# Abstracts

## Age of cassiterite mineralisation at the Zaaiplaats Tin Mine, South Africa: implications for the age of the Bushveld Complex

**Anita S. Andrew, Brian L. Gulson, Mel T. Jones** and **Peter J. Pollard**

Tin-tungsten-rare-earth-element mineralisation at Zaaiplaats is hosted by the Bobbejaankop and Lease granites: miarolitic, brick-red alkali feldspar granites which form at high levels within the Lebowa Granite Suite of the Bushveld Complex. Hydrothermal minerals occur as pervasive alteration and within miarolitic cavities. Cassiterite occurs as a cavity filling, as a replacement mineral in tabular, subhorizontal zones and in shallowly-plunging and branching pipes, and as disseminated mineralisation unrelated to fracture systems.

The age of mineralisation at Zaaiplaats has been determined by U–Pb dating of cassiterites. Bulk fractions of cassiterite have $^{206}Pb/^{204}Pb$ ratios from 30–3,500. Uranium–Pb data for five cassiterites with the highest $^{206}Pb/^{204}Pb$ ratios lie on a chord with intersections at $2{,}099 \pm 3$ Ma and $\approx 300 \pm 20$ Ma (MSWD = 0·44). Four samples are from pipe systems and one from cavity fill, suggesting a common age within 6 Ma. The $2{,}099 \pm 3$ Ma age is at the upper limit of published $^{87}Rb/^{86}Sr$ estimates for emplacement of both the Lebowa Granite Suite ($2{,}046 \pm 55$ Ma) and the Rustenberg Layered Suite ($2{,}061 \pm 27$ Ma) and identical within error of an $^{40}Ar/^{39}Ar$ age of $2{,}096 \pm 12$ Ma for the Upper Zone of the Rustenburg Layered Suite.

The precise U/Pb dating of cassiterites at Zaaiplaats suggests that mineralisation occurred early in the cooling history of the Bobbejaankop and Lease granites. This is consistent with fluid inclusion and stable isotope data which show that cassiterite and the related brick-red alkali feldspar alteration result from high temperature (>250°C) interaction of magmatic fluids with the cooling granite.

## The origin and geotectonic setting of Andean granites

**Michael P. Atherton** and **Nicholas Petford**

The Andean magmatic cycle began in Peru with the formation of a major depositional structure, the West Peruvian Trough, the westerly component of which has a volcanic facies indicating it formed very rapidly in a relatively deep-sea spreading/ridge system during the Albian. Beneath this major deposystem is an arch-like structure (density of $3{\cdot}00\,g\,cm^{-3}$) made up of mafic, mantle-derived material. Fracturing and splitting of the crust above this structure was associated with intensive dyking and intrusion/extrusion of basaltic material during the Albian.

The Coastal Batholith was intruded (101–37 Ma) into this linear edifice, and is confined mainly within it. Intrusion was permissive at 3–4 km from the surface, and was accompanied by large synplutonic basaltic dyke swarms, emphasising further the role of extension during batholith emplacement. The tonalitic–granitic rocks of the batholith formed on melting of this "new" basaltic crust at shallow depth on adiabatic decompression during the extension following basin inversion. About 20 Ma, granitic magmatism jumped to the E, producing small stocks within coeval "plateau" basalts (52·5–12 Ma). Intrusion occurred during a major faulting phase and took the form of stocks, domes, breccia pipes and dykes.

The last magmatic events in northern Peru include the Cordillera Blanca Batholith (12–13 Ma) which was intruded into a major strike-slip transtensional zone. Chemical, mineralogical and isotopic data indicate a much deeper source than that for the Coastal Batholith, which is considered to be newly accreted lower crust beneath the batholith.

Thus, the tectonic environment during the Andean in Peru was dominantly extensional, the magmatism younging to the E. All extensional systems are orthogonal to the Andean trend and relate to rifting associated with spreading systems opening up in the same direction. The relation to subduction is unclear.

## The Grayback Pluton: magmatism in a Jurassic back-arc environment, Klamath Mountains, Oregon

**Calvin G. Barnes, Kenneth Johnson, Melanie A. Barnes, Tore Prestvik** and **R. W. Kistler**

The Late Jurassic Grayback Pluton was emplaced in a back-arc environment (Mesozoic remnant arc) behind a contemporaneous Late Jurassic arc. The main stage of the pluton consists of an early unit of reversely zoned tonalite to gabbro that was subsequently intruded by synplutonic noritic and gabbroic magmas. Late-stage tonalitic and granitic dykes typically contain mafic enclaves and zones of hybrid tonalite and quartz diorite. The mafic rocks in the pluton are predominantly calc-alkaline, with magnesian clinopyroxene, calcic cores in plagioclase, and elemental abundances similar to $H_2O$-rich arc basalts. Some mafic samples contain relatively Fe-rich clinopyroxene, lack calcic plagioclase and are compositionally similar to evolved high-alumina tholeiite. Both groups of mafic rocks lack depletions of HFSE that are typical of arc magmas. Intermediate rocks span a wide range of elemental compositions that can be explained by mixing of calc-alkaline or tholeiitic mafic magmas with tonalitic or granitic magmas, combined with variable degrees of crystal fractionation. Initial $^{87}Sr/^{86}Sr$, $\varepsilon_{Nd}$, and $\delta^{18}O$ range from 0·7028–0·7045, 4–9, and 7·8–14‰, respectively. Late-stage felsic rocks have the highest $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ and display arc-like depletions of HFSE. These data suggest depleted mantle sources for the mafic magmas but a heterogeneous (young remnant arc) crustal source for both the tonalitic and granitic magmas. Mixing of mantle-derived basaltic magmas with isotopically variable crustal melts gave rise to the observed range of compositions. The heterogeneity and compositional range of the Grayback Pluton suggest a complex crustal plumbing system that allowed for injection of batches of mafic magma (derived from at least two types of mantle source rocks), mixing with pods of crustal melts (some tonalitic and some granitic) and partial homogenisation of the mixtures to form the main stage of the pluton.

## Forceful emplacement in the southern Adamello Massif, Italian Alps: intrusive history of the Lago della Vacca Suite

**Jonathan D. Blundy** and **Barbara E. John**

The Lago della Vacca Suite (LVS) is a small plutonic body, exposed over $20\,km^2$, in the southern Adamello Massif, Italy. The LVS was emplaced 40 Ma at ~200 MPa, into warm but consolidated precursor granitic and ultramafic rocks, and Triassic dolomites. The suite exhibits crude concentric zonation from dioritic margins through tonalite, to a granodiorite core, each rock type representing a discrete magmatic pulse, emplaced before the previous pulse was fully solidified. Synplutonic dykes and mafic inclusions are widespread.

High-temperature foliations are well-developed in all units, and define steeply inward-dipping concentric trajectories defined by the planar alignment of plagioclase, amphibole and biotite, and flattened (oblate) mafic inclusions. Lineations are rare and unsystematic. Foliation is deflected around a large rigid body of mafic/ultramafic country rock, but passes continuously into warm precursor granites, consistent with radial expansion against wall rocks of variable rheology. Thin aplite dykes and small-scale shear zones also have orientations consistent with radial expansion.

Mafic inclusions used as strain markers indicate a general trend of decreasing strain toward the centre of the suite. In detail, the strain distribution is very heterogeneous, with decametre wide zones of high strain ($9 \leq X/Z \leq 12$), within broader zones of lower strain ($X/Z \leq 3$). The high-strain zones are concentric, laterally discontinuous and characterised by fine-grained dioritic rocks. Compositionally, these rocks resemble undeformed synplutonic mafic dykes.

Amphibole-plagioclase thermometry constrains the temperature of deformation to 850–750°C. There is no evidence of a low temperature component, despite evidence of grain-size reduction and recrystallisation in the most deformed diorites. Amphibole in these rocks is characterised by high K contents and low *mg#* relative to amphibole in undeformed rocks of comparable composition, suggesting interaction of the deforming rocks with evolved interstitial melts. We conclude that the syn-intrusive deformation of the LVS occurred at magmatic temperatures, and propose that strain partitioning reflects local variations in temperature.

## A-type granite magmatism in the western Mediterranean

**Bernard Bonin**

The Permo-Triassic period was characterised in the western Mediterranean area by abundant magmatic activity just after the end of the Variscan orogenesis. Volcanic–plutonic complexes were emplaced mainly in the internal parts of the orogen and constitute a 4,000 km-long province stretching from Morocco through Corsica and the Alps to Austria. The magmatic activity has taken place during two discrete episodes:

(i) The mid-Permian (*c.* 270 ± 5 Ma) was marked by the emplacement of the first A-type formations, with ignimbritic traps, and ring complexes made up by a gabbro–monzonite pink to red subsolvus biotite granite association.

(ii) At the Permian-Triassic boundary (245 ± 10 Ma), numerous A-type caldera-related ring complexes were emplaced along the future Alpine belt under an incipient rift regime. The suite is characterised by a basalt–trachyte–rhyolite (comendite) association, syenites, and a large variety of hypersolvus to subsolvus, peraluminous to peralkaline, grey-green to pink A-type granites.

Sources and conditions of differentiation of A-type granite magmatism changed with time. At the end of the Variscan orogenesis, a new mantle source replaced the old complex system of mixed oceanic-continental crust-mantle sources. Primary mantle-derived melts were probably trapped at the crust-mantle boundary where they evolved through high-pressure fractionation to intermediate compositions. Intermediate melts were collected in shallow magma chambers, placed at the ductile-brittle transition in the crust, where they evolved through low-pressure fractionation to granitic residual melts. Felsic melts were subsequently less and less contaminated by crustal host rocks. Strong correlations between hydrothermal events, mineralisations and crustal isotope signatures suggest that crustal contribution relates essentially to percolating fluids.

## Magmatism and hydrothermal metasomatism in Mesozoic Damaraland granites, northern Namibia

**Peter Bowden, Judith Kinnaird, Michael Diehl** and **Franco Pirajno**

The fracturing of Gondwanaland as part of the larger Pangaean fragmentation has been chronicled by numerous geological features, including examples of magmatism oriented along major zones of weakness in the continental lithospheric segments of S America and Africa. Following the widespread outpouring of the Karoo basalts, Jurassic-Cretaceous magmatism was finally concentrated along several major lineaments linked to the development of a series of transformed fracture systems in the S Atlantic Ocean. This activity was marked on the southwestern African continent by the emplacement of a number of felsic-mafic complexes, granite centres, carbonatites and kimberlites.

The Damaraland zone of anorogenic complexes in northern Namibia extends more than 400 km as a well-defined series of NE-oriented lineaments between the Ugab and Khan rivers. The lineament zone coincides with the axis of the Damaran (Pan-African) orogen. Twenty Mesozoic granitic centres have been identified along this zone. Based on evidence from these centres, the marginal zones of granite intrusions are the best places where hydrothermal overprinting of an original magmatic assemblage can be observed. The fluids of magmatic origin causing endogenetic hydrothermal metasomatism by intergranular exchange are derived from the consanguineous crystallisation residua of the host pluton. There is also the possibility, in multicentred anorogenic granites, that residual fluids are expelled from later adjacent intrusions whose fluid chemistry may be out of equilibrium with the bulk chemistry of the earlier crystallised pluton. This involves mass transfer of components to form new subsolidus assemblages.

## Origin and distribution of granitic and related rocks in the Coast Plutonic-Metamorphic Complex, N American Cordillera, southeastern Alaska, U.S.A.

**David A. Brew**

Discrete chrono-lithological granitic rock units occur in both continuous and discontinuous belts that run the 1000 km-plus length of the late Mesozoic and Cainozoic Coast Plutonic-Metamorphic Complex (CPMC) in southeastern Alaska and the adjacent parts of British Columbia. The CPMC has four main zones that are characterised by specific granitic units and to some extent by specific metamorphic protoliths: the western metamorphic zone or belt, the central metamorphic and granitic zone, the central granitic zone, and the eastern metamorphic zone.

There are four major granitic belts in the CPMC. The tectonic setting of the oldest, pre-Late Triassic, belt is uncertain; the two youngest major belts, the 85–55 Ma Great Tonalite Sill belt and the 55–45 Ma Coast Mountains belt, are generally related to the alternately transpressive and transtensive accretion of the Wrangellia-Alexander and Chugach tectonostratigraphic terranes (Insular Superterrane) to the previously emplaced Yukon prong and Stikine terranes (Intermontane Superterrane). The tectonic settings of the next-to-oldest major belt, the Admiralty-Revillagigedo belt of magmatic-epidote-bearing tonalite, is probably similar. The tectonic setting of the minor 110–100 Ma Klukwan Duke Alaskan-type ultramafic belt is enigmatic. Calcalkalic, island-arc affinity rocks are predominant in all belts. However, each has a somewhat different origin that is reflected in its structural, modal compositional and major, minor, trace, and rare-earth-element compositional characteristics. Three minor granitic belts, of Late Triassic and Early Jurassic, early Early Cretaceous, and of Late Oligocene age, are also present in the CPMC.

## Transpression and granite genesis

**Michael Brown, Richard S. D'Lemos** and **Robin A. Strachan**

Transpression involves horizontal shortening across and vertical lengthening along a zone of transcurrent shear. This thickens crust and inverts sedimentary basins, which leads to high-temperature metamorphism and anatexis. Shear zones provide convenient paths of ingress for volatiles as well as ascent paths for magma, and deformation enhances melt segregation during anatexis. Mantle-deep terrane boundary faults provide access for mantle-derived magma to intrude and interact with the crust. In the Cadomian Belt of northwestern France, arc-related outboard terranes have been amalgamated with inboard terranes, interpreted to represent elements of a behind-arc basin sedimentary sequence, during sinistral transpression. In the outboard terranes, post-kinematic plutonic complexes comprise diorite-to-granite with evidence for local co-mingling of magmas. More extensive mixing between depleted and enriched components is evidenced by the geochemistry and in the isotopic signature of the granitic rocks. By contrast, in the inboard terranes, thickening of the Brioverian succession during transpressional terrane accretion has resulted in fluid-present anatexis in the St Malo migmatite belt. The St Malo migmatite belt is imbricated by steep, sinistral strike-slip shear zones which contain syn-kinematic granites, suggesting that shear zone deformation and anatexis were broadly coeval. Further inboard, the high-level Mancellian granites are intruded into Brioverian rocks. By analogy with the shear zone system to the W, these granites may have been emplaced into pull-apart structures along a jog in the E–W-trending zone of sinistral shear at the S margin of the belt of transpression. The St Malo migmatites/anatectic granites and the Mancellian granites have like petrographical features, statistically indistinguishable chemical compositions, and similar Nd isotopic characteristics. These features suggest a common origin for the St Malo migmatites/anatectic granites and the Mancellian granites, which is interpreted to be by anatexis of the immature arc-derived turbidites of the Brioverian succession.

## Three-dimensional analysis of the crystallisation sequence and textural development in two Peruvian granitoid rocks

**David Bryon**

Microscopic geometrical and textural characteristics of crystallisation sequences, and inferences regarding the rheological properties of crystallising granites, cannot be properly quantified without three-dimensional textural analysis. Three-dimensional analysis utilising serial sectioning and image digitisation has been used to interpret textural development in two granodiorites from the Linga superunit of the Coastal Batholith, Peru. The high level of emplacement of these granodiorites (Atherton 1984) and limited deformation allows excellent preservation of the primary textures. Despite their very similar modal and normative compositions, the two rocks' different textures reflect the variation in *nucleation density*, *growth rate* and *timing* of crystallisation of individual phases. Serial geometries produced for all the major phases identify the individual role that each phase plays during the three main stages of crystallisation, namely: (i) early crystallisation from a melt containing a high proportion of melt, where crystal growth proceeded relatively uninhibited; (ii) development of a touching three-dimensional crystal framework (R.C.M.P. of Arzi 1978); (iii) subsequent interstitial crystallisation where the growth of individual crystals was controlled by the already crystalline surrounding material. All the geometries support the modelled crystallisation path deduced from the An : Ab : Qz : Or system, and suggest that all the major phases had started to crystallise by stage (ii), i.e. the development of a crystal framework.

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## Geochemical contrasts between intersecting Devonian and Carboniferous magmatic belts in the eastern Lachlan Fold Belt

**Paul F. Carr, Bruce W. Chappell** and **Brian G. Jones**

The subvolcanic Marulan Batholith is the same general age as most batholiths in the Lachlan Fold Belt and constitutes part of a world-wide magmatic event about 400 Ma. The Marulan Batholith is closely associated in the field with several Carboniferous contact-aureole plutons and, therefore, marks the intersection of a southern Devonian magmatic belt with a northern Carboniferous magmatic belt.

Differences in the sources for the Devonian and Carboniferous granites are reflected in pronounced geochemical differences between these granites. The Devonian plutons are characterised by a continuous and fairly uniformly distributed range of compositions from 56–73% $SiO_2$. In contrast, the Carboniferous plutons have a weak bimodal distribution of compositions and have significantly higher average $Na_2O$ and Sr contents. Rare-earth-element patterns for the Carboniferous granites show considerably more fractionation and enrichment in LREE than the geographically associated Devonian plutons.

