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Growth of wedge-shaped plutons at the base of active half-grabens

S. W. Richards and W. J. Collins

ABSTRACT: Combined field and geophysical data show that plutons from the Bega Batholith are elongate, meridional, wedge-shaped bodies which intruded during a period of regional east–west extension in the Palaeozoic eastern Lachlan orogen, eastern Australia. Plutons within the core of the batholith have intruded coeval, syn-rift sediments and co-magmatic volcanics. The batholith is bound by high-temperature, dip-slip faults, and contains several major NE-trending transtensional faults which were active during batholith construction. In the central part of the batholith, the Kameruka pluton is an asymmetric, eastward-thickening, wedge-shaped body with the base exposed as the western contact, which is characterised by abundant, shallow-dipping schlieren migmatites which contain recumbent folds and extensional shear bands. A shallow (<30°), east-dipping, primary magmatic layering in the Kameruka pluton steepens progressively westward, where it becomes conformable to the east-dipping basal migmatites. The systematic steepening of the layering is comparable to sedimentary units formed during floor depression in syn-rift settings. The present authors suggest that the wedge-shaped plutons of the Bega Batholith are the deeper, plutonic expression of a hot, active rift. The batholith was fed and sustained by injection of magma through sub-vertical dykes. Displacement along syn-magmatic, NE-trending faults suggests up to 25 km of arc-perpendicular extension during batholith construction. The inferred tectonic setting for batholith emplacement is a continental back-arc, where modern half-extension rates of 20–40 mm yr^{-1} are not unusual, and are sufficient to emplace the entire batholith in ∼1 Ma. This structural model provides a mechanism for the emplacement of some wedge-shaped plutons and is one solution to the 'room problem' of batholith emplacement.

KEY WORDS: Bega Batholith, extension, Lachlan Fold Belt, pluton emplacement.

The generation and emplacement of granitic magmas are fundamental aspects of crustal evolution, yet the tectonic control on these two processes is vigorously debated. Granitic magmas may be generated during lithospheric extension, an ideal environment for adiabatic decompression melting of the asthenosphere (e.g. McKenzie & Bickle 1988), which supplies advective heat to the crust via basaltic intrusion, leading to granite magma production (e.g. Thompson 1999; Petford & Gallagher 2001). Intuitively, extensional environments also seem capable of solving the enigmatic 'room problem' associated with the emplacement of large batholiths, but tectonic strain rates are considered to be generally too low to accommodate pluton growth (e.g. Paterson & Fowler 1993). Alternatively, magma emplacement may occur during orogenic contraction or transpression because syn-magmatic upright folds, sub-vertical foliations and S/C-type fabrics are both temporally and spatially associated with the plutons (e.g. Brown & Solar 1998; Paterson & Miller 1998).

Plutons emplaced during compression are generally thicker and preserve steeper margins with respect to their thin, tabular counterparts emplaced during extension (Vigneresse 1995; Benn *et al.* 2000). Many plutons are also asymmetric and wedge-shaped (e.g. Vigneresse 1995; Cruden 1998), with growth commonly explained by lifting of the roof (e.g. Dixon & Simpson 1987; Benn *et al.* 2000) or subsidence of the floor (Cruden 1998). Such models overcome the perceived accommodation problems associated with low strain rates, but imply minor tectonic control on generating space for batholith emplacement. However, such plutons can be generated in an extensional setting at recorded tectonic strain rates, as explained below.

The present authors offer field and geophysical evidence that describes the geometry, internal structure and contact relations of plutons in the Bega Batholith in the eastern Lachlan orogen, eastern Australia, which suggest that it formed in a graben. Internal, primary magmatic features suggest that these plutons can be described like 'sedimentary' deposits formed as a series of cumulate layers on an aggrading magma chamber floor, with the layers recording a progression of pluton growth (Weibe & Collins 1998). From the orientation of way-up structures, the present authors deduce that the plutons underwent progressive tilting to form wedge-shaped structures during construction and inflation at the base of an actively developing half-graben. This model implies that a major tectonic control on batholith construction and pluton growth rates can occur within a rift setting.

1. The Bega Batholith

The 420–405-Ma-old Bega Batholith (Fig. 1) is over 300 km long, but only 50 km wide, and comprises a series of N–S trending suites (Chappell 1996), which contain one or more co-genetic plutons. Plutons and suites of plutons exhibit a pronounced N–S alignment: the Glenbog suite extends over 150 km along the western margin of the batholith, but is <10 km wide. The suites exhibit remarkably coherent geochemical patterns along strike, but rapid chemical variation across strike (Chappell 1996). The ages of the suites decrease eastward (Chappell *et al.* 1991). The proportion of plutonic to coeval supracrustal rock decreases northwards in the batholith (Fig. 1). These supracrustal rocks are dominated by volcaniclastics and co-genetic volcanics (e.g. Wyborn & Chappell

