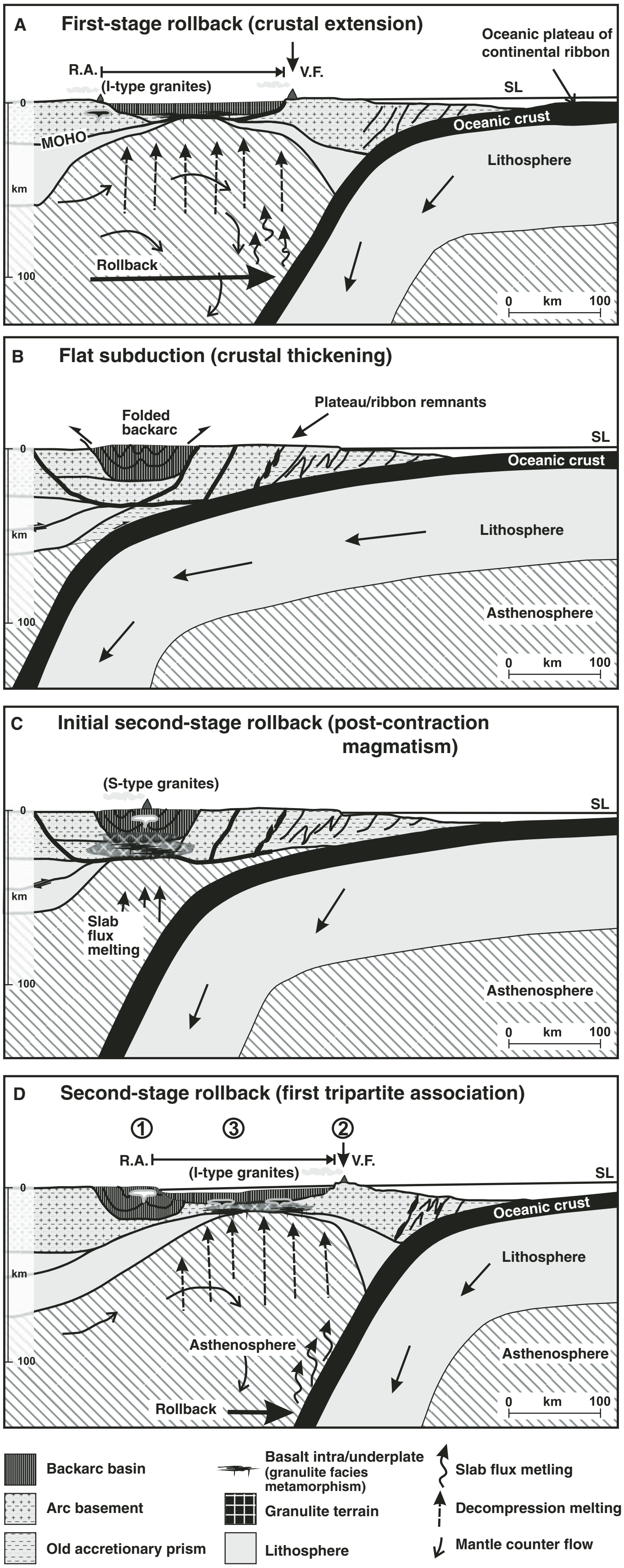

Figure 2. Model for S-type granite generation in circum-Pacific context. A: Slab rollback induces arc retreat and produces oceanic backarc basin, which fills with turbidites. Arrival of anomalously buoyant crust induces flat subduction and transient crustal thickening. B: Once anomaly is subducted, slab rollback and arc magmatism recommence, and thickened backarc crust is melted to produce S-type granites. C: Tripartite association begins, but is not fully developed until stage D. 1—S-type granite and HTLP complex; 2—outboard arc; 3—backarc basin; R.A.—remnant arc; V.F.—volcanic front. Ongoing backarc extension is not associated with S-type magmatism.

backarc basin, which may fill with turbidites (Fig. 2A). Resistance of a buoyant anomaly to subduction drives the slab hinge inboard, causing transient subduction advance and crustal thickening (Fig. 2B). Once the positive buoyancy forces are overcome, usually by conversion of the anomaly to eclogite, it subducts, rollback reinitiates, and the arc is reestablished, which is when S-type plutonism occurs (Fig. 2C).

As the arc reestablishes, the critical thermal input is the advective burst of mantle-derived heat from basaltic arc magmas into the fertile, thickened, metasedimentary crust (e.g., Annen et al., 2006). Arc magmatism, hence heat transfer to the crust, is enhanced if the lithosphere is actively thinning, because it increases the degree of decompression melting (e.g., Pearce and Parkinson, 1993). The strong slab-flux signature in basalts associated with the 430 Ma S-type Murrumbidgee batholith (Healy et al., 2004) confirms that the vast eastern Lachlan S-type batholiths formed in an arc setting. Similarly, in the Delamerian orogen, 500 Ma Glenelg S-type granites were associated with subduction-related boninites (Kemp, 2003).

S-type granites herald the slab retreat phase because the initial burst of mantle-derived arc magmatism weakens the lithosphere along the arc locus (Fig. 2C), which becomes the site for crustal extension as rollback progresses. This explains the consistent association of S-type granites with HTLP metamorphic (or anatectic) complexes, including some core complexes, which are commonly regarded as extensional (e.g., Wickham and Oxburgh, 1985; Sandiford and Powell, 1986). In these environments, gravitational collapse and radiogenic crustal heating are unimportant processes of granite generation. The tripartite association links the post-collisional extensional phase of the old orogen with the inception of the new outboard orogen, so that elements of each orogen overlap (Fig. 1).

With ongoing extension, the locus of stretching moves outboard, the former backarc is progressively thinned (Fig. 2D), and lesser amounts of sediment become available for melting as the new backarc region expands; so the granites lose their S-type character. This explains why, in many retreating accretionary orogens, I-type granites typically follow S-types and became more widespread, as in the Lachlan orogen (White and Chappell, 1988).

Nonetheless, the Tasmanide orogenic system is unusual, as other circum-Pacific orogenic systems do not contain significant amounts of S-type granites. Typically, I-type granites dominate these continental arc settings, including the North American and South American Cordillera. There, relatively narrow plutonic belts reflect protracted magmatism within a generally nonretreating arc, where the deep crust is typically metaigneous, a result of protracted magmatic underplating.

However, a tripartite association appears to have existed in the North American Cordillera during the Middle-Late Jurassic, albeit disrupted by Cenozoic strike-slip faulting. There are 170–160 Ma S-type granites in the Sierra Nevada and axial Peninsula Ranges batholiths (Ague and Brimhall, 1987; Shaw et al., 2003); those in the latter are associated with HTLP complexes. The offset, outboard oceanic arc and extensional backarc system would include the Josephine (164–162 Ma) and Coast Range (170–164 Ma) ophiolites, which have suprasubduction zone signatures (e.g., Coleman, 2000). The backarc basin sequence includes the 157–152 Ma turbidites of the Galice Formation (e.g., Harper, 2003). Potential S-type source rocks would include correlatives of pre–170 Ma backarc basin sequences such as the San Hipolito Formation in Baja California (Busby et al., 1998), the Julian Schist in the Peninsula Ranges (Shaw et al., 2003), and the turbidites in the Luning Fencemaker fold-and-thrust belt of Nevada (e.g., Wyld et al., 2001). The setting would be similar to the phase one highly extensional arc system envisaged by Busby et al. (1998), but the S-type magmatism requires a pre–170 Ma crustal thickening event, at least locally.

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