Isotopic data for Devonian plutons form three groups, two of which have parallel isochrons with early Devonian ages and initial ratios of 0·7062 and 0·7071, respectively. Variations within these two groups may be explained by feldspar fractionation. Plutons in the third group do not fit an isochron, have the highest initial $^{87}Sr/^{86}Sr$ ratios (0·7077–0·7100 at 395 Ma), and have a linear array on a plot of initial $^{87}Sr/^{86}Sr$ versus 1/Sr. Variations within this third group possibly reflect derivation from a heterogeneous source.

Initial $^{87}Sr/^{86}Sr$ ratios for the Carboniferous plutons are appreciably lower and range from 0·7047–0·7052. The isotopically more primitive source for the Carboniferous magmas may have underplated the crust during the early Devonian and initiated partial melting to produce the Marulan Batholith.

## Evolution of the Indian Peak Volcanic field, western U.S.A.: implications for the origin of A- and I-type granites in subduction settings

**Eric H. Christiansen, Myron G. Best** and **Joaquin Ruiz**

The Indian Peak caldera complex erupted 10,000 $km^3$ of magma 32–27 Ma. Nd-Sr isotopic data and temporal-spatial patterns show that these high-K calc-alkaline rocks formed in an open magma system, driven by mafic magma derived from a southward-migrating thermal anomaly. The migration may be associated with progressive foundering of subducting lithosphere away from the overriding continental plate. As the thermal anomaly stagnated in the southern Great Basin, the high power input optimised magma generation in the crust. Small volumes of andesitic lavas are derivatives of this mantle power supply. They are compositionally diverse and not co-magmatic, but all have low $TiO_2$, negative Nb-anomalies and REE patterns which lack Eu anomalies. Three large-volume crystal-rich dacite tuffs have all of the characteristics of I-type granites, but isotopic and elemental mixing trends suggest that they formed by mixing of andesite and rhyolite magmas rather than by melting a distinctive source in the crust. The death of the magma system was marked by the eruption of a trachytic tuff with plagioclase, clino- and orthopyroxene, and oxides. Nd isotope ratios are higher and Sr isotope ratios lower than in the dacites but similar to andesites. The trachyte has many of the characteristics of A-type granites, including a high eruption temperature, high alkalies, Ba, Zr and Ga, but it can be modelled as a product of clinopyroxene-dominated fractionation from andesitic magma at relatively high temperatures and does not require a distinctive crustal source.

## Contact metamorphosed granites: their metamorphic zonation and implications upon emplacement mechanisms

**A. P. Clare**

Petrological and structural studies of the contact metamorphic effects of one granite upon another and the surrounding hornfels are presented for the Bendemeer Adamellite (41 km NE of Tamworth, N.S.W.) and the Gwydir River Adamellite (30 km W of Armidale, N.S.W.) in the southern part of the New England Batholith. The Permian Bendemeer Adamellite intrudes the Carboniferous S-type microcline and cordierite-bearing Banalasta Adamellite, the late Permian Gwydir River Adamellite intrudes the middle Permian I-type orthoclase-bearing Yarrowyck Granodiorite. Both aureoles are shown to have essentially identical metamorphic zonations.

A mineralogical and microstructural examination of the

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metagranites away from the later intrusives reveals three distinct zones: (1) a regional unaffected zone (to within 4 km of the Bendemeer Adamellite and to within 1·5 km of the Gwydir River Adamellite); (2) a low-grade strained zone (between 4 and 1·5 km and between 1·2 and 0·35 km, respectively, for the Bendemeer and Gwydir River plutons) characterised by high K-feldspar triclinicities and deformational microstructures; and (3) a high-grade annealed zone (within 1·5 and 0·35 km, respectively, of the Bendemeer and Gwydir River plutons), characterised by low to zero K-feldspar triclinicities and recovery and recrystallisation microstructures. The hornfelsic rocks in both areas record metamorphic changes up to the hornblende-hornfels (brown, granoblastic tschermakitic hornblende) in the metabasalts and cordierite-K-feldspar facies in the pelitic rocks.

This study has revealed two distinct, emplacement-induced domains within the aureoles: an outer strained envelope recording minor ductile deformation and an inner thermally annealed envelope. The discordant nature of the intruding pluton's contacts, low contact temperatures (650°C) and negligible observed shortening in the aureole preclude emplacement mechanisms by doming, melt zoning or ballooning diapirism. The meridonal trend of the plutonic suites in the New England Batholith (sub-parallelling major regional faults and a once-convergent plate margin), the metamorphic zonation outlined and its implications upon emplacement-induced deformation and thermal annealing and negligible shortening, favour an emplacement mechanism involving dyke propagation at depth and, at high levels, stoping with associated minor late-stage diapiric accommodation.

## Mid-crustal contamination of granitic magmas

**W. J. Collins** and **R. H. Vernon**

In the Anmatjira Range, Arunta Inlier, central Australia, Proterozoic (1,820–1,760 Ma) megacrystic granitic magmas have intruded as sheet-like bodies at mid-crustal levels (10–20 km depth). The sheets show a remarkable mineralogical and geochemical coherency with their enclosing country rocks; cordierite-rich, garnet-rich and orthopyroxene-rich (charnockitic) granitic sheets, all containing megacrystic K-feldspar, occur within cordierite-rich, garnet-rich and orthopyroxene-rich gneisses/granofelses, respectively. The distinctive mineralogy of the granite sheets in the Anmatjira Range is reflected geochemically. Cordierite granites have high MgO, Ni, Cr and Zn contents, but low Na/K ratios, typical of S-type granites. Garnet granites have high Fe/Mg ratios and are typically silicic (>73% $SiO_2$). Orthopyroxene granites, which usually are hornblende-bearing, have higher CaO contents and Na/K ratios, and an extended silica range (65–75% $SiO_2$). The latter are typical of I-type granites and they form a *continuous* geochemical lineage from 50–75% $SiO_2$ with the enclosing mafic granofelses.

The 10–20 km-depth of emplacement for the granite sheets is that estimated for magma chambers in magmatic arcs. Thus, it is suggested that the Anmatjira Range is an analogue for the internal zones of a continental magmatic arc, and that considerable contamination of granites can occur in this environment. With repeated emplacement of granites at this level, and passage of granitic magmas to higher levels, the resultant low-pressure–high-temperature metamorphism in the mid-crustal "aureole" reaches upper amphibolite facies conditions and migmatites develop, which sufficiently reduce the viscosity of the host rocks to allow physical disaggregation and incorporation into the granite magmas. Either S- or I-type granites can be produced, depending on the chemistry of the enclosing country rock. The data suggest that many granites acquire their geochemical characteristics at mid-crustal levels.

## The multiple origin of peraluminous granites: consequences for their metallogenic potential

**Michel Cuney** and **Jean-Marc Stussi**

Peraluminous granites represent about 70% of the plutonic activity of the European Variscan. They are characterised by a high peraluminous index, but show distinctive mineralogical, geochemical and genetic characteristics when compared with the typical Australian S-type granites. They have been subdivided into three groups, each being marked by either increasing or decreasing peraluminous index (I.A. = Al − K − Na − 2Ca) with differentiation (I.D. = Fe + Mg + Ti). Modelling by the least squares method of these chemical variations gives a quantitative evaluation of the amount of fractionating minerals or of magma mixing:

(i) S-type granites typically show a strong decrease of their peraluminous index IA with differentiation (ID). They are best modelled by the fractionation of biotite, cordierite and/or garnet, quartz and plagioclase which may represent restitic minerals (resitite unmixing).

(ii) AKG granites (Aluminopotassic granites similar to the Gueret Batholith (5,000 km$^2$) in the northern French Massif Central (FMC), taken as a reference) are characterised by a slight increase of the peraluminous index despite large variations of ID. The peraluminous minerals cordierite and muscovite do not present, or present very limited, fractionation. This type of chemical variation is best modelled by mixing the most peraluminous facies with an intermediate metaluminous hornblende-bearing magma. No significant metal deposit is related to them.

(iii) AKL granites (Aluminopotassic granites, leucocratic and from Limousin, western FMC, where they are well exposed) are muscovite ± sillimanite ± andalusite ± garnet-bearing. Their peraluminous index shows a slight to strong increase for a limited variation of ID. The best model implies the fractionation of biotite, plagioclase, orthoclase and quartz. Most Variscan economic U, Sn, W, Li, Ta, Be deposits are related to this type of granite.

## Redeposited and primary volcanic facies in the middle to late Silurian Tumut Trough: deposition on an unstable continental edge

**Kelsie Dadd**

Late Silurian rocks of the Tumut Trough in the southeastern Lachlan Fold Belt of N.S.W., Australia, comprise a conformable sequence of dacitic volcaniclastic rocks, sedimentary rocks and pillow basalt intruded by mafic and felsic igneous bodies. Massive dacitic volcaniclastic rocks (MDV) in the sequence have been interpreted as subaerial ash flow and ash fall deposits. However, facies analysis of the MDV and surrounding rock units indicates that this interpretation is unlikely. The MDV are considered to be very proximal, submarine, mass-flow deposits resulting from the redeposition of large volumes of unconsolidated pyroclastic material soon after eruption.

In the W, the MDV is interstratified with marine sedimentary rocks in both massive and graded beds, and units of chaotic limestone boulder conglomerate. Pillow basalt occurs at the top of the sequence. To the E, the MDV occurs with bedded volcaniclastic rocks that grade upward from dacitic pebble conglomerate to laminated siltstone, deposited from turbidity currents and large allochthonous blocks of limestone.

The MDV lacks stratification, implying very rapid accumulation from dense flows. Phenocryst content in the dacite is typically 30–50%. This high crystal content probably added to the buoyancy of the flows, increasing their competence and mobility and also inhibiting the development of grading. There is no evidence for hot emplacement.

Previous interpretations for the Tumut Trough include a continental rift setting (Lightner 1977; Wyborn *et al.* 1981), a pull-apart basin in a strike-slip fault system (Stuart-Smith 1990), a fore-arc basin (Crook 1980), a back-arc rift (Crook & Powell 1976; Ashley *et al.* 1979) and the upwelling of hot mantle and crustal stretching along a transform fault (Packham 1987). The interstratification of dacitic volcaniclastic rocks, turbidites, chaotic limestone boulder conglomerate and marine basalt favour deposition at the foot of an unstable slope in an arc environment. The S-type geochemistry indicates this had a substantial sialic basement.

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## The Middle Proterozoic rhyolite-hosted Pea Ridge iron and rare-earth-element deposit: a magmatic source for Olympic Dam-type deposits in the midcontinent region of the U.S.A.

**W. C. Day, G. B. Sidder, R. O. Rye, L. M. Nuelle** and **E. B. Kisvarsanyi**

An origin for the ore fluids that deposited iron, copper, rare-earth elements (REE), and gold in Olympic Dam-type deposits remains enigmatic. However, recent research on one such deposit in Missouri, U.S.A., indicates that the ore fluids were magmatic and may have formed from immiscible liquids derived from magmas cogenetic with the host terrane.

The Pea Ridge deposit is one of several apatite-bearing magnetite bodies that intrude Middle Proterozoic anorogenic high-silica rhyolite in southeastern Missouri, U.S.A. At Pea Ridge, REE-rich breccia pipes cut the ore body and exhibit fluidisation textures, with clasts of iron ore and host rock supported in a matrix of monazite, barite, xenotime, apatite and rock flour. Evidence for boiling is seen in the primary fluid inclusions in quartz from the breccia pipes. $\delta^{18}O$ quartz-magnetite and $\delta^{34}S$ barite-pyrite equilibrium temperatures show that the early ore solutions were hot (680°C), clearly in the temperature range of magmatic systems, but cooled through time (300°C). The primary ore fluids had a heavy $^{18}O$ signature (+15‰), controlled by equilibrium with a heavy $^{18}O$ magma of crustal origin.

Trace element modelling indicates that the ore deposit formed from an immiscible melt generated from the iron-rich trachyte suite. The magnetite ore and REE-bearing breccia pipes formed as a coherent system that underwent secondary boiling and caused catastrophic brecciation during emplacement of the REE-bearing breccia pipes.

## Characterisation and petrogenetic subdivision of A-type granites

**G. Nelson Eby**

A data bank of published and unpublished analyses has been established for the A-type granites (and associated felsic volcanics) from a variety of geological settings. All of the suites plot within the WPG field of Pearce *et al.* (1984) and the A-type fields of Whalen *et al.* (1987). Compared to the I- and S-type granites, the A-types have greater FeO/MgO ratios and higher absolute abundances of a number of incompatible trace elements. Utilising various indicators of magmatic evolution, of which the Eu/Eu* ratio (a measure of feldspar fractionation) is one of the most useful, A-type granites generally have higher abundances of Ga, Nb, Y, REE (except Eu), Ta, Zr, Hf and Th than I- and S-type granites at a similar stage of magmatic evolution. These observations suggest that most, if not all, A-type granites are not the product of extreme fractionation of I-type magmas.

On the basis of the chemical data, the A-type granites can be divided into two groups ($A_1$ and $A_2$). The $A_1$ group consists of suites from oceanic islands, intracontinental rift zones and regions of crustal doming. These suites often have associated mafic rocks, thus showing a bimodal character. They are characterised by a number of trace element ratios (such as Y/Nb and Yb/Ta) similar to those of oceanic island basalts. The $A_2$ group consists of suites which have higher Y/Nb and Yb/Ta ratios (similar to those of continental margin basalts), are generally less enriched in incompatible elements and were usually emplaced in post collision-post orogenic environments. These suites appear to have originated either in the subcontinental mantle or within the continental crust. On the basis of the chemical characteristics, it is suggested that the $A_1$ group represents granites derived by fractionation of magmas similar to those which give rise to oceanic island basalts and thus have a mantle source. The $A_2$ group, which includes the Gabo and Mumbulla suites of the Lachlan Fold Belt, may represent granites derived from the remelting of lithospheric crust (or mantle?) as proposed by Collins *et al.* (1982).

A number of elemental screens have been developed to facilitate the identification of the $A_1$ and $A_2$ groups. The most useful screens are those utilising Y/Nb, Yb/Ta, Ga/Al and Rb/Sr ratios and three component diagrams utilising Y, Nb, Zr, Hf, Th, Ce, Yb, Ta and Ga.

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## Magmatic evolution of Late Proterozoic ultrapotassic syenites in northeastern Brazil and metasomatic mantle source

**Valderez P. Ferreira, Alcides N. Sial** and **James A. Whitney**

Ultrapotassic peralkalic silica-saturated plutons (580 Ma) are widespread in the Cachoeirinha-Salgueiro foldbelt, northeastern Brazil. They consist of alkali-feldspar syenites carrying pyroxenite as co-magmatic inclusions, syn-plutonic or late-stage dykes, which have the same mineralogical phases as the host syenites, (aegirine-augite, microcline, sphene, apatite, ±blue amphibole, ± magnetite), only proportions differ. Rare inclusions of a "mixed" rock (about 50% syenite +50% pyroxenite in an emulsion-like texture) are also observed. Pyroxenes in the three rocks are all only slightly zoned, silica-saturated and extremely low in Al (0·2–1·4%), suggesting crystallisation at low pressures. Amphiboles are mostly K-rich richterite, characterised by high $SiO_2$, low $Al_2O_3$ and $TiO_2$ contents and low Mg#.

The three rock types are characterised by an overall enrichment in incompatible elements, with negative spikes at Nb, Sr, P and Ti in spidergram-type diagrams. They have similar REE chondrite-normalised patterns, with negative slopes and lack of Eu anomaly, with the total REE in the pyroxenites greater than the total REE in the syenites. The pattern for the mixed rock is between the ones for the pyroxenites and syenites in both REE and spidergram diagrams.

The rocks have similar, high $\delta^{18}O$ values (average w.r. +8‰ SMOW, corrected from pyroxene), similar, high $\delta^{34}S$ (average +11‰ CDT), similar, high $^{87}Sr/^{86}Sr$ initial ratios (about 0·710) and similar, low $^{143}Nd/^{144}Nd$ ratios (average 0·51104).

Altogether, field and geochemical characteristics indicate chemical equilibrium among the three rock types and suggest liquid immiscibility between syenite and pyroxenite, the mixed rock representing magma composition before splitting.

The unusual isotopic signatures as well as the enrichment in LIL elements point to an anomalous enriched mantle source. Phlogopite pyroxenite xenoliths, assumed to be source fragments, display carbonate minerals and replacement textures, suggesting $CO_2/H_2O$ metasomatism. Sm/Nd model age indicates that the enrichment took place at about 2.1 Ga ago.

## Structures in metasedimentary inclusions as "windows" into granite source regions

**Peter D. Fleming**

Deformation structures preserved in metasedimentary restite inclusions can provide valuable information on the deformation history in the granite source area up to the time of melt generation, particularly if the inclusions record more deformations than undergone by the country rock by emplacement time. The data can add details to the view through the "window" to the source that is given by current petrological and geochemical arguments. The improved view can give extra information about the nature of the source rocks and their structural/tectonic history.