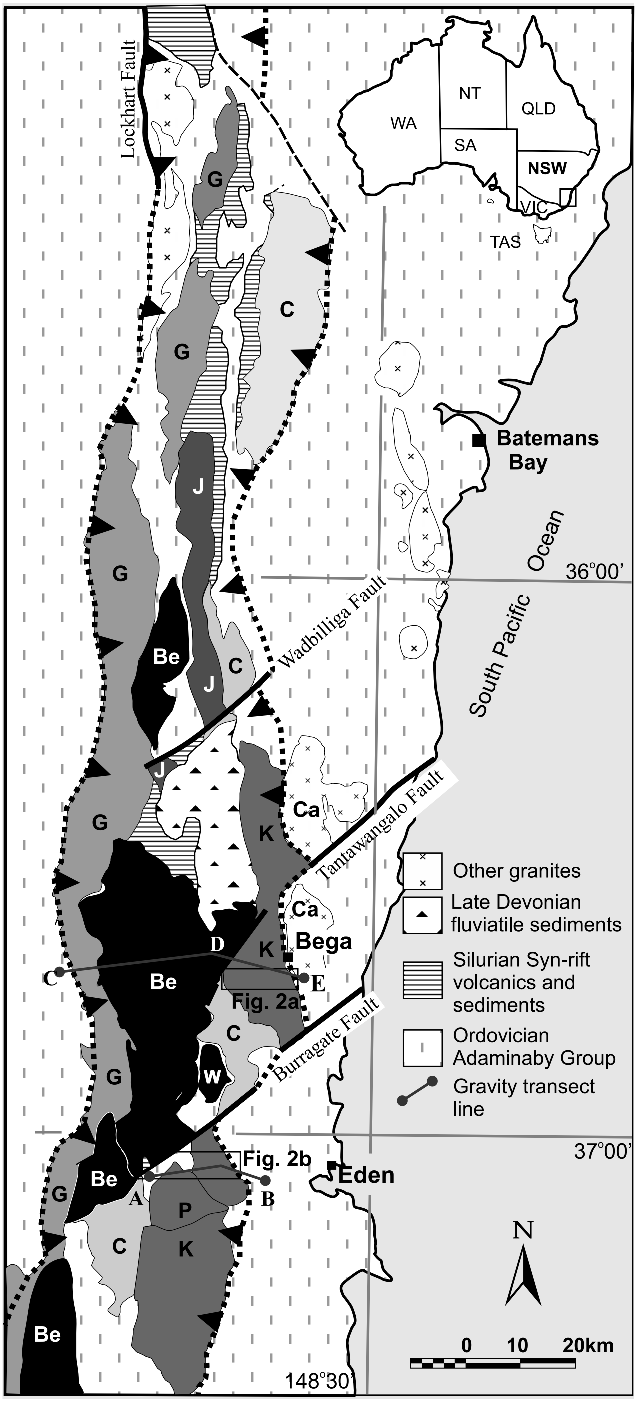

Figure 1 Map of the Bega Batholith, southeastern Australia, showing relevant suites of the batholith and syn-rift supracrustal rocks restricted to the northern extent, but within the bounds of the batholith (suites after Chappell 1996): (K) Kameruka; (P) Pericoe; (Be) Bemboka; (C) Candelo; (G) Glenbog; (J) Jillicambra; and (Ca) Cobargo. Dashed lines with barbs represent the inferred limit of graben based on gravity profiles and field relations. Note contrasting amounts of offset for different suites on the Burragate and Tantawangalo faults. Cover rocks beyond the batholith margin have been removed for clarity.

1986), and are contained within a narrow structural lithotectonic belt that is the northern extension of the Bega Batholith.

The highly elongate batholith is parallel to, and highlights, an intense, N–S trending structural grain developed within the poly-deformed, regional, low-grade turbiditic metasediments of Ordovician age. This relationship suggests a strong structural control on batholith construction. However, although the plutons intruded highly cleaved metasediments (Fig. 1), they are generally non-foliated. This suggests that they post-dated the major contractional deformation event.

The batholith is bound on the eastern and western sides by high-T, dip-slip shear zones, but they are largely obliterated by later intrusion. Most of the western edge of the batholith is occupied by the Glenbog suite, which has intruded a steep, N–S striking, east-dipping, high-temperature mylonite zone that is preserved at the northwest extremity of the batholith. This zone, preserved within the 30-km-long Lockhart complex, is characterised by tectonically interleaved lenses of gneissic granite and 'amphibolite'. The 'amphibolite' contains euhedral plagioclase and hornblende laths which define a steep inward dipping lineation (62→110). These laths are strongly aligned, but not strained, suggesting that the mafic body was cooling from magma during fault movement. These features imply magma emplacement into an active fault zone.

On the eastern side of the batholith, the eastern margin of the Kameruka pluton is sharp and abuts a narrow (<0·3-km-wide) cordierite-biotite-muscovite-quartz bearing hornfels. The hornfels is a high-strain, high-T aureole characterised by isoclinal folding and shearing. It contains a sub-vertical foliation with a steep lineation defined by elongate, 3-mm-long cordierite porphyroblasts, and P–T conditions of ~500° and 1–2 kbar are estimated. Enclaves within the adjacent granodiorite also define a steep sub-vertical lineation. These features suggest sub-vertical movement along ductile faults within the aureole and adjacent granite during emplacement of the Kameruka pluton, similar to that observed on the western side of the batholith.

The Cobargo suite of plutons lies to the east of the Kameruka pluton, beyond the high-T, high-strain zone at the eastern margin of the batholith (Fig. 1). These plutons have subrounded shapes and sharp discordant margins. The aureoles are narrow and characterised by hornfels containing small, randomly oriented cordierite grains, typical of static growth during emplacement. These characteristics differ considerably from other plutons within the Bega Batholith. Furthermore, the Cobargo suite appears to be younger (~395 Ma) than the main batholith (Chappell *et al.* 1991). For these structural and geochronological reasons, the present authors consider that the Cobargo suite formed well after the bounding shear zones associated with major batholith emplacement.

Age variations across the batholith highlight the variable timing of the emplacement of the various plutons and suites of plutons. The relative timing of pluton emplacement is well constrained based on cross-cutting and intrusive contact relations. The Glenbog suite and Kameruka pluton cross-cut the Candelo suite, and therefore, establish that the Candelo suite as one of the earliest emplaced suites in the Bega Batholith. Mixing between the Pericoe and Kameruka plutons suggests that the Pericoe pluton intruded late during construction of the Kameruka pluton. In turn, the Bemboka pluton, which intrudes the Kameruka pluton along its northwestern margin, has been determined as the last significant suite emplaced in the Bega Batholith. The order of emplacement tightly constrains the model of construction of the Bega Batholith.

