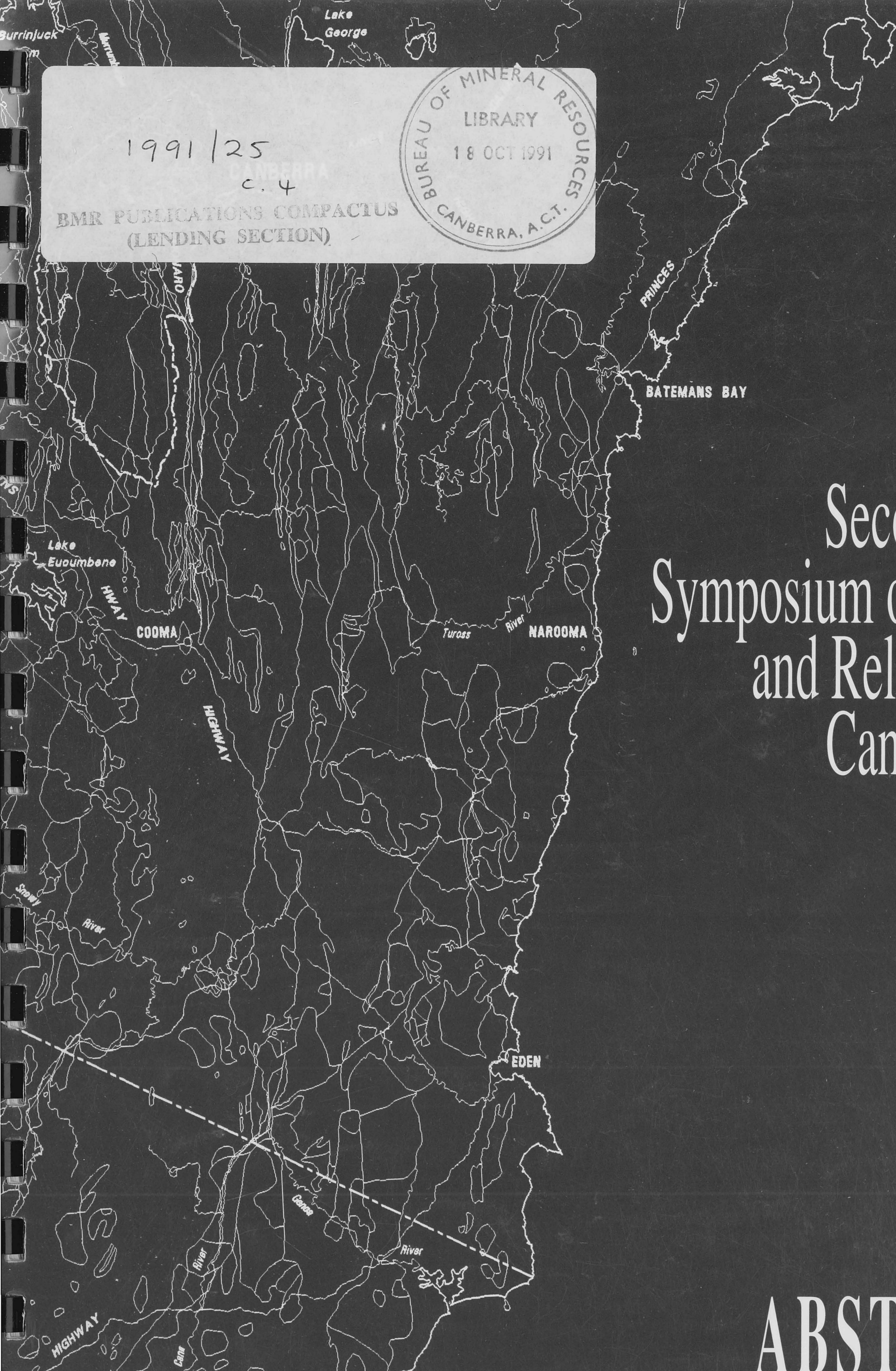

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Second Hutton Symposium on Granites and Related Rocks Canberra 1991

ABSTRACTS

edited by B.W.Chappell

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A NESTED TWO DIAPIR MODEL OF A REVERSELY ZONED PLUTON: THE TURTLE PLUTON, SE CALIFORNIA, USA

Charlotte M. Allen (Department of Geology, The Australian National University, Canberra, ACT)

Most zoned plutons described in the geological literature have mafic rims and felsic cores and are referred to as normally zoned. Relatively few reversely zoned intrusions (felsic rims and more mafic cores) have been described. This unusual zonation pattern has been attributed to *in situ* processes, or to reordering of an underlying, vertically stratified magma chamber either by intrusion through an orifice or by emplacement of composite diapirs.

The Turtle pluton is an Early Cretaceous (*ca* 110 Ma), reversely zoned, subcircular intrusion that can be divided into four facies. The rim is an orderly, zoned facies varying from bt+ilm±musc granite to hb+bt+mt+ttn granodiorite. In contrast the core is relatively homogenous hb+bt+mt+ttn granodiorite to quartz monzodiorite. A 10 to 20 m wide zone of high strain, called the schlieren zone, occurs at the contact of the rim and core facies and characteristically contains screens of Proterozoic gneiss similar to exposed country rock which is not observed elsewhere in the pluton except close to country rock contacts. Along much of their contact the rim and core facies have similar compositions , thus the schlieren zone appears to be a structural and not a compositional discontinuity. A dike of core facies intrudes the rim facies at one location near the schlieren zone. A fourth facies, an eastern lobe, has similarities to other facies but its intrusive relationship with the other facies is unknown.

The Turtle pluton has two unusual petrographic features for a calcalkaline pluton. First, observed textures suggest that biotite crystallized before hornblende. Second, in all granodioritic rocks, plagioclaseis oscillatory zoned with an overall increase of anorthite toward the rims, and commonly has a narrow overgrowth of albitic plagioclase. Hornblende geobarometry indicates emplacement pressures of 0.2 to 0.4 GPa. Liquidus temperatures are 730 to 790^{o} C based on comparison to crystallization experiments.

Field relationships described above, strain distribution as deduced from measurements of axial lengths of ubiquitous microgranitoid enclaves, geochemical and isotopic studies (including change of initial $^{87}Sr/^{86}Sr$ (SRI) from 0.7085 to 0.7065 across the rim and into the core of the pluton) suggest that the Turtle pluton is the result of composite emplacement of two diapirs each derived from the same underlying, vertically stratified magma chamber, and that the stratification is chiefly the result of mixing of intermediate and felsic magmas from distinct sources and partially the result of minor fractional crystallization. Models based on the linear major and trace element trends on variation diagrams coupled with Sr isotopic analyses suggest a felsic magma of 76 wt% SiO_2 and SRI= 0.7108 and mafic magma of 65 wt% SiO_2 and SRI=0.7065 mixed to form the rim facies. Enclave measurements indicate flattening strains with values that are lowest adjacent country rock, variable across the the rim facies, highest in the schlieren zone; strains in the core facies are similar to the lowest measured values in the rim facies. These data do not readily fit a balloon inflation model and suggest instead that the rim facies was in place and partially to fully crystalline at the time the core facies was emplaced.

AGE OF CASSITERITE MINERALIZATION AT THE ZAAIPLAATS TIN MINE, SOUTH AFRICA: IMPLICATIONS FOR THE AGE OF THE BUSHVELD COMPLEX.

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Tin-tungsten-rare earth element mineralization at Zaaiplaats is hosted by the Bobbejaankop and Lease Granites - miarolitic, brick-red alkali feldspar granites which form at high levels within the Lebowa Suite of the Bushveld Complex. The Lebowa Suite was emplaced as a large, stratified sheet between the Rustenberg Suite and the granophyric granites of the Rashoop Granophyre Suite. Pervasive hydrothermal alteration of the granites resulted in replacement of original biotite with chlorite, sericite, carbonate and Ti oxides, development of coarse vein and patch perthite and antiperthite in alkali feldspar, and precipitation of hydrothermal minerals in miarolitic cavities. Cassiterite occurs as a cavity filling and replacement mineral in tabular, subhorizontal zones and in shallowly-plunging and branching pipe systems in the granites. Disseminated cassiterite mineralization exhibits no relationship to fracture systems, and hydrothermal fluids appear to have evolved essentially in situ during crystallization.

A new approach for determining the age of mineral deposits is the U-Pb and Pb-Pb dating of cassiterites. Bulk fractions of cassiterite from Zaaiplaats have $^{206}Pb/^{204}Pb$ ratios varying from 30 to 3500. Uranium-Pb data for 5 cassiterites with the highest $^{206}Pb/^{204}Pb$ ratios lie on a chord which intersects concordia at 2099±3 Ma and ≈300±20 Ma (MSWD=0.44). Four samples are from pipe systems and one from cavity fill; these data indicate a common age within 6 million years for both pipe and cavity fill mineralization. The age of 2099±3 Ma is at the upper end of ages for the Lebowa Suite (eg. Makhutso Granite 2046±55 Ma (Rb-Sr) and 2049+69/-72 Ma (Pb-Pb)) and within error of an $^{40}Ar/^{39}Ar$ age of 2096±12 Ma for magnetite gabbro from the Upper Zone of the Rustenburg Layered Suite (Walraven et al., 1990).

The U/Pb age from cassiterites of 2099±3 Ma indicates that cassiterite mineralization must occur 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 (Pollard et al., 1991).

From intrusive relationships, the Bobbejaankop and Lease Granites represent one of the latest phases of the Bushveld Complex to be emplaced. The inferred high temperature for cassiterite deposition suggests that 2099±3 Ma is close to the emplacement age for the Bobbejaankop and Lease Granites, and that crystallization of the Bushveld Complex was rapid as would be expected if the felsic magma were formed by melting of the lower crust due to intrusion of the mafic magmas.

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LATE-STAGE IGNEOUS PROCESSES AND THEIR EFFECT ON Sr AND Nd ISOTOPIC SIGNATURES, THE TIN-MINERALIZED GRANITES OF CORNWALL, ENGLAND

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This study documents the redistribution of elements during late-stage magmatic and hydrothermal processes for the S-type granites of Cornwall, England and the effect of chemical mobility on Sr and Nd isotopic values. Three phases of the batholithic sequence are studied: the two-mica equigranular phase, the "megacrystic" phase, and the late-stage, crosscutting topaz-bearing granite. The study includes microprobe analyses of feldspar and mica compositions for these phases of the granite, neutron activation analysis of whole-rock samples and their constituent biotite, muscovite, plagioclase, and potassium feldspar mineral separates, and Sr and Nd isotopic analyses of the same material as used for the neutron activation analyses.

The equigranular and megacrystic phases of the granite have similar LREE-enriched patterns (20 to 30 times chondrite); the topaz-bearing granite has much lower ΣREE, a flat LREE slope (0.5 times chondrite), and a large negative Eu anomaly (characteristics documented also by Darbyshire and Shepherd, 1985, 1987). Despite these differences in REE concentrations all three phases of the granite, and their constituent minerals, have similar ϵ_{Nd}(300 Ma) of -5.5, implying that all phases are comagmatic. ϵ_{Nd} values are identical to those reported for other portions of the batholith and resemble average values for Hercynian-aged granites throughout Europe. Model ages (t_{DM}) of 1.4 Ga, which on the basis of SHRIMP data on zircons (Gebauer and Williams, 1990) should be interpreted as average crustal residence times, require that the source materials are Precambrian basement.

Sr isotopic compositions are strongly affected by the redistribution of Rb and Sr in the late-stage processes. Those minerals, such as the micas, and whole-rock samples, such as the topaz-bearing granites, with high Rb/Sr show the strongest effects of remobilization. Examination of minerals, such as plagioclase, and whole-rock samples with low Rb/Sr suggests that the $^{87}Sr/^{86}Sr_i$ of the magma was 0.711 to 0.712. These values, although implying mature crustal source materials for the magmas, are too modest for pelitic lithologies with an average crustal residence of 1.4 Ga. They are more appropriate for metagraywacke or felsic metaigneous rocks.

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THE ORIGIN AND GEOTECTONIC SETTING OF ANDEAN GRANITOIDS

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The Andean magmatic cycle began in Peru with the formation of a major depositional structure, the West Peruvian trough; one of a series of narrow basins developed along the entire Pacific, Andean margin. The westerly component has a volcanic facies indicating it formed very rapidly in a relatively deep sea spreading system - the main volcanism occurring in the Albian.

Beneath this major deposystem is an arch-like structure with a density of 3.00 gr cm^{-3}, made up of mafic mantle derived material. Fracturing and splitting of the continental crust above this structure was associated with massive dyking and intrusion/extension of basaltic material during this major Albian extensional phase.

The Coastal Batholith was intruded (101 - 37 Ma) into this linear orifice, and is confined mainly within it. Structural evidence indicates intrusion was permissive at 3-4 km from the surface, and was accompanied by large synplutonic dyke swarms of basaltic composition, 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 decompression during the extension following basin inversion.

At about 20 Ma, granite magmatism jumped to the east of the batholithic lineament producing small stocks within the 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 of relatively acid character.

The last magmatic events in northern Peru include the Cordillera Blanca Batholith (12 - 3 Ma) which was intruded into a major strike-slip transtensional zone. Chemical 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 magmatic sequence, tending to young to the east, being: extension with basin subsidence and a mantle derived volcanic fill -> dyking, spreading -> inversion (minor shortening) -> cratonisation -> extension with fracturing: batholith intrusion, synplutonic dyking -> "plateau" basalt extrusion with associated stocks, pipes -> batholith intrusion in a strike-slip transtensional system.

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.

Equilibrated granodiorite blocks ejected from Crater Lake caldera, Oregon: Natural examples of progressive partial melting

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Blocks of medium-grained granodiorite porphyry to 4 m, and minor aplite and diabase clasts, are common in ejecta of the 6845 B.P. caldera-forming eruption of Mount Mazama. Many of the clasts were partially melted but very few have adhering juvenile magma. Degree of melting, which is uniform in each block, ranges from 0 to 35-40 vol.%, suggesting that material with higher melt fractions had been stirred into the magma chamber. Unlike most partially fused wallrocks of shallow intrusions or xenoliths in lavas, the Crater Lake rocks remained in a conductive thermal regime for sufficient time (800 to 8000 years on the basis of Zr concentration gradients around zircons in glass) to equilibrate partial melts and mineral phases. From data on pre-eruptive H_2O content of climactic magma, the granitoids equilibrated under a minimum pressure of 1.0-1.8 kb.

Primary crystallization of the granodiorite produced phenocrystic pl+hyp+aug+mt+il+ap +zircon, followed by qz+hb+bt+alkali feldspar (af). Presence of fluid inclusions in all samples suggests complete crystallization before any subsequent melting. Subsolidus exchange with meteoric hydrothermal fluids prior to melting is evident in $\delta^{18}O$ values of -3.4 to +4.9 ‰ for granitoid quartz and plagioclase (fresh lavas from the surrounding region have $\delta^{18}O$ values of +5.8 to +7.0 ‰). Oxygen isotope fractionation between qz, pl, and glass in partially fused granitoids is consistent with equilibration at $T \geq 900$ °C ($\Delta^{18}O_{qz\text{-}pl} = +0.7 \pm 0.5$ ‰). Heating caused progressive reaction or dissolution of hb, af, bt, and qz, so that samples with the highest melt fractions have residual pl+qz and new or reequilibrated af+hyp+aug+mt+il in rhyolitic glass. Because bulk compositions of granodiorite blocks do not vary greatly, changes in mineral compositions with increasing melt fraction reflect increasing T and systematic variation in paragenesis as successive coexisting phases disappear. The actinolitic hb breaks down before bt and does not exhibit systematic compositional differences between unmelted granodiorite and samples with low melt fractions. Biotite, pyroxene, and feldspar compositions, however, do vary with increasing T and melt fraction: Na, Ti, F, and Mg/Fe increase in bt; Ca increases in hyp and decreases in aug; pl has rims or overgrowths of increasing Ab and Or content on $An_{\sim 40}$ cores, and af ranges through anorthoclase to a single feldspar of $An_{14}Ab_{73}Or_{13}$ composition.

High-silica rhyolitic interstitial melt (75-77% SiO_2) is uniform in major element composition in samples with sufficient glass for microprobe analysis. Several samples have filter-pressed glass veins 1 to ≥5 mm thick that are compositionally and physically continuous with intergranular melt. Relative to coejected aplite blocks interpreted as differentiates of granodioritic (dacitic) magma, glasses have higher Ti, Sc, K, Rb, Cs, HFSE, HREE, and Y, and lower Al, Mg, Ca, Sr, Eu, and Ba. High-T glass in granodiorite has Ba/La, Eu/Eu*, and K/Cs 0.3x those of the aplite, 0.5xRb/Cs, 2xBa/Sr, 7xRb/Sr, and 3xK/Ba; HFSE ratios are similar. Many of these chemical effects result from a large fraction of residual pl and growth or reequilibration of af in partially fused granodiorite.

Temperatures for equilibrated mt-il pairs (Andersen and Lindsley, 1988) range from 732 to 834 °C for samples unaffected by melting and 842 to 1006 °C for partially melted rocks. Oxygen fugacities for partially melted samples are generally higher than those of the notably oxidized Mazama climactic magmas. Hb is absent in rocks with Fe-Ti oxide temperatures >880 °C, and bt above 970 °C. Mineralogic and isotopic evidence for high temperature, and sums of microprobe glass analyses near 100%, suggest liquids in the hotter samples were nearly anhydrous.

The occurrence of granodiorite blocks at all azimuths around the 8x10 km caldera implies derivation of the granitoids from one shallow pluton. Compositional similarity between granodiorite and young dacites of Mount Mazama suggests the pluton may have crystallized as recently as ~50 ka. The violent climactic eruption regurgitated blocks, plucked from the granitoid walls of its early Holocene magma chamber, that are remarkable natural examples of equilibrated partial melts. The history of crystallization, hydrothermal alteration, and remelting of these granitoids may be characteristic of crustal silicic magma bodies in long-lived igneous systems in which the balance between hydrothermal cooling and magmatic input changes repeatedly over intervals of 10^4 to 10^6 years.

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Genesis and evolution of mafic magmatic enclaves through various types of interactions between coeval felsic and mafic magmas.

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The genesis and evolution of mafic magmatic enclaves of granitoids result from many different types of hybridization processes affecting contrasting coeval magmas (e.g. review in "Enclaves and Granite Petrology", Didier and Barbarin, eds., in press). The main processes are thorough magma mixing, mingling with exchanges of blobs of magma, mineral, chemical, and thermal transfers. These interactions are especially effective in the plutonic environment because there is a long time span from injection of mafic magma into felsic magma at depth, to cooling of plutons in the upper crust. Mechanical interactions, which are favoured by convections, occur at depth, and in the feeding conduits during the emplacement of plutons, whereas chemical exchanges are dominant mainly after emplacement. The physical properties of the coeval magmas constrain the role of each process. These hybridization processes are complementary and tend to reduce the contrasts between the magmas and, where achieved, to produce homogeneous hybrid rocks.

Mafic magmatic enclaves represent only 1 to 2 % of the volume of the whole pluton, while isotopic data suggest that the volume of mafic magma involved in the formation of calc-alkaline granitoids can be up to 30 % (DePaolo, 1981). Enclaves then represent the tiny part of the volume of mafic magma which was not able to thoroughly mix with the crustal melt mainly because of highly-constrasting physical properties between the two end-members and/or absence of mechanical brewing at certain periods of the history of the pluton. The relatively scarce mafic magmatic enclaves or xenocrysts represent however excellent petrographic indicators of the involvement of contrasted endmembers, and of their physical and chemical interactions.

The complex and successive mechanical and chemical interactions, and especially strong isotopic equilibration, mask the original identities of the felsic and mafic magmas. Because of these interactions, the origin of the parental magmas of mafic magmatic enclaves remains a subject of controversy. The identical chemical compositions of minerals, the parallel chemical evolution and the similar isotopic compositions of enclaves and the host granitoids either indicate the same origin, or are produced by the hybridization processes. Detailed studies of other mafic rocks associated with the granitoids and in which some interactions are limited (i.e. associated mafic intrusions, large enclaves, synplutonic dykes) suggest that the two magmas were initially distinct and that most similarities are due to the interaction processes.

THE LAYOS GRANITE, HERCYNIAN COMPLEX OF TOLEDO (SPAIN): AN EXAMPLE OF PARAUTHOCHTHONOUS RESTITE-RICH GRANITE IN A GRANULITIC AREA.

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The Layos granite forms elongated massifs within the Hercynian Complex of Toledo (Central Spain). It is late-tectonic with respect to the F2 regional phase and simultaneous with the metamorphic peak of the region, which reached a maximum temperature of 800-850°C and pressures of 0.45 -0.55 GPa. Field studies indicate that it is an intrusion belonging to the "regional migmatite terrane granite" type, in a granulitic area.

This granite is typically interlayered with sill-like veins and elongated bodies of cordierite/garnet-bearing leucogranites. Xenolithic enclaves are widespread and comprise restitic types (quartz lumps, biotite, cordierite and sillimanite-rich enclaves) and refractory metamorphic country-rocks including orthogneisses, amphibolites, quartzites, conglomerates and calc-silicate rocks.

The granitoids vary from quartz-rich tonalites to melamonzogranites and define a S-type trend on a QAP plot. Cordierite and biotite are the mafic phases of the rocks. Particularly notable is the high proportion of cordierite (10%-30%) which varies inversely with the silica content. Sillimanite is a common accessory mineral always included in cordierite suggesting a restitic origin.

The mineral chemistry of the Layos granite is similar to that of the leucogranites and country-rock kinzigites, indicating a close approach to equilibrium. The uniform composition of plagioclase (An_{25}), the high albitic content of the K-feldspar, the continuous variation in the Fe/Mg ratios of the mafic minerals, and the high Ti content of the biotites (2.5-6.5% wt) are all suggestive of a genetic relationship.

Geochemically the Layos granite is strongly peraluminous. Normative corundum lies between 4% and 10% and varies inversely with increase in SiO_2. The CaO content is typically low (<1.25% wt) and show little variation; similarly the LILE show a limited range. On many variation diagrams linear trends from kinzigite gneisses to Layos granite and associated leucogranite can be observed. The chemical characteristics argue against an igneous fractionation or fusion mechanism for the diversification of the Layos granite.

A restite unmixing model between a granulitic composition (represented by the kinzigites) and a minimum melt (leucogranites) could explain the main chemical variation of the Layos granite. Melting of a pelitic protolith in anhydrous conditions (biotite dehydration melting) could lead to minimum melt compositions leaving a residuum strongly peraluminous.

For the most mafic granites (61-63% SiO_2) it is estimated that the trapped restite component must be around 65%. This high proportion of restite is close to the estimated rheological critical melt percentage (RCMP), but field evidences suggest that this critical value has been exceeded. This high restite component implies high viscosity of the melt which together with the anhydrous assemblage of the Layos granite and the associated leucogranites indicate water undersatured melting scenarios. Under such conditions the high viscosity magma (crystal-liquid mush) has a capacity for only restricted movement leading to para-authochtonous plutonic bodies.

INTERACTION OF MAFIC AND FELSIC MAGMAS, GRAYBACK PLUTON, KLAMATH MOUNTAINS, OREGON

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The Grayback pluton is a large, heterogeneous body that intruded metasedimentary and metavolcanic rocks of the Klamath Province in late Middle Jurassic time. The pluton was emplaced in the continentward side of an arc-backarc assemblage and apparently represents the final stages of an active remnant arc or magmatism adjacent to a transpressional backarc rift edge. The oldest rocks in the pluton range from gabbro to tonalite. Quartz-bearing rocks are predominant and the pluton typically displays reverse zoning, with the most quartz-rich samples near the margins. Throughout the pluton, but especially in the south-central part, gabbroic, noritic, and pyroxenitic rocks form broad (km-scale) zones that display complex intrusive relations. Most commonly, several textural varieties of mafic rocks are intrusive into quartz diorite or tonalite; however, quartz diorite is locally intrusive into gabbroic rocks. Several of the mafic zones are characterized by broad (10's of meters), dike-like hybrid zones with gabbroic enclaves in a leucogabbroic host. This range of intrusive relations is interpreted to indicate that mafic and intermediate magmas coexisted during much of the history of the Grayback magmatic system. These early ("main stage") rock types are intruded by tonalitic and granitic dikes. Both dike types contain oblate to cuspate mafic magmatic enclaves and some contain zones of hybrid intermediate composition.

Mafic rocks are broadly calc-alkaline, but evolved low-K, high-Al tholeiitic rocks are also present. Elemental compositions of the mafic rocks vary widely (e.g., K_2O from 0.2 to 2.0 wt. %; Al_2O_3 from 13 to 19 wt. %; P_2O_5 from 0.1 to 0.45 wt. %; Sr from 290 to 650 ppm; Sc from 20 to 60 ppm). Similar compositional ranges are observed in cumulate gabbro, pyroxenite, and anorthosite. Elemental variation among rocks from hybrid dikes are colinear with compositional variations of main stage rocks; an indication that magma mixing (± fractional crystallization) can explain at least some of the intermediate compositions in the pluton. The striking range of mafic compositions in the Grayback pluton requires varying degress of partial melting of two or more mantle sources.

With rare exceptions, all mafic components in the pluton have been contaminated by crustal material. Initial $^{87}Sr/^{86}Sr$ (Sr_i) ranges from 0.7028 to 0.7044 and all but one of the main phase samples have $Sr_i \approx 0.7042$. However, two mafic enclaves in a late-stage hybrid zone have $Sr_i \approx 0.7028$. Sr_i of tonalitic and granitic dikes ranges from 0.7036 to 0.7044. $\epsilon_{Nd}(t)$ and $\delta^{18}O$ of the main phase and late dikes range from +4.1 to +5.4 and +7.6$^o/_{oo}$ to +14.4$^o/_{oo}$, respectively. $\delta^{18}O$ values > 9$^o/_{oo}$ occur only among the felsic dikes. Modelling indicates that the isotopic values of the main phase rocks were the result of (1) assimilation of primitive metasedimentary rocks or (2) mixing of basaltic magma with crustal melts derived from metasedimentary rocks. Apparently, the magmatic conduit became insulated from crustal contamination during the late stages of Grayback magmatism, permitting rise of uncontaminated late-stage basalt.

Evaluation of Thermodynamic Models for Albite-Water Melts*

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Thermodynamic models for *ab-w* melts can be divided into two categories: formulations based principally on H_2O speciation data for quenched *ab-w* melts ("speciation" models), and formulations founded largely on *P-V-T* data and/or heterogeneous phase-equilibrium data for *ab-w* melts ("empirical" models).† Speciation models explicitly account for observed variations in X^L_{OH} and $X^L_{H_2O,mol}$ with total water content of the melt (e.g., via an equilibrium constant). With empirical models, the nature of H_2O speciation is inferred from one or more calculated bulk thermodynamic mixing properties of *ab-w* melts (e.g., f^L_w, γ^L_w and G^{ex}).

Key criteria for evaluating speciation models are accurate reproduction of H_2O speciation data and good accord between calculated and experimentally-determined heterogeneous phase relations. Existing speciation models (e.g., Silver and Stolper, 1989) only satisfy the first criterion. Published heterogeneous phase-equilibrium data for the *ab-w* system are generally in good agreement. Thus, it can be concluded that existing speciation models do not yield highly accurate calculated values for a^L_{ab} and a^L_w.

The single existing empirical model for *ab-w* melts was developed by Burnham and Davis (1971, 1974). Ostensibly consonant with the postulate that water dissolves exclusively as OH groups, the Burnham and Davis activity equations yield values of γ^L_w and G^{ex} which are consistent with the alternative hypothesis (Silver *et al.*, 1990) that: (1) OH groups predominate at very low total water contents; (2) molecular water is stable in *ab-w* melts and its solubility increases with increasing X^L_w; and (3) $X^L_{H_2O,mol} > X^L_{OH}$ at high total water contents. It is proposed that dissolution of molecular water in *ab-w* melts and dissolution of potassium in binary nepheline-kalsilite crystalline solutions are analogous in terms of their effects on bulk thermodynamic mixing properties.

To further investigate the thermodynamic mixing properties of *ab-w* melts, the two-parameter Margules and three-parameter Redlich-Kister formulations have been used to calculate $a^L_{ab} = f(T, X^L_w)$ and $a^L_w = f(T, X^L_w)$ at *P-T* conditions delimited by the reactions $Ab + V \leftrightarrow L$ and $Ab \leftrightarrow L$. Calculations were performed for 1.0, 2.5, 5.0 and 8.0 kbar. Input data for the calculations were: (1) the enthalpy and entropy of fusion of *Ab* at 1 bar (Stebbins *et al.*, 1983); (2) the volume of fusion of *Ab* (modified from Kress *et al.*, 1988); (3) estimated values for $X^{L(Ab)}_w$ and $X^{L(V)}_w$; and (4) a value for $X^{V(Ab,L)}_w$ (Clark, 1966). Resulting calculated values for γ^L_{ab}, γ^L_w, a^L_{ab}, a^L_w, and G^{ex} are in excellent agreement with corresponding values calculated from the Burnham and Davis activity equations. Therefore, *P-V-T* data are not required to obtain accurate calculated values for a^L_{ab} and a^L_w.

The heterogeneous and homogeneous equilibria of the *ab-w* system are linked thermodynamically by the identity $a^L_w = a^L_{H_2O,mol}$. Therefore, an appropriate method for thermodynamic modeling of *ab-w* melts is to: (1) develop empirical equations for $a^L_{ab} = f(P,T,X^L_w)$ and $a^L_w = f(P,T,X^L_w)$ that yield accurate calculated heterogeneous phase relations for the *ab-w* system; and subsequently (2) use the a^L_w equation derived in step 1 and spectroscopic data on X^L_{OH} and $X^L_{H_2O,mol}$ to develop an equation for $K = f(P,T)$, where $K = (a^L_{OH})^2/[(a^L_{H_2O,mol})(a^L_O)]$.

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†Notation: ab = $NaAlSi_3O_8$, w = H_2O, H_2O,mol = molecular H_2O dissolved in *ab-w* melt, OH = hydroxyl groups in *ab-w* melt, O = bridging oxygen atoms in *ab-w* melt, Ab = high albite, L = liquid (*ab-w* melt), V = alkali aluminosilicate-saturated H_2O-rich vapor, $L(Ab)$ = L coexisting with Ab, $L(V)$ = L coexisting with V, $V(Ab,L)$ = V coexisting with Ab and L, a = activity, f = fugacity, γ = activity coefficient, G^{ex} = excess free energy, K = equilibrium constant, P = pressure, T = temperature (K), V = volume, X = mole fraction, $f(...)$ = is a function of ...

SOME FUNDAMENTAL PARAMETERS IN GRANITOID METALLOGENY: AN EASTERN AUSTRALIAN PERSPECTIVE

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Metallogenic studies in eastern Australia demonstrate a consistant relationship between the basic granitoid types and their ore element associations. Sn mineralization is associated with F-rich S and I-type suites that are reduced and crystal fractionated. Cu and Au are associated with F-poor, magnetite and/or titanite-bearing oxidised intermediate I-type suites. Mo is associated with both crystal fractionated and less evolved, oxidised I-types displaying variable F enrichment. In eastern Queensland Cu, Au and lesser Mo deposits are often porphyry-like in style and are associated with granodioritic to tonalitic rocks suggestive of arc affinities. W is associated with a variety of granitoids showing little dependence on magma redox.

Only a few granitoid properties appear to be crucial in generating these characteristic ore-element assemblages. These properties are: magma redox; the presence of fractional crystallization as the dominant differentation mechanism, and the concentration of halogens.

Crystal fractionation may significantly increase or decrease ore element and volatile contents in magmas and can be recognized within a variety of mineralized magmatic systems. Suites whose geochemical variation is controlled by restite-unmixing are poorly mineralized and this alone appears to be responsible for the paucity of economic mineralization over much of the Lachlan Fold Belt compared to elsewhere in eastern Australia. Sn granites are the products of prolonged fractional crystallization during which other elements such as W, F, and Li etc also build up. High initial ore element contents are not required in the source regions of these rocks, but a "fertile" source allowing for high degrees of partial melting to produce melt-rich magmas is clearly desirable if fractional crystallization is to progress to any extent.

Magma redox characteristically varies from I-types (relatively oxidised) to S-types (relatively reduced). Some I-types may also be reduced. The oxidation state of granitoid magmas is controlled dominantly by the Fe^{3+}/Fe^{2+} ratio and is inferred to be inhereted from the magmatic source region. The importance of magmatic oxidation state on the behaviour of metals such as Cu, Mo, W, Sn and Au during crystallization is now well established (eg. Candela and Bouton, 1990; Econ Geol. 85:633-640). These elements partition between the melt and oxide and sulphide minerals whose stability is redox dependant. For example, at low magmatic fO_2 sulphides are stable and may remove elements such as Cu and Au from the melt. This is consistent with the observation of Whalen and Chappell (1988; Am. Min 73:281-296) that sulphides are common and texturally early in S-types and less common and texturally late in I-types. Similar considerations also explain why Sn does not build up during fractional crystallization in oxidised I-type suites.

Studies of the halogen content of micas and apatites indicate that the Cl content of S-type granitoids are significantly lower than in I types. F builds up during fractional crystallization while Cl progressively decreases. The observed association of Sn and some W and Mo systems with high F, and Cu and Au with low F and high Cl is a consequence of the behaviour of these halogens during magmatic evolution coupled with the intrinsically lower Cl in S-types. The low fO_2 and Cl concentrations appear to rule S-types out as favourable candidates for Cu Pb Zn type mineralization, a prediction borne out by the observed deposit distribution data for eastern Australia.