Pelitic restite inclusions from the Yabba Adamellite in the northeastern part of the Palaeozoic Lachlan Fold Belt (LFB) of southeastern Australia illustrate the strategy. The 415 Ma-adamellite intruded before and during the first discernible deformation in the Early Ordovician low-grade country rocks, yet the inclusions record at least four deformations in their microstructure. The inclusions and the adamellite have therefore been derived from a source with a tectonic history significantly longer than is recorded in the exposed Early Ordovician rocks. The source is therefore most likely to be a complexly deformed, metasedimentary terrane of pre-Ordovician age. The House Creek Granodiorite and the Cobaw Granite Complex occur respectively 40 km and 250 km to the W across the LFB from the Yabba pluton. Though details vary, similar conclusions can be drawn from studies of the structures recorded in their restite inclusions.

The examples discussed provide support to independent assertions, based on petrological and geochemical grounds, that at least in places the Palaeozoic rocks of the LFB rest structurally over pre-Ordovician continental crust rather than lie directly on oceanic crust. A less favoured alternative is that the complexly deformed sources are of approximately similar age to the exposed country rocks, but have early structural histories developed more or less independently in a tectonically separate terrane now overthrust by the country rock sequence.

## Textural and chemical zoning in the François Pluton, Newfoundland

**R. H. Flood** and **S. E. Shaw**

The François zoned Pluton of southern Newfoundland exhibits only minor silica variation (72–76%) but is strongly zoned microstructurally. The microstructural zones have distinctive U, Th and K values as shown by published airborne radiometric maps.

The François Pluton outcrops as two lobes, with the southwestern lobe truncating the northeastern lobe. Rb/Sr bulk rock data from both lobes indicate an age of $383{\cdot}0 \pm 8{\cdot}7$ Ma, while the average of three biotite/bulk rock pairs give a younger age of $371 \pm 4$ Ma with an initial $^{87}Sr/^{86}Sr$ ratio of $0{\cdot}7048 \pm 0{\cdot}0006$. The pluton is massive, has sharp cross-cutting contacts and has few enclaves. Microcline is the K-feldspar in all microstructural zones regardless of grain-size and is the result of minor deformation.

Both lobes of the François Pluton are concentrically zoned, with an outer medium-grained marginal granite in each lobe grading inward to a coarse-grained leucogranite. The leucogranite in turn has a sharp contact with an inner microgranite that gradationally coarsens to the centre of the pluton. Although the bulk-rock chemistry changes only slightly, the coarser-grained variants have a higher K-feldspar to plagioclase ratio than the finer-grained parts of the pluton.

Changes in microstructure, mineralogy and chemistry result from changing $H_2O$ pressures during crystallisation. Initial $H_2O$ pressure increase during the formation of the outer medium-to-coarse-grained leucogranite produced a grain-size increase and a shift in the feldspar cotectic, causing a progressive increase in K-feldspar. The second stage of crystallisation, that is the microgranite in the sharp contact with the coarse-grained leucogranite against microgranite, is produced by the sudden loss of $H_2O$ pressure. This pressure-quench event produces the narrow zone of microgranite with microstructures similar to those of micrograpitic enclaves. The coarser-grained granite in the centre of the pluton indicates a second increase in $H_2O$ pressure.

## Magma mingling and the origin of the Mannum A-type granite, S Australia

**J. D. Foden** and **S. P. Turner**

The 485 Ma Mannum pluton is a high-level, potassic, rapakivi (A-type) granite. It is part of a late regional bimodal magmatic association in the Delamerian Orogeny. Swarms of contained dioritic enclaves result from mingling of a mafic magma when both phases were partially liquid. Mingling of melts, rather than inclusion of solid xenoliths, is demonstrated by the amoeboid physical shape of the enclaves with plastically deformed outlines. These include and react with alkali feldspar phenocrysts from the host granite and have hybrid margins. Geochemical transects from enclave core to host granite show sigmoidal shapes due to diffusional exchange. Although the profiles for many elements (e.g. Rb) are modelled as a result of diffusional process, those for some elements (REE, Y, Zr) are more complex due to reaction "front" migration, controlled by the preferential growth of sphene, apatite and zircon. The abundance of these minerals is promoted by diffusion-controlled activity gradients between mafic and felsic magma. The mafic enclaves and granite show initial Sr-isotopic equilibrium, indicating efficient diffusional exchange between mafic and felsic liquids. The "screen" of mafic droplets is either the draw-up of a lower layer of a layered magma chamber, or the intersection of the cooling granite body by a dyke. Our evidence is that these compositionally distinct mafic and felsic components did not mix freely, and interaction was restricted to diffusional exchange after mingling. After thermal equilibration, the viscosity contrast between the two magmas was too great for unrestricted mixing. During mingling, fluid motion of the granite was restricted to the regime of laminar flow.

Our evidence for temporal and spatial association of mafic and felsic magmas provides a clear solution to the thermal budgetary problems that may seem to be associated with post-orogenic granites. In fact, our results including Sr and Nd-isotopic data, are quite consistent with a common origin of both granite and enclaves as the products of fractionation of a parental continental tholeiitic basalt magma.

## Early Proterozoic calcalkaline magmatism in the Hooper Complex, West Kimberley, Western Australia

**T. J. Griffin** and **I. M. Tyler**

The Hooper Complex in the W Kimberley region of Western Australia contains the third largest area ($5{,}500\,km^2$) of Early Proterozoic felsic igneous rocks in Northern Australia, after Halls Creek ($9{,}600\,km^2$) and Pine Creek ($8{,}700\,km^2$). This I-type suite, which consists of comagmatic volcanic, hypabyssal and granite rocks dominated by monzogranite, is calcalkaline on an AFM plot.

The felsic igneous activity at ?1,840–1,860 Ma is part of the main cratonising event in the W Kimberley region, the Early Proterozoic Hooper Orogeny. The igneous phase followed moderate to high-grade metamorphism which affected deformed, interlayered, turbiditic sedimentary rocks and mafic sills, and was synchronous with the second deformation ($D_2$). Small areas of anatectic granite formed during the high-grade metamorphism of the sedimentary rocks have S-type characteristics, containing less than half the levels of CaO and $Na_2O$ of the later, dominant I-type granites. A pronounced tectonic foliation is widespread throughout the felsic igneous suite, and is associated with metamorphism under greenschist and amphibolite facies conditions during the compressional Middle Proterozoic Yampi Orogeny.

The Hooper Complex felsic igneous suite is similar to other Early Proterozoic suites in Northern Australia, with high levels of $K_2O$ and incompatible elements such as La, Ce and Rb, and low levels of MgO, CaO and Ni. The majority of rocks are enriched in alkalis; however, the associated mafic and intermediate rocks define the calcalkaline trend. The large volume of felsic igneous rocks of the Hooper Complex appear to be significantly more diverse than other Early Proterozoic orogenic belts of Northern Australia for which there are abundant data, and they exhibit many similarities with calcalkaline rocks in modern convergent continental margins. The Hooper Complex magmatism has sutured the Kimberley Craton, to the N, with the craton to the S which now underlies the Canning Basin. An origin by subduction-related partial melting of underplated material, previously fractionated from the mantle, is proposed for the Hooper Complex felsic igneous suite.

## Petrological characteristics of magmatic epidote-bearing granites of the western cordillera of America

**Jane M. Hammarstrom** and **E-an Zen**

Magmatic epidote-bearing plutons occur in a discontinuous belt within the accreted terranes of the western N American cordillera. The Admiralty-Revillagigedo plutonic belt, southeastern Alaska comprises a regionally extensive suite of diorites, quartz diorites, tonalites and granodiorites. Similar magmatic epidote-bearing rock types are present in the Ecstall Pluton, British Columbia and in the Tenpeak and Oval Peak plutons, northern Cascades, Washington. A more evolved suite (tonalite to trondhjemite) is present along the western margins of the Idaho Batholith. The characteristic mineral assemblage is hornblende, biotite, epidote (±allanite), plagioclase ($An_{15}$–$An_{50}$), quartz, orthoclase, ilmenite ± magnetite ± sphene, ±garnet, and apatite. These rocks are predominantly metaluminous (molar A/CNK = 0·6–1·3). Limited trace element data show that these rocks are high in Sr (300–1,404 ppm) and low in Rb (3–·79 ppm). Oxidation ratios are low (whole-rock $FeO/Fe_2O_3$ ranges from ~1–16), and the relatively reduced nature of the rocks is reflected by the facts that: (1) ilmenite > magnetite; (2) sphene rims some ilmenite, but is not ubiquitous as a primary constituent; and (3) $Fe^{3+}/Fe_{Total}$ for biotite (~0·06–0·07) and hornblende (~0·19–0·31) and pistacite contents of epidote (10–30 mol%) indicate redox states near or slightly more oxidising than those defined by the nickel-bunsenite buffer. Hornblendes are aluminous ferroan pargasites. For both biotite and hornblende, mg# (Mg/(Mg + Fe)) ranges from about 0·4–0·6, but hornblendes have slightly lower mg# than coexisting biotite. Garnet (grossular-almandine; 3–20 mol% spessartine) is present in parts of most of the complexes. Magmatic epidote, hornblende geobarometry, garnet compositions, field relations and pressure estimates from associated metamorphic assemblages all suggest that these plutons crystallised at mid- to lower crustal depths. The presence of magmatic epidote alone is not an unambiguous indicator of pressure. The collective chemical and mineralogical characteristics of this subset of calcalkaline I-type granites may be useful in recognising such plutons elsewhere.

## The effect of boron and fluorine, in mineral additives, on the production of granitic partial melts from greywacke sources

**M. J. Harvey, C. M. B. Henderson** and **D. A. C. Manning**

The granitic melt compositions produced by experimentally induced partial melting of greywackes, with volatile bearing additives, are investigated within a framework of variable pressure, temperature and volatile composition, in an attempt to shed further light on the processes of granite formation. Partial melts have been produced from "dry" and "wet" greywacke systems, at pressures of 0·1 and 0·4 GPa and temperatures between 750°C and 900°C. These systems were then further perturbed by the addition of B and F, added as natural minerals: tourmaline, cryolite, or ulexite. Further runs were executed using simple laboratory reagents to act as control experiments.

The hydrous, alkali-rich, partial melts produced in these experiments are chemically very complex and require particularly careful analysis. The loss of alkalis during electron microprobe analysis has been avoided by the use of a freezing stage attached to a JEOL JXA 6400 analytical S.E.M., allowing the specimen to be cooled to −193°C and permitting analysis to be carried out using a reduced beam current (1.5 nA). Analysis of specimens at a range of temperatures has enabled optimum analytical conditions to be determined; these represent a considerable improvement on standard electron microprobe analysis at room temperature.

Melts produced in this study plot close to the appropriate minima in Qz–Ab–Or, but within the quartz liquidus field. This may reflect the low potassium content of the greywacke starting materials; residual crystalline phases include: cordierite, ilmenite, apatite, zircon, plagioclase feldspar and pyroxene, all K-free phases. The degree of melting increases from "dry", through hydrous to B and F-bearing melts. Tourmaline (added as 10 wt%, approximately equal to 1 wt% $B_2O_3$) is completely consumed, as are equivalent quantities (with respect to the atomic proportions of F in the charge) of cryolite. These experiments demonstrate the probable importance of natural volatile-rich minerals, particularly tourmaline, for the processes of anatectic melting.

## The shoshonite-associated, zone gold skarn system at Junction Reefs, New South Wales, Australia

**R. Hine, A. Mandyczewsky** and **N. Gray**

Within the Junction Reefs and Burnt Yards goldfields there are several different styles of gold mineralisation that we suggest are genetically associated with a suite of Ordovician shoshonitic intrusives ranging from high-K diorite (48% $SiO_2$ 1·4% $K_2O$) to monzonite (58% $SiO_2$, 3·6% $K_2O$). Ore styles include retrogressed skarns, intrusive hosted sheeted veins, fissure veins and hydrothermal breccia pipes. The ores exhibit similar geochemical character, in that they have a strong arsenic-gold association coupled with a low base metal and silver content. Age determinations indicate that the gold skarns and the sheeted veins formed at essentially the same time (i.e. around 400 Ma).

The gold skarns, which are economically the most significant ore type in the district, are hosted by a 39 m-thick, gently tilted sequence of Early Ordovician limestone, siltstone and chert. The skarn is centred on a quartz monzodiorite stock from which the silicate mineralogy varies outwards from a garnet-quartz core zone assemblage, through a pyroxene zone, to a pyroxene-ferrohastingsite zone and an outer retrogressed calcite-chlorite-quartz zone with semi-massive pyrrhotite, arsenopyrite, pyrite and minor chalcopyrite. All of the gold ore bodies are found within the retrogressed zone. The quartz monzodiorite is fractionated and forms part of an intrusive complex centred on a large high-K diorite pluton. The diorite is pre-ore as it hosts both sheeted sulphide-quartz vein and breccia pipe ores.

Emplacement of the diorite, which is chemically the most primitive member of the suite, was not accompanied by any major metasomatic activity. Rather, there is good evidence that the gold mineralising events were initiated, in each instance, by the evolution of magmatic hydrothermal solutions generated by the crystallisation of felsic fractionates of the shoshonitic magma suite in the closing stages of its 30–40 Ma history.

## High level A-type sheet granites of the Wichita Mountains Igneous Province, Oklahoma, U.S.A.

**J. P. Hogan, M. C. Gilbert, B. L. Weaver** and **J. D. Myers**

The Wichita Mountains Igneous Province consists of Cambrian-age mafic and felsic igneous rocks intruded during rifting of the southern margin of the N American craton. Layered gabbros form a ~3–4 km-thick substrate for a ~1·5 km-thick rhyolite pile. Intrusive into the rhyolite are a series of high $SiO_2$ (71·0–77·6 wt%) alkali-feldspar granites of the Wichita Granite Group (WGG). The granites have A-type characteristics (e.g. metaluminous-subalkaline, magmatic fluorite, Zr > 500 ppm) and a "within plate" trace element signature. They occur as thin (~0·5 km) but laterally extensive (20–55 km) sheets. The WGG has been subdivided into three chemical suites. The Mount Scott Suite is impressive for its remarkable chemical homogeneity (i.e. $SiO_2$ 71·0–73·6%; CaO 1·0–1·5%, Rb/Sr ~1·3%) over a distance of at least 55 km. The other suites show more petrographical and chemical variability. Coarse-grained (~1 cm) seriate and fine-grained granophyric microgranite are characteristic. In general, coarser intrudes finer-grained granite, which commonly occurs as stoped blocks. Miaroles at the base of stoped blocks provide evidence for upward volatile migration. Segregation of hornblende ± magnetite in layers exhibiting "crossbedding" is commonly observed near granite contacts. Abundant granophyre, miaroles and intrusion into an approximately coeval volcanics suggest emplacement pressures of $10^2$–$10^3$ bars. Comparison of crystallisation histories of WGG with 1 kbar (1 kbar = 100 MPa) T − $xH_2O$ phase relationships for the A-Type Watergums Granite (Clemens *et al.* 1986) imply liquidus temperatures of 900–975°C and initial $xH_2O$ of <2·8 wt%. Temperatures of ~900°C are indicated by Zr geothermometry (Watson & Harrison 1981). Early crystallisation of hornblende-sphene-magnetite and quartz indicate intrinsic $f_{O_2}$ values greater than FMQ (Wones 1989). Ubiquitous salmon-red alkali feldspars record a pervasive late-stage oxidation. Within granite sheets, hornblende and biotite exhibit antipathetic modal variation. Both phases can be replaced by the assemblage magnetite-fluorite, a trend consistent with increasing $f_{F_2}$ and $f_{O_2}$ during crystallisation.

Gravitational settling, flow sorting and volatile migration are processes suggested to have produced limited compositional and mineralogical variability. In contrast to the high viscosities predicted for "dry" granite melts, these processes and the laterally extensive nature of individual sheets suggest crystallisation from relatively fluid melts. We suggest that high fluorine activities implied for these melts significantly lowered the viscosity of these magmas, enhancing

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the recorded emplacement and crystallisation processes. However, the chemical distinctiveness of the granite suites is not adequately explained by high-level differentiation processes alone and thus must reflect chemical heterogeneities intrinsic to the source regions of these granites.

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## Granites of the Ravenswood Batholith, northern Australia

**L. J. Hutton, I. P. Rienks,** and **D. Wyborn**

The Ravenswood Batholith divides into four major suites using evidence of timing of intrusion relative to deformation, radiometric data and geochemistry. The first major suite is pretectonic and was probably intruded between about 480 Ma and 470 Ma. The suite includes calc-alkaline granite and granodiorite, and tholeiitic gabbro. Some granites may have been formed by mixing and mingling of magma types. Small peraluminous garnet- and muscovite-bearing biotite granites are the only granites in the batholith where feldspar fractionation has played a major role in their genesis. They are included in the pretectonic suite. The second suite is syndeformational. Deformed and undeformed phases occur along a major shear zone and are chemically indistinguishable. Radiometric data indicate an Early Silurian age. The third major suite postdates deformation and was intruded between 425 Ma and 400 Ma. It includes voluminous calc-alkaline granodiorite and tonalite, and minor granite and diorite. Fractionation and crustal contamination do not appear to have played a major role in the genesis of this suite. Compositional variation is probably caused by source rock variation and restite unmixing. Rocks of the fourth suite are from the extensive and chemically distinct Carboniferous to Permian N Queensland Volcanic and Plutonic Province. Migmatitic and peraluminous two-mica granites occur within the Early Palaeozoic basement rocks. The age of migmatisation is not known. Gravity values over the batholith are higher than expected over deep-seated granites, suggesting that most of the granites yield to denser gabbro between 5 km and 10 km deep. Two plutons have low gravity values, however, and are probably more deeply seated. We speculate that the bimodal pre-tectonic suite resulted from the intrusion of a tholeiitic magma into continental crust. The post-tectonic suite is probably derived from partial melting of a mafic source rock, possibly the older mafic underplate.