Several NE-trending strike-slip faults (i.e. Tantawangalo, Burragate and Wadbilliga) cut obliquely across the batholith, and all show differential right-lateral offset for each suite (Fig. 1). For example, the western Glenbog suite shows no major offset along these faults, but the Kameruka suite is offset ~25 km and the Candelo suite is displaced ~31 km by the Burragate fault. The Bemboka suite is partly offset, but only on its eastern side. Farther north, the Wadbilliga fault offsets the Jillicambra pluton by ~12 km, but the Candelo suite is offset by only ~5 km. Strike-slip movement along the faults as well as the lack of any metamorphic grade change across the

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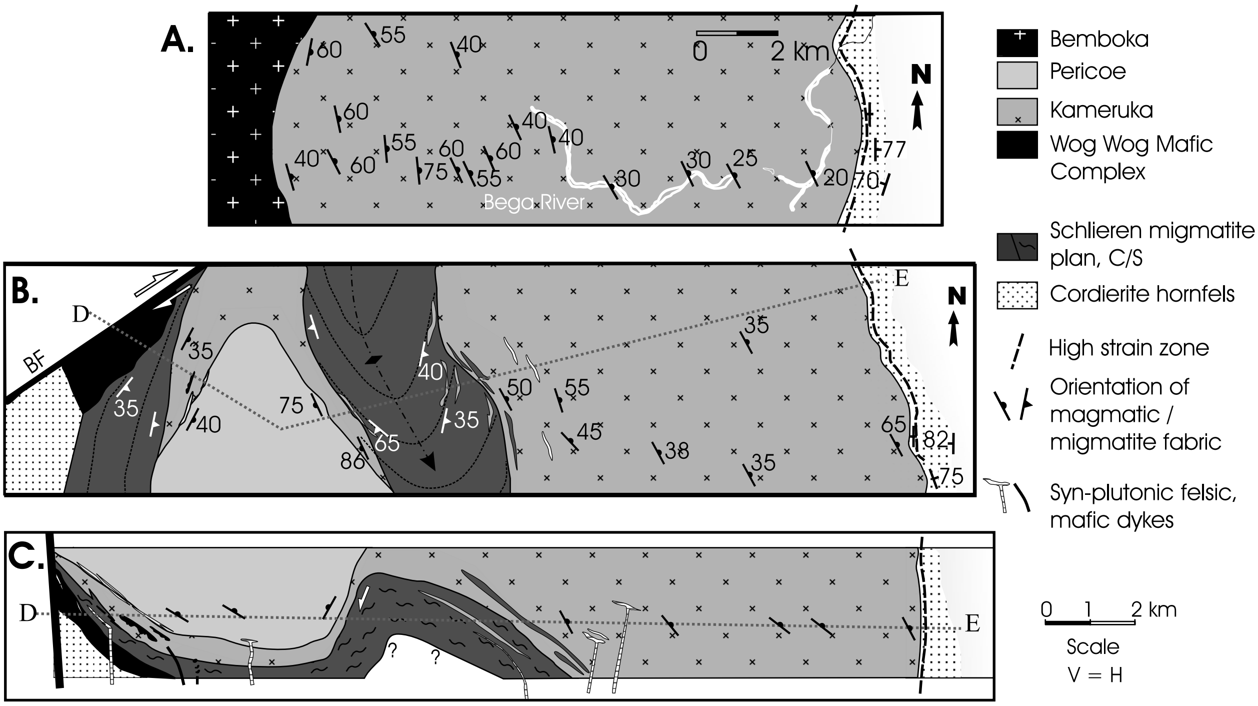

Figure 2 (a & b) Traverses across the Kameruka suite plutons (see Fig. 1 for location) showing systematic steepening of east-dipping primary magmatic features, which become concordant with structurally underlying migmatites and a sheeted gabbro complex at the western contact (b). (c) Cross-section of DŁ shows inferred pluton geometry, based on primary fabrics and the structure of basal migmatites from the southern transect.

faults indicate that these offsets are real values, therefore, this differential movement suggests that these oblique faults were also active during granite emplacement.

1.1. Contact relationships of the Bemboka and Kameruka suites

The Bemboka pluton is granodioritic, approximately 60 km long and <25 km wide, and is widest in the middle, tapering to the north and south (Fig. 1). The northern margin is overlain by shallow-dipping, fine-grained sediments which have been metamorphosed to cordierite hornfels at the contact. These sediments are the southern continuation of the supracrustal assemblages described from farther north (Fig. 1). In contrast, the southern margin either bounds the Burragate fault, or consists of intensely deformed diatexite migmatites which are characterised by an intense, shallow-dipping schlieren foliation. The migmatites occur at the base of plutons within the core of the batholith, forming a high-temperature zone which separates the plutons from underlying, upright-folded metasediments. Somewhat surprisingly, although much of the Bemboka pluton abuts the Burragate fault in the south, it is not deformed by it. Rather, the granites have intruded mylonitised granite and metasediment. This is further evidence for syn-faulting emplacement.

The Kameruka suite, which includes the Kameruka and Pericoe plutons, extends for >160 km, but is a maximum of 14 km wide. The Kameruka pluton is dominated by a coarse-grained megacrystic granodiorite containing pink K-feldspar grains of 3–10 cm in length. It preserves a variably developed, east-dipping primary magmatic fabric, which steepens progressively to the west (Fig. 2). The fabric is highlighted by internal layering, defined by variable grainsize and composition, and is associated with other features including rare alternating granite and mafic layers, flame-type injections and chilled lobate contacts along the lower margins of mafic layers, rare felsic 'pipes' in mafic layers (Fig. 3a), and channels of mafic enclaves. These features are taken as evidence for crystal deposition on