The LFB granitoids demonstrate that magma redox state and the type of magmatic variation mechanism, coupled with variations in halogen contents are important parameters in determining the metal composition and ore potential of suites. Such properties are imparted onto granitoids by their source rocks. Whether or not that potential is realized in the production of economic mineralization however depends on an equally important second tier of parameters that operate during the magmatic emplacement and crystallization stages. These parameters include: level of emplacement and timing of vapour exsolution, magma water content and the local tectonic and stratigraphic environment.

FORCEFUL EMPLACEMENT IN THE SOUTHERN ADAMELLO MASSIF, ITALIAN ALPS: INTRUSIVE HISTORY OF THE LAGO DELLA VACCA SUITE

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The Tertiary calc-alkaline Adamello Massif in the central Italian Alps comprises at least twelve distinct granitoid plutons and associated synplutonic, satellitic mafic dykes and ultramafic bodies. The Lago della Vacca Suite (LVS) forms one of these plutons near the southern margin of the massif, and occupies over 20 km^2. The suite was emplaced at an estimated 2 kb pressure, into warm but consolidated precursor granitoid and ultramafic rocks, and adjacent Triassic dolomites. Strain and temperature studies of the granitiod rocks of the Lago della Vacca Suite imply emplacement related deformation concentrated into narrow zones of intense flattening near solidus temperatures.

The LVS exhibits crude concentric and temporal zonation from diorite to tonalite, in which age decreases, and silica increases away from the margins of the suite. A marginal unit of heterogeneous quartz gabbro, diorite and tonalite, is intruded inward by homogeneous equigranular tonalite (the Vacca tonalite), which is in turn cut by a medium-grained tonalite to granodiorite (the Galliner tonalite) which forms the inner core of the pluton. Synplutonic diorite dykes and mafic inclusion swarms cross-cut the LVS. The dykes and swarms are concentrated near the outer contacts of each of the three units. Dispersed mafic enclaves occur throughout the Lago della Vacca Suite. Younger plutons of the Adamello Massif truncate the northern margin of the LVS.

Variations in foliation attitude and strain across the LVS demonstrate forceful emplacement against apparently rigid discordant walls. High-temperature foliations are well-developed in all units, and define steeply inward dipping concentric trajectories that typically parallel the marginal contact. Stretching lineations are rarely observed. Foliation is most prominent in zones near the margin and is defined by the planar alignment of plagioclase, amphibole and biotite crystals, and by mafic enclaves. Toward the interior of the LVS most enclaves are unaligned, but the Vacca tonalite locally bears a weak fabric, defined by the alignment of plagioclase and amphibole crystals. Within the Galliner tonalite, the quartzo-feldspathic matrix around the coarse-grained minerals shows no evidence of plastic deformation. Foliation in the marginal unit is deflected around a large body of rigid precursor layered ultramafic rocks, but passes continuously into other precursor granitoids indicating a profound influence of country rock rheology on strain variation during emplacement. Attendent small aplite dykes are oriented normal to the foliation. The orientation of small-scale shear zones is also consistent with radial expansion.

Variations in strain related to emplacement within the LVS are documented by the axial ratios of mafic inclusions or blobs. A series of radial traverses was made using 3-D exposures to fully constrain the finite strain ellipsoids. A general trend of decreasing strain towards the core of the LVS is consistent with emplacement by 'ballooning'. In detail, however, strain varies remarkably across decametres wide zones of very high strain ($9 \leq X/Z \leq 12$), and broader zones of lower strain ($X/Z \leq 3$). The highest strains consistently occur in dioritic rocks. In the marginal unit these high strains define elongate zones of intensely foliated diorite parallel to the foliation. In the Vacca tonalite, the highest strain occurs in zones of abundant mafic inclusions near the inner and outer contacts. Strain is consistently low ($X/Z \leq 1.5$) in the Galliner tonalite. Calculated strain ellipsoids for each measured site typically have K-values <1 on a Flinn diagram, implying flattening and radial expansion.

Amphibole-plagioclase thermometry constrains the temperature of deformation to near the tonalite solidus. Despite evidence of grain-size reduction and recrystallization in the most deformed diorites, calculated temperatures (750±50°C) are consistently at or close to the tonalite solidus at the known pressure of emplacement. Amphibole chemistry in the rocks with the greatest recovery have high potassium contents and low magnesium numbers relative to less deformed equivalents of identical initial composition. This suggests interaction of the deforming rocks with interstitial evolved melts. We conclude that the synintrusive deformation of the LVS was at magmatic temperatures. There is no evidence of lower temperature deformation which might be expected if pluton emplacement was into a regionally developed shear zone in the fashion recently proposed for many Caledonian plutons. The heterogeneity of strain in the LVS is best reconciled with small-scale, compositionally determined variations in strain rate maintained over the time scale of pluton emplacement. Detailed laser-fusion Ar-Ar dating of the LVS and surrounding country rocks is in progress to attempt to constrain the timing.

A-Type Granite Magmatism in the Western Mediterranean.

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The Permo-Triassic period was characterized in the Western Mediterranean area by abundant magmatic activity occurring just after the end of the Variscan orogenesis. Volcanic-plutonic complexes were emplaced mainly in the internal parts of the orogen and constitute a 4000 km-long province from Morocco in the south-west to Austria in the north-east. The magmatic activity has taken place during two discrete episodes:

(i) The mid-Permian (ca. 270 ± 5 Ma) is a critical period with a sharp magmatic discontinuity marked by the emplacement of the first A-type granite complexes. Two magmatic alignments, one from Morocco to the southern Alps and the second from the western Alps to the Oslo Rift, define a Y-shaped fault system associated with major sinistral shear zones.

Volcanic products, emitted along distensive fracture zones, are scarce basic lava flows and huge and numerous K-rich red ignimbritic flows and falls. Associated with and postdating volcanic formations, pink to red subsolvus biotite granites are characterized by metaluminous to slightly peraluminous compositions, high amounts of Ba and Sr, relatively low amounts of HFSE, Mg-rich biotite evolving to Al-rich siderophyllite, early Mn-rich Fe-Ti oxides, suggesting a water-rich and oxidizing environment. Basic (gabbro) and intermediate (monzonite) rocks are also present, as net-veined complexes (e.g. Porto in Corsica), or mafic layered massifs (e.g. Peloso in Corsica).

Sr isotopic ratios are relatively high, ranging from 0.704 for the less evolved granites (e.g. Azegour in Morocco, Lugano in Italy-Switzerland) up to 0.722 for highly evolved and Sn-W-Mo-U-enriched granites (e.g. Pastricciola in Corsica), suggesting varying amounts of crustal contribution.

(ii) after a quiescent period lasting until the Permian-Triassic boundary (245 ± 10 Ma), numerous A-type alkaline granite ring complexes were emplaced along the future Alpine belt under an incipient rift regime.

Volcanic products, emitted during various stages of activity of large caldera volcanoes, are characterized by a bimodal basalt-trachyte/rhyolite series, with a slightly peralkaline tendency (comenditic ignimbrites). Plutonic ring-complexes were emplaced beneath caldera volcanoes and are composed of intermediate rocks (syenite) and a large variety of A-type granites. Ba and Sr-poor hypersolvus, transsolvus and subsolvus granites display Fe-rich mafic silicates (fayalite, hedenbergite and aegirine) and F-bearing hydrous minerals (amphiboles: hastingsite -> Fe hornblende series and Fe barroisite -> winchite -> richterite -> arfvedsonite ± riebeckite series, micas: annite -> lepidomelane or silicic mica), suggesting a more reducing environment. F-rich aqueous fluids promote subsolidus hydrothermal alteration and subordinate late-stage oxidation.

Metaluminous, peraluminous and peralkaline compositions can occur in the same complex, e.g. Cauro-Bastelica in Corsica. But most peralkaline granites were emplaced in discrete complexes at the end of the magmatic activity (e.g. Evisa-Calasima and Bonifatto-Monte Cinto in Corsica).

Meta- to peraluminous granites yield intermediate Sr isoropic ratios, ranging from 0.704 (e.g. Porto) to 0.707-0.711 (e.g. Cauro-Bastelica). However, peralkaline granites are characterized by a very low ratio (0.703 at Evisa), even if they are strongly altered with high values of the agpaiitic index Na + K / Al (up to 2.0). Accordingly, peralkaline granites display LILE and HFSE enrichment, which characterizes highly evolved anorogenic granites (e.g. Ririwai in the Mesozoic Niger-Nigeria magmatic line).

Sources and conditions of differentiation of A-type granite magmatism evolve with time. After the end 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. These intermediate melts were collected in shallow magma chambers emplaced at the ductile-brittle transition in the crust, where they evolved through low-pressure fractionation to granitic residual melts. The alkaline melts were subsequently less and less contaminated by crustal host rocks. Strong correlations between hydrothermal events, mineralizations and crustal isotope signatures suggest that crustal contribution relates essentially to percolating fluids.

MAGMATISM AND HYDROTHERMAL METASOMATISM IN MESOZOIC DAMARALAND GRANITES, NORTHERN NAMIBIA

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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 South 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 South Atlantic Ocean. This activity was marked on the southwest African continent by the emplacement of a number of acid-basic complexes, granite centres, carbonatites and kimberlites.
The Damaraland zone of anorogenic complexes in northern Namibia extends more than 400km as a well-defined series of north easterly oriented lineaments between the Ugab and Khan rivers. The lineament zone coincides with the axis of the Damaran (Pan-African) orogen. Twenty Mesozoic complexes have been identified along this zone. Published radiometric dates for some of the complexes range between 170 and 90 Ma. Analytical data for Cape Cross, Otjihorongo, Messum, Spitzkoppies, Paresis, together with some samples from the Brandberg massif, help to cationically define the magmatic lineage for the Damaraland basic-acid anorogenic complexes. In contrast the subalkaline monzonitic feature of the granitic rocks from the Erongo massif strongly suggests that potassic-boron metasomatism has severely disturbed the original magma chemistry.
Based on evidence from Erongo, 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 crystallization residua of the host pluton (autometasomatism). One must also consider the possibility in multicentred anorogenic complexes, that residual fluids are expelled from later intrusions whose fluid chemistry may be out of equilibrium with the bulk chemistry of the earlier crystallizing pluton. This involves mass transfer of components to form new peralkaline subsolidus assemblages. A granite massif where arrested stages of fluid mass transfer can be observed is in the marginal zones of the Brandberg where extensive 'mineral layering' is interpreted as a metasomatic feature caused by the passage of peralkaline fluids along microfractures within granitic sheets, fed by fluid channelways now preserved as fenite veins emanating from adjacent intrusions.

Origin and distribution of granitic rocks in the Coast plutonic-metamorphic complex, northern Canadian-Alaskan Cordillera, southeastern Alaska, U.S.A.

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Discrete chrono-lithologic granitic rock units occur in both continuous and discontinuous belts that run the 1000-km-plus length of the late Mesozoic and Cenozoic Coast plutonic-metamorphic complex (CPMC) in southeastern Alaska and the adjacent parts of British Columbia. The CPMC has four main zones, from southwest to northeast they are: the western metamorphic zone or belt, the central metamorphic zone, the central granitic zone and the eastern metamorphic zone. Each of these zones is characterized by specific granitic units and to some extent by specific metamorphic protoliths. All but the oldest of the four major granitic belts are subduction-related and record 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). Calcalkalic, island-arc affinity rocks are predominant; however, each of the belts has a somewhat different origin that is reflected in its structural; modal compositional; and major, minor, trace, and rare-earth-element compositional characteristics. The distribution of the granitic units is known from USGS reconnaissance mapping of the whole region and the other characteristics are best known from detailed studies in four transects. Three minor granitic belts, of Early Jurassic, early Early Cretaceous, and Late Oligocene age, are present, but are not discussed here.

The oldest granitic rocks occur in the Yukon prong plutonic belt. They are now biotite-hornblende-quartz-feldspar orthogneiss that is apparently confined to the central metamorphic zone of the CPMC. The orthogneiss occurs in kilometer-scale elongate tabular bodies in a discontinuous belt within the migmatite and gneiss units that characterize the Yukon prong terrane. The original rocks were probably mostly granodiorites and tonalites and were of Devonian and perhaps Carboniferous age, as recently determined by zircon-dating studies. There are probably many more such bodies than are presently recognized. Their original emplacement environment is uncertain, but their host rocks are interpreted to have been a Proterozoic to Early Paleozoic continental margin assemblage. They may be related to mid-Paleozoic collisional events that have no other record.

Early Late Cretaceous (about 95 Ma) granitic rocks of the Admiralty-Revillagigedo plutonic belt are entirely within the western metamorphic belt. Most are in country rocks belonging to the Gravina overlap assemblage, but a few occur in mixed Insular and Intermontane superterrane rocks. The plutons range from unfoliated kilometer-scale equant plugs to foliated tens-of-kilometer-scale elongate batholiths and form a relatively narrow discontinuous belt. They range in modal composition from (pyroxene)-(garnet)-(epidote)-(hornblende)-biotite granodiorite through tonalite and quartz monzondiorite to diorite. There are significant chemical variations in the belt, with metaluminous alkalic and calcalkalic types dominant to the north and peraluminous and calcalkalic types to the south. Magmatic epidote and (or) a distinctive plagioclase-porphyritic texture are common features. Some bodies are post- and some syn-tectonic; their apparent unusually deep origin (indicated by the magmatic epidote); variations in size and style; and linear arrangement suggest that they may be primarily related to a deep, narrow crustal feature rather than to the then-ongoing Insular-Intermontane superterrane collision.

Latest Cretaceous and Paleocene (about 84 to 55 Ma) syntectonic plutons of the almost continuous composite Great Tonalite Sill belt define the western boundary of the central metamorphic zone of the CPMC for over 800 kilometers. They are within the migmatite and gneiss units that characterize the Yukon prong terrane, and in mixed Insular and Intermontane superterrane and Gravina overlap assemblage rocks. The individual bodies are generally well-foliated; have well developed down-dip mineral lineations; and are elongate, with widths to 5 km and lengths to 50 km. (Biotite)-sphene-hornblende tonalite, quartz diorite, and granodiorite are the most common rock types. In contrast to the younger plutons in the belt, the older plutons are more deformed and metamorphosed and have chemical features more like the plutons of the Admiralty-Revillagigedo belt. The bodies are calcalkalic, with some parts of the belt being dominantly metaluminous and other parts mixed metaluminous and peraluminous. There is locally an eastward younging across the belt, but there is no apparent systematic age variation along its length. The genesis, emplacement, and deformation of the plutons are all related to the final stages of Insular-Intermontane superterrane collision.

Middle Eocene (about 45 to 55 Ma) plutons of the almost continuous Coast Mountains belt essentially define the central granitic zone of the CPMC for over 1000 km. They are within both the migmatite and gneiss units of the Yukon prong terrane and in Stikine terrane rocks. The individual bodies are equant to elongate, tens of kilometers in both directions, and they adjoin each other to make up a series of composite batholiths that are separated by narrow screens of metamorphic rocks. All together, these batholiths underlie about two-thirds of the CPMC. Homogeneous, unfoliated sphene-biotite-hornblende granodiorite, tonalite, and quartz monzodiorite are dominant, with local occurrences of K-spar porphyritic biotite granite. The plutons are calcalkalic, with metaluminous types generally twice as abundant as peraluminous in the northern part of the belt and peraluminous types dominant in the southern. There are no recognized patterns in the age of the batholiths or their constituent plutons. Some of the plutons in the northern CPMC are closely related to coeval volcanic rocks. The genesis and emplacement of the plutons in this belt are related to the final accretion of the Chugach terrane along the western margin of the Insular superterrane, some 100 km west of the CPMC.

TRANSPRESSION AND GRANITE GENESIS

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Transpression involves horizontal shortening across and vertical lengthening along a zone of transcurrent shear. This process thickens the crust and structurally inverts associated sedimentary basins, which may lead to high-temperature metamorphism and anatexis. Shear zones facilitate fluid migration, they provide convenient paths of ingress for volatiles as well as ascent paths for magma, and deformation will enhance melt segregation during anatexis. Mantle-deep terrane boundary faults provide access for mantle-derived magma to intrude and interact with the crust. Thus, accretionary tectonics in obliquely convergent orogens may lead to hydrous fluxing and crustal thickening, as well as to the juxtaposition of terranes in which granites have been derived from different crustal sources.

In the Cadomian Belt of NW France, arc-related outboard terranes have been amalgamated with inboard terranes, interpreted to represent elements of a behind-arc basin sedimentary sequence, during late Precambrian 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 whole rock geochemistry and in the isotopic signature of the granitic rocks. By contrast, in the inboard terranes, thickening of the late Precambrian (Brioverian) sedimentary 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 crustal 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 petrographic 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 sedimentary succession. We interpret the St. Malo migmatite belt to be a deeper crustal level in comparison with the Mancellian granites, which is consistent with the kinematic evolution suggested by shallow NE-plunging lineations.

INTRUSIVE MECHANISM AND GENESIS OF RAPAKIVI INTRUSIONS IN SOUTH GREENLAND.

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Early Proterozoic rapakivi intrusions in South Greenland occur as thick sheets which have ramp-flat geometry and were intruded along the median planes of active ductile extensional shear zones. These shear zones and their intrusions were linked via transfer zones in a major 3D framework. At high structural levels (ca. 6 km) the rapakivi intrusions develop thermal aureoles which overprint the regional assemblages, whereas at deeper levels in the regional structure they are contemporaneous with regional metamorphism. Thermobarometry on the regional and contact assemblages indicates low pressure granulite facies conditions (0.2-0.4 GPa, 650-800°C) suggesting very high thermal gradients. The rapakivi suite and associated norites have low initial $^{87}Sr/^{86}Sr$ together with positive εNd values, indicating the involvement of predominantly young crust and/or mantle component in the generation of the igneous suite. It is considered that the voluminous norites are closely related to the mafic melts which underplated the juvenile crust to trigger the generation of the monzonitic rapakivi suite. Taken together the data are consistent with a model of Proterozoic lithospheric extension leading to thinning of relatively juvenile continental crust, the compression of mantle isotherms, resulting in high crustal heat flow, basaltic underplating, melting and emplacement of magmas along a linked network of extensional shear zones.

THREE-DIMENSIONAL ANALYSIS OF THE CRYSTALLISATION SEQUENCE AND TEXTURAL DEVELOPMENT IN TWO PERUVIAN GRANITOID ROCKS

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"*Evidence based on the microscopic examination of thin sections is often misleading, because little more than a surface is presented to the eye, and the three-dimensional relations are not revealed.*"
HOLMES 1921

Microscopic geometrical and textural characteristics of crystallisation sequences, and inferences regarding the rheological properties of crystallising granitoids, 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. Their high level of emplacement (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 form a melt contianing 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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Calculated Melt and Restite Compositions of Some Australian Granites

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The thermodynamic relations embodied in the Quasicrystalline Model [1], as recently extended by the author, have been used to quantitatively assess the feldspar-quartz liquidus relations in two I-type (Jindabyne and Moruya) and two S-type (Bullenbalong and Dalgety) suites of Australian granites, using analytical data provided by B.W. Chappell and A.J.R. White. Among the more notable results obtained at a constant pressure of 5.0 kbar and H_2O content of 2.8 wt. % ($X_w^m = 0.30$), for purposes of comparison, are: (1) felsic melts of remarkably uniform, but distinctive, composition can be extracted from each suite, leaving solid residues in amounts up to 67 mol (approx volume) %; (2) all melts from both S-type suites have two feldspars plus quartz on their liquidii, whereas both I-type suites have only plagioclase plus quartz on their liquidii; (3) the total solid residue ranges from 25 to 64 % in the Jindabyne suite, from 15 to 63 % in the Moruya suite, from 30 to 65 % in the Bullenbalong suite, and from 26 to 67 % in the Dalgety suite; (4) liquidus temperatures of the S-type Bullenbalong and Dalgety melts are similar (856±3 and 861±4° C), reflecting similar feldspar compositions of $An_{54}Ab_{40}Or_6$, $Or_{75}Ab_{21}An_4$ and $An_{60}Ab_{34}Or_6$, $Or_{77}Ab_{18}An_5$, respectively; (5) liquidus temperatures of the I-type Jindabyne and Moruya melts, however, are distinctly different (953±5 and 895±4° C.), reflecting correspondingly different plagioclase compositions of $An_{80}Ab_{19}Or_1$ and $An_{52}Ab_{45}Or_3$; (6) the liquidus plagioclase composition throughout a given suite is remarkably uniform (± 1%) and precisely that of the plagioclase residue, which amounts to as much as 46 % of the total rock; and (7) these calculated liquidus and residual plagioclase compositions are also the same, within the uncertainty of measurement, as those of the plagioclase crystal-cores determined optically by A.J.R. White. The only plausible explanation for this remarkable consanguinity in plagioclase liquidus, residue, and crystal-core compositions, hence liquidus temperatures, is that the bulk of the residue is restite, in accordance with the model of White and Chappell [2]. Accordingly, those members of each suite that contain more than 60 % total restite probably closely represent the bulk composition of the source rock, which is noritic for the Jindabyne suite, tonalitic for the Moruya suite, pelitic metagreywacke for the Bullenbalong suite, and feldspathic metagreywacke for the Dalgety suite. As a corrollary, those members with less than 60 % restite must have undergone melt-restite separation, probably during diapiric ascent and emplacement.

[1] Amer. Miner., **71**, 239-263, 1986. [2] Tectonophysics, **43**, 7-22, 1977.

CONTROLS ON METAL RATIOS IN GRANITE-RELATED ORE SYSTEMS : AN EXPERIMENTAL AND COMPUTATIONAL APPROACH

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The size and composition (i.e. bulk metal ratios) of magmatic hydrothermal mineral deposits are affected by a number of processes including the nature of the source region and mode of emplacement. The Magmatic-Hydrothermal Theory for the origin of porphyry, skarn and other deposits predicts that magma chemistry exerts strong controls on the composition of mineralized rocks. Partitioning experiments performed in our laboratory (Candela and Bouton, Econ. Geol. (1990) 85, p. 633, and Lynton et al. (1990) GSA abs w/pgms, 22, p. 181) suggest that oxygen fugacity-dependent crystal/melt partitioning of ore metals leads to different efficiencies of Cu, W, and Mo removal from silicate melts into ore-forming aqueous fluids. For example, the Mo/W ratio in magmatic hydrothermal deposits should increase as the oxygen fugacity of the magma increases. Further, Cu should behave as a crystal-compatible element in water-undersaturated, sulphide-saturated felsic magmas with fO_2 < NNO due to the strong partitioning of Cu into pyrrhotite from the melt.

Cycling of oxidized, hydrated, sulphidised and chlorine-enriched oceanic crust into the mantle can give rise to magmas that contain sulphur but are oxidised (NNO or greater). Further, rapid ascent of crystal-poor magmas with considerable water contents allow the melts to reach shallow levels in arc environments. The combination of high oxidation state, relatively hydrous but shallow conditions and a high Cl/H_2O ratio leads to saturation with respect to water early during crystallisation and loss of a large proportion of magmatic copper to the aqueous phase. Ores formed from these oxidised magmas also possess high Mo/W ratios due to the effect of oxygen fugacity on the sequestering of Mo vs. W.

In less oxidised magmas, Cu and Mo are partitioned into sulphides and Ti-bearing phases respectively, resulting in lower efficiencies of removal of Cu and Mo from melts into aqueous fluids. Further, the partitioning of W into crystallising phases is reduced, producing a more efficient removal of W into ore-forming fluids. This ultimately leads to mineral deposits with higher W/(Mo + Cu) ratios relative to deposits associated with more oxidised systems. Silicic, high-fluorine magmas with $fO_2 \geq$ NNO can be found in tensional environments (e.g. rocks associated with the Climax-type deposits of the Colorado Mineral Belt). High HF/H_2O activity ratios in the source regions yield melts that evolve an aqueous phase late during crystallisation, leading to relatively low ratios of compatible/incompatible elements in the melt at water saturation.

There is little evidence that a high *initial* ore-metal content in magmas is the principal or sole factor in producing Cu, Mo or W-enriched ore fluids. Rather, intensive parameters such as Cl/H_2O and F/H_2O ratios, level of intrusion, initial H_2O concentration and oxygen fugacity act in concert with initial metal concentrations and depositional effects to determine the composition of magmatic-hydrothermal ore deposits.

GEOCHEMICAL CONTRASTS BETWEEN INTERSECTING DEVONIAN AND CARBONIFEROUS MAGMATIC BELTS IN THE EASTERN LACHLAN FOLD BELT

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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 at 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% to 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 to 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 to 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.

PETROGENESIS OF FELSIC I-TYPE GRANITES: AN EXAMPLE FROM FAR NORTH QUEENSLAND

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The origin of very felsic, strongly fractionated granites is controversial. Suggested petrogenetic models include partial melting of residual crust (Collins *et al.*, 1982, Contr. Miner. Pet., 80, 189-200; Manning & Pichavant, 1988, CIM Spec. Vol. 39, 13-24), granulitic crust (Christiansen *et al.*, 1986, Geol. Soc. Amer. Spec. Paper, 205), and fertile sedimentary rocks (Chappell & White, 1990, Geol. Soc. Aust., Abs. 25, 307-308), and also more complex models involving melting of, and mixing with, contemporaneous mantle-derived magmas (e.g. Hildreth *et al.*, 1991, J. Petrol., 32, 63-138).

Extensive Carboniferous felsic I-type granites (CIG) and associated volcanics outcrop over 15000 km^2 in far north Queensland, of which over 80% have SiO_2 greater than 70%. Unlike many other felsic terranes, however, intermediate rocks (56% to 66% SiO_2) are also present, comprising 5% to 10% of the terrane. The granites are post-tectonic and were emplaced in a tensional environment, either a back-arc or post-subduction setting. Petrogenetic models for the CIG are strongly constrained by the geochemical and isotopic characteristics.

Champion *et al.* (1990, Geol. Soc. Aust. Abs. 25, 275) subdivided the CIG into three main groups: the Almaden, Ootann and O'Briens Creek Supersuites (ASS, OSS and OBSS, respectively). The OSS and OBSS granites all contain greater than 70% SiO_2 and comprise over 90% of the granites. Dating and field relations suggest that the highly fractionated OBSS are older than or are similar in age to the OSS and ASS granites.

The OSS and OBSS are undoubtedly crustal melts with low Sr, Sr/Y, and large negative Eu/Eu* and evolved initial $^{87}Sr/^{86}Sr$ and ε_{Nd}. With increasing differentiation the OSS and OBSS granites become strongly depleted in TiO_2, Al_2O_3, FeO*, MnO, MgO, CaO, Ba, Sr, Sc, V, Cr, Ni, Eu, $(Ce/Y)_N$, and K/Rb, and enriched in Rb, Pb, Th, U, and Rb/Sr. Geochemical variation was predominantly controlled by crystal fractionation of primarily plagioclase along with, in the most felsic rocks, quartz and alkali feldspar. The OBSS differ from the OSS in having significantly higher HFSE, HREE and F (0.2 to 0.5+ wt%), and related F effects in the OBSS, i.e. decrease in SiO_2, K_2O and K/(K+Na) and increase in Na_2O with increasing differentiation (e.g. Manning, 1981, Contr. Miner. Pet., 76, 206-215).

The ASS granites are intermediate to felsic (56% to 72% SiO_2) and are characterised by high K_2O, K/(K+Na), Rb, Rb/Sr, Th, U, moderate La/Nb, and relatively low Ba and Sr. Major element contents are similar to some high-K orogenic rocks (e.g. Peccerillo & Taylor, 1976, Contr. Miner. Pet., 58, 63-81; Ewart, 1979, Trondhjemites, Dacites and Related Rocks, 13-121) although lack the high Ba and Sr found in these environments, exhibiting negative Ba and Sr anomalies on primitive mantle normalised plots. K_2O, Na_2O, Rb, Pb, Th, U, Nb and Y, behave incompatibly increasing with increasing SiO_2. The geochemical and isotopic evidence indicate the ASS granites are also crustal melts.

The granites of the ASS, OSS and OBSS have very similar initial $^{87}Sr/^{86}Sr$ and ε_{Nd} of 0.710 and -7.0 to -8.0, respectively, except where the granites outcrop within Proterozoic country rocks; these latter granites have more evolved ε_{Nd} (-8.0 to -10.0). Depleted-mantle model ages cluster around 1.5 Ga., similar to reported ages for deformation and metamorphic events (Black *et al.*, 1979, Tectonoph., 54, 103-137) and to Proterozoic granites related to these events (Black & McCulloch, 1990, Geoch. Cosmoch. Acta, 54, 183-196). The isotope systematics of the granites are generally less evolved than the Proterozoic and Early Palaeozoic country rocks (Black, 1978, Bur. Min. Res. Rep. 200; Black & McCulloch, 1984, Aust. J. Earth. Sci., 31, 49-60; Champion, Unpubl. data), and more evolved than contemporaneous, unrelated, mafic (mantle-derived) rocks. Isotopic data on lower crustal xenoliths (of various age) (Rudnick, 1990, Chem. Geol., 83, 195-208) suggest little evidence for widespread isotopic homogenisation.

Models for the petrogenesis of the CIG all appear to require the involvement of a long-lived, isotopically-homogeneous, crustal protolith, that was underplated in the Proterozoic. Granites of the OSS and OBSS were either derived by varying degrees of partial melting from this protolith of andesitic to dacitic composition (Champion *et al.*, 1990) and/or were produced by a two stage process by remelting of intermediate rocks similar in composition to members of the ASS. Regardless of the model invoked, it appears most likely that the very felsic OSS and OBSS granites were derived from a protolith geochemically similar to the mafic end-members of the ASS.

Compositional Relationships of S- and I-Type Granites in the Lachlan Fold Belt

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The area of exposure of Palaeozoic rocks in the Lachlan Fold Belt (LFB) is approximately 300,000 km^2. Granites comprise 63,000 km^2 of that area and hence make up about 30% of the belt. Related volcanic rocks are also abundant in some parts of the LFB. These rocks apparently all resulted from the partial melting of the deep crust. Because of that source and because of their abundance in the LFB, granites and their associated volcanic rocks provide significant information about the basement rocks of that region. They provide important petrological constraints on the crustal structure of the LFB and its tectonic evolution.

Many granites, particularly the more mafic ones, have chemical compositions that reflect those of their source rocks. This imaging property of granites frequently results from the granite magma carrying unmelted source material, or restite. In the other case of higher temperature and completely liquid magmas, less common in the LFB, the chemical correspondence between source rocks and granites is less marked, but is still present. An immediate consequence of the correspondence between source rock and granite compositions is that those granites derived from older igneous rocks are generally metaluminous, and those that came from metasedimentary sources are peraluminous. These are the I-type (igneous or infracrustal) and S-type (sedimentary or supracrustal) groups. The infracrustal and supracrustal origins of the two groups represent two fundamentally different types of source-rocks. While the isotopic data are somewhat ambiguous, the chemical data on the granites of the LFB suggest that the two types are mostly of distinctive origin, without transitions. In cases such as the Glenbog Suite of the Bega Batholith, where all data point to a mixed igneous and sedimentary source, a detailed examination shows that such mixing must have occurred before partial melting occurred, and in a rather uniform way over widely separated areas.

Granites which formed from magmas that had undergone extensive fractional crystallization are very rare in the Berridale and Kosciusko batholiths, and elsewhere in the Kosciusko Basement Terrane, the region in which the I- and S-types were first recognized some 20 years ago. The absence of such fractionation facilitated that early subdivision, but more recent studies have extended that twofold subdivision into those parts of the LFB in which fractionated granites are more common. Fractionated S-type granites are much more abundant than fractionated I-type granites in this region, and the former can often be distinguished by high P contents and a strongly peraluminous composition, both of these features becoming greater in magnitude with increasing degrees of fractionation. Strongly fractionated I-type granites are weakly peraluminous and have very low P concentrations.

META-SEDIMENTARY INCLUSIONS FROM THE I-TYPE GLENBOG SUPERSUITE

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In four I-type plutons (Blue Gum Tonalite, Weeragua Granodiorite, Anembo Granodiorite and Glenbog Granodiorite) of the Palaeozoic Glenbog Supersuite of the Bega Batholith, southeastern Australia, relatively rare meta-sedimentary inclusions are present, in addition to the mafic inclusions that are dominant among inclusion types. The granites of all four plutons contain hornblende as a major ferromagnesian mineral, and are metaluminous, but they also have high initial $^{87}Sr/^{86}Sr$ ratios (~0.708 to 0.710) and low ε_{Nd} values (-6.0 to -9.0) (Chen et al., 1990), and contain inherited zircons (Williams et al., 1988).

In all the granites studied, the overall abundance of meta-sedimentary inclusions is low (<<0.1%), and most are metapelitic types with a small number being calc-silicate. They range in size from several to about 30 centimeters, have sharp boundaries with the host, and are variable in shape (angular to subrounded). They all have metamorphic fabrics and some are coarse-grained. The metapelitic types consist mainly of plagioclase, K-feldspar, biotite, cordierite, spinel and corundum, in various proportions. Minor and accessory minerals include quartz, sillimanite, tourmaline, apatite, muscovite, magnetite, ilmenite, and zircon. Calc-silicate inclusions are composed dominantly of quartz and clinopyroxene with subordinate amounts of plagioclase, biotite and orthopyroxene.