## Tertiary extension related granite magmatism in the Rhodope Massif, northern Greece

**Catrin E. Jones** and **John Tarney**

Voluminous Tertiary granites intrude the Rhodope Massif in northern Greece, exhibiting an age sequence broadly younging from N to S. The largest, the Skaloti Granite complex, displays rock types varying from strongly foliated hornblende-biotite-tonalites exposed at its southern and western margins to unfoliated garnetiferous corundum-normative leucogranites in upper/central portions. This and other Tertiary granites (Lefkogia, Vrondou) were intruded as large-scale, sub-horizontal N–NE-dipping sheets broadly concordant along major Alpine structural horizons. Smaller, later, unfoliated Tertiary intrusions (Xanthi, Granitis) have more boss-like forms. Fabrics are not related to the waning stages of Alpine deformation, but were developed during or shortly after emplacement of the magmas into active extensional shear zones. Granite magma generation may have been a consequence of the return to a normal thermal regime following subduction and orogeny, but substantially enhanced by the onset in Tertiary times in northern Greece of the extensional regime now affecting the whole of the Aegean region.

The granites have Na/K ratios >1, high K/Rb ratios, high absolute Ba, Sr, P, moderate Ti and low Y and HREE contents. Their mantle-normalised spider-diagrams have slightly positive or no Eu anomalies and large negative Nb anomalies. Many of these characteristics cannot be accounted for by magmatic fractionation, AFC or crustal assimilation processes, but must reflect the geochemical composition of a major mantle source component. Moreover, these chemical signatures are inherent in many sodic granites worldwide. These features may be associated with incongruent melting of amphibole in lithospheric mantle. The generation of potassic granites may instead require their parental magma genesis from a phlogopite-bearing source.

We suggest that the granites of Rhodope were generated under conditions of pure shear lithospheric stretching aided by the breakdown of hydrous mineral phases (mainly amphibole) in the lithosphere that owed their origin to the long pre-history of subduction and fluid activity in the region.

## Deformation structures and intrusion tectonics of Late Cretaceous Obara Granite distributed in the Ryoke Belt of central Japan

**Yuji Kanaori, Shin-ichi Kawakami, Sayuri Onishi, Tomohiro Shinkai, Kenji Yairi** and **Yutaka Nakai**

The Late Cretaceous Obara granite exhibits an open V-shaped geometry, 3–5 km wide and 50 km in length. The body consists of coarse-grained, porphyritic hornblende-biotite granodiorite and medium-grained hornblende-biotite granodiorite, and contains distinctive, elongate microgranitic encalves oriented parallel to a magmatic foliation. The enclave elongation is also parallel to the boundary between the Obara body and other surrounding granites.

Cataclasite zones approximately 50 m wide occur parallel to the magmatic foliation at the northern margin of the pluton. The relationship between the magmatic foliation and enclave elongation suggests that the elongation of the enclaves probably resulted from ductile deformation of melt and crystalline mixtures at high temperatures. Microscopic observations reveal that polygonisation commonly occurred in quartz, and biotite and quartz fill intergranular fractures in plagioclase. This evidence suggests that the quartz and biotite were deformed ductilely while the plagioclase deformed brittlely. The deformation occurred at temperatures between 400°C and 650°C, consistent with the existence of deformation lamellae in quartz and the bending of biotite. The microstructures of cataclasites were also examined, with the quartz and feldspars found to be shattered into fragments. However, the biotite was not shattered and exhibited a kinked or elongated texture. The existence of brittlely-deformed quartz and feldspars, and plastically-deformed biotite implies that the deformation occurred over a temperature range of 250–400°C. The observance of such variously deformed structures suggests that the Obara body has been extensively deformed under a regional stress field over a wide range of temperatures: high temperatures at an intrusive stage to a low-temperature solid stage after cooling.

## Two contrasting styles of plutonism of the Ryukyu Arc, Japan

**Yoshinobu Kawano** and **Hiroo Kagami**

Cretaceous (70 Ma) to Tertiary (19 Ma) plutonic rocks occur on several islands and range from gabbro to granite. From age data, plutonic rocks in the Ryukyu Arc are divided into older and younger groups. Intrusion of the older group took place at 70–54 Ma and that of the younger group at 40–19 Ma. Plutonic rocks from the northern part of the Ryukyu Arc belong to the older group and the others to the younger one. The older group is characterised by higher FeO* and low $Al_2O_3$ contents compared with the younger group and the range of Y content of the former is wider than the latter. In Rb-(Y + Nb) and Nb-Y diagrams, the older group mainly belongs to WPG (within plate granite) and the younger group to VAG (volcanic arc granite).

In Cretaceous times, the Ryukyu Arc was located to the NW of the present position. At that time, the crust underneath the Ryukyu Arc was thick and felsic igneous activity took place in the northern part of the arc and E China and S Korea (Fukken-Ryeongnam

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Belt). It is considered that magmas caused by partial melting of the lower crust were affected by upper crustal material during their ascent through the thick crust. In Tertiary times, the crust underneath the Ryukyu Arc thinned by extension. As igneous activity of the second group took place under these conditions, it was not affected by upper crustal material.

## Magmatism, uranium mineralisation and hydrothermal activity: granitic examples from the Damaran Orogen of Namibia

**Judith A. Kinnaird, P. Bowden** and **G. J. H. Oliver**

The Pan-African Damaran Orogen forms one of the extensive late Proterozoic thermal, tectono-thermal and orogenic belts in the southwestern part of the African continent. The belt comprises: a N–S-oriented zone along the Namibian-Angolan coastline and a 400 km-wide NE-oriented zone between the Congo and Kalahari cratons. This latter belt has been divided into four main zones, of which the central zone is characterised by medium to high grades of metamorphism and extensive granite plutonism. Over 200 plutons occur, covering about 74,000 $km^2$ in area, ranging from over 5,000 $km^2$ in size to small veins and sheets. More than 95% of the plutons are granitic in composition, dominated by monzogranites.

Within the central zone, late-stage leucocratic granitic sheets carry important enrichments of uranium. On a regional scale, these uraniferous leucogranitic sheets and small plutons are spatially associated with domal structures found only along the axial zone of the Damaran belt. They are restricted to a structural zone approximately 50 km wide and extending NE for more than 100 km. Early, post-F1, pre-F2 tectonised (boudinaged) granitic sheets are non-uraniferous. These are cross-cut by post-F3 non-tectonised coalescing uranium-bearing granitic sheets.

Textures in the late leucogranite veins, which originally consisted of granophyric intergrowths of quartz and feldspar, have been modified into a range of textural facies which vary from coarse pegmatitic to micrograntic. Petrographical evidence suggests that following primary magmatic crystallisation of uranium-rich minerals, there were several hydrothermal episodes. The earliest can be related to residual high-temperature magmatic fluids concentrated during the crystallisation of post-F3 granitic intrusions. A lower temperature hydrothermal episode (possibly related to post-Damaran tectonics) was responsible for fluid movement along faulted contact zones between granitic sheets and country rock. A range of secondary minerals dominated by beta-uranophane is related to the latest meteoric fluid circulation along joints.

## Origin and significance of mafic enclaves in peraluminous A-type granites: examples from northeastern New South Wales, Australia

**B. Landenberger**

The Chaelundi Complex of the New England Orogen of northeastern New South Wales comprises an older I-type and a younger A-type suite of granites. The A-type suite is dominated by a leucoadamellite similar to other leucoadamellites in the region. However, the suite is compositionally extended, ranging from quartz monzonite (66% $SiO_2$) to leucoadamellite (76% $SiO_2$). The A-type suite is distinguished from the I-type by higher alkali and high-field-strength element contents, and lower CaO, MgO and $Fe^{3+}/Fe^{3+}$. Systematic major, trace and REE variation within the suite indicates that the leucoadamellite is derived from the quartz monzonite by 60% fractionation, involving removal of plagioclase, K-feldspar and orthopyroxene, along with minor hornblende and ilmenite.

Volumetrically minor mafic mineral clusters, comprising hypersthene, augite and calcic plagioclase, also occur in the quartz monzonite. Such clusters are better preserved as enclaves in the Woodlands Quartz Monzonite. Mineral chemistry and petrographical relations indicate that these enclaves are quenched basaltic liquids. Whole-rock geochemistry reveals that the enclaves have a high-K, high-alumina basaltic composition and have undergone minor mixing with the host granite. Underplating of similar mantle-derived magmas is likely to have initiated melting in the lower crust, producing both the I- and A-type granites present in the region. Subtle differences between these granites suggest a similar, if not identical, source rock. Previously underplated arc basalts would have a composition similar to, but more primitive than, the basalt represented by the enclaves, and are a likely source. Volatile concentrations during partial melting, particularly that of F, probably determines the initial composition, and hence the affinity of these granitic melts.

## Textural evolution of the two-phase granite pluton at Tai Lam, western New Territories, Hong Kong

**R. L. Langford**

The Tai Lam granite pluton is one of many intensely complex, high-level, two-phase plutons that characterise large areas of Hong Kong and the S China coastal granite belt. It is a structurally distinct, leucocratic biotite monzogranite of late Yenshanian (Mesozoic) age, characterised by small relict bodies of coarse- and medium-grained primary-texture granite surrounded by finer-grained, megacrystic granites displaying a wide and complex range of textures produced by remobilisation and recrystallisation. These textures form a continuum from the primary-texture granite through to granites with an entirely derived texture and geochemistry.

Major and trace element abundances show similar trends to those associated with tin mineralisation in granites in Peninsular Malaysia. Textural modification of the coarser primary-texture granite results in an increase in $SiO_2$ and $Na_2O$, while $TiO_2$, $Al_2O_3$, total $Fe_2O_3$, MgO, CaO and $K_2O$ are progressively depleted. Trace-element abundances show a progressive enrichment in Rb, Pb, Cr, Ga, Nb, Sn and W, and there is depletion in Sr, Ce, Ba, La and Zr.

The extensive areas of megacrystic fine-grained and fine- to medium-grained granite represent the syn-intrusive remobilisation and resorption of a partially cooled, deep-seated phase of coarser-grained, weakly evolved granite in response to rapid pressure release during emplacement at a higher level in the crust. The progressive remobilisation of the primary-texture granite by the addition of late-stage, high-level, fractionated residual magmatic fluids appears to be dominated by fluidisation, brecciation and alkali metasomatism. Quartz veins with associated Sn-W mineralisation suggest that hydrothermal activity was important in the later stages of pluton development.

## Timing of emplacement and crystallisation of the Himalayan leucogranites

**Patrick Le Fort, Arnaud Pêcher** and **Stéphane Guillot**

The idea that the High Himalayan Granites are linked to the tectonic evolution of the Himalaya was suggested long ago. Thus, dating of the granite is a choice way of dating the mountain-building. However, detailed investigations of the deformation characteristics and petrology of the granite and surrounding rocks suggest that the relationship is complicated.

In the country rocks of the granites, the early fabric of the Main Central Thrusting (MCT) is overprinted by the structures related to the N Himalayan Shear Zone (NHSZ). Large-scale structures, such as the N-vergent Annapurna fold of central Nepal, belong to this second deformation that may be in part coeval with the continuation of the movement along the MCT at lower levels. In the granitic rocks, the magmatic fabric is often overprinted by a sub-solidus, high-temperature foliation and/or lineation.

The migmatitic source area of the granite has undergone a decompressive phase with development of sillimanite often associated with shear planes preferentially collecting the anatectic material. The plutonic bodies cut the regional structures of collapse type such as the N-vergent Annapurna fold or the N Himalayan Shear Zone. In the thin upper contact aureoles, the metamorphic minerals are associated with a cleavage due to the dynamic emplacement of the granite.

Absolute dating of the granite has proved to be a quite disappointing and debatable matter. U-Pb and whole-rock Rb-Sr

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ages extend from around 25 Ma or less, to 18 Ma; the time-scale for the granite emplacement and crystallisation is of the order of a few Ma. Absolute dating of the periods of deformation is essentially lacking, but they should have lasted around 20 Ma for the first (MCT), and from around one to several Ma for the second (NHSZ). This may explain the complex relationships between the granite and the deformation patterns. Altogether, the emplacement and crystallisation of the High Himalayan Granites is a rather long process that occurs somewhat late in the tectonic evolution of the mountain range.

## Granite emplacement and deformation in the Old Woman Mountains, southeastern California

**K. J. W. McCaffrey, C. F. Miller, K. A. Howard, K. E. Karlstrom and C. Simpson**

Thd Old Woman-Piute Batholith was emplaced into orogenic continental crust and provides an insight into the interplay between plutonism and deformation in the Mojave Desert. Individual plutons are generally sheet-like and concordant to the major regional structure, the Scanlon Nappe, which placed inverted Proterozoic basement and lower Palaeozoic strata on upright Palaeozoic to lower Mesozoic strata. The 73 Ma composite batholith includes both metaluminous granodiorite, which underlies the nappe, and slightly younger peraluminous granite plutons. These intrusions clearly postdate nappe development. Pre- and post-pluton emplacement fabrics were distinguished using strain analysis techniques on Proterozoic gneiss and Mesozoic dykes.

Syn- to post-intrusion deformation is demonstrated by: granodiorite fabrics that are parallel to, but weaker than, those in adjacent country rocks; melt-filled shear zones in granodiorite; and folded gneissic xenoliths and schlieren associated with a strong magmatic fabric in the granodiorite. This deformation continued far below granitic solidus temperatures in shear zones on the pluton margins.

Field relations, strain and kinematic data permit reconstruction of the pluton emplacement style and the role played by the magmatic events in the post-thrusting evolution of the Old Woman Mountains. The cooling history indicated by $^{40}Ar/^{39}Ar$ data suggests rapid denudation of the plutons ending by 65 Ma. Syn-magmatic deformation and later deformation may have contributed to unroofing during this interval. It is plausible that magmatism occurred in response to crustal thickening and profoundly influenced the subsequent extensional collapse of the thrust pile.

## Pb isotopic evidence for deep crustal-scale fluid transport during granite petrogenesis

**M. T. McCulloch, J. D. Woodhead and B. W. Chappell**

The initial Pb isotopic composition has been determined in K-feldspars from Palaeozoic granites of the Lachlan Fold Belt (LFB) of southeastern Australia. In contrast to the wide range in initial Nd and Sr isotopic compositions ($\varepsilon_{Nd(I)} = +3$ to $-8{\cdot}9$ and $^{87}Sr/^{86}Sr_{(I)} = 0{\cdot}70408$–$0{\cdot}71206$), the Pb isotopic compositions for K-feldspars from the Bega and Berridale batholiths in the LFB of southeastern Australia exhibit an extremely limited variation in Pb isotopic composition with $^{206}Pb/^{204}Pb$ ratios of 18·142–18·185, $^{207}Pb/^{204}Pb$ ratios of 15·581–15·630 and $^{208}Pb/^{204}Pb$ ratios of 38·042–38·207. Despite this, there is a relatively good correlation with $\varepsilon_{Nd}$ values, for example, samples having low, and hence more primitive, $^{207}Pb/^{204}Pb$ ratios also having more positive $\varepsilon_{Nd}$ values. There is also an excellent correlation between single-stage Pb-Pb and $T^{Nd}$ model ages. The Pb-Pb model ages, however, have a significantly reduced range of from ~320–440 Ma compared to the $T^{Nd}$ model ages which range from ~800–1,770 Ma.

Previous Pb isotopic studies, particularly of ore bodies, have shown that Pb isotopic compositions are relatively uniform and tend to reflect average values of terranes or upper-crustal segments. Thus in high-level supergene deposits, Pb appears to be particularly mobile in fluid systems. In the LFB, detailed isotopic and geochemical studies have shown that the Palaeozoic (400–420 Ma) granites are derived from complex, dominantly intracrustal, source rocks with a wide range of Sm-Nd depleted mantle model ages (600–1,800 Ma). Furthermore, two chemically distinct types of source rocks have been recognised, infracrustal and supracrustal, producing, respectively, I-type and S-type granites. The Pb isotopic composition of the LFB granites would be expected to reflect this complex source history. The extremely limited range in Pb isotopic compositions and consequent limited range in Pb-Pb model ages, despite the large range in $T^{Nd}$ crust formation ages, is therefore attributed to the mobile behaviour of Pb in deep, crustal-scale fluid circulation systems that were established immediately before or during granite plutonism. The fluid circulation system probably affected whole crustal segments and operated over length scales of $\sim 10^3$ km, and may play an important role in the redistribution of soluable elements as well as the convective transport of heat within the crust.