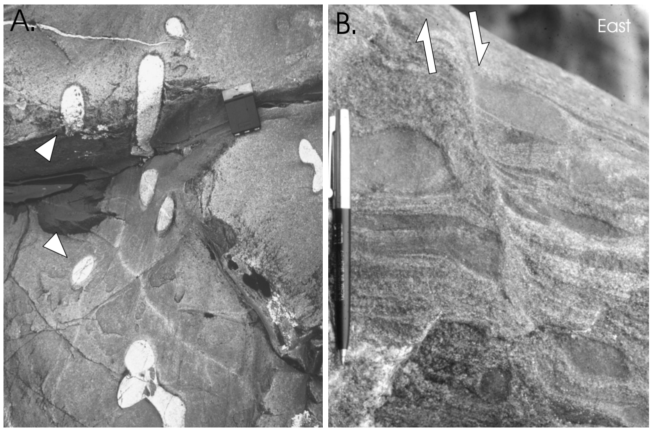

Figure 3 (a) Steeply plunging orientation of felsic granite 'pipes' intrusive into a mafic body near the base of the Kameruka pluton. Arrows indicate sections of the same pipe (base of photo ~50 cm). The 'pipes' are formed during upward, forceful injection of felsic material into the base of an overlying, viscous mafic layer. The process is primarily gravity-driven, and hence, the pipes consistently form in vertical orientations and can be used to determine the palaeo-horizontal (see Weibe and Collins 1998). (b) Well-developed, sub-horizontal schlieric fabric in the migmatites below the Kameruka pluton. The fabric is cut and deflected by leucosome-rich, sub-vertical shear zones with a normal sense of movement (pen for scale). The photo is representative of normal shears observed at the centimetre to decimetre scale.

a progressively aggrading floor of crystal mush in the pluton, but they are also indicators of 'way-up' (Weibe & Collins 1998). These geopetal indicators indicate top to the east, which requires that the western contact is the basal one.

Like the Bemboka pluton, the Kameruka has contrasting pluton–country-rock contact relationships. The hornfelsic eastern margin contrasts with the western margin, which is gradational from granite to migmatite. The western contact is characterised by a complex, 500-m-wide zone where migmatite, megacrystic granite and a myriad of hybrid phases are

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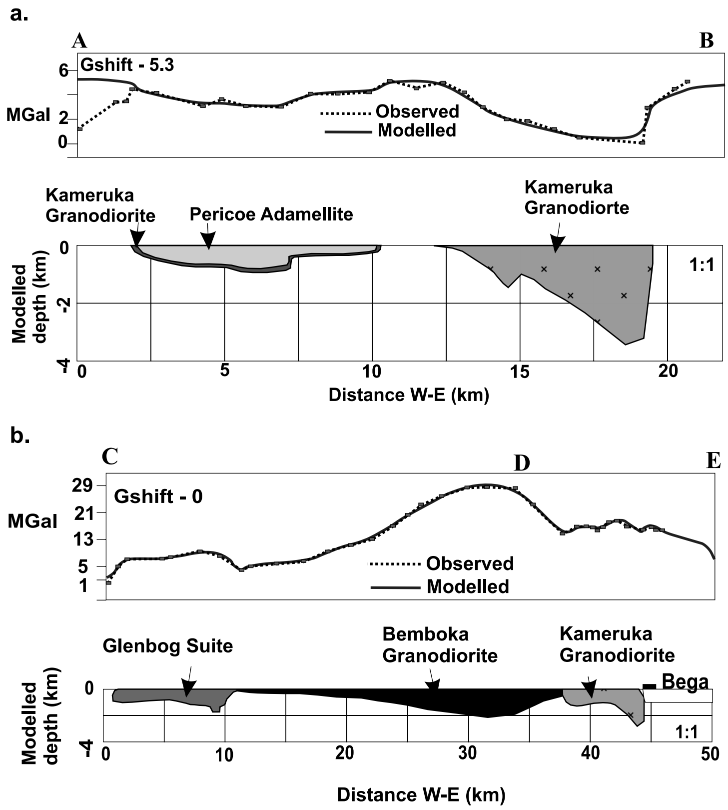

Figure 4 (a & b) Observed and modelled gravity profiles across the traverses in Figure 1 showing the modelled wedge-shaped geometry of the Kameruka and other Bega Batholith plutons. The model profile fits closely with the observed data with the addition of the polygons. The location and geometry is, in part, constrained by surface field measurements. In both transects, the eastern and western limit of the modelling was constrained by either major structures or rapid changes in rocktype. In (a), the dip in the observed gravity profile on the western margin reflects the presence of a pluton belonging to the Candelo super suite, which has been removed for this discussion. One major outlying point has been removed from transect C–E.

intimately inter-sheeted, indicating that the migmatites developed coevally with magma emplacement. Abundant cordierite-rich metapelitic blocks contain sillimanite and biotite hosted in a leucosome matrix, suggesting P–T conditions of >600 °C and 2–3 kbar. This reflects greater depths of equilibration compared with the eastern margin, and supports the way-up criteria that the western margin is the lower (basal) contact of the Kameruka pluton. Thus, the hornfelsed contacts of Bemboka and Kameruka appear to be the upper or roof contacts, whereas the migmatites appear to be the basal contacts of the plutons, and of the batholith.

The migmatites exhibit an intense, sinuous, sub-horizontal to moderately east-dipping schlieric foliation that anastomoses around remnant metapelitic blocks, and resemble σ-porphyroclasts within mylonites. They also contain local, syn-migmatitic recumbent folds outlined by relict bedding, schlieren and folded microgranite dykes. Steeply inclined, leucosome-rich normal shears cut the shallow-dipping migmatitic fabric (Fig. 3b). Significantly, the migmatites are extensively hybridised with the granites, with leucosomes commonly containing the characteristic K-feldspar megacrysts of the Kameruka granodiorite. Thus, the granite emplacement and migmatite formation occurred synchronously.