Apart from the calc-silicate types, all other meta-sedimentary inclusions have low SiO_2 (50 - 53%), high Al_2O_3 (20-23%), and high but variable Na_2O (2.0-4.5%), K_2O (2.8-6.4%), and CaO (3.9-6.7%). The abundances of some trace elements are: Ba, 500-1100 ppm; Rb, 240-300 ppm; Sr, 160-360 ppm; and Cr, 120-180 ppm. Most of these inclusions are only slightly to moderately peraluminous [$Al_2O_3/(CaO+Na_2O+K_2O)$ ratios range from 0.96 to 1.74 with most being 1.0 to 1.2] because they also have high contents of CaO, Na_2O, and K_2O. The high CaO and Na_2O are particularly significant because Ordovician greywackes and shales that form the country rocks are low in CaO (<1%; Wyborn and Chappell, 1983). The Cooma Granodiorite, which is considered to have derived by partial melting of the local, exposed sediments, is also low in CaO (0.95%; Chappell and White, 1976). CaO abundances in these inclusions are also higher than those in the host granites.

The coase-grained fabrics exhibited by some meta-sedimentary inclusions suggest derivation from a high grade metamorphic terrane. The high CaO content of all meta-sedimentary inclusions precludes them being derived from exposed, low-grade meta-sedimentary country rocks. The zircon inheritance and the evolved Sr and Nd characteristics of the Glenbog Supersuite suggest that a sedimentary component must have been be involved in their petrogenesis. On the other hand, all granites of the Glenbog Supersuite are metaluminous. This means that the sediments which contributed inherited zircons and evolved initial Sr and Nd isotopic compositions to the host granites cannot have been very peraluminous. The meta-sedimentary inclusions studied here can satisfy these requirements. This suggests that the meta-sedimentary inclusions could represent a sedimentary component that was involved in the petrogenesis of the Glenbog Supersuite granites.

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PETROLOGIC EVOLUTION OF THE INDIAN PEAK VOLCANIC FIELD, WESTERN USA : CONTINENTAL INTERIOR MAGMATISM RELATED TO LITHOSPHERIC SUBDUCTION

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The chemical and thermal evolution of a large continental magma system is recorded in the Indian Peak caldera complex — a cluster of 6 dacite and rhyolite ash-flow tuff sources which erupted 10,000 km^3 of calc-alkaline rocks 32 to 27 Ma. Trivial volumes of rhyolitic and andesitic lava were extruded episodically, but chiefly during the early history of the field. The ash-flow eruptions alternated between rhyolite and dacite in a volume ratio of about 1: 8, and culminated with a distinctive trachytic tuff.

Andesitic lavas are compositionally diverse and not co-magmatic; MgO, K_2O, and LREE enrichments range widely but all andesites have low TiO_2, negative Nb-anomalies and REE patterns which lack Eu anomalies. The rhyolitic tuffs and lavas are compositionally similar, containing sparse plagioclase and biotite. The rhyolitic tuffs form multiple cooling units that are normally zoned. The rhyolites were also polygenetic, but were not derived from differentiated caps above "dominant volume" dacite magma bodies. Most rhyolites are low-SiO_2 varieties, but even high-SiO_2 rhyolites have low Fe/Mg ratios, small Eu anomalies, and only moderate concentrations of incompatible elements. The oldest rhyolites have relatively high concentrations of high field strength elements (Th, Zr, Hf, Nb, Ti) compared to other orogenic rhyolites. The three **dacite ash-flow tuffs** (individual volumes range up to 3000 km^3) are crystal-rich and contain plagioclase, biotite, hornblende, quartz, clinopyroxene, and Fe-Ti oxides; titanite also occurs in the youngest dacite sheet. The dacites form extensive simple cooling unit outflow sheets. Detectable differences within each unit are present but cannot be attributed to glass phenocryst fractionation during eruption; pumice compositions span a similar range. Subtle differences in elemental, Nd-Sr isotopic composition, and mineral compositions indicate small genetic differences between dacites. The dacitic tuffs appear to have acquired at least part of their compositional character by mixing of andesite and rhyolite magmas or by assimilation of continental crust by andesite. Nd isotopic compositions are similar to those expected for the Proterozoic basement beneath the caldera complex. The death of the magma system was marked by the eruption of a **trachytic tuff** with strong calc-alkaline affinities. It has an anhydrous mineral assemblage of plagioclase, clino- and orthopyroxene, and oxides. Like early rhyolites, this trachytic unit has relatively high concentrations of HFSE and low CaO. Nd isotopic ratios are higher and Sr isotopic ratios lower than in the dacites. This distinctive unit may have been produced by fractionation of andesitic magma within crust already depleted of its rhyolitic component by previous melting events or crust diluted by the input of mantle derived magma in the roots of the magma system.

Nd-Sr isotopic data and time-space patterns show that these dominantly high-K calc-alkaline rocks formed in an open magma system, driven by influx of mafic magma derived from a southward migrating thermal anomaly in the mantle. The southward migration may be associated with progressive foundering of subducting lithosphere away from the overriding continental plate. As the sweep stagnated in the southern Great Basin near the Indian Peak volcanic field, large volumes of mafic magma were inserted into the continental crust, apparently mostly as extensive horizontal sheets, or sills, in a non-extending, uplifting crust. These sills and the high mantle power input optimized crustal magma generation and dramatically modified the composition of the lower continental crust. The andesitic lavas, although only small volumes erupted, are derivatives of the mantle power supply. The dacites and rhyolites were produced by melting, fractionation and mixing in this dynamic setting.

CONTACT METAMORPHOSED GRANITOIDS: THEIR METAMORPHIC ZONATION AND IMPLICATIONS UPON EMPLACEMENT MECHANISMS.

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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, NSW) and the Gwydir River Adamellite (30 km W of Armidale, NSW) 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 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) 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 either 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.

THE LISCOMB COMPLEX: A MICROCOSM OF PERALUMINOUS GRANITE PRODUCTION IN THE MEGUMA ZONE OF NOVA SCOTIA

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The Liscomb Complex (ca. 250 km2), located in the Meguma Lithotectonic Zone of the Canadian Appalachians, consists of three main lithological components: high grade gneisses, mafic breccia pipes, and peraluminous granitoid plutons. Field relations, and $^{40}Ar/^{39}Ar$ dating (369-377 Ma) embracing all three lithological groups, show that the complex is post-Acadian. The gneisses occur as a domal uplift and represent a mixed volcano-sedimentary package that is structurally, metamorphically, and chemically distinct from the surrounding low-grade metawackes and metapelites of the Meguma Group. The mafic intrusions (quartz gabbro to quartz diorite) have major and trace element compositions (e.g. Ti-Zr-Y, Nb-Zr-Y, Th/Yb-Ta/Yb, REEs) typical of within-plate or volcanic arc materials. The peraluminous granitic rocks range from two-mica granodiorites to leucomonzogranites, and are mineralogically and chemically very similar to granitic rocks elsewhere in the Meguma Zone. Neodymium and strontium isotopic analyses show that: (i) the gneisses have a wide range of εNd and initial strontium isotopic ratios, with Nd model ages generally younger than those of the Meguma Group; (ii) the mafic intrusive rocks represent magmas derived from slightly depleted mantle sources (εNd + 3.3 to +1.4), in part modified by crustal contamination (εNd + 0.5 to -5.0); and (iii) the granitoid rocks isotopically overlap both the South Mountain batholith and the intermediate gneisses of the Liscomb Complex. Age-corrected lead isotope data show that the Liscomb intermediate gneisses could be source rocks for the Liscomb granitoids, however these gneisses can only be part of the source for other large peraluminous granitoids in the Meguma Zone. The combined field, petrological, and chemical evidence suggests that underplating by mafic magmas, followed by thermal doming of the gneisses, diapirism through the Meguma Group, anatexis, and multiple intrusion of both mafic and felsic magmas, best explains the observed relationships in the Liscomb Complex. This model may also apply to granite generation throughout the entire Meguma Zone.

MID-CRUSTAL CONTAMINATION OF GRANITIC MAGMAS

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In the Anmatjira Range, Arunta Inlier, central Australia, Proterozoic (1820-1760 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. Elsewhere in the Arunta Inlier, the dominant granitoids are megacrystic K-feldspar-biotite types, which typically are discordant to the gneisses and bear no mineralogical nor geochemical similarity to their host rocks.

The distinctive mineralogy of the granitoid 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 granitoids and they form a *continuous* geochemical lineage from 50-75% SiO_2 with the enclosing mafic granofelses. However, Nd isotopic signatures do not distinguish between the granites and country-rock types. All Nd isotopic data cluster together, yielding depleted mantle model ages of 2400-2200 Ma, which suggests a substantial inherited crustal component in all the granitoids.

Most granitoid sheets vary from metre- to kilometre-scale and comprise at least half the measured crustal thickness within any given area. Where abundant, the sheets contain isolated elongate lenses and layers of the host rocks, which are progressively coarser grained and acquire a granitic texture where the lenses are smaller. The final product is a heterogeneous banded or schlieric megacrystic granitoid composed of intruded magma and assimilated country-rock.

The granitoid sheets are surrounded by large migmatitic aureoles, similar to the regional-aureole granites of the Omeo and Cooma complexes in the Lachlan Fold Belt. The 10-20 km depth of emplacement 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 granitiods can occur in this environment. With repeated emplacement of granitoids 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 granitoid magmas. Either S- or I-type granites can be produced, depending on the chemistry of the enclosing country rock. Addition of a mid-crustal component at this stage controls the ϵNd-ϵSr mixing array that characterises the granitoids of most orogenic continental margins. Therefore, field and isotopic data suggest that many granitoids acquire their geochemical characteristics at mid-crustal levels.

THE MULTIPLE ORIGIN OF PERALUMINOUS GRANITES CONSEQUENCES FOR THEIR METALLOGENIC POTENTIAL

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Peraluminous granitoids represent about 70% of the plutonic activity of the European Variscan. They are characterized by a high peraluminous index, but show distinctive mineralogical, geochemical and genetic characteristics compared with the typical Australian S-type granites (White et al., 1986). According to their petrographical and geochemical characteristics, they have been subdivided into three groups, each of them being marked by either increasing or decreasing peraluminous index (I.A.=Al-K-Na-2Ca) with differentiation index (I.D.=Fe+Mg+Ti; variables A and B of Debon and Le Fort, 1983, in number of cations). Modelling by the least squares method of the different types of chemical variations observed in the various types of peraluminous granites, allows a quantitative evaluation of the amount of fractionating minerals or of magma mixing between acidic and intermediate melts.

-S-type granites, which exhibit a larger range of composition than the European peraluminous granites, typically show a strong decrease of their peraluminous index (I.A.) with differentiation (I.D). Such a trend, has been only observed in the Royère granites [N Millevaches complex, French Massif Central (FMC)]. It is best modelled by the fractionation of an aluminous biotite, cordierite and/or garnet together with quartz and plagioclase (An_{22-32}) that represent either restitic minerals (as in the "restite unmixing" model) or result from fractional crystallization. These granites present, however, a narrower range of compositions, lower K/Na ratios and higher aluminium content of biotite.

Except for the Royère suite, the other Variscan peraluminous granitoids present distinct fractionation trends. They have been subdivided in two groups :

-G-type granites [the *Guéret* batholith (5000 km2) in the North FMC taken as reference] are characterized by a slight increase of the peraluminous index despite large variations of ID. The peraluminous minerals cordierite and muscovite present no or very limited fractionation contrary to S-type granites. Th, Zr and REE content decrease slightly with differentiation. In the less peraluminous suites (Egletons granites, Millevaches), this type of chemical variation is best modelled by mixing the most differentiated granite facies with an intermediate metaluminous hornblende bearing magma. This model is consistent with the presence of microgranular enclaves in such granites. G-type granites do not present any metal enrichment. No significant metal deposit is related to them. The locally observed mineralizations are related to late leucogranite intrusions.

-L-type granites (from the *Limousin,* Western FMC, where they are well exposed and *Leucocratic*: less than 10% biotic) are muscovite±sillimanite±andalusite±garnet bearing. They were emplaced during the vanishing stages of the Variscan orogeny. Their peraluminous index shows a slight to strong increase for a limited variation of ID. The best model implies the fractionation of biotite, plagioclase (An_{30-40}), orthoclase and quartz. Zr, Th and REE contents strongly decrease with magmatic fractionation. Most Variscan economic U, Sn, W, Li, Ta, Be deposits are related to this type of granite. Variscan Au deposits are located in the surrounding metamorphic rocks a few kms off these granites.

Thus, peraluminous granitoids can be divided to different subtypes. Each of them presents distinct geochemical trends which result from distinct genetic models involving restite unmixing, fractional crystallization or magma mixing and probably distinct source materials. Lachlan Fold Belt S-type granites represent one of these subtypes. Their equivalents are absent in the European Variscan belt, or are represented only by a few granite suites marked by some of the typical S-type granite features as defined by White et al., 1986.

The emplacement of L-type specialized granites corresponds to an important thermal event in the Variscan belt. The thermal event is synchronous with the development of low pressure granulites in the lower crust of FMC (Pin and Vielzeuf, 1983). The U, Sn, Li, F, Rb, Cs, Be, W enrichment of these specialized granites is attributed to the dehydration of the lower crust during late Variscan granulitization. The volatile and metal-rich fluids are channeled by deep rooted lineaments and promote partial melting in the intermediate continental crust.

Redeposited and Primary Volcanic Facies in the Middle to Late Silurian Tumut Trough: deposition on an unstable continental edge.

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Middle to Late Silurian rocks of the Tumut Trough in the Lachlan Fold Belt of southeastern New South Wales, 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 indicate 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 western Tumut Trough the MDV is interstratified with marine sedimentary rocks including pebble conglomerate, sandstone and siltstone in both massive and graded beds, and units of chaotic limestone boulder conglomerate. These rocks were deposited primarily by mass flow processes. Pillow basalt occurs at the top of the sequence overlying and in part interfingering with the MDV. To the east the MDV occurs with bedded volcaniclastic rocks that grade upward from dacitic pebble conglomerate to laminated siltstone and chert and which were deposited from turbidity currents. Large allochthonous blocks of limestone and rare graded sedimentary rocks occur within the dacite outcrop in the east.

Most outcrops of MDV lack evidence for hot emplacement. Thus welding, columnar jointing and gas segregation pipes are notably absent, and no pumice has been recognised. East of the Tumut Trough, dacite welded tuffs are lateral equivalents of the dacitic volcaniclastic rocks and probably mark the subaerial eruptive source region.

The MDV lacks stratification or other sedimentary structures implying very rapid accumulation from dense flows. Phenocryst content in the dacite is typically 40-50%. This high crystal content probably added to the buoyancy of the flows increasing their competence and mobility and also inhibiting the development of grading.

The interstratification of dacitic volcaniclastic rocks of mass flow origin, turbidites, and chaotic limestone boulder conglomerate indicates that the succession was deposited at the foot of an unstable slope. The S-type geochemical character of the dacite and associated cogenetic granitoid indicates a continental source. This places constraints on the tectonic setting of the Tumut Trough in the Middle to Late Silurian. Previous interpretations 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 and Powell, 1976; Ashley et al., 1979) and the upwelling of hot mantle and crustal stretching along a transform fault (Packham, 1987).

The presence of marine basalt, turbidites, limestone and large volumes of dacite favour an arc environment. The 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 UNITED STATES

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An origin for the ore fluids that deposited iron, copper, rare earth elements (REEs), and gold in Olympic Dam-type deposits remain enigmatic. However, recent research on the Pea Ridge deposit, Missouri, U.S.A., places important limitations on genetic models of magnetite-hematite ore deposits hosted in anorogenic granite-rhyolite terranes worldwide. New trace element data indicate that the Pea Ridge deposit formed from magmatic ore fluids that may have been derived as immiscible liquids from magmas of the host terrane. Middle Proterozoic anorogenic igneous rocks of the St. Francois Mountains represent the root zone of an eroded volcano-plutonic complex. Subvolcanic biotite granite massifs are overlain by comagmatic high silica rhyolite, which erupted from caldera complexes that locally underwent resurgence. Amphibole granite and an iron-rich trachyte suite form ring dykes along the caldera margins. The magnetite-hematite ore deposits are hosted dominantly in high silica rhyolite and were emplaced during the waning stages of igneous activity.

The Pea Ridge deposit is an apatite-rich magnetite orebody that intrudes the host metaluminous to peraluminous high-silica rhyolite. The deposit is crudely zoned, with an early amphibole-quartz-magnetite zone (skarn?) that is cut by the magnetite orebody. The top and footwall sides of the depsoit are mantled by a hematite zone. A massive, silicified zone is present in the footwall. REE-rich breccia pipes cut the footwall zone. The breccia pipes exhibit fluidisation textures, with clasts of iron ore and host rock supported in a matrix of monazite, barite, xenotime, apatite, and rock flour. Sanidine phenocrysts in the REE-bearing breccia pipes verify an igneous source for the breccia pipe matrix. Primary fluid inclusions in quartz from the breccia pipes have varying liquid-to-vapour ratios, indicative of entrapment of fluids having variable vapour contents characteristic of boiling.

Sulphur and oxygen stable isotope data indicate that the Pea Ridge ore fluids were magmatic. Delta ^{18}O quartz-magnetite equilibrium temeratures show that the ore solutions were hot, clearly in the temperature range of magmatic systems, but cooled through time. Quartz-magnetite pairs from the amphibole-quartz-magnetite zone yields a temperature of 680°C, one pair from the core magnetite zone yields a temperature of 480°C, and one pair from the younger hematite zone is about 395°C. A barite-pyrite pair, in apparent textural equilibrium from a late-stage REE-bearing breccia pipe, yields a temperature of about 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.

Modelling of trace element geochemical data indicates that the magnetite ore deposit formed as part of an immiscible melt generated from the iron-rich trachyte suite. Neither fractional crystallisation nor partial melting processes can account for the observed compositions. We propose that the REE-bearing breccia pipes formed as fluids derived from the magnetite ore system. As these fluids evolved, they underwent secondary boiling and caused catastrophic brecciation during emplacement of the REE-bearing breccia pipes.

TOWARD A GENERAL MODEL FOR GRANITIC MAGMA GENESIS: GROUND RULES FROM ISOTOPIC STUDIES OF GRANITES AND RHYOLITES.

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One of the most contentious issues regarding granitic petrogenesis concerns the source of the magmas. Many consider the crust to be the primary source of granitic magmas, although those holding this view grant that heat for crustal fusion could be provided by basaltic magma. The other view is that granitic magma is primarily generated by crystal fractionation of basaltic magma, this process generally being accompanied by some assimilation of crustal material, the amount of which can vary from substantial to inconsequential.

Isotopic ratios provide the best hope of determining source materials for magmas. Neodymium isotopes in particular are especially useful because in areas of Precambrian continental crust there is typically a substantial difference in Nd isotopic composition between the continental crust and the mantle magma source materials.

Based on Nd isotopic studies of Mesozoic and Cenozoic granitic rocks in the western U.S. it was proposed that granitic magmas formed by both mechanisms (Farmer & DePaolo, JGR, 1983; 1984) and that the parameters that determined the amount of crustal material present in the end product granitic liquid were the thickness of the crust and the flux of basaltic magma entering the crust. Thin crust and high basalt flux were associated with granitoids that had the isotopic characteristics of differentiates from mantle derived basalt; thick crust and low basalt flux were associated mainly with granitoids that had the isotopic characteristics of the crustal country rocks. This model was modified slightly and called MASH by Hildreth and Moorbath (CMP, 1988).

Recent work by a number of investigators on the Cenozoic large-volume rhyolite occurrences of the western U.S. also show that the crustal contribution to large volume rhyolites varies from very large (>80%) to small (<10%). The crustal contribution, however, shows no correlation with crustal thickness, or with total volume erupted for each volcanic center. Intermediate composition lavas generally show the same amount of crustal contribution as rhyolites, so the incorporation of crustal material occurs mainly as basalt differentiates to andesite in the lower crust. The variation in average crustal contribution from center to center is almost totally accounted for by one parameter - age of the center. All early Oligocene (35 Ma) centers have large crustal fractions (ca. 80% crustal Nd). All late Oligocene (27 Ma) centers have intermediate crustal fractions (ca. 55% crustal Nd). All Miocene and younger (<17 Ma) centers have low crustal fractions (10-30% crustal Nd).

Our interpretation of these data (Perry *et al.*, 1991) is that all of the systems are driven by the influx of basaltic magma to the lower crust, and that the crustal fraction is determined mainly by the ambient temperature at the Moho at the time of volcanism. Crustal thickness plays a role only insofar as thicker crust has higher Moho temperature for the same geothermal gradient. There is evidence that basalt magma flux also plays a role, because for two major centers (Jemez in New Mexico and Yellowstone in Wyoming) there is a correlation of Nd isotopic ratio with eruption rate. Our interpretation of the temporal trend for the Cenozoic rhyolites is that the regional Moho temperature decreased between 35 and 17 ma; simple models of energy balance suggest a decrease from ca. 850°C to less than 600°C corresponding to a ca. 50% increase in lithospheric thickness.

These conclusions are compatible with the earlier work on granites. It is inescapable that most large volume rhyolites (and many granitoids) are formed by crystal fractionation from basalt precursors. The accompanying assimilation of silicic rocks increases the amount of rhyolite produced from a given volume of basalt, so the volume ratios (total basalt/total rhyolite produced) are in the range 2 to 5. The observations bring us close to the possibility of a predictive model for the system evolution, with the major controlling parameters being the initial crustal temperature (modified by crustal composition) and the basalt magma flux.

Can crustal granites exist without mantle basalts ? Some thoughts on the rarity of restites.

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Experimental investigations suggest that melting of various crustal rocks never exceeds 50 %, and leaves a crystalline residue mainly made of aluminous and mafic minerals (Vielzeuf et al., 1990). However, the scarce restites present in most crustal granites represent only a minute proportion of the amount of residue that should be found. Il is then basic to discuss about what happens to the large amount of residue that does not occur as restitic enclaves.

In the Massif Central, France, which is a vast segment (100.000 km^2) of the Hercynian belt of Western Europe, granitoids range in compositions from granites to tonalites. Most of them are intrusive ; only some others associated with migmatites, contain an amount of restites as large as those predicted by experimental works. In the large Velay anatectic complex (80 x 150 km), biotite and cordierite-bearing granitoids contain a huge amount of fragments of metasedimentary or metaigneous restites and restitic crystals (Didier, 1964, 1973 ; Dupraz and Didier, 1988). Restitic materials are also abundant in the deepest parts of the leucogranitic complex of Millevaches (Lameyre, 1966). In contrast, restites are scarce or even absent in most intrusive plutons, whereas mafic microgranular enclaves (Didier and Roques, 1959 ; Didier, 1964, 1973) represent about 1 percent of their volume.

Two main hypotheses are proposed to explain what happens to the melting residue (or resulting restites) of these granitoids which origin is dominantly crustal (Duthou et al., 1984 ; Pin,1990) :
(1) Restites are almost entirely separated fom the low-viscosity granitic magma, and remain in the source area.
(2) Restites are thoroughly disrupted into isolated crystals which are dispersed in the granitic magma (Chappell et al., 1987).

On the other hand, the concept that mafic microgranular enclaves might represent restites still impregnated with some anatectic magma (Chappell et al., 1987) is not convincing. In the case of the Massif Central, all investigators consider that these enclaves are produced by non achieved mixing between mafic and granitic magmas (e.g. Didier, 1964, 1973 ; Barbarin, 1988 a and b ; Belin, 1988 ; Binon, 1988 ; Pin et al., 1990). The mafic magma is of basaltic nature and comes from the upper mantle ; injected into the continental crust, it induces melting of continental rocks and production of a granitic magma with which it mixes more or less completely (Didier and Lameyre, 1969).

Finally, the occurrence of mafic microgranular enclaves may explain the scarcity of restites. Mafic magmas injected into the crust produce through extensive crustal anatexis, hotter and more mobile granitic magmas in which convections are very active (Huppert and Sparks, 1988). In such conditions residues of melting are dispersed as discrete restitic crystals in apparently homogeneous granitic magmas. In contrast, where anatexis is not induced by mafic injections (e.g. Velay anatectic complex), it is less active and the absence of convection leaves the granitic magmas heterogeneous and full of restites.

CHARACTERISATION AND PETROGENETIC SUBDIVISION OF A-TYPE GRANITOIDS

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A data bank of published and unpublished analyses has been established for the A-type granitoids (and felsic volcanics) from a variety of geologic 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 granitoids, 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 granitoids generally have higher abundances of Ga, Nb, Y, REE (except Eu), Ta, Zr, Hf, and Th than I- and S-type granitoids at a similar stage of magmatic evolution. These observations suggest that most, if not all, A-type granitoids are NOT the product of extreme fractionation of I-type magmas.

On the basis of the chemical data, the A-type granitoids can be divided into two groups. One group consists of suites from oceanic islands, rift zones and regions of crustal doming. These suites often, but not always, have associated mafic rocks. They are characterised by a number of trace element ratios (such as Y/Nb and Yb/Ta) similar to those of oceanic island basalts. Associated volcanics show the same chemical patterns and are also included in this group. Given the suggested plume origin for oceanic island basalts, it is suggested that this subgroup be given the designation "P" (for plume). The second group consists of suites which have higher Y/Nb and Yb/Ta ratios, are generally less enriched in incompatible elements and which 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. Given the apparent lithospheric origin of these suites it is suggested that this subgroup be given the designation "L" (for lithospheric). The Gabo and Mumbulla suites of the Lachlan Fold Belt belong to this subgroup, and the data obtained for these suites have been influential in the development of petrogentic ideas concerning the A-type granitoids. It is thus worth noting that these ideas are most likely not applicable to the "P" subgroup.

A number of elemental screens have been developed to facilitate the identification of the A_P and A_L subgroups. The most useful screens are those utilising Y/Nb, Yb/Ta, Ga/Al, and Rb/Nb ratios. In the case of the A_P type, these screens are effective even for suites which have undergone significant crustal contamination. This is due to the high absolute abundance of many of the incompatible elements which effectively buffers the elemental ratios against changes due to crustal additions.

THE CRETACEOUS SILICIC VOLCANIC PROVINCE OF EASTERN QUEENSLAND, AUSTRALIA: A SEGMENT OF THE S.W. PACIFIC RIFT RELATED PROVINCE

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Silicic and minor intermediate and mafic pyroclastics, lavas, and dykes occupy a NW trending zone through the Whitsunday, Cumberland and Northumberland island groups, and local areas on the adjacent mainland, for a distance of 370 km along the central Queensland coast. K-Ar and Rb-Sr data indicate an age range of 95-132 Ma, with the main activity (within exposed sequences) between 100-117 Ma. Associated, broadly comagmatic granites occur, some clearly intrusive into the volcanics, together with two localised areas of Triassic potassic granites (229 Ma), forming the intermediate basement.

The volcanics are dominantly rhyolitic to dacitic lithic ignimbrites, with intercalated surge and bedded tuffs, accretionary lapilli tuffs, and lag deposits. Associated rock types include isolated rhyolite and dacitic domes, together with volumetrically minor andesite flows. The sequence is cut by abundant dykes, especially in the northern region and adjacent mainland, ranging from dolerite through andesites to dacites and rhyolite (dominant). Dyke orientations show maxima between NW-NNE. Isotope data, similarities in petrography and mineralogy, and alteration pattern all suggest dyke intrusion to be broadly contemporaneous with volcanism. The thicknesses of the volcanics are unknown, but in the Whitsunday area a minimum of 4 km is estimated. Eruptive centres are inferred to occur throughout the region, and two major areas of caldera-style collapse are proposed. Much of the volcanic sequences are thus interpreted as intra-caldera facies.

A characteristic feature of the volcanics and dykes is their regional, pervasive low grade hydrothermal alteration. Primary phenocryst phases and compositions are, nevertheless, widely preserved (except orthopyroxene); these comprise plagioclase (An_{28-60}), augite, and Fe-Ti oxides in silicic volcanics; quartz, hornblende, and especially biotite are less common. Silicic dykes are more commonly quartz + hornblende ± sanidine ± biotite-bearing, while the silicic domes are normally near aphyric. Andesite dykes and flows are phenocryst-rich with plagioclase (An_{40-80}) - pyroxene - Fe-Ti oxide; dolerites are charcteristically near aphyric. Augite and hornblende are relatively magnesian, and overlap (in terms of Mg, Fe, Ca) throughout the various volcanic types and compositions. Fe-enriched compositions are only rarely developed in the high-silica rhyolites. Some mixed phenocryst populations are evident. Overall, the mineralogy is similar to modern W. Pacific orogenic lavas. Cretaceous granites vary from granite to less common granodiorite (rarely quartz diorite), characteristically with graphic and porphyritic textures.

Chemically, the volcanics and dykes exhibit continuous variation from mafic to silicic endmembers, with medium- to high-K affinities. Overall, they exhibit similarities to modern W. Pacific calc-alkaline orogenic suites, although not as consistently depleted in the HFSE. The arc-like trends are exemplified by plots of Ba/Nb-La/Nb and Th/Yb-Ta/Yb. REE patterns are LREE enriched, with La/Yb ranging between 5-7 (dolerites), 6-9 (andesites), and 7-10 (rhyolites). Pronounced Eu/Eu* anomalies occur in the high-silica rhyolites. Within-suite variations can be modelled in terms of crystal fractionation and magma mixing. Nd and Sr isotope compositions form a coherent data set for all rock types, with εNd +2.2 to +9.0, and I_{Sr} = 0.7032 - 0.7040 (calculated at 110 Ma). These compositions are more primitive than the New England and Lachlan Fold Belts to the south, and imply mantle and/or juvenile crustal sources.

The arc-like geochemistry of the volcanics is interpreted to be inherited from partial melting of Palaeozoic crustal and lithospheric sources resulting from the long history of subduction-related volcanism in Eastern Queensland. The tectonic setting for Cretaceous volcanism is correlated with rift basin or trough formation during the early stage of continental breakup, culminating in the opening of the Tasman Basin. Cretaceous volcanism is also recognised in the Maryborough Basin (S. Queensland), the Lord Howe Rise, and New Caledonia, indicating the regional extent of volcanism associated with the complex breakup of the whole eastern Australasian continent.

MAGMATIC EVOLUTION OF LATE PROTEROZOIC ULTRAPOTASSIC SYENITES IN NORTHEASTERN BRAZIL AND METASOMATIC MANTLE SOURCE

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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 dikes, 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 crystallization at low pressures. Amphiboles are mostly K-rich richterite, characterized by high SiO_2, low Al_2O_3 and TiO_2 contents and low Mg#.

The three rock types are characterized by an overall enrichment in incompatible elements, with negative spikes at Nb, Sr, P and Ti in spidergram-type diagram. They have similar REE chondrite-normalized 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 that ones for the pyroxenites and syenites in both REE and spidergram diagrams.

The rocks have similar, high $\delta^{18}O$ values (avg w.r. +8 permil SMOW, corrected from pyroxene), similar, high $\delta^{34}S$ (avg. +11 permil CDT), similar, high $^{87}Sr/^{86}Sr$ initial ratios (about 0.710) and similar, low $^{143}Nd/^{144}Nd$ ratios (avg 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

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Careful study of structures in metasedimentary inclusions in granites can provide significant information on the structural style and deformation history in the granite source area up to the time of melt generation. This is most practical and of most interest where the inclusions are pelitic and record multiple deformations that are more numerous than imprinted in the country rocks at the time of intrusion. The results of such (often microstructural) investigations can add important details to the view through the 'window' to the source that is now given by the currently fashionable inclusion work employing mineralogical, petrological and geochemical data and arguments. The structural aspects of the better view obtained can give useful constraints about the nature and identity of the source rocks and their structural/tectonic history.

The approach described is relatively simple but its potential seems to have been largely unexploited. Futhermore, similar studies of metasedimentary inclusions across a wide region could provide fundamental and otherwise rarely obtainable geological information on large expanses of unexposed crust. These investigations could be particularly rewarding if combined with other remotely obtained data (e.g. geophysical evidence such as deep seismic profiling and/or isotopic evidence such as in the the traverse of SE Australia described by Gray (1990, Aust. J. Earth Sci.,3,331-49). Structural studies on metasedimentary inclusions could thus confirm or modify existing tectonic models involving deeper levels of the crust. It is conceivable, for instance, that sudden and consistent changes in the structural histories recorded in metasedimentary inclusions collected along a regional traverse could mark suspected (or unsuspected) boundaries between terranes or basement terranes.

The more local approach is illustrated using examples of pelitic inclusions from the Yabba Adamellite near Tallangatta in the NE Victorian part of the Lachlan Fold Belt (LFB). This approximately 412 Ma pluton intruded before and during the first discernible penetrative deformation in the Early Ordovician low grade country rocks, yet pelitic inclusions record up to at least four deformations in their microstructure. As first suggested in Fleming *et al.* (1985, Abst. Vic. Lithosphere Sympos. Melb.,14-15) the inclusions and the granite have therefore been derived from a source with a tectonic history much longer than that of the exposed Early Ordovician rocks (locally named the Lockhart terrane). The source is therefore probably a complexly deformed, metasedimentary terrane of pre-Ordovician age. Rocks similar to the inferred source happen to be exposed as the otherwise somewhat enigmatic Gundowring terrane, a multiply deformed complex of gneissic and migmatitic metasediments and granites in fault contact with the Lockhart terrane.

Examples of microstructures in pelitic inclusions from two other plutons in the LFB will also be discussed. In particular, some from the Cobaw Granite Complex, over 200 km across the LFB from the Yabba pluton also record more deformations than in their adjacent country rocks. A program to sample metasedimentary inclusions in plutons from eastern Victoria across the whole LFB and into South Australia should therefore be rewarding and is belng planned. Similar programs elsewhere in the LFB and across other granite-studded belts in the world should also be fruitful, provided of course that plutons containing suitable metasedimentary inclusions occur in the regions of interest.