## A new shear criterion for rocks deformed in the magmatic state: examples from the Thorr Granite, Co. Donegal

**Michele A. McErlean**

A fundamental concept when studying deformation fabrics in granitic rocks is that of relating the time of deformation to the crystallisation state of the magma, hence the subdivision of granite fabrics into magmatic-state and solid-state types. The development of both types of fabric can be related to the operation of non-coaxial strains, including simple shear. Observations about the sense of shear are obviously critical to any structural study. While there are abundant useful shear sense indicators in rocks deformed in the solid state, those deformed in the magmatic state often lack documented sense of shear indicators, such as tiling fabrics. By applying a concept proposed by Fernandez and Laporte, it is now possible to use the subfabrics often observed in granites deformed in the magmatic state to determine the sense of shear during deformation.

The concept relies on the fact that different shapes of grains rotate at different rates when subjected to non-coaxial shear. Crystals with low grain-shape ratios rotate faster than those with higher grain-shape ratios because they have a smaller period of rotation about a fixed axis, thereby resulting in the development of polymodal and asymmetric fabrics.

This has been tested on the Thorr Granite, the oldest member of the Donegal Batholith (418 Ma). The pluton carries a fairly well-developed and pervasive magmatic-state deformation fabric which is defined mainly by feldspar phenocrysts. In areas throughout the pluton, but especially in the central Gola facies, this is markedly bimodal in nature, the subfabrics being defined by two families of feldspar phenocrysts. By visually rotating the subfabric defined by those feldspars with a higher grain-shape ratio through the acute angle towards the subfabric with the lower grain-shape ratios, the sense of shear can be determined, since this is how the crystals would have continued to rotate had the magma stayed hot.

Results from Thorr are predominantly anticlockwise rotations, consistent with sinistral shear along a northerly trend. This supports other data from the margins of the pluton and together they indicate that the Thorr granite lay in the site of a N-trending sinistral shear zone which entirely pre-dated the NE-trending Main Donegal Granite shear zone.

## Emplacement of mid-crustal plutons in the Ross Lake Fault Zone, North Cascades, northwestern U.S.A.

**Robert B. Miller**

The 10 km-wide Ross Lake Fault Zone (RLFZ) exemplifies the relationships between pluton emplacement and strike-slip faults. This terrane boundary was intruded by numerous plutons that record spatial and temporal variations in emplacement mechanisms. Emplacement was particularly influenced by stepover zones between dextral strike-slip fault segments and by a regional change from transpression to transtension.

Plutons were intruded at 87–91 Ma, 60–68 Ma, and 48–50 Ma.

The oldest body, the Black Peak Batholith, shows evidence for both stoping and forcible emplacement. It intruded across a left-stepping jog or bend in the RLFZ at its southern end and a right-stepping one at its northern end. Slip across the southern, contractional stepover was transferred through the pluton by reverse-slip ductile shear zones that strike at a high angle to the strike-slip segments.

The 60–68 Ma plutons were emplaced during regional transpression in which dextral strike-slip and thrusting occurred on different segments of the RLFZ. Tectonic loading occurred before and/or during intrusion. Hornblende barometry for the epidote-bearing Oval Peak Batholith (65 Ma) records crystallisation at ~6 kbar (1 kbar = 100 MPa), considerably greater than the <3 kbar for the nearby Black Peak Batholith. The Oval Peak was intruded syntectonically as an asymmetric expanding diapir along a thrust segment. In contrast to this diapiric pluton, variably deformed 60–68 Ma rocks in a 2 km-wide belt in the thrust footwall intruded as moderately dipping sheets that are typically 1–10 m wide.

The 48–50 Ma plutons were intruded during regional transtension and oblique (dextral-normal) slip in the RLFZ. They lack solid-state deformation, but show strong structural control where numerous sheets and irregular masses form, in map view, a 10 km-long wedge within an extensional stepover.

Collectively, these patterns demonstrate how terrane boundaries may serve as a locus of protracted plutonism during varying tectonic regimes and indicate the importance of stepovers in localising emplacement.

## The contribution of early Proterozoic basement to Caledonian magma genesis in northwestern Britain and Ireland

**R. J. Muir, W. R. Fitches** and **A. J. Maltman**

The source of the inherited Proterozoic lead component in the Caledonian granites has been the subject of much speculation. The apparent absence of a significant volume of early Proterozoic crust in Scotland and Ireland has led to three alternative suggestions for the origin of this isotopic signature: (1) Lewisian crust (2·9–2·7 Ga) thoroughly reworked during the Laxfordian tectonothermal event (1·9–1·7 Ga); (2) Laxfordian granitic material (1·7 Ga); (3) a mixture of Lewisian (2·9–2·7 Ga) and Grenville crust (1·0 Ga). A more likely source for the Proterozoic component is the newly recognised Rhinns Complex in the southern Inner Hebrides.

Precambrian basement on the southern side of the Great Glen Fault zone is exposed on the southern half of the Rhinns of Islay, in northeastern Colonsay and on Inishtrahull. Previous workers have generally correlated this basement with the late Archaean Lewisian complex. However, detailed field, petrographical and geochemical studies have revealed that the basement rocks comprise a deformed igneous association of syenite and gabbro, with minor mafic and felsic intrusions. This association, collectively termed "The Rhinns Complex" has an alkalic composition. Isotopic data indicate that the complex represents new addition of material to the crust at *c*. 1·8 Ga. The igneous protolith was juvenile mantle-derived material, not reworked Archaean crust.

The inherited zircons in the Caledonian granites may reflect the presence of early Proterozoic basement (Rhinns Complex) beneath Scotland and northwestern Ireland. It is important to note, however, that the granites have passed through Moine and Dalradian metasedimentary rocks which also have early Proterozoic Nd model ages and contain Proterozoic zircon. Moreover, at least part of the Dalradian sediment was derived from the Rhinns Complex. Consequently, an alternative explanation of the granite data is contamination by the country rocks. In support of this, many of the granites have isotopic compositions indicative of mixing of early Proterozoic, Dalradian and mantle-derived components.

## The petrogenesis of the Proterozoic Harney Peak leucogranite, Black Hills, South Dakota, U.S.A.

**Peter I. Nabelek** and **Carol Russ-Nabelek**

The peraluminous Harney Peak Granite is associated with one of the largest rare-element pegmatite fields in N America. The granite was emplaced at 3–4 kbar (1 kbar = 100 MPa) as multiple sills and dykes at the culmination of a regional high-temperature, low-pressure metamorphic event. Principally along the periphery of the main pluton and in the satellite intrusions, the sills segregated into granite-pegmatite couplets. The minerals include quartz, K-feldspar, sodic plagioclase, muscovite ± garnet. The predominant ferromagnesian mineral in the granite's core is biotite, whereas at the periphery of the main pluton and in the satellite intrusions it is tourmaline. Oxygen isotopes in most samples equilibrated at magmatic temperatures between >800°C and 650°C. The biotite-containing granites have $\delta^{18}O$ of $11{\cdot}5 \pm 0{\cdot}6$‰ and tourmaline-rich granites $13{\cdot}2 \pm 0{\cdot}8$‰. The difference is best explained by generation from two different sources, consistent with radiogenic isotope data (Walker *et al.* 1986; Krogstad *et al.* 1992). The schists have an identical average $\delta^{18}O$ value to that of the high-$\delta^{18}O$ granites.

$SiO_2$, CaO, MgO, FeO, Sr, Zr, W of the low- and high-$\delta^{18}O$ suites overlap, whereas the concentration of Ba and $TiO_2$ is higher and of MnO and B lower in the low-$\delta^{18}O$ granites. Most samples are more potassic than the $H_2O$-saturated minima, consistent with melting at $a_{H_2O} < 1$ (Holtz & Johannes 1991; Pichavant 1987). These features suggest that the low-$\delta^{18}O$ granites were generated by high-extent, biotite-dehydration melting of more immature metasedimentary source deeper in the crust, whereas low-extent, muscovite-dehydration melting of schists higher in the crust resulted in the peripheral tourmaline granites. The results of this study indicate that chemical and mineralogical variations in pegmatitic leucogranites may be largely due to conditions prevailing in the source regions during melting.

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## Along-arc migration of Cretaceous granitic magmatism and low-P metamorphism in the Southwest Japan Arc: what caused the Cordilleran-type orogeny along the Eurasian Continental Margin?

**Takashi Nakajima**

During the late Mesozoic, before the opening of the Japan Sea, the Pacific plate had subducted beneath the Eurasian continent and caused a Cordilleran-type orogeny including the formation of accretionary prism, low-pressure and high-pressure regional metamorphism and granitic magmatism along the continental margin. These orogenic products are widely exposed in the Southwestern Japan Arc, especially in the northern part of southwestern Japan, where Cretaceous granites and the related volcanics occupy more than half of the ground surface.

The granitic rocks are mainly of I-type and ilmenite series. They are divided into two groups in terms of field occurrence and lithology. "Ryoke-type" granites are associated with low-pressure-type regional metamorphic rocks and are sometimes gneissose, whereas "Sanyo-type" granites intrude cogenetic volcanic rocks and are all massive. They are regarded as the deep and shallow parts of the granitic province, respectively.

Extensive geochronological work has revealed that the isotopic ages of these granites have a systematic lateral variation. Rb-Sr whole-rock isochron ages of the Sanyo-type granites become younger eastwards from 100–70 Ma over 700 km. Rb-Sr/K-Ar biotite ages basically follow the eastward-younging trend with a 5–10 Ma time-lag from the Rb-Sr whole-rock ages for the entire area. The ages of the Ryoke low-pressure metamorphic rocks are fairly consistent with that lateral age variation trend.

From the systematic along-arc age variation of these granitic and metamorphic rocks, we infer the migration of a tectonic setting in which the granitic magmatism and low-P metamorphism took place. The tectonic models for granitic magmatism based on the situation of steady-state subduction cannot explain these geochronological features.

RTT (ridge-trench-trench) migration involving the subduction of the Kula-Pacific Ridge beneath the Eurasia plate might have driven the Cretaceous Cordilleran-type orogeny along the eastern margin of the Eurasian continent. Eastward-younging MORB-type basaltic volcanism within the Cretaceous accretionary prism, as well as widespread occurrence of high-magnesian andesites at the early stage of the granitic magmatism, could be the results of ridge subduction.

## Role of mafic magmas in granite genesis: evidence from enclaves in Silurian Devonian plutons of southeastern Australia

**I. A. Nicholls, C. Carson, C. Legg, R. Maas** and **G. Eberz**

Petrographic and major/trace element studies of abundant microgranular enclaves in the early Devonian I-type Swifts Creek Pluton and middle Devonian S-type Wilson's Promontory Batholith of eastern Victoria support their origin as mafic magma globules which, after injection into pre-existing felsic magma chambers, mingled mechanically with crystal-rich, viscous host magmas and underwent variable mixing. Within some enclaves, "trails" of quartz and feldspar megacrysts derived from the host demonstrate extensive mixing. Other non-megacrystic enclaves show little evidence for mixing, and zoned examples with fine-grained margins indicate rapid cooling against host magma and internal differentiation. Swifts Creek Pluton Sr and Nd isotopic ratios fall into almost distinct "enclave" and "host" fields, which together define a two-component "mixing" trend compatible with involvement of primitive (meta-igneous) and evolved (metasedimentary) crustal magma sources. Trace element systematics are also in broad agreement with a two-component mixing model (Eberz *et al.* 1990).

The late Silurian S-type Deddick Granodiorite in northeastern Victoria, a member of the Bullenbalong Suite of the Kosciusko Batholith, contains abundant gneissic metasedimentary enclaves, ranging from fertile examples with quartzofeldspathic layers to highly residual types dominated by cordierite + biotite + sillimanite + spinel ± andalusite ± corundum assemblages. Microgranular enclaves with igneous microstructures are rare (<10% of enclaves) and comprise biotite-rich microtonalitic types with plagioclase to $An_{85}$ and orthopyroxene to $Mg_{87}$, and microgranodiorites. The host granodiorite remote from enclaves is isotopically uniform (initial $\varepsilon_{Nd} \sim -10$, $^{87}Sr/^{86}Sr \sim 0{\cdot}715$) and contrasts strongly with the enclaves themselves, which show broad variation in isotopic ratios within and between groups. Gneissic enclaves are isotopically more evolved than the host (−10–12, 0·717–0·722), while microgranodiorite enclaves (−4–8, 0·709–0·713) are more primitive. Microtonalite enclaves (−6–12, 0·713–0·717) overlap with the host, but show much greater petrographic and isotopic diversity. Host and enclaves together define a curved $\varepsilon_{Nd}$ – $^{87}Sr/^{86}Sr$ array compatible with two-component mixing, but trace-element systematics are not readily reconciled with this. The simplest interpretations appear to be that gneissic enclaves (at least some originating at shallow depths compatible with andalusite stability) represent fragments of a previously partially melted metasedimentary succession encountered during uprise of host magma, while microtonalite enclaves may represent partially hybridised products of mingling between small volumes of mafic magma and host granodiorite magma already carrying material derived from metasedimentary enclaves. Microgranodiorite enclaves probably represent distinct magmas which intruded the host pluton as small dykes late in its emplacement history and also became involved in limited magma mingling.

Eberz *et al.* 1990. CHEM GEOL **85,** 119.

## Interpretation of the chemistry of the mineral apatite from granitic rocks: a preliminary model calculation for the estimation of initial halogen contents in the Tuolumne Intrusive Suite, Sierra Nevada Batholith, California

**P. M. Piccoli** and **P. A. Candela**

The concentration of the halogens in the mineral apatite can be used to deduce changes in fugacity ratios during the crystallisation of granites. In addition, the initial concentration of Cl and F in the melt and the associated magmatic aqueous phase can be calculated if the temperature of apatite crystallisation can be estimated. Model apatite saturation temperatures (AST) can be calculated given the apatite solubility function determined by Harrison and Watson (1984). Our calculations suggest the following AST for the units of the Tuolumne Intrusive Suite (in °C); Kuna Crest (KC) 928, Half Dome Equigranular (HDE) 901, Half Dome Porphyry (HDP) 915, Cathedral Peak (CP) 925 and Johnson Porphyry (JP) 795. In addition, over half of the apatite crystallises within 60°C of the AST for the KC, HDE, HDP and CP, and within 30°C for the JP. The proportion of crystallisation before apatite saturation has also been estimated: KC (35%), HDE (9%), HDP (9%), CP (8%), and JJP (16%). The ratio of the mole fraction of chlorapatite to hydroxapatite and fluorapatite to hydroxyapatite within the host rocks decreases from the outer to the inner units of the Tuolumne Intrusive Suite: KC (0·080, 1·70), HDE (0·064, 4·57), HDP (0·019, 2·71), CP (0·030, 5·00) and JP (0·016, 8·00).

The composition of apatite can be used in conjunction with the AST to calculate initial F and Cl in the melt and magmatic aqueous phase. Given this information, the following concentrations for Cl (wt%) and F(ppm), respectively, in the aqueous phase have been estimated: KC (44; 45), HDE (32; 100), HDP (10; 65), CP (16; 130), and JP (5; 60). The coexisting magma is estimated to contain the following concentration of Cl (ppm) and F (ppm), respectively: KC (8,200; 190), HDE (5,800; 410), HDP (1,800; 270), CP (3,000; 540) and JP (800; 300). This drop in initial Cl in the melt from the outer to the inner units of the Tuolumne Intrusive Suite corresponds well with the increase in $(Sr^{87}/Sr^{86})^{o}$ determined by Kistler *et al.* (1986). The relationship between decreasing Cl and increasing $(Sr^{87}/Sr^{86})^{o}$ suggests that variations in initial Cl in the melt are controlled by variable amounts of a subduction-related component.

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## Mantle-crust interaction in the European Hercynides: isotopic and geochemical evidence from Spanish Central System granites

**L. Pinarelli, R. Petrini** and **A. Rottura**

The Spanish Central System (SCS) is a major granite complex in the Hercynian Iberian Massif. It consists largely of granitic occurrences associated with minor mafic to intermediate intrusives, emplaced at shallow level in late Hercynian times.

The granites from Bejar in the western SCS consist of porphyritic biotite-monzongranite-granodiorite (BG), often cordierite-bearing (CMG), containing quartz dioritic to tonalitic mafic enclaves. Both BG and CMG are moderately peraluminous (A/CNK = 1·10–1·33) and LREE-enriched; they show pronounced negative Eu anomalies (0·57–0·23) and variable HREE fractionation ($(Gd/Yb)_N$ = 1·5–2·8), with geochemical characteristics similar to those of volcanic arc granites.

The initial (at 300 Ma) Sr and Nd isotopic compositions are variable in both granite types ($(^{87}Sr/^{86}Sr)_i$ = 0·70802–0·70924 in BG and 0·70799–0·70897 in CMG; $\varepsilon_{Nd}$ = −3·9–−8·0 in BG and −4·7–−7·8 in CMG). Mafic enclaves have slightly less evolved isotopic signatures ($(^{87}Sr/^{86}Sr)_i$ = 0·70718–0·70797; $\varepsilon_{Nd}$ = −4·3–−5·5), similar to those of gabbroics occurring in the eastern SCS.