The migmatite zone, which extends for ∼500 m below the Kameruka pluton (Fig. 2c), is concordantly underlain by a 600-m-thick, sheeted gabbro complex which, in turn, is discordantly underlain by highly cleaved, low-grade metasediments. The underlying gabbro complex is layered at the metre-scale with thicker units exhibiting way-up structures, including rhythmically graded layers with chilled, fine-grained bases and coarse-grained tops, which show top to the east. Metre-scale diapirs of coarse dioritic magma have intruded into overlying graded layers, and also indicate top to the east (Collins *et al.* 2000). The orientation of the sheets and dykes is sub-parallel to the fabric within the overlying migmatites and granite layers in the Kameruka pluton, but directly below, the structure abruptly reverts to upright folds, typical of the surrounding low-grade country rock (Fig. 2). The steep axial plane foliation in the underlying turbidites is overprinted by stellate clusters of muscovite and chlorite, indicating contact metamorphism by the gabbro. The metamorphic overprinting and structural discontinuity between the gabbro and underlying metasediments shows that the gabbro was emplaced after regional folding, as is the case for the plutons of the batholith.

The Kameruka pluton is also host to numerous felsic microgranitic dykes which cut through the underlying migmatites, but terminate as diffuse layers at various levels in the pluton. The field relations indicate that they intruded upward through the lower parts of the pluton before spreading laterally along discrete planar surfaces, concordant with primary magmatic layering. Because they emanate from below the pluton but are part of the geochemical system, Collins *et al.* (2000) interpreted these dykes as the feeder conduits to the Kameruka pluton.

2. Gravity data

Two-dimensional (2D) gravity modelling along two E–W transects across the Bega Batholith (Fig. 1) was used to constrain the overall pluton shape. Measurements were taken at 400–500-m spacings and 500- to 1-km spacings along two E–W trending transects across the southern and central Bega Batholith, respectively (Fig. 4). The elevation and position of gravity stations were obtained at an accuracy of 0·5 m and 0·01 m, respectively, using a Trimble TSC1 real-time differential Global Positioning System. Gravity data were measured using a SCINTREX autograv with a precision of ± 0·05 mGal. Figure 4 illustrates the final bouguer anomaly after corrections; free air, bouguer (2·6), latitude correction and regional E–W gradient. Direct-forward modelling (2D) using Model 2D (Roach 1990) allowed construction of multiple polygons with the density of each polygon (pluton) derived from laboratory measurements of the densities of 22 selected, un-weathered field samples of the four main rocktypes, which include the Pericoe Adamellite (av. $2{\cdot}70 \times 10^3$ kg m^{-3}), Kameruka Granodiorite (av. $2{\cdot}72 \times 10^3$ kg m^{-3}), schlieren migmatite (av. $2{\cdot}78 \times 10^3$ kg m^{-3}) and regional schists (av. $2{\cdot}58 \times 10^3$ kg m^{-3}). The densities of an additional 12 samples were measured from the Bemboka Granodiorite (av. $2{\cdot}77 \times 10^3$ kg m^{-3}) and Glenbog suite plutons, corresponding with the rocktypes encountered on the northern transect (Fig. 1). The density of each sample was determined according to the relationship:

Density = (Weight in air)/[(Weight in air)–(Weight in water)].

The average of each rocktype was used in the gravity modelling.

Recent seismic refraction profiles for the eastern Lachlan orogen indicate that Ordovician turbidites extend to ∼15 km depth, below which mafic Cambrian and early Ordovician mafic rocks predominate (Finlayson *et al.* 2002). The plutons of the Bega Batholith have projected depths of <4 km based on the present authors projected surface structural data and gravity models, which are similar to those recognised elsewhere in the central and eastern Lachlan orogen, based on seismic-reflection profiling (Trzebski *et al.* 1999; Trzebski *et al.* 2001; Glen *et al.* 2002; Lennox *et al.* 2002). Therefore, the authors have modelled the plutons as enclosed within metasediments.

The northern transect exhibits a predominantly positive gravity anomaly corresponding with plutons with higher densities than the enclosing schists (av. $2{\cdot}58 \times 10^3$ kg m^{-3}). The final gravity model for the southern transect (Fig. 4b) shows a wedge-shaped profile that extends westward to include the shallow, slightly basin-shaped Pericoe pluton. The northern transect, including the Glenbog Granodiorite, the Bemboka Granodiorite and the Kameruka Granodiorite show a consistent deepening to the east profile with the Kameruka Granodiorite, similar to that modelled for the southern transect (Fig. 1). The Kameruka and Bemboka plutons display a consistent steeper, deeper eastern margin and a shallower, less-inclined base to the west. The consistent asymmetric shape of the Bega Batholith plutons suggests a fundamental structural control on emplacement and pluton growth.

3. The Bega Batholith as a graben

The presence of bounding, high-T, inward-dipping, dip-slip faults in the batholith suggests that it occupies a graben structure. Although the present authors have not determined sense of shear on the faults, the restriction of Silurian and Early Devonian supracrustal rocks to within the batholith, with older basement (Ordovician) rocks beyond the batholith margins (Fig. 1), indicates that it was a structural depression. Given that these coeval supracrustal rocks include bimodal volcanics, such as the Carrawang basalt (Glen 1995), it is apparent that the batholith was emplaced into an active graben. The lowermost syn-rift supracrustal rocks are regarded as the roof of the batholith, and the migmatites are the base of the graben.

The migmatites at the batholith base are considered to be part of an extensional detachment. They contain recumbent folds, shallow-dipping foliations and late melt-rich shear zones with normal sense of movement (Fig. 3b), which imply that the migmatite zone and overlying pluton formed during lithospheric extension. Furthermore, this kilometre-thick zone is underlain by non-foliated gabbros and upright folded metasediments (Fig. 2c). Therefore, the migmatites form a distinct, shallow-dipping zone of extensional shear, and this is best described as a detachment surface that developed synchronously with batholith emplacement.