A PRESSURE-QUENCH CUMULATE ORIGIN FOR MICROGRANITOID ENCLAVES

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The currently popular model for the formation of microgranitoid enclaves as quenched magma globules may account for their fine-grained igneous microstructures but does not readily explain; (a) the often similar mineralogy of enclaves to their host pluton; (b) the unusual chemistry of many of the more mafic enclaves; (c) the common presence within the enclaves of phenocrysts similar to minerals of the host pluton ; (d) the observation that enclaves within S-type granitoids are themselves mostly S-type or; (e) the paucity of enclaves in the more leucocratic granitoids. An alternative model that microgranitoid enclaves are either restite, modified restite or resistite might explain some of the mineralogical similarities of enclave and host, the common observation that many enclaves have chemical compositions not likely to have originated as melts and offers an explanation for the paucity of such enclaves in leucogranitoids. However this model does not readily explain the fine-grained igneous microstructures or the observation that microgranitoid enclaves characterize high-level plutons and mineralogically show little evidence of being derived from depth.

We argue that for most enclaves, the mineralogy and microstructure are primary characteristics and are not the result of minerals of originally different composition being "made over" by reaction with the host magma. We would agree with those authors who suggest that the mineralogy and chemistry of most microgranitoid enclaves indicate that they are cumulates formed from magmas similar in composition to the host pluton. However this model has not been widely accepted because of the common belief that all cumulate rocks are coarse-grained.

A mechanism that explains the fine- to medium-grained cumulate mineralogy and chemistry of microgranitoid enclaves involves their formation as cumulate crystal rafts formed near the roof of the crystallising magma chamber as a result of pressure-quench events brought on by roof rupture, where water pressure exceeds load pressure. The pressure-quench events must not undercool the magma to the degree that prevents the enclaves from extracting components within a large volume of melt. Release of the water overpressure will significantly "undercool" the magma as the liquidus and solidus are displaced to higher temperatures at lower water contents. Such undercooling will initiate rapid and quench-type crystallisation. Importantly, the drop in water activity shrinks the crystallisation fields of quartz and K-feldspar, explaining in part why one or both of these minerals are depleted in the enclaves relative to the host. The continued supression of the near-solidus mineral(s) is due to the heat of crystallisation. Nucleation of quench-minerals on existing phenocrysts (eg K-feldspar and quartz) already in the magma explains the presence of these phenocrysts in the enclaves. Water released from the magma may isolate the solid sides of the magma chamber from the undercooled magma thus preventing crystallisation directly on the walls.

We suggest that the variation in enclave composition depends on the range of magma compositions present in the pressure-quenched volume and on the degree of undercooling. The paucity of microgranitoid enclaves in leucogranitoids reflects the difficulty of obtaining cumulates from magmas of near-eutectic composition and the potential for quenched leucogranitoid enclaves to melt as they sink into the magma. The pressure-quench model explains why microgranitoid enclaves are characteristic of hydrous magmas that crystallise biotite and/or hornblende and are not common in pyroxene bearing monzonites and diorites.

TEXTURAL AND CHEMICAL ZONING IN THE FRANCOIS PLUTON, NEWFOUNDLAND

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The Francois pluton of southern Newfoundland, in contrast to most zoned plutons that show considerable chemical variation perhaps accompanied by structural and microstructural change, exhibits only minor chemical variation but is strongly zoned microstructurally. Published airborne radiometric variations in U, Th and K closely follow the microstructural zonation.

The Francois Pluton outcrops as two lobes with the south-west lobe truncating the north-east lobe. Rb/Sr bulk rock data indicate an age of 383.0 +/- 8.7 Ma while the average of 3 biotite/bulk rock pairs give a younger age of 371 +/- 4 Ma. Initial $^{87}Sr/^{86}Sr$ ratio is 0.7048 +/- 0.0006. The pluton has sharp crosscutting contacts with the meta-granitic rocks into which it is emplaced. It has few if any xenoliths or enclaves and is cut by only a few aplitic dykes. Microcline is the K-feldspar in all microstructural zones regardless of grain-size, a factor probably related to minor deformation.

Both lobes of the Francois pluton are concentrically zoned, with an outer medium-grained marginal granite grading inward to a coarse-grained leucogranite. The leucogranite in turn has a sharp contact with an inner microadamellite that gradationally coarsens to adamellite in the centre of the pluton. Although the bulk-rock chemistry changes only slightly, the coarser grained variants have a much higher K-feldspar to plagioclase ratio than the finer grained parts of the pluton causing much of the modal variation in the pluton to be heteromorphous.

It is argued that the changes in microstructure and trace element chemistry result from changing water pressures during crystallisation. A two-stage crystallisation history is envisaged. Initial water pressure build-up during the formation of the outer medium-grained granite to coarse-grained leuco-granite, results in an increase in grain-size and as a consequence, a shift in the feldspar cotectic that causes a progressive increase of albite solid solution in the K-feldspar. Modally this effect is observed in the coarser grained rocks where K-feldspar increases relative to plagioclase. The second stage of crystallisation is marked by the sharp contact of the coarse-grained leuco-granite with the inner microadamellite. It is envisaged that the abrupt change in grain size is produced by the sudden loss of water pressure initiating quench conditions. The pressure-quench event, which produced the narrow zone of microadamellite with microstructures similar to those of microgranitoid enclaves, can be traced over several kilometers in the south-western lobe and a similar zone has been observed in the north-east lobe. These microadamellite zones probably represent a major roof fracture and/or the onset of an eruption although nowhere are associated volcanics presently recognised. The coarser grained adamellite in the centre of the pluton indicates a gradual change in the second stage of crystallisation to increased water pressures.

MAGMA MINGLING AND THE ORIGIN OF THE MANNUM A-TYPE GRANITE SOUTH AUSTRALIA

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The Mannum pluton is a potassic, rapakivi, (A-type) granite that was intruded at high crustal levels at about 485 Ma. It is part of a regional bimodal magmatic association occurring at the end of the Delamerian Orogeny. This granite contains numerous dioritic enclaves which result from dispersal and mingling of a mafic magma when both phases were at least partially liquid. Evidence for mingling of melts, rather than inclusion of solid xenoliths, is provided by the physical shape of the enclaves which are amoeboid, with plastically deformed outlines. They include and react with alkali feldspar phenocrysts from the host granite and have hybrid margins. Geochemical profiles from enclave core to host granite show classical sigmoidal shapes suggestive of diffusional exchange. Although the profiles of many elements (eg. Rb) can be modelled as such a diffusional process, profiles for some elements are more complex, and originate by reaction "front" migration. P, the rare earth elements, Y and Zr, for instance, are enriched in the margins of the enclaves, their concentrations controlled by the preferential growth of sphene, apatite and zircon. The abundance of these minerals are in turn promoted by diffusion controlled activity gradients between mafic and felsic magma.

The mafic enclaves and adjacent granite show initial Sr-isotopic homogeneity indicating that diffusional exchange between mafic and felsic liquid was efficient at the time of granite intrusion. The "screen" of mafic droplets is either the draw-up of a lower layer of a layered magma chamber or the intersection the cooling granite body by dyke, forming a curtain of mafic droplets. 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, convective motion having either largely ceased or become non-turbulent.

Our evidence for temporal and spatial association of mafic and felsic magmas provides a clear solution to thermal budgetary problems that may seem to be associated with these types of 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.

SIGNIFICANCE OF GARNET-BEARING I-TYPE VOLCANICS AND HIGH-LEVEL INTRUSIVES FROM NORTHLAND, NEW ZEALAND

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Rare garnet phenocrysts and garnet-bearing xenoliths occur in high-silica andesites and dacites (and their high-level intrusive quartz diorite equivalents) from a Miocene calc-alkaline province in Northland, New Zealand. These garnets are among the most grossular-rich (18-25 mol%) garnets of igneous origin so far recorded in calc-alkaline suite rocks. Associated minerals are dominant hornblende and plagioclase and minor augite, occurring as phenocrysts, in xenoliths and as inclusions in garnet itself. This mineralogy points to the I-type character of the garnet bearing host magma compositions, and contrasts this garnet occurrence with the more frequently recorded grossular-poor (3-10 mol%) garnets with hypersthene, plagioclase, biotite and cordierite, found in S-type volcanic and intrusive host rocks.

The host rocks for the Northland garnets span the normative composition range from metaluminous to peraluminous and, together with a mixed metaluminous (hornblende, augite) and peraluminous (garnet) phenocryst mineralogy, provide a natural example of the piercing of the low-pressure thermal divide between such compositions. This is achieved via hornblende (mainly) and augite crystallization at elevated pressure, under hydrous conditions (cf. Ellis and Thompson, 1986; Conrad et al 1988). Detailed experimental work on a glass prepared from one of the garnet-bearing dacites provides close constraints on the conditions under which the natural phenocryst and xenolith mineral assemblages formed.

Experiments were conducted over a pressure-temperature range of 8-20kb, 800-1050°C with 3-8% by weight of added water, defining overall phase relationships for these conditions. Importantly, amphibole only appears at temperatures <900°C and clinopyroxene at >900°C (with 3% H_2O). Orthopyroxene occurs with garnet at lower pressure (~ <15kb with 3% H_2O and ~ <11kb with 5%H_2O). Absence of orthopyroxene from the natural garnet-bearing assemblages indicates pressures above these limits. Plagioclase is markedly suppressed (with respect to temperature) with increasing water content, and for pressures of 10-15kb, the maximum water content possible with retention of clinopyroxene and plagioclase together (as evident in xenoliths) is 5-6% by weight. Finally the lack of quartz in any of the xenoliths suggests water content higher than 3% (where quartz appears with amphibole at 900°C), since the quartz liquidus temperature decreases with increasing water content, and with decreasing pressure. In experiments with 5% H_2O a quartz-free field of garnet-amphibole-plagioclase occurs between 10 and 15kb and temperatures between 850 and 900°C. In addition, detailed experimentally documented compositional trends, together with data for specific experiments with 5% H_2O added and run at 10-13 kb and 850-900°C, suggest that the natural assemblages formed at these conditions. This implies that the parental magma for the dacite must have been derived at mantle depths (the Northland crust is <30km thick), and any basaltic or basaltic andesite precursor must have contained >2-3% wt of water.

The unique nature of the Northland volcanics, preserving evidence of relatively grossular-rich garnet fractionation in the high-pressure crystallization history of an originally mantle-derived magma is attributed to a combination of unusually hydrous conditions in the source region, complex tectonic history involving obduction/subduction, possible incorporation of crustal slivers in a mantle-crust interaction zone and relatively thin (<30 km) crust.

EARLY PROTEROZOIC CALCALKALINE MAGMATISM IN THE HOOPER COMPLEX, WEST KIMBERLEY, WESTERN AUSTRALIA

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The Hooper Complex in the West Kimberley region of Western Australia contains the third largest area (5000 km^2) of Early Proterozoic felsic igneous rocks in Northern Australia, after Halls Creek (9600 km^2) and Pine Creek (8700 km^2). Available geochronological data indicate that these rocks crystallized at about 1840-1850 Ma.

Most of the Hooper Complex comprises a calcalkaline suite of comagmatic volcanic, hypabyssal and granitoid rocks which are dominated by monzogranite. Coarse K-feldspar phenocrysts are characteristic of the extrusive rocks.

The extrusion of felsic volcanics and the intrusion of associated granitoids are part of the main orogenic event in the West Kimberley region, the Early Proterozoic Hooper Orogeny. The felsic igneous phase followed high-grade metamorphism which affected deformed, interlayered, turbiditic sedimentary rocks and mafic sills, and was synchronous with the second deformation (D_2). At least some of the volcanic rocks were also folded during D_2, prior to intrusion of the granitoids. Small areas of anatectic granitoid associated with high-grade metamorphism of sedimentary rocks have S-type characteristics, containing less than half the levels of CaO and Na_2O of the dominant I-type granitoids.

A pronounced tectonic foliation is widespread throughout the felsic igneous suite, and is associated with widespread metamorphic recrystallization under greenschist and amphibolite facies conditions during the 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. However, the Hooper Complex lacks bimodal magmatism present in these other suites. It contains a small amount of mafic rock which appears to be part of the same calcalkaline suite as the granitoids. On an AFM diagram the rocks, although enriched in alkalis, plot well below the tholeiitic trend, thus indicating their calcalkaline affinity.

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 is 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 north, with the craton to the south 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.

ORIGIN AND TECTONIC SETTING OF THE RAPAKIVI GRANITES OF SOUTH-EASTERN FENNOSCANDIA

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Recent petrological, geochemical, isotope geochemical, and geophysical studies have brought out abundant new information that can be used to evaluate models for the origin and tectonic regime of the rapakivi granites of southeastern Fennoscandia.

The epizonal 1.65 to 1.54 Ga rapakivi granite complexes represent the prevailing acid members of a bimodal magmatic association in which the basic members are penecontemporaneous tholeiitic diabase dykes and minor gabbroic and anorthositic bodies. The diabase dykes transect the orogenic Svecofennidic 1.9 Ga crust as extensive, mostly WNW-trending swarms, suggesting extensional tectonic regime. Several acid-basic composite dykes verify the simultaneous existence of basaltic and rhyolitic magmas.

Geochemically, the rapakivi granites with their high K, Rb, F, Ga, Zn, Nb, Zr, Y, and REE contents and negative Eu anomalies fit well metaluminous to slightly peraluminous A-type granites or within-plate granites, but show similarities also with post-collisional granites (Haapala & Rämö, 1990).

Sm-Nd isotopic studies indicate that the time-integrated Nd isotopic evolution of the rapakivi granites ($\epsilon_{Nd}(T)$ values range from -2.9 to -0.2 for the 1.64 Ga granites of southeastern Finland and from -3.1 to -1.4 for the 1.58 Ga granites of southwestern Finland) corresponds to the evolution of the 1.9 Ga Svecofennidic crust. Alkali feldspar Pb isotopic data show S&K μ_2 values from 9.57 to 9.98 which also fit the evolution of the 1.9 Ga crust (average μ_2 9.94). Accordingly, the isotopic data suggest that the Finnish rapakivi granites represent remelted Svecofennidic crust. The 1.54 Ga Soviet Karelian rapakivi granites, located at the border zone between the Archean basement and the 1.9 Ga crust, show isotopic composition indicative of significant incorporation of Archean crustal material ($\epsilon_{Nd}(T)$ values -8.1 to -5.7, alkali feldspar S&K μ_2 values about 8.7; Rämö et al., 1990).

Recent deep seismic soundings (Luosto, 1990) show that the Finnish rapakivi granites are located in areas of low crustal thickness; in the Wiborg rapakivi area in southeastern Finland the crust is only about 40 km thick, but gets gradually 10-20 km thicker within 100-200 km toward northeast and southwest.

The data support the model that the rapakivi granites originated in extensional tectonic setting by remelting of pre-existing (lower) continental crust. The melting was presumably related to mantle upwellings, which also may be the reason for the extensional tectonics and the bimodal (mantle-derived and crust-derived) character of the magmatism.

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Petrologic characteristics of magmatic epidote-bearing granitoids of the western cordillera of North America

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Cretaceous magmatic epidote-bearing plutons occur in a discontinuous belt within the accreted terranes of the western margin of the North American cordillera. The Admiralty-Revillagigedo plutonic belt of SE Alaska (Brew and Morrell, 1983, Geological Society of America Memoir 159, p. 171-193) comprises a regionally extensive suite of diorites, quartz diorites, tonalites, and granodiorites that has been sampled from Ketchikan to Juneau. Similar magmatic epidote-bearing rock types are present in the Ecstall pluton of British Columbia and in the Tenpeak and Oval Peak plutons of the northern Cascades of Washington state. A more evolved suite (tonalite to trondhjemite) is present along the western margins of the Idaho batholith. The characteristic mineral assemblage is hornblende (aluminous ferroan pargasite), biotite, epidote (±allanite core), plagioclase (An15 to An50), quartz, orthoclase, ilmenite ±magnetite±sphene, ±garnet, and apatite. These rocks are predominantly metaluminous (molar A/CNK=0.6 to 1.3), plot along calcalkaline trends on AFM diagrams, and although they tend to be calcic (Peacock index), aluminum and alkalis show considerable scatter on variation diagrams. Limited trace element data show that these rocks are high in Sr (300 to 1404 ppm) and low in Rb (3-79 ppm) and resemble relatively primitive island arc granitoids. Oxidation ratios are low (whole rock FeO/Fe_2O_3 ranges from ~1 to 16), and in contrast to many magnetite-rich calcalkaline intrusive suites, the relatively reduced nature of the rocks is reflected in the mineralogy as follows: (1) opaque minerals included in hornblende and biotite are always ilmenite or, less commonly, sulfide is present; (2) modal ilmenite>magnetite; (3) sphene rims some ilmenite but is not ubiquitous as a primary constituent; and (3) Fe^{3+}/Fe_{Total} for biotite (~0.06 to 0.17) and hornblende (~.19 to .31) and pistacite contents of epidote (10 to 30 mole percent) indicate redox states near or slightly more oxidizing than those defined by the nickel-bunsenite buffer. For both biotite and hornblende, mg# (Mg/(Mg+Fe), for total iron as Fe^{2+}) ranges from about 0.3 to 0.6. However, mg# for hornblende is slightly <u>lower</u> than, or overlaps, the range in mg# for coexisting biotite, unlike most other calcalkaline suites where hornblendes are more magnesian (in terms of mg#) than coexisting biotites. Halogen contents of mafic silicate minerals are low (F+Cl generally ≤0.3 and ≤0.5 weight percent for hornblende and biotite, respectively). Garnet has been identified in parts of most of the intrusive complexes and has an unusually calcic composition (grossular-almandine, 3-20 mole percent spessartine, ≤10 mole percent pyrope). Mineralogy (magmatic epidote in the specific mineral assemblage), mineral chemistry (hornblende geobarometry and garnet composition), field relations, and pressure estimates from associated metamorphic assemblages all suggest that these plutons crystallized at mid- to lower crustal depths, although the presence of magmatic epidote alone is not an unambiguous indicator of high pressure. The collective chemical and mineralogic characteristics of this subset of calcalkaline I-type granitoids may be useful in recognizing such plutons elsewhere. For example, the Late Precambrian Ingonish River Tonalite, Nova Scotia, and Paleozoic Ellicott City Granodiorite, Maryland, appear to share many of the characteristics of the magmatic epidote-bearing plutons described here.

THE EFFECT OF BORON AND FLUORINE, IN MINERAL ADDITIVES, ON THE PRODUCTION OF GRANITIC PARTIAL MELTS FROM GREYWACKE SOURCES.

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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 further shed 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 boron and fluorine, 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 phase include: cordierite, ilmenite, apatite, zircon, plagioclase feldspar and pyroxene, all K-free phases. The degree of melting increases from 'dry', through hydrous to boron and fluorine 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 fluorine in the charge) of cryolite. These experiments demonstrate the probable importance of natural volatile-rich minerals, particularly tourmaline, for the processes of anatectic melting.

ARCHAEAN GOLD MINERALIZATION AND GRANITOID INTRUSIONS IN THE SUPERIOR PROVINCE OF CANADA: A REVIEW

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Felsic intrusions in the Superior Province of Canada display a diverse range of ages and lithologies. They include tonalitic gneisses of ~3.0 Ga in gneissic subprovinces, syn-volcanic diorite of 2.7 Ga, monzonite-syenite suites of 2.68 Ga and quartz-rich granitoids of ~2.63 Ga in greenstone belts. Archaean gold camps are very sparse in old gneissic-granite terrains. All major gold deposits occur within the greenstone belts and adjacent granitoid terrains. The gold deposits are spatially associated with late Archaean intrusions, ranging in age from 2.70 to 2.67 Ga. Most of these intrusions postdate the age of the volcanism, which had formed the greenstone belts. For example, the two largest gold deposits in the Abitibi belt, the Hollinger-McIntyre deposit in Timmins and the Kirkland Lake deposit, are principally hosted by late-kinematic felsic intrusions. Over 25% of gold deposits in the Superior Province occur within syn- to late-kinematic alkalic to sub-alkalic felsic intrusions, which constitute less than 10% of the greenstone belts and over 90% of economic deposits contain felsic intrusions in their properties (e.g., Hodgson & McGheehan, 1982). The spatial association of gold deposits and intrusions and the roughly contemporaneous nature of the two in very late Archaean time led to a model linking the magmas for the intrusion with mineralization (e.g., Burrows et al., 1986; Cameron & Hattori, 1986). The magmas provided the source for CO_2-rich fluids and the constituents for the mineralization. Lack of variations in carbon isotopes from gold deposits and the oxidized nature of the magmas were considered to support the model.

This model is however challenged by the diverse compositions of the igneous rocks and recent U-Pb age determinations. The host rocks vary from syn-volcanic diorite in the Val d'Or camp, syn-volcanic tonalite in the Malartic camp, to late-kinematic syenite in the Kirkland Lake camp. U-Pb age determination of zircons from several intrusions hosting mineralization show significantly older ages for the principal host (e.g., Marmot & Corfu, 1989). U-Pb studies of igneous zircon and hydrothermal titanite and rutile also confirm that the intrusion of the main hosts was much older than the mineralization (Zweng, 1991).

Although it is unlikely that the auriferous fluids were exsolved from the magmas of the host igneous rocks, the intrusions appeared to have played a significant role in mineralization. The brittle nature of the intrusions compared with the supracrustal rocks produced dilation zones for the fluids which assisted in localizing the mineralization in and near the intrusions. The physical characteristics of the intrusions and the vertically elongated shape of the intrusions were favourable for providing the conduit for auriferous fluids from depth. In addition, recent Pb-isotope studies have shown that vein-forming hydrothermal activity took place in the host igneous rocks and caused leaching of vein constituents from the rocks. The intrusions have provided some metals for the veins (Moritz et al., 1989; Hattori & Shimizu, 1991).

Although it is now accepted that there is no direct linkage between the mineralization and the magmas of the intrusions, identification of "desirable" intrusions still serves as one of the best exploration tools in targeting potential areas. The loci of syn- to late-kinematic intrusions manifest the structurally favourable sites for the mineralizing fluids. Igneous intrusions emplaced in such dilatant zones display characteristic features due to volatile and heat loss from the magmas during the ascent, such as oscillatory zoning and porphyritic textures. Oxide and silicate mineralogies are also indicative of intrinsically oxidized magmas (e.g. Hattori, 1987). Oxidized alteration related to the intrusions, common in such igneous rocks, are also ascribed to the structural settings which were conducive to significant later mineralization in the area.

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Late Archaean granitoids of the southeastern Yilgarn Block, Western Australia: Age, geochemistry, and origin

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Geochronological data for plutonic and volcanic rocks from the Kalgoorlie-Norseman region of Western Australia obtained using the SHRIMP ion microprobe show that the felsic rocks have a close temporal relation to a Late Archaean greenstone-forming event. At Norseman, eruption of a 6-8 km thick sequence of pillowed basalts with minor komatiitic interbeds began ~2715 Ma ago. Basement includes a succession of 2938±10 Ma felsic volcanic and volcaniclastic rocks containing older (to 3100 Ma) xenocrystic zircon. It appears that the Kambalda Komatiite horizon, with an age of 2702±4 Ma (Claoué-Long et al., 1988), may be continuous over a strike length of >200 km, from south of Norseman to Ora Banda, 70 km northwest of Kalgoorlie. The komatiites are overlain by more basalts, which are in turn overlain by thick sequences of felsic volcanic and volcaniclastic rocks, eruption of which began 2687±3 Ma ago. Abundant old (to 3450 Ma) zircon xenocrysts are interpreted as providing evidence for the presence of much older basement. The felsic volcanic rocks are intruded by thick (to 1km or more), internally differentiated mafic sills, two of which have ages of ~2683 Ma.

An early (2690-2685 Ma) felsic plutonic episode, inferred to be consanguineous with the coeval felsic volcanic rocks, is characterised by biotite-hornblende- and biotite-hornblende-titanite granodiorites but includes also K-feldspar megacryst-bearing granites, and Na-rich tonalites. The granodiorites generally have <3 wt.% K_2O, chondrite-normalised rare earth element (REE) patterns with steep slopes, LREE enrichment and HREE depletion (relative to greenstone basalts), relatively small negative Eu anomalies, large negative anomalies for Nb and Ti, small negative anomalies for Zr, and little or no Sr depletion relative to elements of similar compatibility. The combination of little or no Sr depletion and small negative Eu anomaly is interpreted as indicating that feldspar was not an important residual phase during the melting event that produced these rocks. Initial Pb, Sr and Nd isotopic compositions, and the presence of old (3100-3200 Ma) zircon cores, are consistent with derivation through anatexis of much older, complex primitive (andesitic) crust.

Much of the 'granite' terrain of the southeastern Yilgarn is underlain by K-feldspar megacrystic biotite granite emplaced 2665-2660 Ma ago. Smaller, compositionally diverse (including Na-rich tonalite; diorite; syenite; and strongly fractionated granite) plutons of similar age were intruded into the deformed greenstone sequences. The volumetrically much more significant granites generally have high K_2O contents (3.5-4.5 wt.%), REE patterns with steep slopes and large negative Eu anomalies, and prominent depletions in Nb, Sr, Zr and Ti. The combination of Sr depletion and negative Eu anomaly is interpreted as evidence for an important role for feldspar-liquid separation in the origin of these rocks. Similar isotopic compositions to those of the 25 Ma older granodiorites indicate derivation from a similar source.

Small plutons as young as 2600±12 Ma occur, but are volumetrically unimportant. At the broader scale, plutons of similar (2690-2660 Ma) age are known from most of the Yilgarn craton. The heat source for this regional-scale crustal anatectic event is inferred to be the head of a mantle starting plume. Decompression melting within the plume head and axial conduit gave, respectively, the basalts and komatiites of the greenstone sequences; conductive transfer of heat from the top of the plume head resulted, after a time lag of 25-30 Ma, in anatexis of the lower crust, while partial melting at higher crustal levels followed 25 Ma later.

THE SHOSHONITE ASSOCIATED, ZONED GOLD SKARN SYSTEM AT JUNCTION REEFS, CENTRAL NSW.

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Within the Junction Reefs and Burnt Yards Goldfields of central NSW there are several distinct styles of gold mineralization that are spatially associated with a suite of Ordovician shoshonitic intrusives. Compositions range 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 (eg. Sheahan-Grants, Frenchman's Cornishmen's ore bodies), intrusive hosted sheeted veins (eg. Glendale, Glendale North deposits), fissure veins (eg. Gold Hills deposit) and hydrothermal breccia pipes (eg. Prince of Wales deposit). All exhibit similar geochemical character in that they have a strong arsenic-gold association coupled with a relatively low base metal and silver content. Isotopic age determinations indicate that the gold skarn at Sheahan Grants, and the intrusive hosted sheeted veins at Glendale, formed at essentially the same time (i.e. around 440 m.y.).

The skarn hosted gold ores, which are the most economically significant, are hosted by a 39 metre thick sequence of Early Ordovician limestone, siltstone and chert known locally as the "Ore Beds" horizon. The known deposits, which are best characterized by the Sheahan-Grants ore body, are located within the retrogressed outer halo of a skarn system centred on a small quartz monzodiorite stock, the Junction Reefs Monzodiorite. The skarn mineralogy varies progressively outwards from a garnet-quartz-pyroxene dominated core zone assemblage, through a pyroxene-ferrohastingsite zone to an outer retrogressed calcite-chlorite-quartz zone. All of the known skarn ore bodies are found within the outer alteration zones. The mineralization terminates at a sharp metasomatic front anywhere from 350 to 600 metres from the stock. There is an association between gold ore and presence of massive to semi-massive sulphides in the skarn. Pyrrhotite is the dominant sulphide along with arsenopyrite, and pyrite. Chalcopyrite is minor.

The Junction Reefs Monzodiorite is one of several stocks that are peripheral to the central and volumetrically much larger Prince of Wales Diorite. The latter is clearly a pre-ore mass as it forms the host both to the sheeted sulphide-quartz vein zone of the Glendale deposit and the breccia pipe at the old Prince of Wales mine.

Emplacement of what we consider to be the parent magma of the suite, the Prince of Wales Diorite, at around 470 to 480 m.y., does not appear to have been accompanied by any major metasomatic activity. Rather, we infer that the gold mineralizing event was associated with the emplacement, some 30-40 m.y. later, of a series of volumetrically small, fractionated stocks such as the Junction Reefs Monzodiorite.

TEXTURAL, MINERALOGICAL AND CHEMICAL VARIATION IN SHALLOW, A-TYPE, SHEET GRANITES OF THE WICHITA MOUNTAINS IGNEOUS PROVINCE, OKLAHOMA, U.S.A.

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The Wichita Mountains Igneous Province in southwestern Oklahoma consists of a bimodal association of Cambrian age mafic and felsic plutonic and extrusive rocks. Layered gabbros form an extensive substrate ($\approx$3-4 km thick) for an overlying rhyolite volcanic pile. Intrusive into the base of the volcanic pile are a series of high SiO_2 (71.0-77.6 wt.%) hornblende-biotite-magnetite alkali-feldspar granites of the Wichita Granite Group. The granites display typical A-type characteristics (e.g. metaluminous-subalkaline, magmatic fluorite, elevated Zr > 500 ppm) with minor and trace element abundances that have a "within plate" signature. The granites intruded as a series of thin ($\approx$0.5 km) but laterally extensive (20-55 km in length) sheets. The sheet form of the granites is evident from mapping and from an absence of gravity anomalies in the regional Bouguer high of +75-100 mgal. Major element chemistry allows subdivision of the granites into three distinct, but internally homogeneous, chemical suites. The Mount Scott Suite is impressive for its distinctive petrography and remarkable chemical homogeneity (i.e. SiO_2 71.0-73.6; CaO 1.0-1.5 Rb/Sr$\approx$1.3) over a distance of at least 55 km. The other granite suites show more petrographic and chemical variability. Trace element chemistry suggests no simple process relates the granites to one another. Limited geochronological data suggest igneous activity occurred over a prolonged period (<50 Ma). In general, mafic magmatism preceded felsic magmatism. Igneous activity was coeval with active extension and rifting of the southern margin of the North American craton during opening of the Iapetus Ocean (Southern Oklahoma Aulacogen).

The Wichita Granites crystallized from high temperature, relatively dry magmas, emplaced at very high levels in the crust. The abundance of granophyre, miarolitic cavities, partially resorbed quartz, stoped contacts, angular enclaves and intrusion into an $\approx$coeval volcanic pile are suggestive of emplacement at pressures as low as the 10^2 bar range. Comparison of crystallization histories of Wichita Granites with the experimentally determined 1-kb T-xH_2O phase relationships for the A-Type Watergums Granite (Clemens et al., 1986) imply liquidus temperatures in the 900-975°C range and initial xH_2O of <2.8 wt.%. Temperatures of $\approx$ 900°C are also suggested from measured Zr concentrations (Watson and Harrison, 1984). The granites are characterized by the ubiquitous salmon to red color of the alkali feldspars due to a pervasive late stage oxidation. However, the granitic melts initially may have been relatively oxidized as evidenced by early crystallization of hornblende-sphene-magnetite and quartz (Wones, 1989).

Several textural and mineralogical varieties of Wichita Granite exist. Coarse-grained ($\approx$1 cm) seriate and fine-grained granophyric, microgranite predominates. Porphyritic granites, rare pegmatitic granite and aplite dikes are also present. In general (with the exception of aplite dikes) coarse-grained granite intrudes fine-grained granite. Fine-grained granite is commonly observed as stoped blocks in coarse grain granite. Abundant miarolitic cavities at the base of stoped blocks of fine grain granite provide evidence for upward volatile migration. In addition to typical late intrusive aplite dikes, aplites with more diffuse gradational contacts provide evidence for segregation of residual liquids during the late stages of crystallization. Within individual granite sheets, domains "characterized" by distinct mafic mineral assemblages (i.e. Hb-Mt-Sp, Bi-Mt-Fl) are recognized. Complex reaction relationships exist among the minor and accessory minerals. For example, hornblende and biotite exhibit antipathetic modal variation, and in some domains both phases are replaced by the final assemblage magnetite-fluorite, a trend consistent with increasing fluorine fugacity and oxidation state during crystallization. Segregation of mafic minerals (e.g. Hb) in layers is commonly observed near granite contacts. This layering may exhibit patterns similar to crossbedding. Internal magmatic contacts, defined by changes in the grain size and modal abundance of quartz also produce a subtle layering within broadly, texturally homogeneous granite.

Field observations suggest that gravitational settling, flow sorting, volatile migration and multiple intrusions are differentiation processes likely to have produced the limited compositional and mineralogic variability within individual granite sheets. In contrast to the high viscosity commonly visualized for "dry" high SiO_2 granites, the occurrence of these processes and the laterally extensive nature of individual sheets suggest that these granites crystallized from relatively fluid melts. We suggest that high fluorine activities implied for these melts significantly lowered the viscosity of these magmas enhancing the recorded emplacement and crystallization 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.

EXPERIMENTAL INVESTIGATION OF PHASE RELATIONSHIPS IN THE HAPLOGRANITE SYSTEM. THE INDIVIDUAL EFFECT OF PRESSURE, H_2O ACTIVITY, AND EXCESS Al.