Trace-element patterns and isotopic features of the SCS granites, along with the close association in space and time with mafic rocks, suggest an involvement of mantle derivatives, through a complex mechanism of mantle-crust interaction. Simple two-component mixing calculations (depleted mantle model) would indicate a range of 40–60% mantle component in the granites. The narrow range of Sr and Nd isotopic composition in gabbroic to granitic rocks suggests two alternative conclusions: either the granites are simply fractionated from the hybrid gabbroic magma, or, more probably, all the gabbro-granite suite is produced by a complex steady-state balance between crystallisation, crustal assimilation and new magma input, causing the magma to evolve chemically but not isotopically. In the last case, the buffering effect on the isotopes would impede a realistic estimate of the increasing crustal contribution in the progressively more evolved lithologies.

## The Rosses multi-pulse Pluton: fractures and fractals

**W. S. Pitcher**

The Rosses Pluton of Donegal, Ireland, is a typical example of a nested grouping of near-circular intrusions, here representing four consecutive magma pulses, $G_1$, $G_2$, $G_3$ and $G_4$. Advantage has been taken of the excellent exposure on glaciated pavements to re-examine the contacts, metre by metre. All have been found to be sharp, with fining directions and hanging-wall pegmatite providing ample evidence of younging.

The linear, angular outline of the contacts is clear at all scales down to a few centimetres, and each intrusion has an overall polygonal outline. The contact planes of each of the intrusions conforms to a simple, structural pattern, seemingly controlled by a coeval fracture system akin to that of jointing, a view confirmed by the spalling off of rectangular joint blocks of the country-rock granodiorite at outer contacts, and of earlier pulse members at internal contacts. Though there are some common features, a contact-fracture pattern is specific to each intrusion event.

Overall, the emplacement is envisaged as being due to the collapse, during domal uplift, of arches of just consolidated granite which diminished in diameter with time.

All this is merely a refinement of the original work of Pitcher (1953, 1972), but the re-examination was motivated by the possibility of applying fractal analysis to this almost ideal example of igneous fracturing. On the gross scale, i.e. with a "stride" greater than about 250 m, the fractal dimensions of the contacts turn out to be self-similar and self-affine, but the D-values (degree of roughness) are generally low, expressing an approach of the contact planes to a Euclidean line. Of course, mathematical precision is difficult to obtain in the field from field measurements, but the preliminary results are: Thorr Pluton (the country rock) against $G_1$, $D = 1{\cdot}059$; $G_1$ against $G_2$, $D = 1{\cdot}016$, a very low value possibly expressing a low rigidity of $G_1$ at the time of the intrusion of $G_1$; a view consonant with other field observations; $G_2$ against $G_3$, $D = 1{\cdot}064$, the same as the outer contact yet surprisingly low considering the obvious angularity. On a stride scale smaller than 250 m the fractal dimensions turn out to be even lower in value, yet still self-similar. The reason for this is obvious in the field, where the variation in degree of angularity or roughness is seen to be very variable in the sense that long linears are broken by short, discontinuous lengths of small-scale, angular re-entrants. It is difficult to understand why this should be so in reasonably homogeneous materials, but perhaps disorder is more natural than order!

As earlier suspected by Pitcher, certain principal linears parallel the early regional joint system and it is envisaged that the overall shapes of the contacts were controlled by the interplay of a regional and a local, intrusion-centred, stress system. At the joins of the tangential linears, the change in direction required to follow an overall arcuate form results only after a number of "trail" fractures filled by granitic apophyses.

It is hoped that this very elementary attempt to use fractals will encourage their more general use and engender discussion.

Pitcher, W. S. 1953. PROC GEOL ASSOC **64,** 153–82.
Pitcher, W. S. & Berger, A. R. 1972. *The geology of Donegal: A study of granite emplacement and unroofing.* New York: Wiley-Interscience.

## A peraluminous passing to metaluminous intrusive suite by means of a complex mixing process: geochemical evidence from the Miocene-Pliocene intrusive rocks from southern Tuscany and the Tyrrenian Sea, Italy

**G. Poli, P. Manetti** and **S. Tommasini**

The Miocene-Pliocene intrusive rocks of the Tuscan Magmatic Province (TMPI) have been found on the mainland, on islands of the Tuscan archipelago, as well as in boreholes. TMPI range in composition from granodiorite to alkaligranite, with a strong predominance of monzogranites. The rocks can be divided into five facies on the basis of field and petrological constraints, whereas from a geochemical viewpoint three trends exist in any Harker's diagram using major and trace elements. Aluminium Saturation Index (ASI) increases with differentiation and TMPI straddle the I-type and S-type fields. Genetic models that relate these chemical variations, as a whole and within individual plutons, to the segregation of major and accessory mineral phases are inconsistent with major, trace and rare-earth element abundance data. A simple two-end-member mixing process fails also to explain the geochemical characteristics of the plutons, either as a group or singly. The petrogenetic model that is able to explain all the petrographical and geochemical features shown by TMPI involves a three-stage process as suggested by Poli and Tommasini (1991). The model consists of three main stages concerning injection, evolution by means of a contamination and fractional crystallisation (CFC) process, and mixing processes which the mafic magmas underwent when injected into anatectic crustal environments.

The CFC process involved crustal peraluminous magma and mafic magma of probable subcrustal origin which formed microgranular enclaves, and a mixing process between the same crustal peraluminous magma and different evolved magmas derived from the mafic magma. The felsic peraluminous end member could be the leucocratic facies of the Giglio Pluton, whereas the mafic end member could be similar to the Capraia volcanic rocks. Thus, the petrogenetic model proposed for TMPI is able to explain the dichotomy between S- and I-type granite characteristics.

## Structural controls on granite genesis in transpressional shear zones

**R. John Reavy**

Existing attempts to classify and account for granite magmatism from a genetic or environmental standpoint still do not explain fully the diversities encountered in various settings. This is because such schemes only loosely address the geological effects of tectonism and do not consider in detail how tectonic processes could actually control melt generation, magma ascent and pluton emplacement. In this contribution, the Hercynian belt of Iberia is compared to the Caledonian of the British Isles. Although there are marked contrasts of granite type between these two orogens (the causes of these differences are addressed here), they are both belts in which transpressional tectonics prevailed at the time of magmatism.

As transpression thickens the crust, there is the potential to generate granitic magma in such zones. In the Hercynian transpressional shear zones of Iberia, thickening together with hydrous fluxing created intracrustal wet melting of fertile Gondwanan sediments to produce syntectonic peraluminous two-mica granites. In the northern part of the British and Irish Caledonides, the association of compositionally-expanded granites with a major mantle input and transpressional shear zones may be explained by melting of continental crust at the lower limits of transpressional faults detaching into the Moho.

Individual transcurrent shear zones may, therefore, not only simply control the ascent paths, siting and emplacement mechanisms of plutons, but more fundamentally may also, due to the thickening inherent in the geometry of transpression, be ultimately responsible for granite genesis in such zones.

## Alteration effects of trioctahedral micas as a contribution to petrogenesis of granitic rocks from the Elbe lineament (Saxonia)

**A. Renno** and **W. Schmidt**

Within the comprehensive examination of the Variscan and Prevariscan granites of the Elbe lineament in southeastern Saxonia (Schmidt 1992) a detailed investigation of the trioctahedral micas has been carried out. The mineral separates were analysed using classical wet chemical and trace-element methods and were characterised by X-ray diffraction and Mössbauer spectroscopy. Such investigations give valuable hints about petrogenesis. But one has to keep in mind the fundamental methodical difficulties, particularly the impossibility of separation of single mineral generations and the significant influence, on chemical analysis, of inclusions of accessory minerals and mineral alteration. The micas from different rock types were classified as $Mg^{-}$ and $Fe^{2+}$ biotites following Foster (1960).

With the help of statistical methods, we examined the effects of alteration to the major and trace-element concentrations in micas. Factor analysis shows that the formation of hydrobiotite has the most significant influence (30·6 variance%). The factor scores show a congruent behaviour of Rb, MnO, Li, $Fe_2O_3$, Nb, $H_2O$, B and L.O.I. Discriminant analysis was used to examine which element contents support the empirical division into normal and "changed" (hydro) biotites. We controlled the influence of the biotite classification in the first discriminant analysis, and proved that $H_2O$, Ba, Pb, L.O.I., Cr and Sn support our division. We can point out that even changes of micas, which are scarcely visible and difficult to identify by chemical methods, have a decisive influence on the starting values of petrogenetic interpretation (particularly $Fe^{2+}$ and $Fe^{3+}$).

According to our results of major element analysis and X-ray diffraction, we can distinguish two different alteration processes (chloritisation, and the formation of hydrobiotite-vermiculitisation). The chloritisation is found in variable degrees in all examined rock types, but the formation of hydrobiotite is limited to a spatial and temporal section, which are additionally characterised by the martitisation of magnetite. The process seems independent of the rock type.

Schmidt, W. 1992. LITHOS (submitted).
Foster, M. D. 1960. US GEOL SURV PROF PAP **354B**.

## Lachlan orogen pluton-emplacement structures

**M. J. Rickard**

There are three types of granite body in the Lachlan Fold Belt. Large homogeneous batholiths, elliptical plutons in strings or isolated, and narrow lenticular bodies. There is little deformation effect in the country rock adjacent to plutons or batholiths, and most have a sharp steep contact with a narrow contact hornfels aureole. Only a few small plutons show evidence for forceful intrusion. The S-type granites tend to be foliated (biotite and xenoliths), and this probably results from "ballooning pressure" against the country rock during intrusion a short distance from source. Some I-type plutons show marginal "flow foliation" that traces parallel to the contact around elliptical bodies. A tectonic mylonitic fabric is in places superimposed on both the above foliations. It is recognised by flaser quartz strings and new cross-cutting growth of biotite. A particularly broad and intense zone parallels the eastern edge of the Murrumbidgee Batholith along the trace of the S-I line. Evidence that aplite dykes intrude parallel to later diagonal fault directions suggests that emplacement was in a wrench regime. Some of the large thin lens-like bodies may have intruded up major extensional Reidel shears.

The similarity and regularity of pluton and fault spacing suggest that magma was ponded at the base of the brittle upper part of the crust about 8–10 km thick and that this carapace warped and faulted, permitting plutons to emplace passively. (Rickard & Ward 1981; Rickard (in press).) Deformation was initially and subsequently by compression and strike-slip faulting, but the huge extent of granitic material indicates considerable extension during the time of emplacement.

Rickard, M. J. & Ward, P. 1981. J GEOL SOC AUST **28**, 19–32.
Rickard, M. J. (in press). PROC 7TH INT BASEMENT TECTONICS CONF. Amsterdam: Kluwer.

## S-type granites of the Lachlan Fold Belt: are Proterozoic source rocks really necessary?

**Allan G. Rossiter**

A new model for the generation of S-type granite suites within the LFB eliminates the need for Proterozoic source rocks and the geological difficulties which accompany it. It is envisaged that melting of early Cambian tholeiitic basalts (and dolerites) and overlying middle-late Cambrian sediments took place when mantle-sourced shoshonitic magma ponded at the interface between them. The anatectic process was controlled by the breakdown of hornblende in the (meta)tholeiites and biotite in the (meta)sediments. Experimental data and the observed restite phases are consistent with the melt zone lying between depths of about 10 km and 18 km. Mixing of mantle material and crustal melts generated near the interface (which was at a depth of some 15 km) produced the low-Si endmember of each suite. As more and more shoshonitic magma entered the system, more and more tholeiite and sediment melted so that the low-Si endmember was limited to $SiO_2 > 63\%$ and initial $^{87/86}Sr \geqslant 0{\cdot}708$. Variation in the mantle component was responsible for most of the chemical differences between suites. Mixing of the low-Si endmember and melt derived purely from sedimentary rocks (the high-Si endmember) occurred as the entire contents of the melt zone moved towards the upper crust. The chemical (including isotopic) variation in S-type granites containing up to 72–73% $SiO_2$ can be explained in this way. Crystal fractionation in high-level magma chambers appears to have played a part in the formation of more siliceous varieties. Some of the I-type granitic rocks of the Lachlan Fold Belt were probably derived by partial melting of early Cambrian(?) calc-alkaline, continental-margin rocks. The I-type granites contain more Al and less Fe than LFB andesites and mantle melts may have been involved in their genesis as well.

## A re-evaluation of granite types of the Calabrian Arc, Italy in the context of the southwestern Hercynian belt

**Alessandro Rottura** and **Raffaellamaria Campana**

The late-Hercynian granites of the southern Calabrian Arc have been referred in the past to two different suites, one predominantly calc-alkaline, weakly peraluminous (biotite ± hornblende quartz gabbro/diorite to granodiorite) and the other strongly peraluminous (two-mica ± Al-silicate-bearing trondhjemite to granite). In particular the Villa S. Giovanni (VSG) and Capo Rasocolmo (CR) strongly peraluminous granites, coeval but not spatially related to the calc-alkaline granites, have been considered S-type.

A geomathematical approach to their geochemical composition indicates that the VSG and CR granites are distinguishable from the calc-alkaline granites, as well as from the classic S-type granites of southeastern Australia. The calc-alkaline granites show basically I-type compositional characteristics, and have trace-element patterns suggestive of subduction zone processes during development of their source, and of a plagioclase-dominated mineralogical control. They have recently been interpreted as having been generated by interaction of subcontinental mantle-derived magmas with crustal components, in a context dominated by crustal recycling. The strongly peraluminous granites have an S-type signature in terms of enclaves and mineralogy, while their geochemical characteristics are similar to those of volcanic arc granites. They have high Sr and Ba, low Rb and highly-fractionated REE patterns ($La_n/Yb_n = 78–27$; $Yb_n < 4$), suggestive of hornblende (±garnet)-dominated fractionation processes and similar to those of the Archaean tonalite-trondhjemite-granodiorite suites. Therefore, they cannot be directly related to the associated calc-alkaline granites by high-level fractionation, and must represent separate melts.

Geochemical and petrographical evidence indicates a trondhjemite-dominated composition for the VSG and CR granites, with crystal-liquid mixing coupled with metasediment assimilation as the leading process for their genesis. Whether the trondhjemitic magma is due to mantle input at the time of granite production or represents a crustal melt derived from a meta-igneous source (gt-amphibolite), is still an open question. $Nd_{DM}$ model ages (1·2–1·8 Ga) are not conclusive.

## Volcanic plutonic connections, Uralla Igneous Centre, N.S.W.

**S. E. Shaw** and **R. H. Flood**

The late Permian Uralla Igneous Centre consists of K-rich andesitic lavas and pyroclastic flows (Harnham Hill volcanic rocks), the

Terrible Vale Pluton which is microstructurally zoned from dacite-tuffasite to quartz-monzodiorite, the Uralla granodiorite-diorite Pluton, and the Kentucky diorite Pluton. The Harnham Hill volcanic rocks and underlying sedimentary rocks are intruded and contact metamorphosed by the Terrible Vale Pluton, which is crescent-shaped, the dyke-like extensions of which follow possible ring fractures. The preservation of the outlier of volcanic and sedimentary rocks suggests cauldron subsidence.

The Terrible Vale Pluton, although uniform in composition, is microstructurally zoned from a narrow marginal two-pyroxene dacite-tuffasite zone, to an inner coarser-grained porphyritic quartz-monzodiorite facies. The dacite-tuffasite which occurs along intrusive margins has elongate fragmented phenocrysts and shard-like devitrified glass fragments aligned in a sub-vertical foliation. Superficially, the tuffasite has many features in common with ignimbrite flows. In the quartz-monzodiorite facies both the groundmass and phenocryst plagioclase grains are zoned and rectangular, but quartz occurs as polygonal aggregates rather than as interstitial grains, and biotite forms poikilitic grains that enclose or partly enclose quartz.

The Terrible Vale Pluton appears to represent the preserved parts of a high-level magma chamber that vented to the surface during a major roof-fracture event but then crystallised more slowly to produce the observed microstructural zonation. The volcanic, subvolcanic and plutonic rocks are inferred to be parts of a geochemically coherent igneous centre, one of many such short-lived centres within the New England Batholith that formed during the late Permian and early Triassic.

## The Walcha Road adamellite: an example of a large restite-poor zoned pluton

**S. E. Shaw** and **R. H. Flood**

The Walcha Road Pluton of southern New England is 30 km long, 20 km wide and is elliptical in outline except where minor faults off-set the margin. Biotite/bulk-rock Rb/Sr ages for the pluton and two quartz micromonzonite stocks along the southern and western margins give late Permian ages of approximately 247 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0·7046.

A foliation defined by the preferred orientation of the long axes of both feldspar crystals and microgranitic enclaves is generally margin-parallel and is sub-vertical along the southern margin. The pluton is concentrically and smoothly zoned from a discontinuous outer margin of quartz monzonite (colour index = 35) with hornblende in excess of biotite, to two central areas of hornblende-free biotite-adamellite (colour index = 6). The marginal quartz-monzonite is even-grained and grades over a few tens of metres into a porphyritic mafic adamellite with more than 8% pink K-feldspar megacrysts up to 20 mm in length. This zone grades inwards over several hundred metres into a more leucocratic adamellite with larger (50 mm) but less abundant pink K-feldspar megacrysts. Closer to the pluton centre the abundance of K-feldspar megacrysts reduces to near zero, although the total modal K-feldspar changes little from margin to core.

The zoning results from the crystallisation of the more mafic rocks along the margin as cumulates, and the felsic residual melt collecting in the centre and near the top of the magma chamber. Calculations based on pluton shape as deduced from outcrop mapping and feldspar foliation measurements suggest that the felsic central parts of the pluton are volumetrically small compared with the more mafic marginal rocks. The quartz-micromonzonite stocks along the southern and northwestern margins of the pluton are sufficiently fine-grained to show that intermediate-composition magmas with little restite were present at the time.