The structural evidence for widespread E–W extension in the eastern Lachlan orogen throughout the Silurian–Devonian, during intrusion of the extensive batholiths, is the formation of north-trending rift basins, some with volcanic-hosted massive sulphide (VHMS) mineralisation (Glen 1992, 1995). The basins comprise typical syn- and post-rift sediments, which were inverted during later contraction (Glen 1995; Collins 2002b). An extensional model is also consistent with seismic reflection profiles of the central–eastern Lachlan orogen, which show Wyangala Batholith plutons localised within an inverted graben (Glen *et al.* 2002, fig. 12). The profiles indicate that steep, normal faults link at shallow depths (<5 km) with major listric faults which extend into the middle crust (10–15 km). These faults were reactivated during later compressive deformation. Equally, all the Silurian–Devonian rifts in the Lachlan Fold Belt have been structurally inverted (e.g. Glen 1992, 1995), and the Lockhart fault is considered to be the high-T manifestation of this structural inversion.

4. Growth of the Bega Batholith plutons in active half-grabens

Results from the geophysical survey support inferences from field studies that the Kameruka pluton is an asymmetric, wedge-shaped body, thickening eastward, with the base exposed as the western contact. The Bemboka pluton is also wedge-shaped, but much shallower (Fig. 4). Both plutons have basal contacts dominated by migmatites which exhibit a shallow-dipping, syn-migmatitic schlieren foliation that parallels the shallow dipping base of the pluton, but is highly oblique to the underlying upright metasediments. In the Kameruka pluton, primary depositional features have been interpreted to have formed by progressive vertical accumulation of crystal mush layers, similar to a vertically aggrading sedimentary sequence (Weibe & Collins 1998; Collins *et al.* 2004). Given that the depositional features define the palaeohorizontal (e.g. Fig. 3a), the systematic E–W steepening of the structures (Fig. 2) appears to record progressive eastward tilting of an initially sub-horizontal pluton floor during growth. These features are consistent with the cantilever-style floor depression model proposed by Cruden (1998), but the gradual steepening of the internal primary features with depth closely resemble progressive syn-rift style deposition of sediments in developing half-grabens (Fig. 4).

Construction of the batholith was initiated by sub-horizontal emplacement of the sheeted gabbros in the uppermost crust, probably when the mafic magmas achieved hydrostatic equilibrium (Fig. 5a) and/or a level of crust containing sub-horizontal structural anisotropies, which facilitated sheeted emplacement of the magma. Migmatite formation initiated at this stage, as evidenced by fragments of migmatite within the gabbroic layers and leucosomes cross-cutting some gabbro sheets. Localised, lateral and vertical migration of leucosome caused preferential development of

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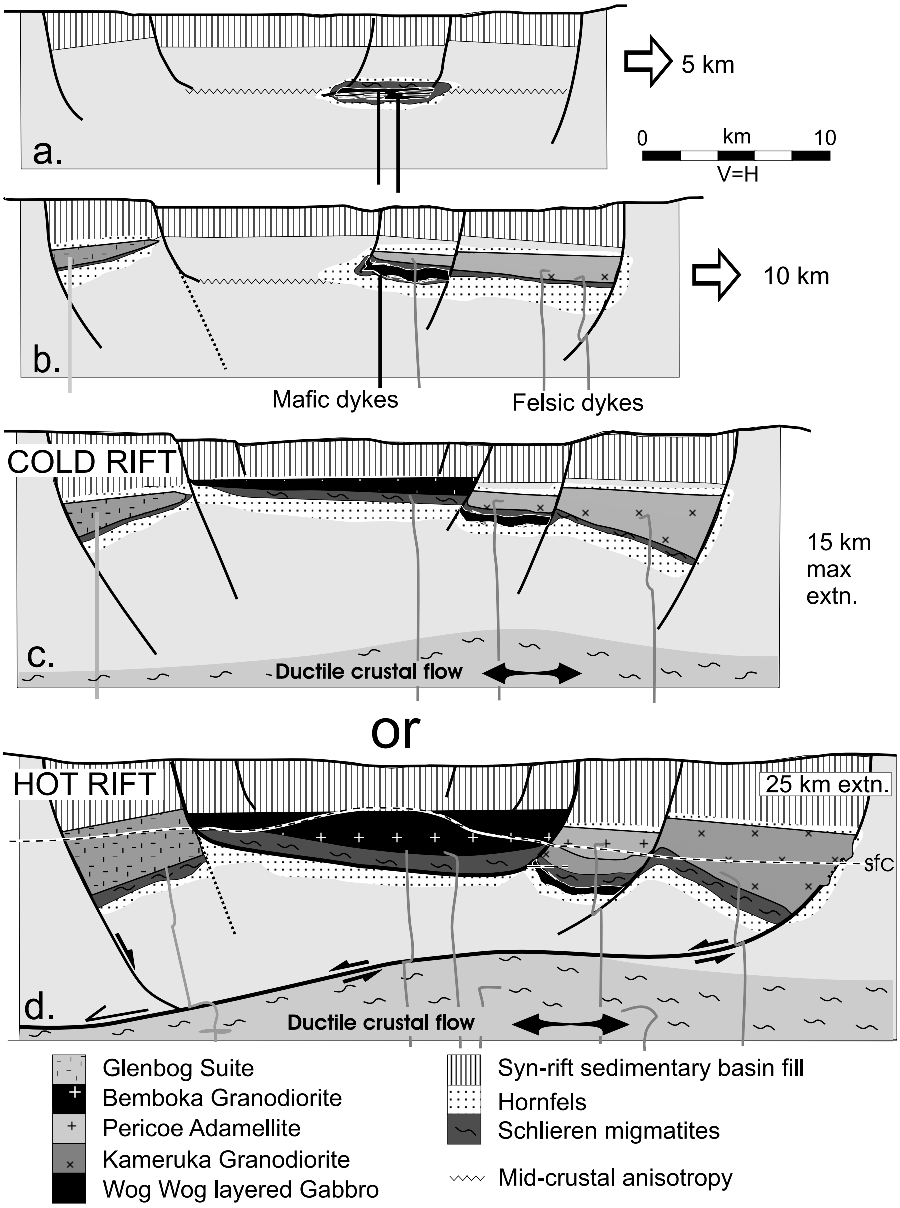