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Solidus and liquidus experiments have been performed in the subaluminous system Qz-Ab-Or(-H_2O-CO_2) and the peraluminous system Qz-Ab-Or-Al_2SiO_5(-H_2O-CO_2) in order to determine the effect of H_2O activity (aH_2O) and excess alumina on phase relationships. Experimental conditions were 2 and 5 kbar, 650 - 900°C, aH_2O = 0.3 - 1.0. Starting materials were natural quartz + synthetic feldspars (+ sillimanite) in solidus experiments and subaluminous and peraluminous glasses in liquidus experiments. The normative corundum (C) content of the peraluminous compositions was 5 - 5.5 %. aH_2O was controlled using a H_2O-CO_2 mixture. Sillimanite (solidus experiments) or mullite (liquidus experiments) was present in peraluminous compositions, implying that the melts were saturated in alumina with respect to these Al-silicate phases.

In the subaluminous Qz-Ab-Or system liquidus temperatures increase with decreasing aH_2O more markedly in Ab-rich compositions than in Or-rich ones. There is no significant change in the position of the quartz-feldspar field boundary, but the minimum composition becomes richer in Or at the expense of Ab with decreasing aH_2O. The temperature of the thermal minimum increases regularly with decreasing aH_2O (e.g. at 2 kbar: 685°C at aH_2O = 1; 775°C at $aH_2O \approx 0.55$; 835°C at $aH_2O \approx 0.45$).

In comparison to the subaluminous system the minimum temperature of the peraluminous system is 25°C lower at aH_2O = 1 and 20°C lower $aH_2O \approx 0.5$ (2 kbar). The position of the quartz-feldspar boundary is shifted towards more Qz-rich compositions in the peraluminous system. The shifting is more pronounced for Ab-rich than for Or-rich compositions. This may be due to the higher corundum content of Qz-Ab melts (4% normative C) when compared to Qz-Or melts (2% normative C). At H_2O-undersaturated conditions the effect of excess alumina on cotectic compositions and temperatures is less pronounced than in H_2O-saturated compositions.

The obtained experimental results show that there is a marked difference in phase relationships between subaluminous and peraluminous compositions and between H_2O-saturated and -undersaturated compositions. The phase relationships defined by Tuttle and Bowen (1958) for the H_2O-saturated subaluminous system may not be adequate to interprete peraluminous granites. The shifting of the minimum towards more Or-rich compositions with decreasing aH_2O suggests that the H_2O solubility is lower in Or-rich melts. This is confirmed by recent solubility data at 2 kbar, showing that H_2O solubility is approximately 1.5 wt% lower in Or-rich cotectic melts than in Ab-rich ones. As viscosity of melts is strongly controlled by their H_2O content, Na-rich residual leucogranitic melts may be significantly less viscous than K-rich ones. The important shifting of the cotectic line towards the Qz apex in peraluminous Na-rich compositions and their high normative corundum content are in good agreement with the observation that Na-rich leucogranites often display not only high Qz but also high normative corundum contents (up to 6 % normative C).

Ascent mechanisms of tectonically emplaced granites: controls on lithospheric deformation rates.

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Current views of granitic ascent tend to preclude diapirism because of the thermal energy budget problem. The only real alternatives to this are diapirs moving while continually attached to their sources (perhaps like magma solitons), or granitic dyke complexes traversing the lithosphere from source to emplacement level. Examination of emplacement mechanisms of granites in recent years in a variety of tectonically controlled settings (in transcurrent shear, extensional shear and in contractional/thrust regimes) reveals that in all three settings the plutons have been constructed by coalescing sheets with boundaries parallel to the enclosing shear zones. Given that many of these tectonic structures must, in essence, traverse the crust then we may be looking at evidence of (an old idea) of magma conduiting. That being so then arrested ascent is being viewed in plutons of these types. Field studies suggest that the width of individual sheets (0.2 - 1 km) are sufficient to overcome objections to ascent based on the likely viscosity of granitic magma (Poiseville's equation); moreover the mechanism may be easily recognised by the presence of ghost stratigraphy.

Many recent studies have also shown that plutons whose emplacement has been controlled by major tectonic structures have commonly been deformed by them before crystallisation. This implies that the shear zones were significantly weakened in the presence of magma. Given that such magma laden tectonic shear zones may locally or commonly network the lower and middle crust then it is clear that, in many instances, they control the rheology of the crust and generally increase the rates of horizontal and vertical crustal movement. This makes a nonsense of empirically derived crustal strength profiles.

There is a paradigm developing here. This begins with tectonics and tectonic structures of every variety (extensional, transpressive, contractional thrust stacking) controlling the site and depth of generation of magmas (mainly by either thinning crust or thickening it); then controlling the ascent paths and velocities of the generated melts which, once involved in the tectonic structures, depending on their crystallisation state, control the rheology of the crust and the rate at which it responds to the major plate tectonic forces.

Granitoids in the Ravenswood Batholith Northeast Queensland

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The Ravenswood Batholith in the Charters Towers-Ravenswood area of North Queensland was formed by three main episodes of granitoid emplacement between the Middle Ordovician and the Early Permian.

Middle Ordovician granitoids were probably emplaced between about 480 ma and 470 ma. They comprise granite, granodiorite and gabbro intruded into a thin Proterozoic or Early Palaeozoic crust. Intrusion of the granitic and gabbroic rocks was broadly synchronous, resulting in widespread magma mixing and magma mingling. Some Middle Ordovician granodiorites may have been hybrid magmas produced by mixing of gabbroic and granitic magmas.

It is proposed that the Middle Ordovician intrusive event resulted from the emplacement of mantle derived gabbroic magma into a thin continental crust, resulting in partial melting and granite generation. This probably took place during continental extension.

The second episode of granitoid emplacement took place between 425 ma and 405 ma and comprises granodiorite to tonalite. These granodiorite to tonalite magmas may have been produced by partial melting of the tholeiitic gabbroic material emplaced in the lower crust during generation of the first episode of granitoids. Geochemical determinations indicate that many Late Silurian to Early Devonian granitoids were generated at or above the eclogite transition.

Carboniferous to Early Permian intrusive rocks probably intruded between about 311 ma and 285 ma, fall into three categories. They are: (1) Gabbro to granite complexes, often with associated volcanics; (2) Granite to granodiorite plutons; and (3) Rhyolitic to trachytic high level plugs, vents and diatremes. These intrusive rocks are part of a much larger North Queensland Igneous Province which overlaps the Ravenswood Batholith.

New gravity data has shown that much of the Ravenswood Batholith has higher gravity values than would be expected from deep seated granitic plutons. An interpretation of this data is that many of the granitoids in the Ravenswood Batholith do not extend to deep crustal levels but give way to denser, gabbroic material at between 5-10 km depth. South of Charters Towers, several Late Silurian to Early Devonian plutons do give the typical low gravity responses and are interpreted as steep sided, ovoid plutons with deep seated crustal roots.

Recent studies have delineated peraluminous, S-type, two mica granitoids in the Ravenswood Batholith. These granitoids are derived from partial melting of Proterozoic or Early Palaeozoic basement. Metamorphic complexes, which are spatially related to these S-type granites, occur in isolated pockets, with roughly concentric isograds. The cause of these metamorphic complexes is not known as they are not spatially related to known granitoids. Their age is similarly not known but they probably formed prior to the Late Silurian to Early Devonian magmatic event.

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THRUSTING AND SYNCHRONOUS GRANITOID EMPLACEMENT, S. E. ALASKA: THE GREAT TONALITE SILL.

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In the S.E. Alaskan coast ranges, the Mesozoic tectonostratigraphic terranes are believed to be separated by a set of major strike slip faults, which record the accretion of "Baja British Columbia". One of these faults, along nearly 1000km strike length, separates the high grade rocks of the Intermontane Superterrane (which includes the Tracy Arm and Stikine terranes) to the east, from the very low grade rocks of the Insular Superterrane (including the Taku, Alexander and Wrangellia terranes) to the west. Work by the authors in the central, 300km long Haines - Juneau - Ketchikan sector, shows that the terrane bounding fault has, as a major component, a 0.3-3 km thick, steeply N.E.-inclined ductile shear zone, with a high angle reverse shear sense of top towards the southwest. In support of these data, Crawford and Hollister (1982) have previously published P-T - time data from British Columbia, which show up to 15km of relative uplift to the east of the boundary.

In a broad zone in the western part of the Intermontane Superterrane, there occurs the Coast Plutonic and Metamorphic Complex - a belt of granites and high grade metamorphic rocks. Intruded into the hanging (eastern) wall of the ductile shear zone, at the leading edge of the Coast Plutonic Complex, is a dense series of deformed, steeply inclined sheets of tonalite-granodiorite composition, which are of late Cretaceous - early Tertiary (55-70Ma) age. Brew and Ford (1981) have shown that these sheets,which are individually 0.5-4.0 km thick and up to 100 km long, form a narrow zone 5-20 km wide, which stretches in excess of 800 km along strike. They have named this enigmatic intrusion "The Great Tonalite Sill". Our work shows that the sill rocks were intruded in a partially crystallized state synchronously with the shear zone deformation and its associated Barrovian metamorphism. The intrusions initially developed a pre-full crystallization (PFC) fabric (Hutton, 1988) of aligned plagioclase laths. With continued deformation after lock-up, a parallel crystal plastic strain fabric, which was partially annealed at high metamorphic grade, was developed. This is best developed in the oldest, southwesternmost sills, and like the country rocks the fabric exhibits down-dip stretching lineations plus top to the southwest shear sense. Later deformation involves conjugate dextral and sinistral shears which were active during the magmatic and solid state and they imply a continued NE-SW shortening. Down dip extensional shears and late stage low Greenschist facies shears are also developed and the significance of these kinematic indicators here and elsewhere in the belt will be discussed.

Emplacement of magmatic bodies along active contractional shear zones, where the wall rock stresses are directly opposed to and are unlikely to easily permit intrusion, is a general problem magnificently illustrated by the Great Tonalite Sill. Our data so far indicate that a sheeting mechanism is important and we conclude that magmatic sheeting and wedging stresses must exceed wall rock plate tectonic stresses. The implications of this will be discussed.

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MELTING OF PLAGIOCLASE IN GRANITES AND SUBSYSTEMS.

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Melting of plagioclase was investigated in the systems Ab-An at 1 atm., Ab-An-H_2O at 5 Kb, in the tonalite system Qz-Ab-An-H_2O at 5 kb and in the granite system Qz-Or-Ab-An-H_2O at total pressures between 0.5 and 2 kb. In addition to the pure tonalite and granite systems, more complex compositions including Fe, Mg and excess Al were also studied. The aim of the investigations was to elucidate the mechanism of plagioclase melting and the distribution of plagioclase components between partial melts and restite plagioclase crystals.

In all systems investigated, the reaction of plagioclase is "boundary controlled". Diffusion profiles could not be observed, but sharp compositional gaps between the plagioclase of the starting material (An_{66}, An_{60} or An_{42}) and the new plagioclase coexisting with melt. The orientation of the boundary is crystallographically controlled. The phases analyzed in the run products very probably represent equilibrium compositions.

The plagioclase melting kinetics is extremely dependent on temperature and compositions of the starting materials. It is obviously also controlled by local differences in chemistry and by structural defects. In the system Ab-An, melting begins within the first minute, but there are still small volumes of unchanged starting plagioclase after 1000 hours (run temperature 1400°C). In the system Ab-An-H_2O, reaction kinetics is controlled by diffusion of H_2O. The transport of H_2O into the plagioclase structure is especially fast parallel to structural "channels" (a-axis). In the pure tonalite and pure granite system, equilibrium or near-equilibrium distribution between restite plagioclases and melts could only be obtained at temperatures at and above 860°C in runs of long duration (28 days). Addition of components leading to the formation of Al-rich phlogopite or biotite enhanced the melting reaction by an order of magnitude. The addition of alumina alone to Fe- and Mg- free systems had also a similar effect, suggesting that Al_2O_3 activity is (besides K_2O activity) a kinetic controlling parameter. Some of the new minerals (phlogopite, biotite, mullite) associated to the melting process are crystallographically oriented on the surface of the reacting plagioclase.

The fractionation of the plagioclase components between melt and residual crystals obtained in subsystems in previous studies could be confirmed. In the granite system the difference in Ab/An ratios between melt and coexisting plagioclase is very large. Differences of 40 to 50% An were determined by microprobe. Thus the fractionation of plagioclase components as determined by Bowen (1913, Am. J. Sci., 35: 577-599) in the pure system Ab-An is not less, but more pronounced in the more complex natural rock systems.

The petrogenetic meaning of the experimental findings for the formation of migmatites and granites is discussed.

TERTIARY EXTENSION RELATED GRANITOID MAGMATISM IN THE RHODOPE MASSIF, NORTHERN GREECE.

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The voluminous Tertiary granitoids intruding the Rhodope Massif in northern Greece exhibit an age sequence broadly younging from north to south. One of the largest, the Skaloti Granite complex, displays rock types varying from strongly foliated hornblende-biotite-tonalites exposed in the southern and western margins of the body to unfoliated garnetiferous corundum-normative leucogranites making up the upper/central part. The Skaloti and other Tertiary granitoids (Lefkogia, Vrondou) appear to have been intruded as a series of large-scale, sub-horizontal northerly to northeasterly dipping sheets along major structural horizons established during the Alpine deformation. Other smaller and later Tertiary intrusions in the region (Xanthi, Granitis) have more boss-like forms and the rocks are unfoliated. The structural fabrics are not related to the waning stages of Alpine deformation, but were developed during or shortly after the emplacement of the magmas into active extensional shear zones. Magma generation may have been a consequence of the return to a normal thermal regime following subduction and orogeny, but substantially enhanced in Tertiary times in northern Greece by the onset of the extensional regime now affecting the whole of the Aegean region.

The granitoids have Na/K ratios >1, high K/Rb ratios, high absolute Ba, Sr, P, moderate Ti and low Y and HREE contents. Their mantle normalized spiderdiagrams have slightly positive or no Eu anomalies and large negative Nb anomalies. Many of these characteristics cannot be accounted for in terms of magmatic fractionation, AFC or crustal assimilation processes, but must reflect the geochemical composition of a major mantle component in their source. Moreover, these chemical signatures are inherent in many sodic granites worldwide. This feature may be associated with incongruent melting of amphibole in lithospheric mantle. Geochemical and isotopic data from the sodic Newer Caledonian granites of western Scotland and elsewhere are consistent with their parental magmas being derived from a hornblende-bearing source. The generation of potassic granitoids, exemplified by the eastern Scotland Caledonian granites, may instead require parental magma genesis from a phlogopite-bearing source.

We suggest that the granitoids 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

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The Late Cretaceous Obara granite exhibits an open V-shaped geometry, 3 to 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 microgranitoid enclaves 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 50m 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 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 to 400°C. The observance of such variously deformed structures suggests that the Obara body had 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 state stage after cooling.

Two Contrasting Plutonism of the Ryukyu Arc, Japan.

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The Ryukyu Arc comprises 118 islands. Cretaceous (70 Ma) to Tertiary (19 Ma) plutonic rocks occur in several islands and consist of gabbro to alkali feldspar granite. From age data, plutonic rocks in the Ryukyu Arc are divided into the first and second groups. Activity of the first group took place at 70 to 64 Ma and that of the second group at 40 to 19 Ma. Plutonic rocks from the northern part of the Ryukyu Arc belong to the first group and the others to the second one.

In the chemical compositions, the first group is characterized by high FeO* and low Al_2O_3 contents compared with the second group and range of Y content of the former is wider than the latter. In the Rb-(Y+Nb) and Nb-Y diagrams (Pearce *et al.*,1984), first group mainly belongs to WPG (within plate granite), while the second group to VAG (volcanic arc granite). Initial Sr ratios of the first group are higher than those of the second group.

It has been considered that Cretaceous Ryukyu Arc located to the northwest of the present position. In that time, crust underneath the Ryukyu Arc was thick and acidic igneous activity took place in the northern part of the arc and East China and South Korea (Fukken-Ryeongnam Belt). A part of the arc may be located in the margin of the Fukken-Ryeongnam Belt. It is considered that magmas caused by partial melting of the lower crust or upper mantle were affected by upper crustal material during their ascending through the thick crust. In Tertiary, the Ryukyu Arc moved toward the southeast, which is connected with rifting, and crust underneath the Ryukyu Arc thinned by extension. As igneous activity of the second group took place under such a condition, it was not affected by upper crust material.

	First Group	Second Group
Place	North	Central to South
Age (Ma)	70 to 65	40 to 19
Al_2O_3 wt%	Low	High
FeO* wt%	High	Low
Y (ppm)	Variable	Narrow
SrI	0.70464 to 0.70982	0.70406 to 0.70610
ε Nd(T)	-5.38 to 1.37	-1.73 to 1.70
Rb-(Y+Nb)**	WPG	VAG

* Total FeO **Pearce *et al.*(1984)

THE CHARNOCKITE MAGMA SUITE: A new and geochemically distinct magma suite, its characterization and petrogenetic implications.

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The formation of charnockite by the metamorphic dehydration of amphibolite facies gneisses has been well documented from Sri Lanka and India. These **Metamorphic Charnockites** are the result of CO_2-flushing whereby amphibole breaks down to form the characteristic charnockite assemblage of orthopyroxene+biotite+feldspar+quartz. Many charnockites show no evidence for this CO_2-flushing and occur instead as plutons and dykes exhibiting distinct igneous features (e.g. intrusive contacts, magmatic layering, enclave swarms, high crystallization temperatures). We have found these **Magmatic Charnockites** to be completely distinct in geochemistry, and to define a hitherto unrecognised class of igneous rock: the **Charnockite Magma Suite** (CMS). The CMS can be geochemically distinguished from the Metamorphic Charnockites on the basis of major element abundances, with the Metamorphic Charnockites consistently richer in CaO, and lower in K_2O, P_2O_5, and TiO_2 for a given SiO_2 value. The Metamorphic Charnockites have bulk compositions not dissimilar from common calc-alkaline magmas.

The CMS occurs in predominantly Proterozoic terranes and has been found in Australia (Musgrave Ranges), Antarctica (Windmill Islands, Mawson Coast, Prince Charles Mountains, and Bunger Hills), Africa (Limpopo Belt), North America (Adirondacks), Scandinavia, and Sri Lanka.

The CMS in addition to and whilst containing magmas with true charnockite characteristics, i.e. granitic composition with orthopyroxene + biotite, also covers a wide range of SiO_2 values (45 to 78 %) with associated cumulates and derivative magmas all sharing the characteristic CMS geochemical signature of very high TiO_2, P_2O_5, and K_2O, with depletion in CaO throughout the suite. The high TiO_2 and P_2O_5 of the CMS and generally low Mg/(Mg+Fe) numbers is manifest as high modal abundances of apatite and opaque minerals. Within the Ardery Charnockitic Intrusions, Windmill Islands, apatite has recorded changing magmatic conditions within the magma chamber with variation in the F content between early and late crystallizing apatites... The similar appearance of Magmatic and Metamorphic Charnockites strongly suggests that their assemblage of stable orthopyroxene and biotite is due to similar conditions of crystallization and recrystallization respectively. The role of phases other than H_2O, such as CO_2, F, and Cl is considered important in producing the charnockite assemblage.

The quartz normative CMS is enriched in K_2O, has low Cr and Ni, and the few Nd/Sr isotopic values show very evolved compositions suggesting a crustal origin. However the CMS geochemical signature is unlike any known crustal melt and the TiO_2 and P_2O_5 values are particularly extreme for a crustal derived melt.

Comparison to other magma types shows that the quartz normative CMS is distinctive from nearly all common calc-alkaline magmatism. However striking similarities have been found between the CMS and 'enriched' (in P_2O_5, and TiO_2) Continental Flood Basalts (CFB), particularly those which occur on the constituent parts of Gondwana. There is general correspondence, within the reconstructed Gondwana, of areas of CMS occurrence and 'enriched' CFB. The 'enriched' CFB are predominantly Mesozoic or younger and have been derived from an enriched sub-continental lithosphere. It is unlikely that the more siliceous CMS is derived from the same source, but it is proposed to have a shallower source which underwent similar 'enrichment' processes. The 'enriched' CFB and those CMS rocks so far analysed (unpublished data) have similar Nd deleted-mantle model ages of 2000 ± 400 Ma which appears to record a significant mantle enrichment event. The CMS whilst being much older than the 'enriched' CFB share a similar distinctive geochemical signature which appears to indicate the long term survival and attachment of zones of enrichment below the early protocontinents of Gondwana, and that such long term survival would result in the diffusion of the geochemical distinction between crust and subcontinental mantle lithosphere.

MAGMATISM, URANIUM MINERALISATION AND HYDROTHERMAL ACTIVITY - GRANITIC EXAMPLES FROM THE DAMARAN OROGEN OF NAMIBIA.

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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 Damaran orogenic belt comprises two parts: a north-south oriented zone along the Namibian-Angolan coastline and a 400 km wide north-east oriented zone between the Congo and Kalahari cratons which extends through Namibia into Zambia. 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.

More than 200 plutons occur covering about 74,000 km^2 in area. They range from bodies more than 5000 km^2 in size to small veins and sheets, and from alkali granite and syenite to tonalite, trondjhemite and gabbro in composition. However, more than 95% of the plutons are granitoid 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 north-east for more than 100 km.

Structural evidence indicates that there are post-F1, pre-F2 suites of tectonised (boudinaged) granitic sheets. These are cross-cut by post F3 non-tectonised coalescing granitic sheets which are currently being exploited for their uranium mineralisation.

Textures in the granitic veins, which originally consisted of granophyric intergrowths of quartz and feldspar with a very low content of mafic minerals have been modified into a range of textural facies which range from coarse pegmatitic to microgranitic. Field and petrographic studies have suggested that following the primary magmatic crystallisation of uranium-rich minerals there were several hydrothermal episodes. The earliest hydrothermal episode can be related to residual high temperature magmatic fluids concentrated during the crystallisation of post-F3 granitic intrusions. A later, lower temperature hydrothermal episode (possibly related to late or post-Damaran tectonics) was connected with fluids moving along the faulted contact zones between the granitic sheets and the country rocks. The latest fluid circulation appears to have been joint controlled and was responsible for the formation of a range of secondary minerals dominated by beta-uranophane. The relative importance of these fluids on the re-distribution of uranium will be discussed.

Origin and significance of mafic enclaves in peraluminous A-type granites: Examples from northeastern New South Wales

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The Chaelundi Complex in the New England Fold Belt, northeastern New South Wales, comprises an older I-type and a younger A-type suite of granitoids which are both Triassic in age. The A-type suite is dominated by a leucoadamellite that is mineralogically and geochemically similar to the Triassic group of post-orogenic leucoadamellites, which constitute the youngest group of intrusives in the New England Batholith. However, the suite is compositionally extended, ranging from quartz monzonite (66% SiO_2) to leucoadamellite (76% SiO_2). In contrast, the I-type suite is compositionally restricted (67-69% SiO_2). The I- and A-type suites share many common geochemical features, and at 66-68% SiO_2, the latter is only distinguished by higher alkali and high-field strength element contents, and lower CaO, Mg# ($MgO/(MgO+FeO_T)$) and Fe^{3+}. Al_2O_3 contents are similar to those in the I-type, resulting in corundum normative values of 0.2%-0.6%. The mafic A-type end member, the quartz monzonite, is characterized by sodic plagioclase (An11-An31), relatively Fe-rich biotite (Mg# 30), hornblende (Mg# 35) and ferrohypersthene (Mg# 35). Systematic REE variation in the suite indicates that the quartz monzonite is parental to the leucoadamellite. The complete range is achieved by 60% fractionation, involving removal of plagioclase, K-feldspar and orthopyroxene, along with minor hornblende and ilmenite. This extreme degree of fractionation is also reflected in trace element concentrations, which vary up to an order of magnitude over the measured SiO_2 range.

Volumetrically minor mafic mineral clusters, comprising hypersthene (Mg# 73), augite (Mg# 75) and skeletal calcic plagioclase, also occur in the quartz monzonite. Such clusters are better preserved as enclaves in the Woodlands Quartz Monzonite, which crops out 30km to the northwest. Mineral chemistry and petrographic relations indicate that these enclaves are quenched basaltic liquids, and field relations indicate injection and mingling of these liquids into the host granitoid magma. Whole rock geochemistry reveals that the enclaves have a high-K, high-Al basaltic composition and have undergone minor mixing with the host magma. The dispersed mafic mineral clusters in the Chaelundi A-types represent the almost complete physical disaggregation of these quenched mafic magmas. 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 granitoids, suggest a similar, if not identical source rock. The lower crust in the New England region, at this time, was likely to have consisted of underplated rocks of basaltic composition, associated with arc magmatism, and are represented by older gabbros which crop out in the region. These underplated arc magmas would be a likely source for granitoids of this age in New England. Conditions during partial melting, particularly the presence of volatiles such as water and fluorine, probably determines the initial composition, temperature and viscosities of these granitic melts. Fluorine may either have concentrated in the source after the initial melting and dehydration that produced the I-type magmas, or it may have been expelled during the later stages of fractionation within the newly underplated, mantle derived magmas. Granitoid magmas produced under low a_{H_2O} and high a_{F_2} conditions would be hotter, have lower viscosities, and have compositions enriched in the alkali and high field strength elements; which are the general characteristics of A-type magmas.

TEXTURAL EVOLUTION OF THE TWO-PHASE GRANITE PLUTON AT TAI LAM, WESTERN NEW TERRITORIES, HONG KONG

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Detailed field mapping and petrographic study of the Tai Lam Pluton, supplemented by geochemistry and geochronology, has improved our understanding of the intensely complex nature of high-level two-phase plutons that characterize large areas of Hong Kong and the South China coastal granite belt.

The Tai Lam Pluton is a structurally distinct, leucocratic biotite monzogranite of late Yenshanian (Hercynian) age. The pluton is characterized 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 remobilization and recrystallization of the primary-texture rocks. Such plutons have been termed two-phase variants in Peninsular Malaysia. These textures form a continuum from the primary-texture granite through to granites with an entirely derived texture and geochemistry.

The granite outcrop has been divided into textural types based on field relations and petrography, and on the size and abundance of megacrysts. The presence of microcrystic infiltration and the inequigranularity of the groundmass were used to refine the model. The suggested sequence of textural variations in two-phase granites is:

primary-texture	coarse- and medium-grained granite with little or no textural modification or addition
microcystic	texturally modified coarse- and medium-grained granite with up to 50% infiltration of secondary fine-grained granite
megacrystic	secondary fine-grained granite with up to 50% relict subhedral megacrysts
ineqigranular	secondary fine-grained granite with fine-grained relicts of the coarser primary-texture granite

Modal analysis indicates that there is no difference between rocks of differing grain size. In samples where well-defined relict megacrysts sit in a secondary fine-grained matrix, the modal composition of the two phases shows no appreciable difference. Major and trace element abundances show similar trends to those associated with tin mineralization 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 remobilization 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 remobilization of the primary-texture granite by the addition of late-stage, high-level, fractionated residual magmatic fluids appears to be dominated by fluidization, brecciation and alkali metasomatism. Abundant quartz veins with associated Sn-W mineralization suggests that hydrothermal activity was important in the later stages of pluton development.

THE PAPOOSE FLAT PLUTON OF CALIFORNIA: A RE-ASSESSMENT OF ITS EMPLACEMENT HISTORY IN THE LIGHT OF NEW MICROSTRUCTURAL AND CRYSTAL FABRIC EVIDENCE

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One of the most outstanding examples in North America of a forcibly emplaced pluton is the Papoose Flat pluton of eastern California. Sideways expansion of this granitic pluton, during emplacement into a series of Cambrian shelf strata has been regarded by previous workers as resulting in the observed intense crystal plastic deformation of the pluton's mylonitic border facies and surrounding country rocks. This deformation is evidenced by up to 90% thinning of individual stratigraphic layers within the pluton's metamorphic aureole, although such intense penetrative deformation of the country rocks is not observed outside the aureole.

Previously published quartz c-axis fabrics associated with this deformation (and presented on projection planes oriented perpendicular to lineation) were interpreted as being symmetrical with respect to foliation and lineation, implying almost coaxial deformation histories. Such fabrics could be interpreted as indicating that the pluton evolved by "ballooning" as a result of new magma being intruded into its core during emplacement. However, a major problem with applying the strict ballooning model to the Papoose Flat pluton is that whilst oblate strains would be expected to develop in association with a ballooning mechanism, the mylonitic rocks of this elongate WNW-ESE trending pluton and its aureole are characterised by both a strongly developed foliation, which is concordant with the pluton's margin, and an intense, NW trending, shallow plunging stretching lineation.

Previously published fabrics from the Papoose Flat pluton and its metamorphic aureole have been rotated on to a projection plane oriented parallel to lineation and perpendicular to foliation. Examination of the fabrics in this projection plane has revealed that they are in fact dominantly asymmetrical, and that a constant sense of asymmetry is detected across the pluton, suggesting a consistent (top to the SE) shear sense. This new interpretation is strongly supported by microstructural and petrofabric analysis of additional samples collected, during recent fieldwork, from both the aureole and the pluton's gneissic border facies.

Thus pluton emplacement and related deformation could have involved large-scale consistently oriented translation and associated shearing, rather than passive 'blister-like' coaxial deformation. It should be noted that mylonitic deformation is restricted to the western half of the pluton; features indicative of a more 'permitted' emplacement mechanism being found in the eastern portion of the pluton. The detected top to the SE shear sense is compatible with SE directed overthrusting of the cover rocks during pluton emplacement, the western margin of the pluton suffering intense mylonitic deformation, whilst the eastern margin was located in a 'stress-shadow' region facilitating a more 'permitted' mode of emplacement. Alternatively the detected shear sense could be interpreted as indicating that the granitic material forming the western part of pluton was forcibly intruded in a northwestward direction from the pluton source as a nearly solidified mass beneath a static cover of sedimentary rocks.

TIMING OF EMPLACEMENT AND CRYSTALLIZATION OF THE HIMALAYAN LEUCOGRANITES.

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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 the relations are 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 North Himalayan Shear Zone (NHSZ). Large scale structures such as the north 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 north vergent Annapurna fold or the North 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 proven to be a quite disappointing and debatable matter. U-Pb and whole rock Rb-Sr 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 one (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.

GRANITOID EMPLACEMENT AND DEFORMATION IN THE OLD WOMAN MOUNTAINS, SOUTHEASTERN CALIFORNIA.

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The Old Woman - Piute batholith was emplaced into orogenic continental crust and provides insights into the interplay between plutonism and deformation. The 73 Ma composite batholith includes both metaluminous granodiorite and slightly younger peraluminous granite plutons. Individual plutons are generally sheet-like and concordant to structures in metamorphosed country rock.

The most obvious regional structure is the Scanlon Nappe, which places inverted Proterozoic basement and lower Paleozoic strata over upright Paleozoic through lower Mesozoic strata. The major peraluminous granite sheet overlies the nappe, whereas the largest pluton of the batholith, the metaluminous Old Woman granodiorite, underlies it. Both intrusions clearly postdate the nappe emplacement as they send dikes across the fault. In addition, the granitoids pervasively inject concordant sills into the nappe, preserving a ghost tectonic stratigraphy. Pre- and post-pluton emplacement fabrics may be distinguished using strain analysis techniques on upper plate Proterozoic gneisses and dikes (Jurassic as well as Cretaceous in age) that intrude the nappe. The Proterozoic and Jurassic rocks display variation in strain ellipsoid shape but generally plot close to the k=1 line on a Flinn diagram whereas Cretaceous rocks show more consistent k values close to O. Neither Proterozoic nor Mesozoic rocks show evidence for simple shear related to nappe emplacement; instead, both have symmetrical fabrics that postdate peak metamorphism in the metasedimentary rocks and may be due to post-nappe flattening.

Observations that demonstrate syn- to post-intrusion deformation in the Old Woman Mountains include; granodiorite fabrics that are geometrically identical to, but weaker than, those in adjacent country rock; melt-filled shear zones in granodiorite; internal structures that demonstrate flattening similar to that in the overlying nappe (e.g. folded gneissic xenoliths and schlieren associated with a strong magmatic fabric in the host granodiorite). Kinematic indicators associated with this syn-magmatic deformation demonstrate an asymmetry component with top-to-the-west, normal sense in the nappe structure above whereas reverse shear sense is recorded beneath the pluton. This deformation continued to be active far below the granite solidus temperatures in shear zones on the pluton margins.

Consideration of field relations and 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 area. The cooling history indicated by $^{40}Ar/^{39}Ar$ data suggests rapid denudation of the plutons ending by 65 Ma. The nature of the syn-magmatic deformation and later deformation contributed to unroofing during this interval. It is plausible that magmatism occurred in response to an earlier crustal thickening event and probable that magmatism profoundly influenced the subsequent extensional deformation (gravitational collapse?) of the thrust pile.

Pb Isotopic Evidence for Deep Crustal-Scale Fluid Transport during Granite Petrogenesis

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It is generally recognised that the primary mechanism for the intracrustal differentiation of the continental crust is via magmatic processes, with for example variable composition magmatic rocks making-up different segments of the crust. However fluid movement within the continental crust is also undoubtedly an extremely important process (Torgersen, 1990), but its role as an effective mass transport agent remains equivocal. In metamorphic terranes, particularly those in which deformation has involved the operation of solution-precipitation creep processes, mass transfer on the scale of metres to kilometres have been recognised (Etheridge et al., 1983, 1984; Cox et al., 1986). Fluids also play an important role in high-level crustal metamorphism and in ore genesis, especially in faults and shear zones where strongly focussed fluid flow combined with high fluid/rock ratios ($>10^3$) can result in substantial mass losses (10%-20%). Transport of metals by migrating fluids is also the principal mechanism leading to the formation of a wide range of ore deposits (Fyfe et al., 1978). Whether mass transport via fluid flow is important in the large scale processes responsible for the differentiation of the upper and lower crust remains to be established.