## Late Precambrian epidote-bearing calc-alkalic intrusive suite in northeastern Brazil: oxygen isotopes and depth of crystallisation

**A. N. Sial, V. P. Ferreira** and **R. V. Fodor**

Over 50 late Precambrian (~600 Ma) Conceiçao-type meta- to peraluminous tonalites and granodiorites intruded phyllites of the Cachoeirinha-Salgueiro Fold Belt (CSF) in northeastern Brazil, and contain primary epidote (based on criteria of Zen & Hammarstrom 1984). Petrographically equivalent epidote-bearing granites (EBG) intruded schists of the Serido Fold Belt (SFB), a northward extension of the CSF, and amphibolite-grade metasediments of the Riacho do Pontal Fold Belt (RPF), a southern extension of the CSF. Magmatic epidote is also found in trondhjemitic plutons that intruded Salgueiro schists as well as in plutons in three other Fold Belts. This phase is observed in four textural relationships, two of them indisputably magmatic and two from sub-solidus reactions.

In the CSF, contemporaneous EBG solidified around 6–7 kbar (1 kbar = 100 MPa) if all Al variation in hornblende is ascribed to pressure. Lower pressure for quartz diorite enclaves results from Al loss by subsolidus reaction with plagioclase, generating granular epidote. Temperatures of equilibration for hornblende-plagioclase assemblages are in the range 700–800°C. They differ from Mesozoic EBG in N America in that they intruded phyllites, likewise Palaeozoic plutons in Argentina, New England and New Zealand.

In the SFB, Al in hornblende indicates emplacement around 2·5–4·0 kbar, and 5·5 kbar when they only intruded basement rocks. Temperatures for equilibration of hornblende-plagioclase assemblages in this case are in the range 680–760°C.

In the CSF, EBG exhibit moderate Sr, Ba and Zr, low Nb (<20 ppm), are LREE-enriched and HREE-depleted, with discrete negative Eu anomaly. In the SFB, they are higher in Sr, with Ba contents equivalent to CSF granites, Zr slightly higher and low Nb. They exhibit less steep REE-patterns with negative slope, lacking or exhibiting discrete Eu anomaly. EBG in the CSF display high $\delta^{18}O$ (+11–+13‰) and amphibolite xenoliths, probably from the source, have $\delta^{18}O$ values around +10.5‰. Equivelent plutons in the SFB display $\delta^{18}O$ values slightly lower (+6·2–+8·2‰) which are lower than equivalent epidote-bearing tonalites and trondhjemites in northwestern N America (+7·5–+9·0‰, e.g. Hazard Creek Complex, Idaho). This demonstrates that EBG form from more than one kind of source material, always with the presence of a component in the magma derived from sedimentary or altered volcanic rocks. Processes leading to their formation are repeated through geological time and magmas intrude different crustal levels.

Zen, E-an & Hammarstrom, J. M. 1984. GEOLOGY **12,** 515–8.

## Tracking magmatic arc evolution across contrasting lithosphere settings in southwestern N America

**Leon T. Silver**

Two great batholiths of the southern Cordillera, the Peninsular Ranges and the Sonoran, are tectonically dislocated elements of a formerly continuous magmatic arc produced in a single cycle. The cycle was initiated in earliest Cretaceous time and continued into the Palaeocene. (The commonly employed distinction between coastal batholiths and "Laramide" plutons of the interior must be reassessed.) The magmatic arc transgresses time and space northeastward, continuing across contrasting lithospheric settings ranging from Mesozoic oceanic lithosphere in the W to early Proterozoic crust-lithosphere in the E. Petrological, chemical and isotopic properties of the plutonic rocks show dramatic changes in many forms. This particular geological setting provides an opportunity to investigate the relation of various initial isotopic signatures ($^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, Pb isotopes, $\delta^{18}O$) and trace-element indices to tectonic setting. The volume of plutonic rocks exposed in the Sonoran Batholith, which extends from southern Arizona to southern Sinaloa and from the Gulf of California to Chihuahua, is fully comparable to the Peninsular Ranges Batholith, although plutons of the former are more dispersed to the E. These volumes provide a major challenge in modelling various source regions and petrogenetic mechanisms. Further, in the Sonoran Batholith region, earlier Jurassic and Triassic magmatic arcs had extensively taxed the putative source regions for significant quantities of volcanic and plutonic differentiates. From where has all of this material been derived? How much is from the mantle? How much is recycled? Where did the energy for mobilisation come from and how was it applied? Finally, from where did the mid-Tertiary magmatic cycle represented by the great Sierra Madre Occidental volcano-plutonic arc, which is superimposed on the Sonoran Batholith, derive its materials? Observations, discussion and some possible insights are offered; all of the answers are not yet in hand.

## Granites in the late Cainozoic arc-type magmatic associations of the southwestern Pacific

**Ian E. M. Smith** and **Donald S. Clarke**

Granites, as individual plutons and as small-scale clusters of plutons, are a subordinate component of the suites of dominantly andesitic volcanic rocks which comprise the late Cainozoic arc-type magmatic associations of the southwestern Pacific. This association of magmatic rocks dominates the late Cainozoic geological record of the southwestern Pacific margin from Papua New Guinea to northern New Zealand.

High-level granite intrusives (porphyries) are commonly associated with the volcanics. In only a few areas, notably in Papua New Guinea and New Zealand, granitic plutons represent deeper levels of the magmatic systems; these are temporally but not always spatially associated with the arc-type volcanism. In New Caledonia, granites of comparable type and age occur without coeval volcanics.

The structural setting of these granites shows considerable diversity. In Papua New Guinea, granites occur as discrete pluton complexes with or without associated volcanics and as pluton within metamorphic core complexes. In New Caledonia, they occur as isolated plutons intruding an ophiolite. In New Zealand, granitic plutons constitute a part of arc-type volcanic associations, although they are usually spatially separate from coeval volcanic rocks.

The granites of these southwestern Pacific arc systems are mainly diorite and granodiorite, but include adamellite and minor mafic diorite and monzonite. In southeastern Papua New Guinea there are also shoshonitic pluton complexes dominated by monzonite and syenite, and including gabbro and cumulate pyroxenite; these are associated with volcanic rocks of similar geochemical character. Variation in chemical compositions correlates with tectonic setting and also with the complexity of earlier geological history. In general terms, the rocks are mainly M-type granites. Petrogenetic hypotheses involve a subduction-related component as well as a chemical component linked to deep crustal levels.

## Mantle and crust involvement in the genesis of subduction-related granites: evidence from the calc-alkaline magmatism of central Peru during the Andean orogenesis

**Pierre Soler**

During the Andean orogenesis (Albian to Present), the space and time distributions of the calc-alkaline magmatic rocks of central Peru have been tightly controlled by the features of the subduction of the Nazca (previously Farallon) plate. Over this time, the calc-alkaline volcanic rocks and I-type granites display complex variations in their geochemical features.

For a given period, overall similarities in their space distribution and compositions imply that both types of rock were derived from the same source, an enriched mantle modified by fluids extracted from the subducted slab. Subordinate chemical differences indicate, however, that the crustal histories of the magmas leading to plutonic or volcanic rocks diverge at an early stage, and that the plutons are not simply the magma chambers of the volcanoes.

The variations of their compositions in time correspond mostly to crustal processes in deep magma chambers which include: (1) diffusive exchange between magmas and crust, a selective and self-limiting process which accounts in particular for the variation from medium- to high-K contents; (2) assimilation of the country rock at an early stage of differentiation; (3) modifications of the mineralogy of the crystallising phases, with the appearance of garnet at the liquidus and the later crystallisation of plagioclase which lead to lower HREE, Sc, Mn, and higher Sr and LREE in the intermediate and felsic rocks.

The observed evolution is a succession of compositional jumps which are contemporaneous with the tectonic events and associated crustal thickening and are interpreted as the result of an increasing degree of crustal assimilation and an evolution under higher pressure at the early stage of differentiation.

The evolution of the chemical and isotopic features of the calc-alkaline magmatic rocks of central Peru may be regarded as the geochemical fingerprint of the orogeny upon mantle-derived magmas which do not appear to have changed in time.

## The origin of Cooma Supersuite granites: protoliths and early magmatic processes

**D. A. Steele, R. C. Price, P. D. Fleming** and **C. M. Gray**

The Siluro-Devonian Yabba adamellite is a residue/inclusion-rich, syn-tectonic pluton located between the late Cambrian(?) Gundowring migmatite terrane and lower-grade early Ordovician Lockhart terrane in the high-*T*, low-*P* Wagga Metamorphic Belt, southwestern Australia. This body is compositionally and isotopically similar to the Cooma Supersuite (CS) granites of the Lachlan Fold Belt (LFB). Both are characterised by regional-style contact aureoles and by low CaO–$Na_2O$, highly peraluminous compositions; the latter has been considered indicative of derivation from the extensive feldspar-poor Ordovician turbidites exposed in southeastern Australia (e.g. Chappell 1984). These characteristics distinguish the Yabba and CS granites from the voluminous contact aureole S-type granites of the LFB.

Petrographical, structural and geochemical comparison of metasedimentary enclaves in the Yabba body with the two "host" tectonometamorphic terranes indicates: (1) the Yabba adamellite and, by implication, the CS granites were derived from the late Cambrian(?) Gundowring terrane, *not* from the Lockhart terrane or the other exposed Ordovician flysch; (2) one of the quartzofeldspathic lithologies found in the Gundowring terrane is absent from the inclusion population and represents the "fertile" source component.

The partial melting and virtually complete extraction of the fertile quartzofeldspathic gneisses gave rise to residue-rich magmas that almost perfectly image their sources. The chemical variation observed within the Yabba adamellite reflects the incorporation of various residual and non-melted source components during magma genesis. The metasedimentary enclaves represent non- or partially melted (infertile) protolith.

The Gundowring terrane and/or its tectonic/compositional equivalents probably underlie the monotonous Ordovician turbidite sequences and thus form part of the basement to the LFB. The CS granites were probably derived from this basement. Geochemical evidence precludes the derivation of the voluminous contact aureole S-type granites (e.g. the Bullenbalong Suite) from the Gundowring terrane by simple partial melting. A more immature (feldspathic) metasedimentary protolith or a multi-component process (e.g. Gray 1984) are required to produce the chemical characteristics of these S-type granites.

Chappell, B. W. 1984. PHILOS TRANS R SOC LOND **A-310,** 693–707.
Gray, C. M. 1984. EARTH PLANET SCI LETT **70,** 47–60.

## Geochemical constraints on fractionation and source models for an A-type granite: the Mt Walsh granite in the New England Fold Belt, eastern Australia

**C. J. Stephens**

Recent reviews of A-type granites (Eby 1990) defined two sub-groups based on geochemical criteria: a group that have distinct OIB-like trace-element characteristics, and a second group that display trace-element characteristics closer to calc-alkaline volcanics, and which are often associated with I-type granite plutonism. This paper describes the geology and geochemistry of a late Triassic A-type granite in eastern Australia that is of this latter type.

The Mt Walsh granite is a discrete, circular intrusion that straddles the margin of a coeval silicic I-type cauldron. The intrusion is 60 $km^2$ in area, flat topped, and exposes 570 m of relief. Dissection of the intrusion along fractures provides an opportunity to sample vertical and horizontal variations within the stock. The intrusion is predominantly metaluminous to weakly peralkaline, high-silica alkali granite displaying granophyric textures. Low silica granite occurs high within the core of the stock, and alaskite forms a thin (<30 m) cap across the top of the stock. A high level of intrusion is indicated by the abundance of miarolitic cavities, and by intrusion of the stock 400 m into intracaldera ignimbrite. The mineralogy comprises embayed quartz and perthitic potassium feldspar, with minor sodic plagioclase (especially in low silica granite), interstitial annite-rich biotite, phenocrystic edenitic amphibole, and accessory magnetite, zircon, apatite and allanite. The biotites contain up to 2·2% F, and show trends of decreasing $Al^{IV}$ and increasing Fe/Fe + Mg with increasing host rock $SiO_2$ and alkalinity. This trend contrasts with the increasing $Al^{IV}$ with Fe/Fe + Mg observed in peraluminous granites. Biotite and amphibole Fe/Fe + Mg ratios are typical of ilmenite series granites, consistent with an inferred $f_{O_2}$ close to NNO. $P_{H_2O}$ is inferred to be less than 1 kbar (1 kbar = 100 MPa).

Trace-element abundances define a zone depleted in Ba, Sr and Zr, and enriched in Rb and La, across the top and extending down the margins of the stock. High values for Rb/Ba define a thin zone across the top of the stock corresponding to alaskite. These variations are consistent with crystal fractionation occurring via sidewall crystallisation, and can be modelled in terms of Rayleigh fractionation of an assemblage comprising potassium feldspar-plagioclase-allanite-zircon ± quartz. The isotopic composition is indistinguishable from the associated I-type granites ($\varepsilon_{Sr} = -10$, $\varepsilon_{Nd} = +4{\cdot}3$, $\delta^{18}O = -8$‰) and defines an identical age (221·8 Ma) and $I_{Sr}$ (0·70354 ± 0·00001). Modelling of REE data shows that partial melting of restite or tonalite sources is incapable of generating the REE compositions of low-silica A-type granite. Partial melting of an anhydrous (?granulite) source is unlikely because modelling of the I-type granite sources excludes the presence of all but recently accreted crust within the source area. Low-silica A-type granite cannot be derived by (A)FC from any of the I-type granites, but can be modelled closely by Rayleigh fractionation from associated mafic volcanics that have primitive mantle-like geochemistry (Ba/La < 10). The mafic volcanics, nevertheless, show evidence for contamination by a calc-alkaline component, a feature reflected in the calc-alkaline spidergrams shown by all igneous rocks of the complex.

It is interpreted that the A-type Mt Walsh granite was produced by crystal fractionation from a basaltic parent derived from a primitive mantle source. The basaltic magma was contaminated with a calc-alkaline source, probably within the crust, before the evolution of the Mt Walsh silicic magmas. The silicic magmas underwent crystal fractionation after emplacement into a high-level magma chamber, with REE-enriched magma produced by sidewall crystallisation ponding at the top of the stock, and crystallising as alaskite.

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## The geology and petrology of arfvedsonite granites, Hinchinbrook Island, N Queensland

**P. J. Stephenson, B. W. Chappell, M. McCulloch, M. T. Frost** and **E. Reid**

Permian arfvedsonite granites occur within a 16 km-long batholith over a vertical range of 1,100 m, in rugged wilderness. Some earlier and later felsic dyke units are related chemically. The granites are dominantly hypersolvus with relatively low modal biotite and/or arfvedsonite. Near-horizontal layering occurs in numerous places and some indicates downward solidification (Stephenson 1990). Geochemically, the rocks are A-type (sense of Whalen *et al.* 1987), and strongly fractionated. They contrast with country rock I-type granites and volcanics. Four traverses from summits to sea were used to test vertical fractionation, but no consistent variations were found. Considerable trace element fluctuations occur. Few rocks are peralkaline in the sense of agpaitic index, but rather peraluminous, consistent with the low arfvedsonite modes, less than 2%. Classic textures suggest that most of the rock features are primary, with amphibole-biotite growth (commonly in cavities) from late residual fluids.

An Rb-Sr isochron gives 275 ± 5 Ma (Sr* 0·701138 ± 0·008, MSWD 13·5), and this isochron appears to be coincident for the I-type granites in the nearby Palm Islands. Sm-Nd results are more dispersed and give a considerable range of model ages ($\varepsilon_{Nd}$ − 1·3–8·0). Evidence suggests that the arfvedsonite granites evolved almost simultaneously with the I-type Palms granites, with close consanguity.

The batholith is interpreted to contain a thick "roof" facies, passing down into slightly more calcic and aluminous rocks beneath. Of possible alternatives, partial melting of crustal tonalite to granodiorite (Creaser *et al.* 1991) is preferred to a residual source model (Collins *et al.* 1982). Considerable fractionation occurred, but details are not established.

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## Classification and nomenclature for Hong Kong granites

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The first systematic geological survey of Hong Kong in the late 1960s recognised four main phases of Upper Jurassic syntectonic plutonic intrusion. Widely mapped lithological units were assigned to a phase according to their appearance and mutual cross-cutting relationships, but no attempt was made to delineate individual plutons. Considerable textural variation within some bodies resulted in an unworkable system of naming and classification.

Recent field mapping by the Hong Kong Geological Survey at scales of 1:20,000 and 1:5,000, together with geochemistry and whole-rock Rb-Sr geochronology, has resulted in the establishment of a pluton-based nomenclature for the granite, granodiorite and syenite of Hong Kong. Fifteen intrusive units have been identified ranging in age from late Jurassic to early Cretaceous, and these have been subdivided into two suites: the Lamma Suite and the Lion Rock Suite.