Figure 5 Model of batholith emplacement showing the stages of intrusion and inflation relative to half-graben development: (a) Sub-vertical normal faults propagate from the surface to link with the sheeted gabbro complex, which was probably emplaced at the level of hydrostatic equilibrium or at a structural discontinuity in the crust. (b) With ongoing extension, the faults propagate, allowing half-graben development and emplacement of the Kameruka pluton as sub-horizontal sheets above the gabbro complex. (c) Continued magma replenishment from dykes accompanies progressive tilting of the chamber floor at the base of individual half-grabens, allowing a maximum of 15 km eastward directed extension during 'cold' rifting. (d) Alternatively, stretching is focused at the batholith base, producing the shallow-dipping extensional fabric observed within the migmatites. Accelerated ductile stretching within this basal zone during 'hot' rifting can provide the additional 10 km of extension.

schlieren migmatites above the garbbroic body, which subsequently developed into a leucosome-rich shear zone. Heat and deformation were focused into the thermally softened detachment, and it became the locus for sheeted emplacement and construction of the overlying plutons (Fig. 5b, d).

However, much of the late extension is accommodated by the NE-trending strike-slip transfer faults. The Burragate, Tantawangalo and Wadbilliga faults record varying amounts of eastward displacement of the Kameruka and Candelo suites during emplacement of the Bemboka pluton (Fig. 1). Note that much of the eastward displacement of Kameruka and Candelo suite plutons, corresponding to widening of the batholith near Bega (Fig. 1), can be accommodated by removal of the Bemboka suite along the Burragate and Tantawangalo faults. To the north, the NE-striking Wadbilliga fault dextrally offsets the Jillicambra pluton by some 20 km, but the adjacent Glenbog suite is not offset. This fault also corresponds to a zone of widening in the batholith (Fig. 1). These relationships suggest that these NE-trending transfer faults facilitated emplacement of the Bemboka suite plutons.

5. How are plutons constructed in developing half-grabens?

Felsic and mafic dykes continuously fed magma to the pluton (Collins *et al.* 2000), ensuring the longevity of the magmatic system. The microgranitic dykes, which can be modelled as a parental liquid to the Kameruka suite granites (Healy 1999), migrated through the migmatites underlying the Kameruka pluton and intruded into the granite as syn-plutonic dykes. Additionally, migmatite fragments within many of the granite

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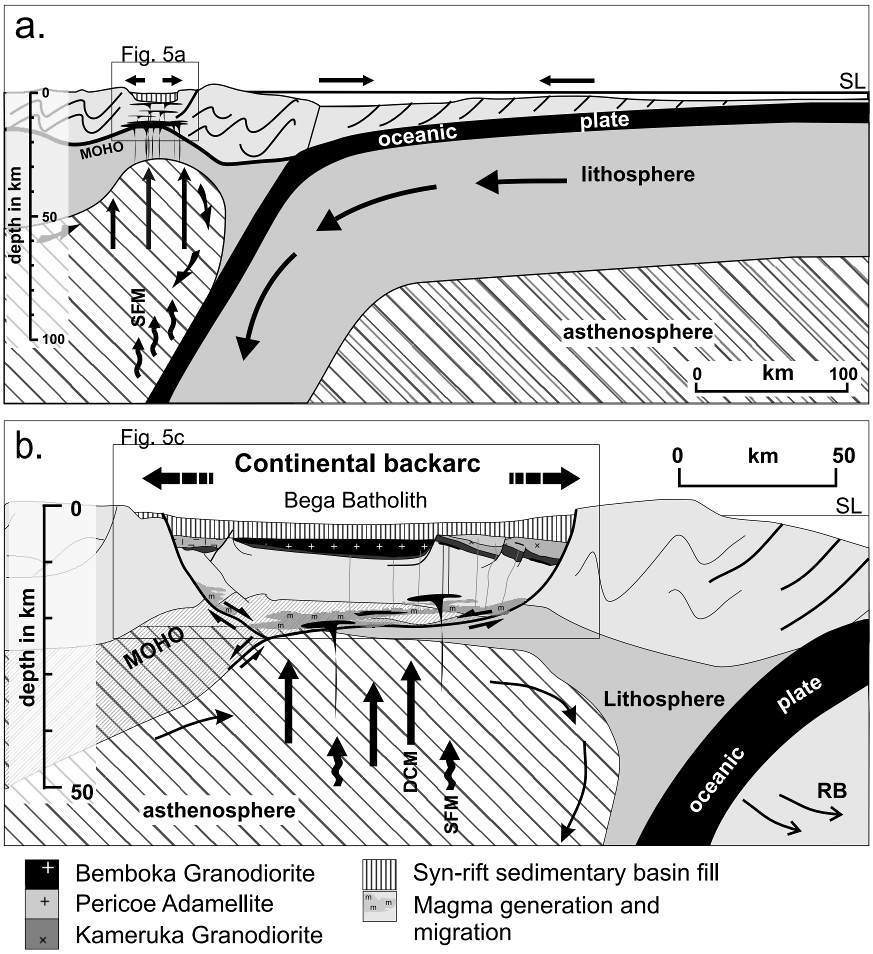

Figure 6 Tectonic setting of the Bega Batholith within a developing continental back-arc: (a) Extension is driven by the eastward retreat of the oceanic plate, resulting in lithospheric thinning, as well as initial generation and emplacement of mafic magmas associated with decompression and slab flux melting (Collins 2002a). (b) Construction of the Bega Batholith occurs in the developing back-arc. Eastward movement of the lower plate is accommodated by extension on the major west-dipping detachment that links to the zone of ductile stretching. The western margin of the system is bound by an antithetic normal fault that remained stationary during extension, causing preferential displacement on the eastern margin of Bega Batholith plutons. Key: (RB) slab rollback; (DCM) asthenospheric decompression melting; (SFM) slab flux melting; and (SL) sea level.