In an attempt to more fully understand the role of fluid transport during intracrustal differentiation, the initial Pb isotopic composition has been determined in K-feldspars from Paleozoic granites of the Lachlan Fold Belt (LFB) of southeastern Australia. 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 (Doe and Zartman, 1979; Zartman and Doe, 1981), implying transport and rehomogenisation in relatively large fluid circulation systems. Thus in high level supergene deposits, Pb appears to be particularly mobile in fluid systems. In the LFB detailed Sr-Nd isotopic (McCulloch and Chappell, 1982; McCulloch et al.,1982) and U-Pb zircon ages (Williams et al.,1990), combined with major and trace element geochemical studies, have shown that the Paleozoic (400-420 Ma) granites are derived from complex, dominantly intracrustal, source rocks with a wide range of Sm-Nd depleted mantle model ages (600 Ma to 1800 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 granites would therefore be expected to reflect this complex source history, unless modified by transport processes associated with intracrustal differentiation.

In contrast to the wide range in initial Nd and Sr isotopic compositions ($\varepsilon_{Nd(I)}$ = +3 to -8.9 and $^{87}Sr//^{86}Sr_{(I)}$ = 0.70408 to 0.71206), 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 to 18.185, $^{207}Pb/^{204}Pb$ ratios of 15.581 to 15.630 and $^{208}Pb/^{204}Pb$ ratios of 38.042 to 38.207. Despite this, there is a relatively good correlation with ε_{Nd} values, for example, samples having low, and hence more primitive, $^{207}Pb/^{204}Pb$ ratios also having more positive ε_{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 Ma to 440 Ma compared to the T^{Nd} model ages which range from ~800 Ma to 1770 Ma. 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 attributed to the mobile behaviour of Pb in deep, crustal-scale fluid circulation systems that were established during granite plutonism. Further evidence is provided by the long-term Th/U ratio inferred for the granite protoliths from Pb isotopic compositions which have $K^{Pb} \sim 4$, in contrast to the Th/U ratio measured in island-arcs of ~2. The higher long term Th/U ratio (K^{Pb}) of the granite source rocks is typical of the continental crust and, assuming subduction zone processes are important in the growth of post-Archean crust, implies loss of U from the continental crust via fluid transport and recycling of U into the deep mantle. Fluid circulation systems of this type also provide a mechanism to account for the general enrichment of $\delta^{18}O$ observed in the continental crust relative to the mantle. Isotopic evidence therefore suggests that fluid circulation systems probably affected whole crustal segments and operated over length scales of $\sim 10^3$ km, playing an important role in the redistribution of soluble elements and the convective transport of heat within the crust.

DEFORMATION FABRICS IN GRANITIC ROCKS: EXAMPLES FROM PALAEOZOIC CALEDONIAN PLUTONS IN SCOTLAND AND IRELAND.

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A basic starting point when examining granite fabrics is to classify them according to the time of deformation relative to the crystallization state of the magma. Thus, the terms pre-full crystallization (PFC) fabrics and crystal plastic strain (CPS) fabrics (Hutton, 1988) are commonly used to describe the nature of the fabrics observed in deformed granites. However, what these terms actually describe are end member cases and in reality what we apparently see are the products of complex interactions between processes responsible for the formation of PFC and CPS fabrics. In addition, CPS fabrics can be sub-divided into low temperature types, which produce dynamic deformation textures, and less obvious high temperature types. Illustrative examples will be described from the deformed Caledonian plutons of Thorr and Ratagain.

In the Thorr pluton, NW Donegal, deformation related to shear zones adjacent to the pluton is apparently continuous throughout the cooling history, resulting in the modification of PFC fabrics by both high and low temperature CPS fabrics, especially close to the margins of the pluton. In contrast, high temperature CPS fabrics are largely absent in the Ratagain pluton because a hiatus occurs in the deformation history due to episodic movement on the Strathconan fault, with which the pluton is intimately associated. Thus the sequence of fabrics can be related to the continuity of fault/shear zone movement throughout the crystallization history of the plutons.

A significant feature of the fabrics in both plutons is the development of bimodal and even polymodal preferred orientations of phenocryst phases during the formation of PFC fabrics. The relationship of these alignments to the symmetry of strain will be discussed, and in particular, whether they are related to the development of shear planes (i.e. s-c fabrics) and/or the rotation of rigid particles in a viscous matrix being deformed by shearing (i.e. Jeffrey's orbits theory).

The significance of this study is that it will hopefully be corroborative in our understanding of the relationship between the tectonic controls on the deformation of granitic magmas and rocks and the processes involved in producing the observed fabrics.

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Evidence for Ascent of Differentiated Liquids In Silicic Magma Chamber Found in Granitic Pluton

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Experimental and theoretical fluid dynamic modeling of crystallizing calc-alkalic magma bodies has predicted that differentiated liquids will ascend as boundary layers and that accumulation of these buoyant liquids near chamber roofs will result in compositionally stratified magma chambers. This paper reports physical features in La Gloria pluton in the Andes of central Chile that can be interpreted as trapped ascending differentiated liquids. Leucogranitic layers decimeters thick, which are themselves locally stratified, are trapped beneath overhanging wall contacts. The same felsic magmas were also preserved where they were injected into the wallrocks as dikes and as large sill complexes.

These rocks do not, however, represent differentiated magmas produced by crystallization along the exposed walls because the felsic layers occur *at* the wallrock contact, not inboard of it. I speculate that evolved felsic liquids are generated not at chamber margins but by crystallization all across the deep levles of chambers (because adiabats for convecting magma are steeper than liquidi) and that initial melt segregation occurs by flowage of melt into tension fractures produced by movements of crystal-rich mush in response to faulting or stoping. Because dilatant fractures can form in a mush only when there is a contiguous crystal network that can sustain brittle fracture, i.e., at crystallinities >80%, this separation process favors production of small melt fractions, in contrast to crystal compaction, which is biased toward separation of large melt fractions.

Crystal-liquid mushes might be expected to behave brittlely on short time scales, but deform ductilely over the larger life of a chamber. This property would facilitate separation of evolved liquids. Melts that flow into low-pressure zones of tension fractures will form bodies large enough to have significant ascent velocities as diapirs during the intervening periods when the host magma deforms ductilely. Such diapirs could be expected to survive the low-intensity convection that would characterize silicic magmas. The high viscosities of the magmas would suppress, though certainly not entirely prevent, mixing between the diapiric leucomelt and the host magma in its path. Leucomelt diapirs that encountered the chamber margins before losing their identity through mixing would be constrained to rise along the sloping walls, where evidence of their ascent could be preserved beneath steps in the wall contacts. It would be preserved because the more-mafic and therefore denser magma of the body of the chamber could not displace it beneath overhangs.

The ascending liquids did not feed a highly differentiated cap to La Gloria chamber, as the composition at the roof, although the most felsic in this vertically and concentrically zoned pluton, is considerably more mafic than the trapped leucogranitic liquids. This suggests that these extremely differentiated liquids were usually mixed back into the main body of the chamber, perhaps the fate of most of the ascending diapirs: progressive mixing with the granitic magma in its path until it becomes so like the surrounding magma in density that its buoyant rise ceases. Only those diapirs that ascend just a short distance before encountering the sloping walls of the chamber are likely to retain their highly evolved compositions intact. This backmixing process may be general in continental-margin magmatic systems, which rarely produce volcanic rocks more silicic than rhyodacite. That the highly differentiated liquids are preserved at all at La Gloria is a result of the unusual stepped nature of the contact, the entirely passive mode of emplacement of the pluton (which, in contrast to ballooning in place, does not result in wallzones being "scoured"), and the pluton being a simple, isolated body that has not had its margins disturbed by the emplacement of multiple magma pulses or other nearby plutons. In contrast to continental-margin arcs, magmatic systems in intracontinental extensional settings commonly produce significant volumes of rhyolite and high-silica rhyolite. Perhaps they are more common there because the extensional environment provides more opportunities for formation of dilatant cracks in crystal-liquid mushes and consequent separation of highly evolved melts, as well as more spaces into which these liquids can escape, accumulate, and be preserved as discrete melts.

GRANITE MAGMATISM IN THE BRITISH TERTIARY IGNEOUS PROVINCE

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The peralkaline-peraluminous ('A-type'), epizonal granitic rocks of the British Tertiary Igneous Province are petrogenetically rather less controversial than two decades ago : for most intrusions there is general acceptance of both the Mantle (basaltic differentiate) and crustal components dictated by the isotopic and trace element data. However interpretations range from mildly (selectively?) contaminated basaltic differentiates to 'largely crustal melt' compositions. The crustal component was derived from diverse sources including Lewisian gneisses, Torridonian arkose, Dalradian/other post-Lewisian basement, Lower Palaeozoic turbidites/Caledonian granitoid (?) and Hercynian granite : it tends to be largest in the earliest granitic intrusions at each central complex. Basement-wise the greatest uncertainty is for the Irish central complexes, the closest to the Caledonian Iapetus Suture and whose granites (initial ε_{Nd} around - 4 and $(^{87}Sr/^{86}Sr)_o$ 0.707 -0.714) have markedly more radiogenic Nd-isotopic compositions than their Skye counterparts.

The last two decades of research on the province have established the following:-

(1) A compositional diversity of potential basaltic (/picritic?) parent magmas including 'MORB-like' low-alkali tholeiites.
(2) Varying degrees of meteoric water-rock interaction at the central complexes - ranging from severe (e.g. Skye, Mull) to mild (e.g. Mourne Mountains) - with in general remarkably little modification of the pristine granite chemistry.
(3) Highly varying degrees of fractionation throughout the spectrum of granitic (and rhyolitic) magmas - principally the result of crystal fractionation.
(4) Granitic rocks with cumulate texture (in addition to the more typical granophyres).
(5) Magmatic pulses in the emplacement of some of the granites - evidenced by field mapping and trace element geochemistry (e.g. W. Mourne Mountains).

Thus some of the granites evolved by extreme (feldspar - dominated) crystal fractionation from more primitive felsic melts with both Mantle and crustal components. Fuller understanding of the crustal involvement in this classic province must be achieved along with better quantification of the crustal component in the individual granitic intrusions. This will require improved radiometric dating (e.g. Rb-Sr data for individual granitic pulses) and full Sr-Nd-Pb isotopic data for each central complex (with magmatic $\delta^{18}O$ values where these can be inferred), together with critical evaluation of the following genetic models for the granites:-

(1) Mixing of basic magma and crustal melt in the lower crust followed by high level fractional crystallisation;
(2) AFC in high level basic magma reservoirs;
(3) Mixing of basaltic differentiate granite and upper crustal melt (e.g. in a zoned magma chamber situation);
(4) Crystal fractionation of basic melts accompanied by selective crustal contamination.

SOURCE REGIONS OF GRANITOID PLUTONS: EVIDENCE FROM LOWER CRUSTAL XENOLITHS AND INHERITED ACCESSORY MINERALS

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A major goal of studies of crustal evolution is to understand the process of anatexis, including the mechanisms by which it is induced and magma segregation is effected and the nature of chemical fractionation that results from it. Full understanding of anatexis requires knowledge of the nature of crustal magma sources as well as of the igneous rocks produced, but very rarely, if ever, are both source regions and derived rocks exposed. The potential imaging of their crustal sources by granitoid rocks is now widely accepted, but beyond unspecific generalizations this image is commonly poorly focused. The presence of restite is often debatable and where it is present it is typically reequilibrated and does not provide detailed insights into the source region. Two types of studies being carried out in the Old Woman and Piute Mountains, Mojave Desert, southeastern California - one involving fortuitous but not exceptional exposures, the other dealing in more detail with a well known phenomenon - may provide more detailed views of the relation between source region and Late Cretaceous granitoids that have previously been demonstrated to be crustally derived.

Xenoliths exposed in mid-Tertiary dikes in this region clearly represent residues of extensive partial melting (Hanchar, 1990; Wooden et al., 1990; Hanchar et al., 1990). The great diversity in these rocks (42-86 wt% SiO_2) is partially a result of initial heterogeneity and partially a result of varying amounts of melt extraction, which mass balance and trace element modelling suggests ranged from <10 to >70%. All xenoliths are moderately to extremely enriched in garnet (to 70%) and rutile is typically abundant. Most xenoliths with quartzofeldspathic (sedimentary and igneous) and aluminous (sedimentary) protoliths contain quartz and plagioclase, but biotite is sparse and K-feldspar typically absent; kyanite is present in aluminous samples. Xenoliths with metaluminous igneous protoliths contain hornblende+plagioclase+ clinopyroxene+quartz. Mineral assemblages and thermobarometry suggest that the melting event took place at at least 750°C and about 10 kb. Present day Sr (0.710-0.756), Nd (ε = -1 to -22), and Pb (206/204 18.1-18.9, 207/204 15.58-15.66) isotopic ratios are highly variable but strongly suggest a Mojave Proterozoic heritage. Model ages are, however, commonly considerably greater than the ca. 2 Ga age of Mojave crust, demonstrating relatively recent adjustment of Rb/Sr, Sm/Nd, and U/Pb ratios. Isotope ratios of Late Cretaceous granitoids are similar but less variable (Miller et al., 1990). The link between these xenoliths and the granitoids remains speculative, but the mineral assemblages, isotopic compositions, and trace element abundances are consistent with their being residues of the Late Cretaceous anatectic event.

The Old Woman-Piute granitoids contain a large fraction of inherited zircon and monazite. SHRIMP investigations show that zircons record essentially all of the Proterozoic events known to have affected the Mojave region (1.1, 1.4, 1.62, 1.68, 1.7, 1.8+ Ga). Data on zonation patterns (backscattered electron imaging, cathodoluminescence) and compositions of the accessory minerals - acquired after SHRIMP analysis - demonstrate a remarkable variety in histories, even more complex than suggested by the geochronological data. Although precise interpretations of the histories implied by zircon patterns remain elusive, euhedral oscillatory zones and synneusis textures suggest periods of igneous growth; rounded unconformities suggest resorption (metamorphic, anatectic, or hydrothermal) or sedimentary abrasion; embayment suggests resorption; and concentric round zones are problematic. Euhedral rims on complexly zoned crystals suggest growth in the Old Woman magma (corroborating concordant ca. 73 Ma SHRIMP points), as do smaller euhedral, acicular crystals. It is noteworthy that many SHRIMP spots straddle zone boundaries and miss important zones. Zoning is less spectacularly apparent in monazites, but rounded cores and euhedral rims are commonly visible. Cores of inherited zircons and apparently inherited monazites are commonly very Y-poor; this same feature is also typical of monazites and zircons from the xenoliths, presumably because of equilibration with abundant garnet. We have not yet identified as broad a range of zonation patterns in the xenolith zircons as we have in the granite zircons, but observed patterns are similar to those identified in the granites.

Both accessories and xenoliths enhance dramatically the potential for probing the crust and understanding anatexis. These xenoliths provide invaluable clues concerning the melting process during this (or some other) event, recording information about nature of source material (heterogeneous, supracrustal-rich), conditions of melting (moderately deep crust, moderately high T, accompanied by partial dehydration), and melt extraction (highly variable, locally extensive). Ion probe U-Pb studies of accessories from both granitoids and xenoliths based upon detailed knowledge of zonation patterns should be extremely fruitful in clarifying the histories of granite source materials and of xenoliths as well as testing the possible relationship between these granites and these lower crustal samples.

EMPLACEMENT OF MID-CRUSTAL PLUTONS IN THE ROSS LAKE FAULT ZONE, NORTH CASCADES, NORTHWEST U.S.A.

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The interrelationships between pluton emplacement and large strike-slip faults are well-illustrated in the 10-km-wide Ross Lake fault zone (RLFZ). This NW-striking terrane boundary was intruded by numerous I-type plutons that record spatial and temporal variations in emplacement mechanisms. Pluton emplacement was particularly influenced by stepover zones between 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, intruded across a left-stepping jog in the RLFZ. Hornblende barometry and greenschist-grade wall rocks along one contact indicate ascent to shallow (< 10 km) levels. Stoping is recorded by abundant enclaves of wall rock near the probable roof, but more forceful emplacement for other parts of the batholith is inferred from moderately strong magmatic foliation and foliation patterns in wall-rock schists. Post-solidus deformation of latest Cretaceous-Paleocene age is recorded by amphibolite-facies mylonites along the SW margin and variably developed solid-state foliation in the southern part of the pluton. Reverse-slip ductile shear zones that strike at a high angle to the regional trend are also widespread in the south and are attributed to the position of the intrusion in a contractional stepover zone.

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 magmatic-epidote-bearing Oval Peak batholith records crystallization at ~ 5.5-6 kbar, considerably deeper than the nearby Black Peak batholith. The syntectonic Oval Peak was emplaced along a thrust segment as an asymmetric expanding diapir. Structural patterns and magmatic and solid-state strains in its margin and in the underlying wall rocks reflect the interaction between pluton expansion and thrust-related shear that occurred before, during and after emplacement. A 2-km-wide belt of 60-68 Ma rocks in the thrust footwall records a distinctly different style of emplacement. This belt is composed of moderately dipping sheets, typically 1-10-m wide, that are elongate parallel to the fault zone. These rocks show variably developed solid-state deformation.

The 48-50 Ma plutons were intruded during regional transtension, which is manifested by oblique (dextral strike plus normal) slip in the RLFZ. These plutons ascended to higher levels than the 60-68 Ma bodies and lack solid-state deformation, but show strong structural control. Numerous sheets and irregular masses of gabbro to granite form an ~ 10-km-long, wedge-like map pattern within an extensional stepover in the fault zone. The sheets locally display strong magmatic foliation, are separated by screens of schist, and contain numerous schist enclaves attaining 10's of meters in size. At the south end of the RLFZ, the Cooper Mountain batholith is elongate oblique to the regional trend and shows gently dipping magmatic foliation. It may have been emplaced in an extensional shear-zone termination during the last stages of dextral slip in the RLFZ.

Thus, these patterns demonstrate how terrane boundaries may serve as a locus of protracted plutonism during varying tectonic regimes. Furthermore, pluton emplacement was localized along stepovers (e.g., Hutton, 1988), including both contractional and extensional varieties.

RHYOLITES AND RHYOLITES: EXAMPLES FROM ARIZONA, SW USA

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The silicic volcanism in the Basin and Range province of the SW U.S.A. is probably a consequence of the extensional tectonics that has been in effect in the region since the Miocene. A comparison of geochemical and isotopic data obtained from three bimodal basalt-rhyolite fields in west-central Arizona, straddling from the Basin and Range to the Colorado Plateau, support the existence of a significant amount of variation in the source of their siliceous end-members despite some petrological similarities. The Castaneda Hills (CH) field, located in the Basin and Range tectonic province, has only high-silica rhyolites (HSR). In contrast, the Kaiser Spring (KS) and Mount Floyd (MF) fields, located in the Transition Zone and Colorado Plateau respectively, have occurrences of low-silica rhyolites (LSR) as well as HSR. A whole-rock isochron for the CH rhyolites indicates an age of extrusion around 13.4 Ma and a high initial $^{87}Sr/^{86}Sr$ (>0.709), whereas the MF rhyolites were emplaced later (6-7 Ma) and show a much less radiogenic initial $^{87}Sr/^{86}Sr$ (~0.7065 for HSR's and <0.7045 for LSR's). In the basalt-dominated MF field, the two rhyolite types show very distinct Pb, Nd, and Sr isotopic compositions that suggest different proportions of crustal and mantle-derived materials were involved in their petrogeneses, with the HSR invariably plotting closer to the basalts than the LSR. In the Kaiser Spring field, the age of volcanism is intermediate between that of the CH and MF, and the isotopic compositions of both rhyolite types are similar to each other but different from that of the basalts.

The absence of LSR's and the high initial $^{87}Sr/^{86}Sr$ of the HSR in Castaneda Hills are consistent with interpretations that the silicic magmas derive their Sr isotopic composition either from a more thoroughly remobilized mid to upper crust in the thinned-out Basin and Range or, alternatively, from an older crust akin to the adjacent Mojave Terrane. However, the small range in the Nd isotopic compositions of the LSR's from MF and KS, the rhyolites from CH, and some basalts from KS and CH (0.5120-0.5122) is consistent with an input from a crust/mantle segment cratonized around 1.8-1.6 Ga. The unradiogenic Pb isotopic composition of LSR's from both MF and KS, and HSR's from KS and CH is not seen in any of the basaltic samples and suggest that an important source for Pb in the silicic volcanics is a part of the crust that suffered an early history of U depletion. In the MF field, the LSR's are also characterized by unradiogenic Sr isotopic composition indicating that the same source also suffered an early Rb depletion event. This source is possibly represented by xenolithic samples of crustal mafic gneiss imbedded in the alkali-basalts of the San Francisco Volcanic Field (Colorado Plateau). The progressive distinction of rhyolite types and geochemistry from the CH to the KS and MF fields suggests that the magma chambers for the LSR and HSR are separated in the Plateau, interconnected in the Transition zone and finally unified in the Basin and Range.

The contribution of Early Proterozoic basement to Caledonian magma genesis in NW Britain and Ireland.

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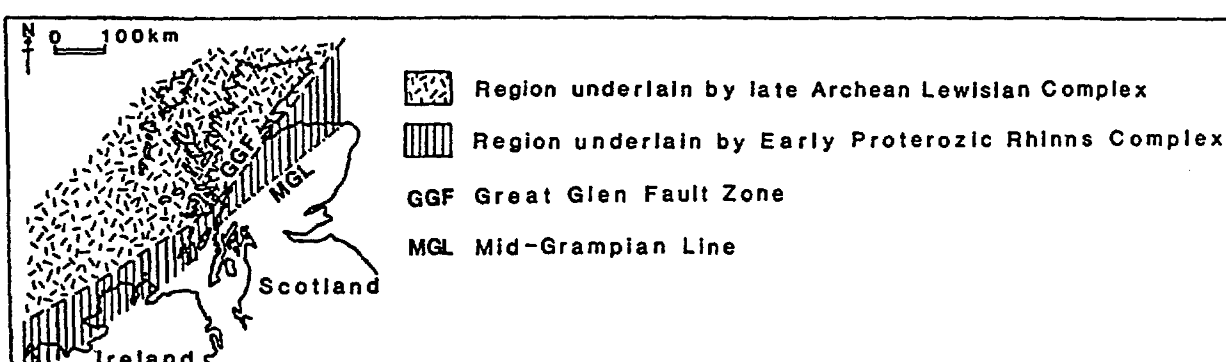
The source of the inherited Proterozoic lead component in the Caledonian granites has been the subject of much speculation. The apparent absence of a significant volume of Early Proterozoic crust in Scotland and Ireland has led to three alternative suggestions for the origin of this isotopic signature:

1. Lewisian crust (2.9Ga) thoroughly reworked during the Laxfordian tectonothermal event (1.9-1.7Ga);
2. Laxfordian granitic material (1.7Ga);
3. A mixture of Lewisian (2.9Ga) and Grenville (1.0Ga) crust.

It is argued here that a more likely source for the Proterozoic component is the newly recognised Rhinns Complex, which appears to underlie much of the Grampian Highlands and NW Ireland.

Precambrian basement on the south side of the Great Glen Fault zone is exposed on the southern half of the Rhinns of Islay, in NE Colonsay and on Inishtrahull. Previous workers have generally correlated this basement with the late Archean Lewisian Complex, on the grounds of lithological similarities. However, detailed field, petrographic and geochemical studies have revealed that the basement rocks comprise a deformed igneous association of mainly 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.1.8Ga. The igneous protolith was juvenile mantle-derived material, not reworked Archean crust.

The Rhinns Complex forms a NE-SW trending crustal block, separated from the Lewisian Complex by the Great Glen Fault Zone. The SE limit of the Rhinns Complex is marked by the trace of the Mid-Grampian Line, which also corresponds to the tip of a crustal wedge imaged on the WINCH seismic profile.



THE PETROGENESIS OF THE PROTEROZOIC HARNEY PEAK LEUCOGRANITE, BLACK HILLS, SOUTH DAKOTA, USA

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The Proterozoic Harney Peak Granite, Black Hills, South Dakota, is an excellent example of peralumious leucogranites and is associated with one of the largest rare-element pegmatite fields in North America. In order to place constraints on its petrogenesis, its mineralogy, petrology and geochemistry were examined. The granite was emplaced at 3-4 kbar as multiple sills and dikes at the culmination of a regional high-temperature, low-pressure metamorphic event into quartz-mica schists. Principally along the periphery of the main pluton and in the satellite intrusions, the sills segregated into granite-pegmatite couplets. The major minerals include quartz, K-feldspar, sodic plagioclase and muscovite. The predominant ferromagnesian mineral in the granite's core is biotite (Mg# = 0.32-0.38), whereas at the periphery of the main pluton and in the satellite intrusions it is tourmaline (Mg# = 0.18-0.48). Alm-spes garnet is also found in the outer intrusions. The HF fugacities indicated by the micas are lower than usually found in topaz or fluorite-containing granites.

Oxygen isotopes among minerals in non-pegmatitic rocks from throughout the pluton equilibrated for the most part at magmatic temperatures between >800 to 650°C. The ∂D values, ranging from -74‰ to -32‰ in muscovite, from -79‰ to -62‰ in biotite, and from -62 to -41‰ in tourmaline, attest to the dominance of magmatic fluids in the Harney Peak system. There is a pronounced difference in the isotopic composition of the biotite-containing granites from the core of the pluton (11.5±0.6‰) and the tourmaline-rich granites from its perimeter and the satellite intrusions (13.2±0.8‰). The difference is best explained by generation of the two granite types from different sources, consistent with Nd isotopic data (1). The average oxygen isotopic composition of the schists is identical to that of the high-$\partial^{18}O$ granites. The isotopic composition of most pegmatites suggests local derivation by differentiation of emplaced batches of magma. In the pegmatitic samples, quartz-feldspar oxygen isotope fractionations point to disequilibrium, probably the result of the sequential crystallization of these minerals and thermal gradients.

There is virtually a complete overlap in SiO_2, CaO, MgO, FeO, Ba, Sr, Zr, W of the low and high-$\partial^{18}O$ suites with no discernable differentiation trends on Harker diagrams, precluding the derivation of one suite from the other by fractionation following emplacement. However, the concentration of TiO_2 is higher and of MnO and B lower in the low-$\partial^{18}O$ granites. The normative Or/Ab ratio is extremely variable ranging from 0.26 to 1.65 in the low-$\partial^{18}O$ granites and from 0.01 to 1.75 in the high-$\partial^{18}O$ granites. Most sample compositions are more potassic than the water-saturated minima and in analogy with experimentally-produced granitic melts (2,3,4), they are best explained by melting at ~6 kbar, $a_{H_2O}<1$ and temperatures ~800°C, consistent with the oxygen isotope equilibration temperatures. Several of the tourmaline granite samples contain virtually no K-feldspar and have oxygen isotope equilibration temperatures 716-775°C. Therefore, they must represent high-temperature accumulations of the liquidus minerals from melts more sodic than the water-saturated haplogranite minima or during fractionation of intruded melts into granite-pegmatite couplets accompanied by selective volatile transfer of the alkali elements.

The indicated high temperatures, $a_{H_2O}<1$ and the minor element concentrations of the low-$\partial^{18}O$ granites suggest that they were generated by high-extent, biotite-dehydration melting of a low-$\partial^{18}O$ metasedimentary source. The ascent of the hot melts through the metasedimentary sequence already heated by a regional metamorphic event may have triggered low-extent, muscovite-dehydration melting of the wall-rocks producing the high-boron, low-Ti melts comprising the periphery of the main pluton and the satellite intrusions. It is suggested that the relatively high Ti concentration in the early melts stabilized biotite, whereas along the periphery of the main pluton and in the satellite intrusions, tourmaline crystallization promoted the observed differentiation into the granitic and pegmatitic layers. The results of this study indicate that chemical and mineralogic 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 THE CRETACEOUS GRANITIC MAGMATISM AND LOW-P METAMORPHISM IN THE SOUTHWEST JAPAN ARC : WHAT CAUSED THE CORDILLERAN-TYPE OROGENY ALONG THE EURASIAN CONTINENTAL MARGIN?

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In Southwest Japan, the Cretaceous granitic rocks are widely exposed for 700km along the Median Tectonic Line. They were formed along the Eurasian continental margin during the Cretaceous (pre-opening of Japan Sea) Cordilleran-type orogeny related to the subduction of the Pacific plate.

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" granitoids are associated with low-pressure type regional metamorphic rocks and are sometimes gneissose, whereas "Sanyo type" granitoids intrude cogenetic volcanic rocks and are all massive. They are regarded as deep and shallow facies of a granitic province, respectively.

An extensive geochronological work revealed that the isotopic ages of these granitoids have a systematic along-arc lateral variation. Rb-Sr whole-rock isochron ages of the Sanyo-type granitoids become younger eastward from 100Ma to 70Ma for 700km. Rb-Sr/K-Ar biotite ages basically follow the eastward younging trend with a 5 to 10 Ma time-lag from the Rb-Sr whole-rock ages for the entire area. The ages of the Ryoke-type granitoids and the low-P metamorphic rocks are fairly consistent with that lateral age variation trend.

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

The RTT(ridge-trench-trench) migration involving the subduction of Kula-Pacific ridge beneath the Eurasia plate might have been driven the Cretaceous Cordilleran-type orogeny along the eastern margin of the Eurasian continent. Widespread occurrence of high-magnesian andesites at the early stage of these magmatism could be a product of high temperature magmatism affected by the heat supply from the subducting ridge.

Feldspar Crystallization Trends in Granitic and Syenitic Magmas

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Changes in feldspar compositions during equilibrium crystallization of granitic and syenitic magmas show similar trends when the H_2O activity of the magma does not increase during crystallization. Such would be the case if the H_2O activity were buffered by a hydrous mineral or a large fluid:melt ratio. Once two feldspars are stabilized, their compositions evolve along paths across the ternary feldspar solvus dome. If joined, these paths would form a polythermal solvus section which involves changes in both temperature and bulk feldspar composition as crystallization proceeds. Movement in a path described by such a section differs from an isothermal solvus section because the path crosses innumerable isothermal sections which are progressively widening as the temperature drops. The actual path taken by plagioclase, for example, is a combination of two pathway components. One pathway component involves a decrease in An content and an increase in Or content because of the changing melt composition and bulk feldspar compositions similar to the path towards more evolved compositions along as isothermal solvus section. The other pathway component involves a decrease in Or content with decreasing temperature because of expansion of the solvus. Importantly, however, under "H_2O-buffered" conditions, the change in temperature during crystallization is small; hence, the expansion of the isothermal sections is not very great and the pathway remains similar to that of an isothermal section, that is, one characterized by a decrease in An content and slight increase in Or content of the plagioclase and decrease in Or content of alkali feldspar.

If the H_2O content of granitic and syenitic magmas increases during crystallization (i.e., "H_2O-unbuffered" conditions), the crystallization temperature interval will increase dramatically which will. have a definite effect on the evolutionary paths of both magma types. However, the region of the solvus encountered during crystallization of granitic magmas is not highly sensitive to temperature and feldspar evolutionary paths remain similar to the buffered case with, however, a reduction of the Or gain of the plagioclase and the An gain of the alkali feldspar.

For syenitic (and trachytic magmas), however, feldspar crystallization is more complex. During H_2O-buffered crystallization, the feldspars of syenitic magmas traverse the solvus to compositions much closer to the curve connecting the consolute points on successive isothermal sections. This region of the solvus is characterized by great changes in the composition of feldspars with small changes in temperature. Unlike for granitic magmas, for syenitic magmas, the effect of temperature dominates over the effect of changing melt composition in dictating the evolutionary path of the feldspars. Plagioclase compositions change by a decrease in Or and very little change in An content and the alkali feldspar compositions follow a curved path of initial decrease in Or content followed by a strong increase in Or content with decreasing temperature. This path is enhanced with low bulk water content to the point where plagioclase compositions may evolve along an An isopleth!

Based on these results, zoning of feldspar in natural trachytic and syenitic rocks could prove a sensitive indicator of the role of H_2O during crystallization of the magmas.

ROLE OF MAFIC MAGMAS IN GRANITE GENESIS - EVIDENCE FROM ENCLAVES IN DEVONIAN PLUTONS OF SE AUSTRALIA

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Petrographic and major/trace element studies of abundant microgranular enclaves in the Early Devonian metaluminous (I-type) Swifts Creek (or Reilly's Creek) pluton and Middle Devonian strongly peraluminous (S-type) Wilson's Promontory batholith of eastern Victoria support their origin as fluid mafic magma globules which after injection into pre-existing felsic magma chambers mingled mechanically with crystal-rich, viscous host magmas and underwent variable chemical mixing. Within some of these enclaves, "trails" of quartz and feldspar megacrysts leading to the host demonstrate extensive mingling. Other non-megacrystic enclaves show little evidence of magma mingling, and zoned examples with fine-grained margins indicate rapid cooling against host magma and internal differentiation. Sr-Nd isotopic data for enclaves and hosts of the Swifts Creek pluton fall on hyperbolic "mixing" trajectories compatible with the involvement of two end-member magmas - relatively unradiogenic tonalite-granodiorite "enclave magma" and more radiogenic granodiorite-granite "host magma" - both probably produced by deep crustal melting. Trace element systematics are also in broad agreement with a two component magma mixing model.