The Lamma Suite comprises two small relatively unfractionated batholithic bodies, Tai Po Granodiorite and Sung Kong Granite, which represent the oldest intrusive units in the Territory. The Lion Rock Suite encompasses several cross-cutting, well-defined, normal to highly fractionated granite plutons which are assigned to three subgroups. Subgroup I includes two large elliptical plutons of Tsing Shan and Tai Lam, both in excess of 20 km. Subgroup II embraces the large (>20 km) elliptical plutons of Lantau and Sha Tin, plus two bodies of quartz syenite: Cape D'Aguilar and Lantau syenites. The almost circular plutons of Kowloon, Stanley, Chi Ma Wan, South Lamma, Mt Butler, Kwun Tong and the small (2 km-diameter) King's Park Pluton make up subgroup III.

## Petrological diversity in I-type granites due to variation in $H_2O$ fugacity during melting of amphibolite

**J. H. Tepper**

Petrological diversity (quartz diorite-granite) is characteristic of granites in I-type batholiths, and is generally ascribed to crystal fractionation, restite separation, and/or magma mixing. However, data from the Chilliwack Batholith (North Cascades, Washington) support an alternative hypothesis, in which the diversity reflects differences in $H_2O$ fugacity during melting of amphibolitic lower crust.

REE patterns of Chilliwack granites vary systematically with $SiO_2$ content (Tepper *et al.*, 1989). Intermediate plutons have Eu/Eu* < 0·85, whereas siliceous plutons have little or no Eu anomaly. All samples from the same pluton have similar patterns. The lack of a Eu anomaly in the siliceous plutons precludes their having undergone significant crystal/restite fractionation. Geochemical data for these plutons are modelled by 20–30% melting at elevated $f_{H_2O}$ of amphibolite having trace element and Sr/Nd isotopic characteristics of Chilliwack gabbros. Data for intermediate plutons are modelled by 30–50% melting of a similar source, but at lower $f_{H_2O}$. The main effect of $f_{H_2O}$ variation is to change the proportions of plagioclase versus amphibole in the residuum (cf. Beard & Lofgren 1991). This strongly influences melt composition, with higher $f_{H_2O}$ (residuum = amph + cpx ± plag) resulting in magmas with high $SiO_2$ and low MgO and FeO (and no Eu anomaly) compared to magmas generated at low $f_{H_2O}$ (residuum = plag + cpx + opx). The $f_{H_2O}$ differences probably reflect additions of $H_2O$ to the lower crust from crystallising basaltic magmas having a range of $H_2O$ contents. Individual granitic plutons are interpreted as discrete magma batches that underwent limited modification by fractionation, etc. during ascent. Based on geochemical and lithological similarities, this model may be applicable to other I-type batholiths.

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## Genesis of A-type granites: trace element and isotope constraints from Oligo-Miocene Yemen alkaline granites

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Yemen was the site, in Oligo-Miocene times, of extensive magmatic activity which brought about the formation of a basalt plateau and the emplacement of several granitic plutons. This activity developed in two phases which climaxed at 30–26 Ma and 22–20 Ma, respectively. During the second phase, alkaline granites and granophyres were emplaced. They consist of light grey to pinkish, medium to coarse-grained rocks, having characteristics from subsolvus to hypersolvus with emplacement depths in the range of 0·05–0·2 GPa. Three main groups have been distinguished on the basis of the presence of different ferromagnesian minerals: alkali amphibole granite, alkali amphibole plus biotite granite, and calcic amphibole plus biotite granite.

Yemen granites are emplaced in anorogenic settings, and have typical physicochemical characteristics such as high temperature, high halogen and low $H_2O$ contents, and high HFSE abundances of A-type granites. They fall well outside VAG and CG fields, indicating that crustal partial melting did not play a leading role in their genesis. Moreover, the ratios of HFSE of basaltic rocks belonging to the Yemen plateau relate to those of the granites. This fact suggests a genetic link between basalts and granites. However, the variation in radiogenic isotope ratios recorded from the Yemen granites precludes an origin solely through closed-system processes. The absence of crustal xenoliths, magmatic enclaves and contact aureoles supports an assimilation plus fractional crystallisation (AFC) process, where the heat required for assimilation was provided by the latent heat of crystallisation. The genesis of the most and least alkaline granites can be accounted for by FC (ol + pl + cpx+/−mt) process from a parental alkali and transitional basalt, respectively, accompanied by different degrees of assimilation at different levels in the crust.

## Derivation of A-type magma by fractionation of basaltic magma with an example from the Padthaway Ridge, S Australia

**Simon P. Turner, John D. Foden** and **Robert S. Morrison**

Various petrogenetic schemes have been proposed for A-type granite and volcanic rocks, a popular one being re-melting of a melt-depleted source. However, simple modelling shows that the high incompatible/compatible element ratios characteristic of A-types are not readily obtainable from such a source, because the first melting event has already lowered this ratio. Instead, extended fractionation of a mantle-derived basaltic magma will produce high incompatible to compatible element ratios and also explains the high-temperature nature of A-types, their typically low initial $^{87}Sr/^{86}Sr$ ratios and their bimodal association with mafic rocks. Granophyres from layered mafic intrusions provide evidence for this origin of A-type magma, as do new data presented here for a suite of A-type granites and volcanics from the Padthaway Ridge in S Australia. Mineralogical, chemical and isotopic arguments show that the Padthaway Suite evolved from the same basaltic magma that formed contemporaneous gabbroic plutons which themselves contain A-type granophyres. Olivine, pyroxene and hypersolvus feldspar assemblages in the granites and volcanics document temperatures of 900–1,000°C and $H_2O$-undersaturated conditions with $H_2O < 3\%$. Curvilinear geochemical trends and large negative Eu anomalies indicate a history of protracted fractionation involving pyroxene and feldspar. High $\varepsilon_{Nd}(+2-3)$ and low initial $^{87}Sr/^{86}Sr$ (0·703–0·706) for the whole suite of granites, volcanics, gabbros and granophyres indicate a mantle-derived parental magma. Major- and trace-element modelling confirms that these A-type magmas can be produced by fractionation (*c.* 90%) of such a magma, though it must be somewhat enriched, indicating either a lithospheric mantle source (K-rich layer) or limited crustal contamination. While there may be various kinds of A-types, their high temperatures dictate that mantle magmas be invoked on thermal grounds in any petrogenetic model. In the fractionation model outlined here, the ratio of mafic to silicic magma is likely to be ~9:1. This suggests that A-type suites, which typically intrude in extensional or post-orogenic settings, mark episodes of crustal growth in which considerable mantle material is added to the crust.

## Some thoughts on cordierite-bearing granites: are host-rocks the clue?

**J. M. Ugidos** and **C. Recio**

Cordierite-bearing granites (CBG) form batholiths in some collisional domains. Determining the original I/S character of such granites may be controversial. The possibility of assimilation should be considered based on the following facts: (1) the high content of prismatic cordierite in high-grade hornfelses, migmatitic hornfelses and contact migmatites in thermal aureoles (TA); (2) syn-orogenic metamorphism is of the intermediate P type; (3) frequently CBG are late orogenic. Point (1) indicates the high capacity of some host-rocks to produce cordierite and that high temperatures have been reached at low pressure. This resulted from the addition of heat input to the pre-heated host-rocks. Then, if pressure drops, fluid absent reactions are expected in the host. If the metasediments involved have pelitic composition, the reactions will result in cordierite/garnet + Kfd + $H_2O$ or melt. In the first case, subsequent increments of T may result in the equilibrium q + ab + kfd + cord + $H_2O$ = melt; in the second case, melt is produced directly because of the fluid-absent reaction. The amount of melt is small, but the important point is the generation of intercrystalline melts in the TA of an intruding granite. Point (2) implies possible restites being left behind after regional anatexis. If restites are affected also by a lowering of pressure, reactions transforming the restitic parageneses into lower-P parageneses are to be expected. The interaction of a granite magma with any of these possible rock-types developed in its TA can result in granites with apparent S character, since even small assimilation percentages may drastically modify the original granite mineralogy and normative corundum content. Andalusite-bearing, sillimanite-bearing or garnet-bearing cordierites, or other kinds of cordierite-rich rocks found in TA, are important points that must be taken into account when considering the significance of S-type mineralogy in some granites.

## Subdivision of I-type granitic rocks in the Archaean Murchison Province, Western Australia

**Liang G. Wang, Neal J. McNaughton** and **David I. Groves**

Three major suites of granitic rocks can be identified in the Archaean Murchison Province of Western Australia on the basis of this work (Wang in prep) and that of Watkins and Hickman (1990): Suite I comprises monzogranites and granodiorites which occur as homogeneous regional batholiths; Suite II consists of trondhjemite and tonalite plutons; and Suite III includes A-type (Loiselle & Wones 1979) monzogranite and syenogranite plutons. Each of the three suites have coherent but distinct geochemical and isotopic (Pb, Sr and Nd) characteristics indicative of their derivation from distinct source regions. Suite I can be interpreted as being derived from partial melting of underlying tonalitic continental crust. Suite II from partial melting of subducted/underplated oceanic crust and Suite III from partial melting of dehydrated siliceous granulite.

According to Chappell and White (1974), both Suite I and Suite II granites, which have contrasting compositions and origins, have to be classified as I-type granites. It is proposed here that granites

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derived from earlier granites or gneisses comprising continental crust should be termed G-type granites (e.g. Suite I), and that granites derived from a basaltic source should be termed I-type granites (e.g. Suite II).

The above subdivision of the I-type granites of Chappell and White (1974) may have important tectonic implications. The G-type granites may be generated during anatexis of continental crust within various tectonic environments, whereas the newly-defined I-type granites, with more restricted compositions and specific source, are likely to be indicators of subduction/underplating tectonic regimes.

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## Proterozoic granites, with some characteristics of A-type magmas, in the Arunta Block, central Australia

**R. G. Warren** and **S.-S. Sun**

Assessment of 800 analyses in the BMR ROCKCHEM database of Proterozoic rocks from the Arunta Block shows that most felsic igneous rocks fall into one of three classes: two showing typical low-Sr, high-Y Proterozoic signatures in multi-element plots, and the third with *flat profiles* (high-Sr, low-Y). The low-Sr, high-Y classes subdivide into a *normal* Proterozoic type (cf. Kalkadoon-Leichhardt-Ewen association), and an *enriched* type. Both have the characteristics of Sr-depleted felsic magmas, especially high incompatible elements. Enriched types have higher U, Th, K, Rb, REE and Y relative to normal types but, commonly, lower K/Rb and higher Th/U. High LREE and Th are contained in allanite or monazite and, in some, high F in fluorite. Some chemical characteristics of the enriched suites, particularly the high incompatible elements, hint at affinities with true A-type magmas (rare in the Arunta Block); but some enriched types have high Ba, not all have high F, and Al/Ga is in the same range as in normal types. The normal and enriched types occur throughout the block, the flat-profile type mainly in the SE. Distinct suites, delineated within both major types from subtle chemical variations, perhaps reflecting source, have an areal distribution with probable time-tectonic significance. Regional variations among enriched suites mimic those of the normal types in the same areas, suggesting a evolutionary link, supported by sparse Nd isotope model age data. Field evidence shows that the enriched suites were emplaced later, either syn- or post-tectonic. Their low Cs and high Rb/Cs dictate a refractory source, while low-Sr, high-Y dictate a shallow source. Overall, the evidence suggests enriched magmas formed through regional metamorphism of high-*T,* low-*P* style, possibly with variable addition of second-stage melts from source regions, either during renewed extension or through A-subduction.

## A granite geochemical and isotopic transect of the southern Canadian Appalachian orogen

**Joseph B. Whalen, Ernst Hegner, George A. Jenner** and **Frederick J. Longstaffe**

From W to E, the four major Appalachian tectonostratographic zones are Humber (HZ), Dunnage (DZ), Gander (GZ) and Avalon (AZ). Recent deep seismic reflection studies have defined three main lower crustal blocks (LCB) beneath this orogen: Grenville (under HZ and western DZ), Central (under eastern DZ and GZ) and Avalon (under AZ). All zones are intruded by late to post-orogenic Siluro-Devonian granites. In addition, GZ and AZ contain pre- to syn-orogenic Ordovician and pre-Iapetus Precambrian granites, respectively. Based on $Na_2O$ and Al index values (generally >3·2 wt% and <1·1) and high-field strength element contents, most granites are I-types; some have "A-type affinities".

$\varepsilon_{Nd}$ data map three contrasting groups of granites: HZ + DZ, GZ and AZ. Positive $\varepsilon_{Nd}$ values for HZ, DZ and AZ granites indicate melting of predominately juvenile sources. Higher $^{207}Pb/^{204}Pb$ and $\delta^{18}O$ values of AZ granites could reflect incorporation of a minor radiogenic supercrustal component which has produced elevated Pb and O but has had little effect on their juvenile Nd signature. Negative $\varepsilon_{Nd}$ and elevated $^{207}Pb/^{204}Pb$ and $\delta^{18}O$ values for GZ granites are consistent with reworking of older (1·1–1·8 Ga) crust containing a significant supercrustal component.

Granite data suggest that different protoliths are juxtaposed at the DZ–GZ and GZ–AZ boundaries. As Nd data effectively rule out Grenville basement as a source for HZ + DZ granites, the seismically defined Grenville LCB is either not "Grenville-like" compositionally and/or it is composite. The geochemical and isotopic similarity between Ordovician and Siluro-Devonian GZ granites indicates that no major post-middle Ordovician basement-cover detachments have occurred in GZ. GZ, therefore, probably is the surface expression of the underlying Central LCB. Contrasting $\varepsilon_{Nd}$ signatures from AZ and GZ granites help substantiate the seismic interpretation that GZ and AZ are underlain by different crustal blocks; i.e. Precambrian Avalon basement is not a suitable protolith for GZ granites.

## Inherited and detrital zircons—vital clues to the granite protoliths and early igneous history of southeastern Australia

**Ian S. Williams, Bruce W. Chappell, Yadong D. Chen** and **Keith A. W. Crook**

The SHRIMP ion microprobe has been used to measure the U–Th–P isotopic composition of over 1,000 zircons from more than 20 plutons and enclaves from the Palaeozoic batholiths of southeastern Australia. The ages of the principal components in the granites' sources have been established and a start made on determining the areal variation in the relative abundances of those components.

The granites range in age from 440–380 Ma. Zircons with inherited cores are rare in the I-type granites, but virtually every zircon in the S-types contains an older core. In most granites, most of the cores are 650–450 Ma old, there is a lesser group 1,075–800 Ma old, and a lesser group again with ages up to 3,350 Ma. Not all age groups are represented in every granite, and there is a marked lack of the two older groups in the I-type granite enclaves. There is little difference between the I- and S-type granites in the relative abundances of cores of different ages. The inherited zircon becomes older and more abundant westwards across the I-type Bega Batholith.

Zircons from the Bega Batholith's Ordovician sedimentary country rock show the same age groups as the inherited zircons in the granites, but the 650–450 Ma age group is significantly less abundant in the sediments than in the granites.

It appears that 1,075–800 Ma ago, and again 650–450 Ma ago, there was considerable igneous activity in southeastern Australia and nearby regions that produced both the immediate sources for the I-type granites and their precursors (probably by underplating of the crust) and also generated, through volcanism, much of the detritus which became the source for the S-type granites. Recycling of those sediments produced much of the early Palaeozoic flysch. The presence of 1,100–3,350 Ma inherited zircon in many of the I-type granites is evidence for a small component of sediment in those magmas. The chemical and isotopic trends across the Bega Batholith suggest that the amount of that sediment increases westwards.

## Geochemical and isotopic study of granites in the Arunta Inlier, central Australia: implications for Proterozoic crustal evolution

**J.-X. Zhao, M. T. McCulloch** and **R. G. Warren**

The Arunta Inlier, the largest in central Australia (~200,000 $km^2$), is situated on the southern margin of the early Proterozoic Northern Australian Orogenic Province. Systematic geochemical variations are observed in granites from the Arunta Inlier. Overall, 20 granite suites identified are classified into three broad geochemical groups, a high-Na, Sr calcalkaline-trondhjemitic group (CAT), a "normal" granite group, and a high-heat-production group (HHP). The CAT group occurs only in the southern and southeastern margin, and consists of two subgroups, i.e. gabbro-diorite-tonalite-trondhjemite suites analogous to modern continental margin calcalkaline intrusions, and tonalite-trondhjemite-granodiorite suites similar to Archaean TTG suites. The HHP group is confined mainly within the northwestern inland section, where it intrudes coexisting normal granites. It is exceptionally enriched in Th, U, K, Rb, Pb and LREE and depleted in MgO, CaO, Ba and Sr. The above geochemical diversity suggests that the Barramundi Igneous Association is insignificant in the Arunta Inlier.

Although geochemically diverse, the Arunta granites are relatively uniform in terms of Nd isotopic signatures. Most of the granites analysed yield $T^{Nd}_{DM}$ model ages ranging from 1·95–2·35 Ga, which are significantly older than those obtained from the Musgrave Inlier to the S, suggesting two distinct provinces forming during separate crustal formation events.

It is considered that the inland section of the Arunta Inlier was dominated by plume-driven ensialic rifting processes, while the southeastern margin was controlled by subduction-driven plate tectonics. The origin of the CAT group is related to the subduction processes. The normal granite group was derived by partial melting from a plume-derived mafic underplate. The younger HHP group was generated by partial melting of the normal group during anorogenic events.

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