'feeder' dykes indicate that the dykes were able to intrude through actively deforming migmatitic rocks at the base of the pluton. The dykes intruded throughout the deformational and magmatic history of the migmatites and Kameruka pluton, as indicated by the abundant evidence for hybridisation between the dykes and migmatites, and by the presence of folded dykes in the migmatites. These syn-plutonic and syn-migmatitic dykes suggest magma ascent via fractures which penetrated through overlying active structures. Possibly the ascent rate (magma pressure) was sufficient for magmas to fracture through the underlying mid-crustal detachment, or that structure did not exist during much of the emplacement history. If the latter is correct, which the present authors consider more likely, the envisaged listric faults bounding the graben structure and enclosing the batholith did not link until the advanced stages of extension (Fig. 5c or d).

6. Tectonic control on magma emplacement rates

On the tectonic scale (Fig. 6a, b), the present authors consider that the batholith represents the base of a series of tilted half-grabens, represented by the N-trending plutons, developed during the eastward retreat of an arc–back-arc system, above a west-dipping subduction zone (cf. Collins 2002a). The measured but variable eastward displacement of the eastern side of the batholith (Fig. 1) indicates that this margin was the migrating boundary during extension. The lack of displacement along the western margin (Glenbog suite) suggests that this boundary is the major antithetic fault to the extensional system during batholith construction. This might indicate that the master detachment dipped eastward under the batholith, but this configuration would place the western (continent) side of the batholith as the lower retreating plate (terminology after Lister *et al.* 1986). However, the variable eastern margin of the batholith suggests that the major detachment dipped westwards, beneath the batholith. The lower plate migrated eastwards during the retreat of the subducting oceanic plate (Fig. 5d)

An eastern, retreating lower plate is consistent with the eastward younging of granite suites in the Bega Batholith, and with the general eastward migrating nature of plutonism in the eastern Lachlan Fold belt (e.g. Collins & Vernon 1992; Collins 2002a). It is consistent with slab rollback models for construction of the modern-day southwestern Pacific (e.g. Lister *et al.* 1986), and with uniformitarian tectonic models which invoke eastward (outboard) growth of the Palaeozoic eastern Lachlan, above a west-dipping subduction zone (e.g. Powell 1984; Collins & Vernon 1992; Foster & Gray 2000).

The composition of primitive mafic rocks in the batholith also favours extensional models. Primitive basaltic syn-plutonic dykes and gabbros from the batholith, including the sheeted gabbro complex, have compositions which closely resemble the active arc–back-arc basin system of the Lau Basin-Taupo Volcanic Zone in the southwest Pacific (Collins 2002b). These mafic rocks are being generated in regions where the lithosphere is <30 km thick and the tectonic regime is clearly extensional (e.g. Walcott 1987). They are forming during the eastward retreat of the west-subducting Pacific plate. A similar geodynamic environment can be envisaged for the Lachlan orogen during emplacement of the Bega Batholith.

The active rift model requires that some batholiths can grow at tectonic rates. Using the present authors' emplacement model for the Bega Batholith, the rift is 25–50 km wide and initially bound by normal faults which developed near the margin of the peripheral plutons (Figs 1 & 5). Based on approximate reconstructions of pre-rift geometry and experimental simulation of 'cold' rift basin development (Ellis & McClay 1988), the batholith could have formed by half-graben development during ~24% extension (Fig. 5a–c), which accounts for ~15 km eastward translation, some 10 km less than the 25 km measured movement.

The necessary additional 10 km of movement can be explained by ductile stretching at the base of plutons in a 'hot' rift environment. Post-Kameruka arc-perpendicular displacement is ~17 km, much of it recorded along the NE-trending faults during Bemboka suite emplacement (Fig. 1), but the cold rift model only accounts for ~3 km of this displacement. Thus, the present authors suggest that the additional stretching occurred by ductile flow along a shallow-dipping detachment focused in the migmatites observed directly below the Bemboka pluton (Fig. 5d). The detachment may have initiated as the western extension of the migmatites at the base of the Kameruka suite plutons (Fig. 5b). Extension below the migmatites may have been accommodated by pure shear above a master mid-crustal detachment, which is inferred to form by this stage (Fig. 5d). In plan view, this late extension was asymmetric and scissor-like, increasing in degrees of displacement southward and maximised along the NE-trending oblique transfer faults, where the batholith is widest (Fig. 1).

A southwest Pacific arc–back-arc basin system has already been used as a modern analogue for the eastern Lachlan in Silurian–Devonian times (Collins 2002b). Half-spreading rates for this modern system vary between 38 and 11 mm yr^{-1} (e. g. Malahoff *et al*. 1982), which imply that the maximum 25 km, arc-perpendicular extension on the Burragate fault could have developed in 1–2 Ma. Thus, it is possible that the entire batholith was emplaced in wedge-like, half-graben structures at inflation rates compatible to the 2-Ma period calculated by Petford *et al*. (2000), using the power-law inflation curve. However, Coleman *et al*., (2004) have demonstrated that magma chambers which undergo incremental construction during repeated injection of felsic magma (Weibe & Collins 1998) may remain active for up to 10 Ma. This implies that construction of the Bega Batholith may have also been long-lived and that the rate of chamber or batholith construction may be, in part, controlled by the rate of extension. The data imply that magma inflation rates can be readily achieved at tectonic rates in extensional arc–back-arc environments. The present authors suggest that the plutons of the Bega Batholith underwent progressive chamber construction during repeated injection of felsic and mafic magma at the base of active half-grabens.

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