The Late Silurian strongly peraluminous Deddick Granodiorite in north-eastern Victoria, a member of the Bullenbalong Suite of the Kosciusko Batholith, contains very abundant high-grade gneissic xenoliths (many of them extremely peraluminous and showing clear evidence for extraction of a silicic melt) and related microxenoliths and megacrysts (especially garnet and cordierite). Microgranular enclaves are relatively rare (<0.5% of exposed volume), and some are very similar in petrography and chemistry to small dykes within the granodiorite. In spite of the relatively weak geological evidence for the involvement of two or more magmas in the origin of the Deddick pluton, Sr-Nd isotopic data for enclaves and host again fall on hyperbolic trends compatible with two component mixing. Enclaves are significantly less radiogenic ($\varepsilon_{Nd} \sim -5$, $^{87}Sr/^{86}Sr \sim 0.710$) than the host granodiorite (-10, 0.715) and gneissic xenoliths (-12, 0.720). Although the simplest interpretation of the microgranular enclaves is that they represent a distinct relatively mafic "enclave magma", as in the case of the Swift's Creek pluton, apparent volume relationships and trace element systematics are not readily reconcilable with a simple two magma model. More complex models involving processes such as restite unmixing and crustal assimilation appear to be required.

EVOLUTION OF CRUSTAL MAGMA SOURCES THROUGH TIME: GRANITES AND RHYOLITES FROM THE NORTHWESTERN U.S.A.

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Silicic magmatism in the northwestern U.S. provides a record of active crustal evolution spanning the last ≈120 Ma. During this time, the tectonic environment of the region changed from a continental margin volcanic arc in the mid-late Cretaceous, to an intracontinental rift setting in the Miocene-Recent. The transition from convergence and compressional deformation to extension and rifting was not a simple step function but appears to have passed through a strike slip stage during the Eocene-Oligicene. Each of the three major stages (Cretaceous compression/convergence, Eocene-Oligocene strike slip, Miocene-Recent extension/rifting) was accompanied by voluminous silicic magmatism that allows a coupled view of crustal magma sources and tectonic setting through time.

Cretaceous activity (120-65 Ma) produced the Idaho batholith (Kg). At least 6 lithologic units have been recognised: the batholith is zoned from tonalite at its margins, through a granodioritic main phase to a granitic core. Cretaceous volcanic rocks are rare to absent in this region, but syn-plutonic mafic dykes are present. Eocene volcanic and plutonic rocks belong to the Challis magmatic episode (Tc). Tc rocks are largely intermediate to silicic in composition with minor basalt. Two suites of Eocene plutonic rocks have been recognised, one dioritic and the other granitic. Dacitic to rhyolitic ash-flow tuffs and granitic plutons are volumetrically dominant. Miocene-Recent silicic rocks comprise rhyolitic ash-flow tuffs and lava flows (Tr). Tr magmas were unusually hot (>900°C), dry (hydrous phases absent), and erupted from mid-lower crustal depths without the formation of distinct calderas. In contrast, silicic Eocene volcanism is usually associated with calderas. No Miocene plutonic rocks have been recognised in this area. The syn-plutonic mafic dykes in the Kg, minor Tc mafic lavas and intermediate composition mixed magmas, and basalt flows commonly associated with or just following Tr eruptions imply a mantle-derived magmatic component that accompanied and/or induced the silicic activity during all three stages.

Significant compositional differences between silicic rocks of these three suites suggest a temporal evolution of crustal magmatic sources. Below we highlight differences between the Kg and Tr suites; in many respects the Tc rocks are transitional. Some of the observed temporal changes in silicic magma composition include: (1) Na/K decreases. Kg typically have $Na2O > K2O$, Tc have $Na2O \approx K2O$, and Tr have $Na2O < K2O$. (2) La/Yb decreases. All units are enriched in LREE, but the Kg have steeply dipping HREE whereas Tr have flat and relatively enriched HREE patterns. (3) The magnitude of the Eu anomaly (En*) increases. Tonalitic and granodioritic Kg have negligible to small negative Eu*. Tr on the other hand have large negative Eu*. (4) Sr concentrations decrease. Kg have high Sr concentrations (600-1200 ppm), whereas Tc are notably poor in Sr (typically <120 ppm). (5) Mineralogy and geochemistry suggest a general progression in characteristics from I-type in Kg to S-type in Tr.

These observations suggest that the Idaho batholith was generated from a mafic-intermediate composition source region at sufficient depth to stabilise garnet over plagioclase. In contrast, Tr magmas were produced largely from a feldspathic upper crustal-type source with residual plagioclase. Tc magmas have mixed crustal and mantle charcteristics. Decreasing depth of silicic magma genration may be related to progressive development of an extensional stress regime, decreasing crustal thickness following extension, or increasing density of the lower crust following prolonged history of basalt intrusion and melt extraction. The temporal progression from a sodic, tonalitic batholith lacking Eu anomalies and depleted in HREE, to potassic rhyolites with large Eu anomalies and enriched in HREE broadly corresponds to the sequence observed in many Archaean terrains. Therefore, Cretaceous-Cenozoic magmatism in northwestern America may provide analogues for processes which shaped the early evolution of the continental crust.

TRIASSIC "GONDWANA" GRANITES OF THE NORTH PATAGONIAN MASSIF

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The voluminous granitic plutons that constitute the core of the North Patagonian Massif (NPM) have previously been regarded as of Late Palaeozoic (Carboniferous to Permian) age: it has been suggested that they were related to an active margin to the north prior to Permo-Triassic collision of a Patagonian with the rest of southern South America. Recent Rb-Sr geochronology (including re-analysis of the supposed Carboniferous granites of the Somoncura batholith) suggests that their age is generally younger, mostly within the range 250-200 Ma. Granites with a similar age range occur as a discrete belt in the Antarctic Peninsula to the south and in the Andean chain to the north; in all cases older granites are known but are subsidiary in volume, and in the latter they are spatially associated with partly contemporaneous and compositionally equivalent acidic volcanic rocks (Choyoi group).

The predominantly Triassic NPM granites are massive and were emplaced into metamorphic basement rocks and earlier orthogneissic granites of late Precambrian and early Palaeozoic age. They exhibit a compositional range of hornblende-biotite granodiorite through monzogranodiorite to biotite monzogranite, K-feldspar megacrystic granite and leucogranite, but the metaluminous types are subordinate to the abundant highly siliceous (<70% SiO_2) and peraluminous varieties. Despite this compositional bias, the granites are almost entirely calcalkaline and I-type, and have volcanic-arc rather than intraplate trace element characteristics. However, initial $^{87}Sr/^{86}SR$ ratios range from 0.705 to 0.708 and $e_{Nd}(t)$ from -2.5 to -11, indicating a range of source compositions dominated by older continental crust. Depleted mantle model ages range from 500 to 1500 Ma).

According to Mpodozis & Kay (Revista Geológica de Chile, 1990), this is part of an extensive Gondwana magmatic province in which late Carboniferous subduction was followed by Permian terrane collision and Permo-Triassic crustal melting. The NPM granites are now seen as relating to the later events in this scenario. They are intermediate, both in age of formation and geographical location, between the Choyoi and Chon-Aike (Tobifera) groups. This implies a gradual southward migration of the climax of melting in South America, from Permian to Jurassic times.

Textural, compositional and isotopic disequilibrium within inherited zircons: implications for granite provenance studies

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Inherited zircons remain the only unambiguous restite that has been routinely identified within granites and as such may contain valuable information concerning granite source regions. For example, the presence of inherited U-Pb isotope ratios may give direct age information on granite sources. In addition, if zircons also remain closed with respect to other isotope systems, and elemental exchange in general, then refractory zircons may possess other information regarding their original sources. This study presents evidence from the Strontian (Caledonian, NW Scotland) and Kameruka intrusions (Lachlan Fold Belt, SE Australia) that refractory zircons in granites remain closed systems with respect to the exchange of Hf, Y, the REE, Th and U, and to isotopic exchange in the Sm-Nd system.

Using backscattered electron (BSE) imaging two broad textural types of zircon have been identified: 1) zircons containing a single anhedral or subhedral core with an epitaxial overgrowth (ie. grains which show simple two-stage growth histories); and 2) zircons cores which have undergone repeated periods of growth, resorption, mechanical abrasion, fracturing and fracture-healing (ie. grains which show multi-stage growth histories). In addition, between cores the internal zoning structures are commonly very diverse. Ion imaging using an ion microprobe has shown that Hf, Y, the REE, Th and U are the elements which are principally responsible for the zoning patterns observed using BSE imaging. Quantitative analysis (electron and ion microprobe) has shown that the cores, in addition to being texturally diverse, are also compositionally diverse.

The textural and compositional evidence suggests that inherited zircons do not chemically equilibrated internally, or externally with their host melt. This conclusion is consistent with Sm-Nd isotopic analyses of the zircons from the Strontian intrusion which show that refractory zircons retain their original Sm-Nd isotopic composition, and were out of isotopic equilibrium with the other REE-bearing phases at the time of granite crystallization.

The diversity in composition and zoning shown by individual zircon grains, and the complex growth histories of some grains, implies that the inherited zircon component has a wide variety of ultimate sources. The inherited isotopic and chemical information may be diagnostic of the original environment of zircon growth and thus of the original sources of the inherited grains. Detailed studies of inherited zircon populations which combine geochronological, isotopic and chemical information should prove to be a powerful indicator in granite provenance studies.

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.

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The concentration of the halogens in the mineral apatite can be used to deduce changes in fugacity ratios during the crystallization of granitoids. In addition, the initial concentration of C1 and F in the melt and the associated magmatic aqueous phase can be calculated if the temperature of apatite crystallization 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 (°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 crystallizes within 60°C of the AST for the KC, HDE, HDP and CP, and within 30°C for the JP. The proportion of crystallization prior to 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 C1 in the melt and magmatic aqueous phase. Given this information, the following concentrations for C1 (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 C1 (ppm) and F (ppm), respectively: KC (8,200; 190), HDE (5,800; 410), HDP (1800; 270), CP (3,000; 540) and JP (800; 300). This drop in initial C1 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 C1 and increasing $(Sr^{87}/Sr^{86})^{o}$ suggests that variations in initial C1 in the melt are controlled by variable amounts of a subduction related component.

Zircon Th-U-Pb systems as indicators of source rocks and magmatic processes : a SHRIMP study of four granites from the Scottish Caledonides

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The presence of inherited zircon and low ε_{Nd} values demonstrate a significant crustal component in Caledonian granitoids from northern Scotland (Pidgeon and Aftalion, 1978; Halliday et al.,1979; Halliday 1984). Pidgeon and Aftalion (1978) determined the presence of inherited zircon using conventional U-Pb analyses. However, this technique is limited as analyses are invariably made on complex zircons grains consisting of a nucleus of inherited zircon encased in magmatic zircon. Using the ion microprobe SHRIMP we have overcome this limitation by analysing selected 30 micron sized areas within complex zircon crystals. The results show that the granite source rocks have Lewisian (2600-2700Ma), Laxfordain (1600-1900Ma) and Grenvillian (1000-1200Ma) components. A strong Grenvillian component has been detected in zircons from the Findhorn and Ben Vuirich granites. The Findhorn granite also contains a Lewisian and a Laxfordian signature whereas other inherited zircons in the Ben Vuirich granite are of Laxfordian age. Inherited zircons from the Inchbae and Vagastie Bridge granitic gneisses are also of Laxfordain age. The restriction of Grenville zircon components to the Findhorn and Ben Vuirich granitoids suggests that Grenville aged source rocks are restricted to the Southern Highlands. Further work is needed to confirm whether a detailed investigation of inherited Th-U-Pb sytems in zircons from the Caledonian granitoids will provide a means of determining the nature and extent of deep crustal units forming the Palaeozoic basement at the time of the Caledonian orogeny.

Ion miocroprobe Th-U-Pb analyses of oscillatory zoned magmatic zircon from the Findhorn granite suggests distinct growth stages in the crystallisation history of the zircon. It is proposed that characterisation of these growth stages by ion microprobe will provide fundamental information on the crystallisation history of individual plutons.

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THE ROSSES MULTI-PULSE PLUTON : FRACTURES AND FRACTALS

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The Rosses Pluton of Donegal, Ireland, is a typical example of a nested grouping of near-circular intrusions, here representing four consecutive magma pulses. 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 conform 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. This pattern is apparently specific to each intrusion event and is not simply a continuity of tangents. Both regional and intrusion-centred, stress systems were involved.

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

All this is merely a refinement of the original work of Pitcher (1953), but the re-examination was motivated by the possibility of applying fractal analysis to this almost ideal example of igneous fracturing. Not unexpectedly the fractal dimensions turn out to be self similar and self-affine, but their D-values are generally low, i.e. Thorr - G_1/1.055, G_1 - G_2/1.020, G_2 - G_3/1.066, expressing the approach of the contact planes to a Euclidean line, in this case a circle. Possibly these D values are related to the relative rigidity of the particular host at the time of intrusion: certainly the G_1 - G_2 contact is less obviously abrupt than those of the outer Thorr - G_1 and inner G_2 - G_3 contacts.

It is hoped that this rather amateur attempt to use fractals will generate sufficient discussion to educate the author.

The Miocene-Pliocene Intrusive Rocks of southern Tuscany and Tyrrenian Sea (Italy) - Complex Magma Mixing of a Peraluminous - Metaluminous Suite.

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The Miocene-Pliocene intrusive rocks of the Tuscan Magmatic Province (ITR) range in composition from granodiorite to alkali-granite, with a strong predominance of monzogranites. They can be distinguished into five facies on the basis of field and petrological constraints:
1) Inclusions: Xenoliths of angular or resorbed blocks of country rocks are not common and usually occur near the margins of plutons. Microgranular enclaves (ME) are granodioritic and are interpreted as blobs of mafic, high temperature magma chilled within a cooler more silicic host.
2) Main Phase (MF) consists of inequigranular grey biotite monzodiorite with accessory apatite, zircon, monazite, tourmaline, sphene, and scarce primary muscovite. ME is always present, but rarely more than 1-2% in volume.
3) Leucocratic facies representing small outcrops of fine grained, sometimes inequigranular rock in the MF. Compared to MF, biotite is less abundant and primary muscovite more abundant. Cordierite is present in some samples. ME is absent.
4) Granite Porphyry outcrops in some plutons as masses or dykes, and consist of phenocrysts of plagioclase, orthoclase, quartz (partly resorbed) and biotite in a groundmass of the same mineralogy. ME are rare.
5) Microgranites, Aplites, and Pegmatites outcrop as masses, dykes and veins. The microgranites and aplites are pale grey, fine grained and consist of plagioclase, quartz, K-feldspar, biotite and tourmaline.

Three types of variation are displayed on Harker chemical variation diagrams: 1) negative correlation (e.g. Mg, Cr, Co), 2) positive correlation (e.g. Rb, some REE's), 3) concave-downwards (e.g. HFSE, some LILE and REE's). REE patterns have strong negative Eu anomalies, and light and heavy REE's have variable fractionation. Aluminium saturation (ASI) increases with differentiation and ITR straddle the I and S fields, with the more mafic rocks broadly I-type and the high silica rocks S-type.

A simple two end member mixing process fails to explain the chemical characteristics of the plutons, either as a group or singly. The petrographic and chemical variation can be explained by a three stage process as suggested by Poli & Tommasini (J. Petrol.,in press).
Stage #1: a felsic magma is intruded by a hotter and less viscous mafic magma without mixing.
Stage #2 at comparable temperatures and viscosities with the felsic magma, the mafic magma convectively mingles and undergoes crystal fractionation and contamination (CFC) with the felsic magma in a number of repeated cycles. This results in the formation of both microgranular enclaves and an evolved mafic liquid. At stage #3 the evolved products of the mafic magma and the felsic magma participate in a two end-member mixing process. The felsic endmember could be the leucocratic facies.

The petrogenetic model for the ITR indicates that the I and S classification must be used only after a complete petrogenetic study.

Structural controls on granitoid genesis in transpressional shear zones

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Existing attempts to classify and account for granitoid 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 granitoids 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.

A STABLE ISOTOPIC ($\delta^{18}O$,δD) STUDY OF THE LATE HERCYNIAN GRANITES AND THEIR HOST-ROCKS IN THE CENTRAL IBERIAN MASSIF (CIM, SPAIN)

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Stable isotopic ratios (mainly $^{18}O/^{16}O$, but also D/H and $^{34}S/^{32}S$) have been measured for the three most important types of late-Hercynian granites -and their hosts- in the western area of the Central Iberian Massif (CIM, Spain). These granites are Amphibole-bearing biotite granites (average apatite-corrected A/CNK= 1.05), Biotite granites (av. A/CNK= 1.09) and Cordierite-bearing biotite granites (av. A/CNK= 1.18). No intrusive relationships have been observed amongst them. The contacts between granites are always gradual. Cordierite-bearing biotite granites are most frequent in marginal areas of the batholith. Towards internal areas, cordierite contents decrease, and when no cordierite is left, the rock changes into a Biotite granite. Microgranular (tonalite-quartzdiorite) enclaves are abundant in all three granite types, and some gabbro enclaves have also been found. The host-rocks range from common hornfelses to cordierite-rich contact migmatites (Nebulites, av. A/CNK= 1.83). Predominant country-rocks are the Precambrian / Cambrian shales of the so called "Complejo Esquisto-Grauváquico" (CXG, schist-greywackic complex). Whole rock $\delta^{18}O_{SMOW}$ values obtained are as follows: Amphibole-bearing biotite granites 8.9±0.58‰ (1σ, n=17); Biotite granites, 9.0±0.55‰ (1σ, n=13); Cordierite-bearing biotite granites, 9.6±0.49‰ (1σ, n=21). $\delta^{18}O$ values for Nebulites, into which some of these granites are emplaced, are significantly higher, at 11.05±0.58‰ (1σ, n=13). The unmetamorphosed Precambrian to Cambrian shales of the CXG gave an average value of $\delta^{18}O$=11.9±1.23‰ (1σ, n=5). Whole-rock oxygen isotopic ratios indicate that the protolith of the granites were neither purely crustal rocks nor pristine mantle melts. $\delta^{18}O$ values close to 9.0‰ require a composite protolith, with an important participation of a recycled component. Microgranular, tonalitic-quartzdioritic enclaves with $\delta^{18}O$ as low as 6.6‰ have been found. Oxygen isotopic results are compatible with the cordierite-bearing granites being generated by assimilation of nebulite-like material by a biotite granite magma. $^{18}O/^{16}O$ ratios determined in mineral separates obtained from the three different granites and the nebulite indicate, however, that equilibrium, if ever reached, has not been preserved. The reason for isotopic equilibrium being modified is attributed to fluid activity, but mineral-pair δ-δ plots demonstrate that the granite-system always behaved as a closed one, and therefore the fluid had to be of deuteric (magmatic) origin. This implies that if assimilation did happen, it occurred at a temperature higher than the closure temperature of the different minerals to isotopic exchange. In a $\delta^{18}O$ vs δD plot, hornblendes and biotites separated from the granites plot inside the igneous field. A simple mesocrustal anatectic origin for the peraluminous late Hercynian granites of the western area of the CIM is difficult to sustain in view of these stable isotope data, and earlier field, petrographic and geochemical evidence. Cordierite in the cordierite-bearing granites is not "restitic" from the source area, but xenocrystic from the high-grade metamorphic country rock.

ALTERATION EFFECTS OF TRIOCTAHEDRAL MICAS AS A CONTRIBUTION TO PETROGENESIS OF GRANITOID ROCKS FROM THE ELBE LINEAMENT (SAXONIA).

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Bergakademie Frieberg.

Within the comprehensive examination of the Variscan and Prevariscan granitoids of the Elbe lineament in SE Saxonia (1) a detailed investigation of the trioctahedral micas has been carried out.

The mineral separates were analysed with 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 by inclusions of accessory minerals and mineral alteration. The micas from different rock types were classified as Mg- and Fe^{2+} biotites according (2).

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 hydro-biotite 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 (chloritization and the formation of hydrobiotite - vermiculitization). The chloritization 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 martitization of magnetite. The process seems independent of the rock type.

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LACHLAN OROGEN PLUTON - EMPLACEMENT STRUCTURES

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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 "balloonong pressure" against the country rock during intrusion a small 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.

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 suggests that magma was ponded at the base of the brittle upper part of the crust at depths of 8 - 10 km and that this carapace warped and faulted permitting plutons to emplace passively. 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.

A poster shows examples of these structures.

S-TYPE GRANITES OF THE LACHLAN FOLD BELT: ARE PROTEROZOIC SOURCE ROCKS REALLY NECESSARY?

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Among the oldest known rocks in the Lachlan Fold Belt are metamorphosed Early Cambrian boninites, low-Ti andesites and MORB-like basalts and dolerites. In modern situations this association of rock types is known only from Western Pacific-type settings involving island arcs and back-arc basins. Accordingly a subduction-related, intra-oceanic environment has been inferred for the early history of the Lachlan Fold Belt (Crawford & others, 1984).

Another feature of the fold belt is the presence of S-type granitic rocks whose low Ca, Na and Sr contents and high initial $^{87/86}Sr$ ratios imply derivation from source rocks that have been through at least one sedimentary cycle (Chappell & White, 1974). The bulk of the S-type granitoids show significant differences when compared with the exposed Cambro-Ordovician sediments of the region. This has led some authors (e.g. Chappell & others, 1988) to propose that buried Proterozoic rocks must be present despite the apparently-ensimatic Early Cambrian setting. Sr and Nd isotope studies have produced a strongly covariant array for the S-type granitoids which suggests derivation from sediments about 1400 Ma old (McCulloch & Chappell, 1982). However as Gray (1984, 1990) has pointed out, the isotopic data are also consistent with mixing between a mantle-like component and an isotopically-evolved (Early Palaeozoic) crustal component.

Attempts to resolve the above paradox have generally suggested that Proterozoic sialic material was thrust beneath southeastern Australia during the Late Ordovician-Early Silurian Benambran Orogeny (e.g. Crawford & others, 1984). The considerable problems associated with models advocating underthrusting on this scale have yet to be satisfactorily addressed, however. For example, if a large block of buoyant sialic material was thrust beneath central Victoria (where there are abundant S-type granitoids and volcanic rocks) during the Benambran Orogeny, why is the crust here relatively thin (some 30 km) and why did the region remain a sedimentary basin for about 50 Ma following the orogeny?

These difficulties are overcome by a newly-developed model which asserts that most of the S-type granitoids of southeastern Australia were produced when mantle-sourced (apparently shoshonitic) magma mixed with crustal melts derived from Early Cambrian back-arc, tholeiitic basalt (and dolerite) and Early Palaeozoic sedimentary rocks. The last appear to have been richer in Ca, Na and Sr than the Early Ordovician sediments currently exposed in the Lachlan Fold Belt and were probably of Middle-Late Cambrian age: rocks of appropriate composition and inferred age occur in the Gundowring Terrane of the Wagga-Omeo Metamorphic Belt (Fleming & others, 1985).

It is envisaged that melting of Early Cambian tholeiites and overlying Middle-Late Cambrian sediments took place when mantle-sourced magma ponded at the interface between them (at a depth of about 15 km). The anatectic process seems to have been controlled by the breakdown of hornblende in the (meta)tholeiites and biotite in the (meta)sediments. The hydrous mineral contents of the two source components probably determined the degree of melting (and the melt compositions) in each as suggested by Clemens & Vielzeuf (1987). Mixing of mantle material and tholeiite- and sediment-derived melts (and perhaps unmixing of the two restite fractions) presumably occurred as the entire contents of the melt zone moved towards the upper crust. The chemical (including isotopic) variation in S-type granitoids 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 such as occur in the Stavely Belt and the Jamieson and Licola segments of the Mount Wellington Belt. Andesitic rocks from these areas do not match the I-type granitoids precisely (they contain too little Al and too much Fe in particular) and mantle melts may have been involved in their genesis as well.

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

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Large amounts of late-Hercynian granitoids are exposed over an area of about 1,250 sq. Km in the southern Calabrian Arc. In the past, they have been referred to two different granitoid suites: a predominant calc-alkaline, weakly peraluminous one (biotite ± hornblende quartz gabbro/diorite to granodiorite), and a strongly peraluminous one (two mica ± Al-silicate-bearing trondhjemite to granite). In particular, the Villa S.Giovanni (VSG) and Capo Rasocolmo (CR) strongly peraluminous intrusions, coeval but not spatially related to the calc-alkaline ones, have been considered S-type. The two granitoid types have similar Sr and Nd isotope compositions.

The calc-alkaline intrusives are mostly I-type granitoids, and they have been most likely generated by interaction of mafic magmas with crustal components. This magmatism is probably dominated by crustal recycling, a feature typical of the European Hercynides, which makes it difficult to recognize mantle contributions. Alternately, mantle components derived from an enriched domain and showing no significant isotopic contrast with the overlying continental crust, could have been involved.

A geomathematical approach to their geochemical composition confirms that the VSG and CR strongly peraluminous intrusions are distinguishable from the calc-alkaline ones, and cannot be directly related to the latter by high level fractionation or AFC processes in a frame of monogenetic evolution. Therefore, they must represent separate melts. Principal components analysis of the strongly peraluminous group (VSG+CR) indicates that a single process could be responsible for the variation in the data. Factor coefficients indicate that both Al-Ca-femic and K-Rb components strongly affect the first eigenvector, but with opposite behaviours. In addition, several lines of evidence (i.e. texture, mineralogy, trace and REE geochemistry), suggest that the mixing of two components, a dominant trondhjemitic mantle-derived one and a metasediment-derived one, produced the VSG and CR granitoids. The trondhjemitic component is high-Al type, and has positively fractionated REE pattern (La_n/Yb_n = 64; Yb_n = 4) with slight positive Eu anomaly.

Whether the trondhjemitic component is due to mantle input at the time of granite production, via fractional crystallization dominated by hornblende and plagioclase, or it represents a crustal melt derived from a meta-igneous source (gt-amphibolite), is still an open question. Both these processes are considered viable. Available Nd_{DM} model ages, in the range 1.2-1.8 Ga, are not conclusive. They are, however, quite similar to those of Western European Hercynian peraluminous granites interpreted as mostly derived from a meta-igneous source.

Our conclusion is that the strongly peraluminous granitoids of the southern Calabrian Arc represent mixtures of igneous mantle-derived and metasediment-derived components, while true S-type granites are absent.

MANTLE-CRUST INTERACTION IN THE EUROPEAN HERCYNIDES: ISOTOPIC AND GEOCHEMICAL EVIDENCE FROM SPANISH CENTRAL SYSTEM GRANITOIDS

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The Spanish Central System (SCS) consists of large granitic occurrences, associated with minor basic to intermediate intrusives, occurring as small bodies and stocks. Mafic microgranular enclaves and mega-enclaves of intermediate composition are present in most granitic plutons.

The Eastern part of the System has been extensively studied from a geochronological point of view: Rb/Sr whole rock ages range between 252 and 379 Ma, while Rb/Sr mica ages cluster to 290-300 Ma. Rb/Sr dating of the Western part of the SCS yielded a whole-rock isochron age of 312 ± 21 Ma, with significant scatter of data points; biotite-whole rock ages are in the narrow range 298-306 Ma.

This paper reports on geochemical and Sr-Nd isotopic data on granitoids from the Bejar region, in the Western SCS, which mainly consist of porphyritic-biotite monzogranite-granodiorite (BG), often cordierite+/-muscovite bearing (CMG). These rocks often contain qtz-dioritic to tonalitic mafic enclaves of different size.

Both BG and CMG are moderately peraluminous (normative Corundum in the range 1.5-3.6), and show major element variations linearly correlated with silica; nevertheless some trace elements as Sr and Rb are scattered mostly in the CMG samples. They are moderately LREE enriched, showing pronounced negative Eu anomalies and significant LREE/HREE fractionations, and have geochemical characteristics similar to those of volcanic arc granites.

The initial Sr isotopic compositions are in the range 0.70802-0.70910 and 0.70799-0.70894 in BG and CMG respectively. A qtz-dioritic mega-enclave some meters in size and a small microgranular tonalitic one have significantly lower initial $^{87}Sr/^{86}Sr$ ratios than the host granitoids ($^{87}Sr/^{86}Sr$=0.70718 and 0.70797 respectively).

The initial ε_{Nd} values in BG range between -4.9 and -8.0, while in CMG they range between -5.3 and -7.8. The qtz-dioritic enclave and the microgranular one have an initial ε_{Nd} value of -4.3 and -5.5 respectively.

The geochemical and isotopic features of the Western SCS granitoids, along with the close association of mafic rocks and granites and the widespread occurence of mafic enclaves, strongly suggest that a basic magma component deeply interacted with the crustal melts. AFC or binary mixing modelling do not satisfactory account for the chemical and isotopic features of the studied granitoids. A more complex scenario, involving interactions at different scale between basic melts possibly derived from an enriched, geochemically composite mantle source and products of crustal partial melting, is therefore suggested.

THERMAL, MECHANICAL AND ISOTOPIC CONSTRAINTS ON GRANITE GENESIS WITH APPLICATION TO THE SOUTHERN ADELAIDE FOLD BELT

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At typical orogenic strain rates the low thermal conductivity of the crust precludes granites emplaced early in, or during, convergent deformation being generated as the conductive response to crustal thickening alone. Rather, such granites may reflect: (1) a dramatic increase in the sub crustal heatflux, for example by thinning the mantle lithosphere, or (2) the emplacement of mantle magmas. The strong temperature dependence of lithospheric rheology implies that both mechanisms may have profound consequences for the distribution and rates of deformation within the orogen. Therefore the two mechanisms can be compared by modelling the mechanical consequences of granite generation. For driving forces appropriate to the generation of orogens with crustal thickness of ~50 km and a simple lithospheric rheology consisting of quartz-dominated crust and olivine-dominated mantle we show for *mechanism 1* that the generation and emplacement of granites may provide sufficient weakening to initiate transient (< 3 Ma) high strain rate deformation with ε_z up to 10^{-14} s^{-1} and finite crustal thickening strain increments up to 10%. The magnitude of the thermal weakening effect is sensitive to the critical temperature for granite segregation, T_{crit}, and the depth of intrusion with the highest strain increments for intrusions at $T_{crit} < 800°C$ emplaced at depths less than ~10 km. Importantly, for $T_{crit} \geq 800°C$ the thermal weakening effect is limited because the absolute strength of the lithosphere is very small by the time granites are generated and, consequently, the potential energy of the deformed lithosphere is already close to the maximum attainable. Significantly higher crustal thickening strain increments (up to ~30%) may be attained for *mechanism 2* when mafic magmas are intruded into the upper mantle/lower crust with temperatures significantly lower than 800°C. The implication is that any significant crustal thickening attendant with granite intrusion occurs primarily in response to mafic magma input. In the Southern Adelaide Fold Belt granite intrusion spans a ~25 Ma convergent deformation cycle initiated within 10 Ma of the cessation of sedimentation. Sporadic magmatic activity was continuous both during sedimentation and orogeny with convergent deformation resulting in crustal thickening to ~45-50km. Metamorphism is spatially restricted to an axis of magmatic activity where, at least during granite emplacement, the intensity and complexity of deformation is much greater than in adjacent low grade areas. The implication is that granite generation and emplacement is a causative factor in localising deformation The Nd- and Sr- isotopic composition of the granites reflect mixed sources with components derived both from the depleted contemporary mantle and the older crust, consistent with transgression of the Moho by mantle melts appropriate to *mechanism 2*.

DISEQUILIBRIUM MELTING AND THE DIFFERENCE BETWEEN THE TRACE ELEMENT CONTENTS OF MIGMATITE LEUCOSOMES AND GRANITES.

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Migmatites have been viewed as an initial stage in the formation of granitic magmas, and more recently as "failed granites". However, new chemical data shows that many migmatites have trace element contents that are distinct from those of granites. Why should migmatite melts differ in composition from granites?

Migmatites formed by the partial melting of metabasalts in the Grenville Front and from granodiorites in the Opatica Belt both contain innumerable, small volume (10^3 to 10^4 cm^3) leucosomes located mainly in dilatant structures, such as shear bands and boudin necks, that formed during syn-melting heterogeneous deformation. The residual rocks to the melting event are nearby, and imply short melt transfer distances of 10-100 cm. The leucosomes are depleted in Ti, Fe, Mn, Mg, Co, Cr, Ni, Sc, V, the REE, Hf, Zr, P, Th, Nb and Ta relative to their source rocks. These elements are enriched in the residua. Such compositions are consistent with disequilibrium melting, for example, Zr is depleted (12-68 ppm) by up to a factor of 8 in the leucosomes relative to the estimated Zr content (110 ppm) of an equilibrium melt of similar major oxide content.

Partial melting of the granodiorite gneisses in the Opatica Belt has also produced several types of granite body. 1) *In situ*, patches (10^5-10^6 m^3) of coarse-grained granite with compositions that are either similar to the source gneisses, or are depleted in mafic components, but enriched in Ba, Rb, K, Zr, Th and the REE relative to the gneisses. These granite patches contain scattered gneiss schlieren. 2) Granites that have moved from the source region, these have higher SiO_2, Cs, Ta and Th contents than the *in situ* granites and are divided into, a) small stocks and sheets with individual volumes up to a km^3 that have migrated relatively short distances and, b) melts that have migrated several kilometers to form dyke and sill arrays in lower-grade hosts; individually these have volumes of perhaps 10^3-10^5 m^3, but collectively may amount to as much as a km^3. All the granites have much higher trace-element contents than the migmatite leucosomes and are an approximation to equilibrium batch melts.

Based on the results from these two regions where partial melting occurred it is proposed that:

1) Small volume melts, characteristic of migmatites, cannot be the source of most granitoid plutons because of their low trace-element contents.

2) The disequilibrium compositions of migmatite melts may arise if the melt and solid were separated before complete chemical equilibrium between their respective volumes was reached. At the low temperatures of migmatisation (<750°C) diffusion of trace elements between melt and solid requires more time than the process of melt segregation - especially if segregation is driven by the pressure gradients resulting from heterogenous deformation. Melt migration rates of 2 cm a^{-1} at 750°C are sufficient to preserve disequilibrium compositions.

3) Anatectic melts with volumes >few m^3 are typically equilibrium melts. This may be because they formed at higher temperatures (>850°C) where the higher diffusion rates allow chemical equilibrium between melt and solid to be reached before segregation can take place. It is estimated that melt migration rates of >35 cm a^{-1} would be required to maintain disequilibrium compositions at 850°C.

GEOCHEMISTRY AND GEOCHRONOLOGY OF HONG KONG GRANITOIDS

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The granitoid rocks of Hong Kong comprise dominantly biotite granites of calc-alkaline affinity. Whole rock geochemistry and Rb-Sr geochronology confirm the existence of two plutonic suites that reflect different source compositions.

Granodiorite and granite of the Lamma Suite are the oldest intrusive units in the Territory. Granites are metaluminous to slightly peraluminous and moderately fractionated (SiO_2 = 71-75 wt%). Compositions are characterised by high Na_2O (>2.8 wt%) and CaO (1.4 - 2.7 wt%), low Nb and Y contents, and low FeO*/MgO ratios (3 - 8). REE patterns are LREE-enriched (Ce_N/Yb_N=7.0 - 7.37), with negative Eu anomalies (Eu/Eu*=0.62 - 0.63). Calculated initial $^{87}Sr/^{86}Sr$ for the granodiorite at T=150 are relatively high (0.71279 - 0.71618) and one sample has yielded a large negative epsilon Nd value (-10.5). Petrographic characteristics suggest derivation from an I-type or meta-igneous source.

The Lion Rock Suite comprises three subgroups. The oldest subgroup includes deformed, moderately to highly fractionated granites (SiO_2=72.5 - 78 wt%) that are characterised by high Y/Nb ratios (2.5 - 6) relative to other members of the suite. The least-fractionated compositions have LREE-enriched patterns (Ce_N/Yb_N=14, Eu/Eu*=0.34) whereas the most evolved have flat patterns with large Eu anomalies (Ce_N/Yb_N=0.48, Eu/Eu*=0.03). The granites are best interpreted as highly fractionated I-types.

Granites of subgroup II are metaluminous to slightly peraluminous, with silica contents ranging from 72.8 to 77.2 wt%. Highly fractionated compositions are characterised by strong enrichments in Rb, Nb, and Y, and depletion in Ba. Whole rock Rb-Sr data for for coarse-grained granites from one pluton yield an age of 148±9 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7060±6 (MSWD=0.1). LREE-enriched patterns (Ce_N/Yb_N=14.6 - 7.07) in the most fractionated compositions have negative Eu anaomalies (Eu/Eu*=0.73 - 0.15) and the rocks yield epsilon Nd values ranging form -4.4 to -7.1. Genetic classification is difficult although I-type affinities are suggested.

Subgroup II comprises undeformed granites which are metaluminous to slightly peraluminous and moderately to highly fractionated (SiO_2=72.5 - 77.9 wt%). Highly evolved compositions are marked by extreme enrichment in Y, Nb, and Rb, depletion in Ba and Zr, high FeO*/MgO ratios (10 - 150), and relatively flat REE patterns with large negative Eu anomalies (Ce_N/Yb_N=0.68, Eu/Eu*=0.04). Rb-Sr whole rock isochron ages for individual plutons vary from 139±2 to 136±1 Ma. Corresponding initial Sr ratios are 0.7076±3 (MSWD=5.9) and 0.7092±6 (MSWD=1.4) and epsilon Nd values are in the range -4.8 to -6.1.

The Late Mesozoic history of southeastern China is one of volcano-plutonism related to subduction along the continental margin. Two phases of granitoid emplacement have been reported: an early phase ranging from 190 - 140 Ma, and a late phase from 135 - 70 Ma. The ages of the Hong Kong granites place them at the boundary between these early and late phases. Compositional differences in the source regions of the granite magmas together with structural data suggest a transition from compressional to mildly tensional tectonics.

VOLCANIC-PLUTONIC CONNECTIONS, URALLA IGNEOUS CENTRE N.S.W.

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The Uralla Igneous Centre consists of a series of K-rich andesitic lavas and pyroclastic flows (Harnham Hill volcanic rocks), the Terrible Vale pluton, microstructurally zoned from dacite-tuffasite to quartz-monzodiorite, the Uralla pluton, zoned from granodiorite to diorite, the Kentucky Diorite and the Yarrowyck Granodiorite to the north of Uralla.

The Harnham Hill volcanic rocks and underlying sedimentary rocks are intruded by the Terrible Vale pluton in part along dyke-like extensions that are possible ring fractures. The Kentucky Diorite occurring within the Terrible Vale pluton is inferred to be intrusive and to be related to the magmatic event that produced the Uralla pluton which has also intruded the Terrible Vale pluton. The preservation of the andesites and thermally metamorphosed sedimentary rocks partly encompassed by the Terrible Vale pluton suggest they are down-faulted blocks within a cauldron subsidence area.

The Terrible Vale pluton is uniform in composition but is microstructurally zoned from a narrow marginal two-pyroxene dacite-tuffasite zone, to an inner coarser-grained porphyritic quartz-monzodiorite facies The dacite-tuffasite occurs along intrusive margins and is characterised by 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. Microstructures in the quartz-monzodiorite facies of the Terrible Vale pluton, unlike those in the Uralla pluton, have some characteristics more typical of metamorphic than igneous rocks. Quartz occurs as polygonal aggregates, rather than interstitial grains, and biotite forms sieved or poikilitic grains that enclose or partly enclose quartz. The effects of pressure quenching and exsolution-vesiculation in the Terrible Vale magma chamber may well be important in explaining nucleation and subsequent mineral growth.

The volcanic and subvolcanic rocks share strong chemical and isotopic similarities with the Uralla pluton (I-type but transitional to S-type) that intrudes the sequence. In particular they are K-rich and have high normative hypersthene to diopside ratios - modal characteristics also of the tuffasite facies of the Terrible Vale pluton. Rb/Sr data for the Harnham Hill andesites, and facies of the Terrible Vale pluton exhibit little variation although they show some scatter relative to the bulk-rock-mineral isochron of the Uralla Pluton which gives an age of 245 ± 16 Ma and an initial ratio of 0.7064 ± 0.0004. Four biotite Rb/Sr ages from the Terrible Vale, Uralla and Kentucky plutons vary from 251-245 Ma.

The juxtaposition of the volcanic and sub-volcanic rocks suggest that the region has been tilted such that the highest levels are exposed in the north-east and the deepest levels in the south-west as has also been inferred from the asymmetry of the zoned Uralla pluton. 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 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

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The Walcha Road pluton within the southern New England Fold Belt is 60 km long, 20 km wide and eliptical in outline. Botite/bulk rock ages for the pluton and small quartz micromonzonite stocks along the southern and western margin give Late Permian ages of approximately 247 Ma and initial $^{87}Sr/^{86}Sr$ ratios of 0.7047.

A foliation defined by the preferred orientation of the major axes of both feldspar and, where present, microgranitoid enclaves is generally margin parallel. Around the southern margin, dips are steeply inward suggesting a cone shape for that part of the pluton. A lineation present in samples near the margin is consistently down-dip. Modal, chemical and microstructural variations within the pluton define a concentric zoning pattern. The pluton, as exemplified by an E-W traverse along the Macdonald River, is zoned from a discontinuous marginal quartz monzonite (colour index = 35) with hornblende in excess of biotite, to a hornblende-free biotite-adamellite (colour index = 6) in the centre. The marginal quartz-monzonite, which contains white K-feldspar, is even grained and grades over a few tens of metres into a porphyritic mafic adamellite in which the K-feldspar megacrysts are pink and up to 20 mm in length. This zone grades inwards at distances from the contact of 0.5 km into a more leucocratic adamellite with pink K-feldspar megacrysts up to 50 mm in length that, over a further 4 km, decrease in abundance to near zero and, where most sparse, are white in colour. In spite of the marked changes in the K-feldspar megacryst abundance, modal K-feldspar (phenocrysts + groundmass) changes little from margin to core.

Small quartz-micromonzonite stocks along the southern and north-western margins of the Walcha Road pluton are sufficiently fine grained to show that magmas of intermediate composition with little restite were available and could represent the parent magma composition for the Walcha Road pluton.

Like the microstructurally similar Tuolumne Meadows pluton of the Sierra Nevada Batholith, the zoning within this pluton is suggested to result from the crystallisation of more mafic cumulate rocks along the margin with the accumulation of the residual melt near the top of the magma chamber. Calculations based on pluton shape as deduced from outcrop mapping and K-feldspar foliation measurements indicate that the felsic central parts of the pluton are volumetrically small compared with the more mafic marginal rocks.

Genesis of the lower crustal Opx-Grt tonalite (S-type) in the Hidaka Metamorphic Belt, northern Japan.

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The Hidaka Metamorphic Belt in the axial zone of Hokkaido, northern Japan consists of tilted metamorphic layers of an island-arc type crust from lower to upper horizons. The metamorphic rocks grade from greenschist facies in the east (structurally upper) to granulite facies in the west (lower). Granitic rocks (mainly S-type tonalites) are abundantly intruded into various metamorphic layers and are classified, based on their intrusive level and characteristic mineral assemblage, into four depth types; upper granite-granodiorite, middle Crd-Ms tonalite, lower Grt-Crd or Opx-Bt tonalite, and lowest Opx-Grt tonalite. These are intruded into low grade metasediments, greenschist facies to lower part of amphibolite facies gneiss, upper part of amphibolite facies to granulite facies gneiss, and granulite facies gneiss, respectively. These S-type granitoids have been geochemically and petrologically ascribed to have been derived by crustal anatexis in the lower crust than that appeared by thrusting.

The nature of magmatic reactions with their metamorphic enclaves or wall rocks differs according to the intrusive level of the magma. The effect by the lowest tonalite is considerably large, resulting in chemical reactions or assimilation of enclaves and wall rocks, and generation of a small amount of secondary S-type granitic melt from pelitic-psammitic granulites. On the other hand, the magmatic effect is smaller in shallower levels than in the granulite facies metamorphic layers. Textural evidence and compositional zoning of minerals indicate that the crystallization sequence are Grt-Pl-Opx-Bt-Qtz-Crd-Kfs in the lowest Opx-Grt tonalite.

The crystallization experiments were carried out by the internally heated pressure vessel, using natural rock powders of the lowest tonalite, under the conditions of 3-6kb, 700-850°C, with 0-20 wt.% H_2O, and 15, 20, and 25% normative Or, respectively. The result show that the primary S-type tonalite magma is generated at 7-8kb, ca. 900°C with 4-5 wt.% H_2O, that the lowest Opx-Grt tonalite crystallizes at 690°C-720°C, and that the changes of P-T conditions and chemical composition of the magma during ascent will result in formation of the lower to upper S-type granitoid continuously.

LATE PRECAMBRIAN EPIDOTE-BEARING CALC-ALKALIC INTRUSIVE SUITE IN NORTHEAST BRAZIL: OXYGEN ISOTOPES AND DEPTH OF CRYSTALLIZATION

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Over fifty Late Precambrian (~600 Ma) Conceiçao-type meta- to peraluminous tonalites and granodiorites intruded phyllites of the Cachoeirinha-Salgueiro Fold Belt (CSF) in Northeast Brazil, and contain primary epidote (based on criteria of Zen & Hammarstrom, 1984). Petrographically equivalent epidote-bearing granitoids (EBG) intruded schists of the Serido Fold Belt (SFB), a northward extension of the CSF and amphibolite-grade meta-sediments of the Riacho do Pontal Fold Belt (RPF) a southern extension of the CSF. Magmatic epidote is also found in tron-dhjemitic 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, if all Al variation in hornblende is ascribed to pressure. Lower pressure for qz diorite enclaves result from Al loss by sub-soli-dus reaction with plagioclase, generating granular epidote. Temperatures of equilibration for hornblende-plagioclase assemblages are in the range 950-1100 ^{o}C. They differ from Mesozoic EBG in N. America in that they intruded phyllites, likewise Paleozoic 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 930-1000^{o} 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 granitoids, 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 to +13 permil) and amphibolite xenoliths, probably from the source, have delta ^{18}O values (+6.2 to +8.2 permil) which are lower than equivalent epidote-bearing tonalites and trondhjemites in NW America (+7.5 to +9.0 permil, 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.

Tracking Magmatic Arc Evolution Across Contrasting Lithosphere Settings in Southwestern North America

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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 on the west to early Proterozoic crust-lithosphere on the east. Petrological, chemical and isotopic properties of the plutonic rocks show dramatic changes in many forms. This particular geologic 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 Penuinsular Ranges batholith although plutons of the former are more dispersed to the east. 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 mobilization 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.

Granitoids in the late Cenozoic arc-type magmatic associations of the southwest Pacific

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Granitoids, 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 Cenozoic arc-type magmatic associations of the southwest Pacific. This association of magmatic rocks dominates the late Cenozoic geologic record of the southwest Pacific margin from Papua New Guinea to northern New Zealand.

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

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

The granitoids of these southwest 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 granitoids. 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 GRANITOIDS : EVIDENCES FROM THE CALC-ALKALINE MAGMATISM OF CENTRAL PERU DURING THE ANDEAN OROGENESIS (105 - 0 Ma)

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The observed variations with time — from Albian to Pliocene - and in space - along a traverse of the Central Peruvian Andes near 11° of latitude S — of petrographical and geochemical features (major and trace elements, Sr-, Nd-, and Pb-isotopes) of the calc-alkaline magmatic rocks associated with the subduction of the Farallon and Nazca plates under the western part of the South-American continent), and relationships between magmatic activity, the features of the ocean — continent convergence and the orogenic evolution of the continental margin show that:

- The time and space distribution of the magmatic rocks is narrowly controlled by the features of the subduction.
- The calc-alkaline volcanic rocks and the "I type" granitoids of the Andean margin were derived from the same mantle source. Chemical differences indicate however that the crustal histories of the magmas leading to the plutonic and the volcanic rocks respectively diverge at an early stage and that the plutons are not the magma chambers which fed the volcanoes. The source would be an enriched mantle modified by fluids extracted from the subducted slab.
- The variations of the chemical and isotopic features of the calc-alkaline rocks with time during the orogenesis correspond mostly to crustal processes which take place in deep magma chambers and include:
  - diffusive exchanges between the magmas and the crustal countryrock, a self-limitative process which accounts for the medium- to high- K contents of the studied rocks.
  - assimilation of the countryrock at an early stage of differentiation.
  - modifications of the mineralogy of the crystallizing phases, with the appearance of garnet at the liquidus and the later crystallisation of plagioclase which lead to lower HREE, Y, Sc, Mn, and higher Sr and LREE in the intermediate and felsic rocks.

For these elements and the isotopic compositions the observed evolution corresponds to a nearly monotonous succession of jumps which are contemporaneous with the tectonic crisis and subsequent crustal thickening and are interpreted as the result of an increase of the crustal assimilation and an evolution under higher and higher pressure at an early stage of differentiation of the magmas.

Thus the evolution of the chemical and isotopic features of the calc-alkaline volcanic and plutonic rocks of Central Peru may be regarded as the geochemical fingerprint of the orogeny upon mantle-derived magmas, the primary chemistry of which did not evolve noticeably with time.

THE ORIGIN OF COOMA SUPERSUITE GRANITES: SOURCE PROTOLITHS AND EARLY MAGMATIC PROCESSES

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The geochemical characteristics of granite source regions and the nature of early magmatic processes are commonly inferred, given that the vast majority of granitic bodies studied are far removed from their sources. This is certainly the case in the Lachlan Fold Belt (LFB) of SE Australia where 'infracrustal' and 'supracrustal' sources of pre-Ordovician age have been inferred for the voluminous contact aureole I- and S-type granites of the region (e.g. Chappell, 1984, McCulloch and Chappell, 1982).

In contrast, the regional aureole Cooma Supersuite granites are characterised by a low CaO and Na_2O, highly peraluminous chemistry considered indicative (e.g. Chappell, 1984) of derivation from the extensive feldspar-poor Ordovician turbidite sequences exposed in SE Australia.

The Yabba adamellite is a residue-/inclusion-rich, syn-tectonic pluton of Siluro-Devonian age emplaced in the high T, low P Wagga Metamorphic Belt, SE Australia. Chemically, the Yabba pluton is identical to the Cooma Supersuite granites. The high grade late Cambrian(?) Gundowring terrain (Fleming et al., 1985) is located along the pluton's gneissic northern margin. A clearly intrusive contact with the lower grade early Ordovician (Kilpatrick and Fleming, 1980) Lockhart terrain defines the southern edge of the body. The unique juxtaposition of two tectonometamorphic terrains has allowed constraints to be placed on the age and composition of the metasedimentary protolith for the Yabba magma and by inference the granites of the Cooma Supersuite.

Petrographic, structural and geochemical comparison of the metasedimentary inclusion population in the Yabba adamellite with the two 'host' tectonometamorphic terrains indicates:

1) that the adamellite was not derived from the early Ordovician Lockhart terrain nor from the other exposed Ordovician flysch in SE Australia. The source for the Yabba adamellite, and by implication the granites of the Cooma Supersuite, is best represented by the gneisses and migmatites of the late Cambrian(?) Gundowring terrain,

2) that one of the quartzofeldspathic lithologies found in the source is absent from the inclusion population and represents the "fertile" component in the protolith.

A model for magma generation is proposed involving the partial melting and virtually complete extraction of the fertile parts of the source giving rise to residue-rich magmas that almost perfectly image their sources. The chemical variation observed within the Yabba pluton reflects the differing incorporation of the various residual and non-melted source components during magma generation. The non- or partially melted (infertile) rock types are represented by the metasedimentary inclusions observed throughout the Yabba body.

The Cooma Supersuite granites were derived from the Gundowring terrain and/or its equivalents that probably underlie the monotonous Ordovician turbidite sequences and thus form part of the basement to the LFB. However, the chemistries of the Gundowring gneisses exposed in the Tallangatta region preclude the derivation of the voluminous 'S-type' granites (e.g. the Bullenbalong Suite) by a simple partial melting mechanism. Either a more immature (feldspathic) metasedimentary protolith or a more complex model (e.g. Gray, 1984) have to be invoked to produce the chemical characteristics of the contact aureole 'S-type' granites.

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SPATIAL, COMPOSITIONAL AND RHEOLOGICAL CONSTRAINTS ON THE ORIGIN OF ZONING IN THE CRIFFELL PLUTON, SCOTLAND

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ABSTRACT

This contribution examines the interplay of chemical and physical factors within the spatial framework of the Criffell zoned granodiorite-granite pluton. Specifically addressed is the extent to which closed and/or open system processes are responsible for the observed zonation. This study demonstrates that, for the Criffell example at least, first-order zonation characteristics are due to open system processes upon which closed system effects are superimposed. Compositional variation is considered to be due primarily to heterogeneities in the source and consideration is given to contrasts in the rheological properties of melts derived from a mixed I- and S-type source, and to mechanisms of reversing the expected density-driven emplacement sequence of acid to basic.

The Criffell pluton (397 Ma, a Newer Granite of Caledonian age) is concentrically zoned with outer granodiorites (lowest SiO_2 of 58%) of typically I-type aspect (amphibole-bearing, metaluminous, $(^{87}Sr/^{86}Sr)_i \approx 0.7055$, and $\delta^{18}O \approx 9‰$) passing into inner granite (highest SiO_2 of 73%) with more evolved characteristics (2-mica, peraluminous, $(^{87}Sr/^{86}Sr)_i \approx 0.7068$ and $\delta^{18}O \approx 11‰$). Whole rock analyses have been performed on 180 samples and the zonation is examined in terms of the compositional topography of bulk parameters such as SiO_2 and Rb/Sr. Discontinuities identified by spatial derivatives are consistent with field observations of internal contacts between magma pulses. Compositional variation is best modelled as multi-pulse, there being greater variation between pulses than any within-pulse variation; this feature is rarely apparent in 2-dimensional variation diagrams. This model is consistent with published variations in εSr, εNd and O isotopes which reflect the interaction of magmas and/or contaminants from isotopically distinct sources. Effects of mingling with mafic magmas (basic enclaves) and restite separation in the early granodiorites, and fractional crystallisation in the late granites, are superimposed but are less effective at differentiation.

Such interplay of different processes is far from unique in the Caledonian Newer Granites and reflects the involvement of a dominant infracrustal I-type magma with magma derived from more evolved crustal rocks (mainly metasediments of varying ages and maturities). The generation of large masses of multiply-sourced magmas implies that the source itself is likely to be a mixture of primitive and evolved components. Experimental fluid-absent melting of amphibolite and metapelite at about 900°C can generate significant quantities of melt, respectively with I-type and S-type characteristics. Despite having similar bulk compositions these melts have very different viscosities for the same H_2O contents ($\eta_{S\text{-type}} > \eta_{I\text{-type}}$ while $\rho_{S\text{-type}} \leq \rho_{I\text{-type}}$). If their escape from the source region follows complex tortuous pathways then the more fluid I-type melts should migrate more rapidly than the more viscous (and only slightly less dense) S-type melts. This constraint could have the effect of reversing the expected bouyancy-driven emplacement sequence, and may represent an alternative rheological differentiation mechanism for the formation of some zoned plutons.

THE GEOLOGY AND PETROLOGY OF ARFVEDSONITE GRANITES, HINCHINBROOK ISLAND, NORTH QUEENSLAND

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Hinchinbrook Island is noteworthy for the occurrence of late Permian arfvedsonite granites in its main east pluton, over a distance of 16 km and within 1100 m of topographic relief and is a thickly forested wilderness, with the alkali granites forming a backbone of precipitous peaks.

The regional context is comprised of older felsic volcanics (Upper Palaeozoic?), intruded by I-type granites. These are cut by a felsic ring dyke, the main eat pluton and a final local felsic dyke swarm.

The granites comprising the east batholith are dominantly hypersolvus, with quartz, microperthite, relatively minor biotite and/or arfvedsonite and a variety of accessories. At lower altitudes along the east coast there are pink two-feldspar granites which appear to underlie the hypersolvus granites, within the same zoned pluton.

The rocks in the east pluton contain near-horizontal layering structures, which confirm downward solidification in those places where directional growth ca be interpreted (Stephenson, 1990). The roof of the pluton was supposedly close above the present mountains.

Geochemically the main pluton rocks are clearly A-type (after Whalen et al. 1987), with strongly fractionated characteristics (e.g. very low Ca, Sr). Specimen sequences were examined for possible vertical geochemical fractionation in four profiles from summits to sea level, but trends are inconsistent. Overall the rocks show considerable trace element fluctuation, but without the extreme concentration of some elements found in some arfvedsonite-bearing granites elsewhere. few of the arfvedsonite granites are peralkaline (*Al* vs *Na+K*), reflecting the low arfvedsonite mode (<2%).

In general the rocks display well-developed primary crystallisation textures. In many specimens the arfvedsonite has classic late textures, occurring in miarolitic cavities with quartz, degraded biotite and accessory minerals. Convining evidence for metasomatism (commonly invoked for other peralkaline granites) is absent, and the distributions and characteristics of the amphibole suggests growth from late melt (or fluid?) developed from the original magma. This must have been a fluorine and iron-rich silicate melt. Arfvedsonite-bearing granites appear to occur in several thick zones, disposed parallel to the layered structures.

Isotopic Rb-Sr results for the Hinchinbrook alkali granites and I-type granites in the Palm Islands directly to the south provide a relatively tight isochron with an initial ratio close to 0.7 and an age of 275 Ma. This age compares with previously measured K-Ar determinations for the east pluton, Hinchinbrook (257-271 Ma) and for the Palms (274-282 Ma). Sm-Nd results are much more dispersed with a range of model ages. A youger age of emplacement is inferred for the main east Hinchinbrook pluton, based on the common mafic dyke swarms which cut the Palms granites but are virtually absent in the Hinchinbrook rocks.

The arfvedsonite granites evolved almost simultaneously with the I-type Palms granites, and with some consanguinity given their similar Sr and Nd systems. The processes responsible for development of the localised, more strongly fractionated granites on Hinchinbrook are unclear.

The main east batholith contains a thick 'roof' facies of directionally-solidified, layered rocks, passing downwards into two-feldspar granites. Partial melting of crustal tonalite to granodiorite (Creaser et al. 1991), followed by considerable crystal fractionation is preffered over a residual source model (Collins et al. 1982)

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CLASSIFICATION AND NOMENCLATURE FOR HONG KONG GRANITOIDS

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The first systematic geological survey of Hong Kong in the late 1960s recognised four main phases of Upper Jurassic syn-tectonic plutonic activity. 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 has established a system of granitoid classification based on the identification of rock textures in the field, with grain size as the main qualifier, and additional terms such as "megacrystic", "microcrystic", "inequigranular" and "micro-" used to distinguish textural variants.

Together with detailed petrology, geochemistry and whole rock Rb-Sr geochronology, the mapping by the Geological Survey has resulted in the establishment of a pluton-based nomenclature for Hong Kong granites. 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. Coarse- to fine-grained porphyritic lithologies predominate.

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; these two-phase plutons are tecturally variable, ranging from coarse-grained granite to megacrystic fine-grained granite.

Subgroup II embraces the large (>20 km) elliptical plutons of Lantau and Sha Tin, and two units of quartz syenite. Granites are characterised by varying textures and grain size, and include some two-phase variants.

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. These plutons, averaging 4-15 km in diameter, are undeformed and dominated by equigranular medium- to fine-grained lithologies, with subordinate megacrystic fine-grained variants.

Granitoid compositions and crustal growth mechanisms

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Although "no growth" constant volume models for the Earth's continental crust were once popular, there is now more of a consensus that the Earth's crust has grown progressively with time, though estimates vary widely as to the rates of growth. The processes of crustal growth are best examined through study of granitoid compositions through time. The depleted DM mantle reservoir has developed in response to extraction of crustal components from the mantle, but other reservoirs involving ocean island sources are required to achieve an acceptable mass balance. Just how these mantle reservoirs have evolved and been preserved through time is a subject of debate, but it is likely that their development is linked to the processes of subduction and the genesis of the continental crust and lithosphere.

This contribution examines critical features of the trace element composition of primary ("I-type") granitoids through time in an attempt to relate granitoid compositions to processes. The voluminous Archaean TTG suites are distinctive and result from shallow level melting of subducted overthickened warm oceanic crust leaving garnet and hornblende in the residuum. Such granitoids can be found in deeper levels of the Andean belt but are rare. In Phanerozoic belts, two different types of granitoids occur with multi-element patterns which are to a large extent complementary. One has generally high Ba and Sr contents, low HREE and high K/Rb; the other has low Ba and Sr, high HREE and low K/Rb ratios. These features probably reflect control of their parental compositions by hornblende or by phlogopite, respectively, in their sources. Both types have negative Nb and Ta anomalies which indicate a subduction-related process operating during development of their sources. Crustal development in the Archaean, Proterozoic and Phanerozoic is dominated by one or other of these granitoid types. It is instructive to review the changing nature of continental crust generation through time, to link this to the thermal evolution of subduction zones through time, and then try to relate these compositions to the growth of possible complementary reservoirs in the mantle (including the sub-continental lithosphere).

The general thesis is that, prior to continental growth, the upper mantle had the composition of PREMA ("PREvalent MAntle), which was slightly depleted, but otherwise much more fertile than present MORB mantle (DM reservoir). This material, which is probably now restricted to the lower mantle, is currently feeding major hotspots such as Hawaii and Iceland and produces over-thickened oceanic crust (elevated oceanic plateaux) that is very difficult to subduct. It was this material which was able to undergo extensive hydrous shallow melting under the high geothermal gradients of the Archaean and contribute to the high rates of crustal generation at that time. But as geothermal gradients eased, melting was restricted more to the mantle wedge, and dominated by fluids released during breakdown of hydrous phases as the wedge is dragged down by induced convection. In this scenario trace element (and subsequent isotopic) characteristics are strongly influenced by the particular mineral phases stable in the mantle wedge, or in the lithosphere if thermal breakdown occurs as a result of extensional rise of hot asthenosphere. Complementary reservoirs (HIMU, EM1, EM2) are formed in the mantle and the lithosphere as a result of these mineral-controlled fractionation processes, and it is possible to link these, at least in a general way, to the processes occurring in or adjacent to subduction zones.

VARIATION IN WATER FUGACITY DURING MELTING OF MAFIC LOWER CRUST AND THE ORIGIN OF PETROLOGIC DIVERSITY IN I-TYPE GRANITOIDS

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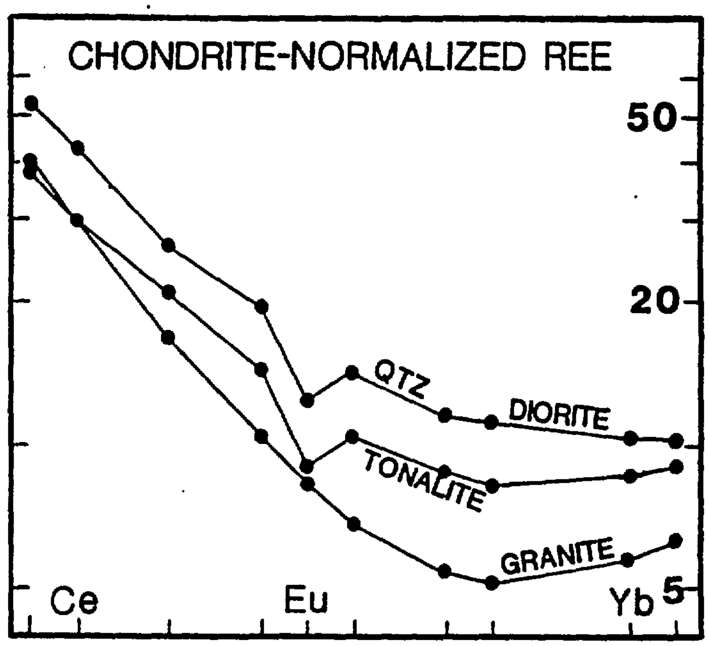
Petrologic diversity (quartz diorite - granite) is a characteristic feature of granitoids in I-type batholiths. Processes that have been suggested to account for this diversity include crystal fractionation, restite separation, and magma mixing. An alternative hypothesis, supported by field, geochemical, and mineralogical data from the Chilliwack batholith, is that the diversity reflects systematic variations in source mineralogy arising from differences in water fugacity during melting of amphibolitic lower crust.



The Chilliwack is a Tertiary calc-alkaline batholith in the North Cascades of Washington and British Columbia. The granitoid plutons span a continuum from quartz diorites to granites (57 - 76% SiO_2). REE patterns change systematically over this range (see figure), but are similar among samples from the same pluton. The lack of a Eu anomaly in the siliceous plutons precludes their having undergone significant fractional crystallization. Major and trace element data for these plutons are modelled by 20-30% melting at elevated f_{H2O} of an amphibolitic source having trace element characteristics of Chilliwack gabbros. Data for quartz diorite plutons are modelled by a comparable degree of melting and a similar source, but at lower f_{H2O}. The main effect of f_{H2O} variation is to change the proportions of plag vs. amph in the residuum (cf., Beard and Lofgren, J. Pet., 1991). This strongly influences melt composition, with higher f_{H2O} (residuum = amph + cpx $\pm$ plag) resulting in magmas with high SiO_2 and low MgO and FeO (and no Eu anomaly) compared to magmas generated at low f_{H2O} (residuum = plag + cpx + opx). The f_{H2O} differences probably reflect additions of H_2O to the lower crust from crystallizing basaltic magmas having a range of H_2O contents. Individual granitoid plutons are interpreted as discrete melt batches that have undergone limited subsequent modification by crystal fractionation, mixing, etc.

Evidence that siliceous plutons in the Chilliwack originated at higher f_{H2O} than intermediate plutons includes their association with aplite and pegmatite dikes, lack of pyroxene, Cl-poor apatites, and higher amphibole Mg-numbers (despite lower whole rock MgO and FeO). Based on geochemical and lithologic similarities, this model may be applicable to other I-type batholiths.

GENESIS OF A-TYPE GRANITES: TRACE ELEMENTS AND ISOTOPE CONSTRAINTS FROM THE OLIGO-MIOCENE YEMEN ALKALINE GRANITES

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Yemen plateau has been the site of two phases of extensive magmatic activity with climaxes at 30-26Ma and 22-20Ma. During the first phase, alkaline to transitional basaltic lava flows with minor felsic products were emplaced. During the second phase, felsic lavas and ignimbrite sheets, with minor basalts were emplaced together with alkaline granites and granophyric bodies which outcrop along a zone parallel to the Red Sea.

Yeman granites and granophyric dykes are light grey to pinkish, medium to coarse-grained rocks and are both subsolvus to hypersolvus indicating shallow emplacement depths of 0.05 to 0.2 GPa. Three main groups have been distinguished on their ferromagnesian mineral content: alkali amphibole granite, alkali amphibole plus biotite granite, and calcic amphibole plus biotite granite. Granophyres contain >95% quartz and alkali feldspar intergrowths with minor biotite and clinopyroxene.

Total alkali contents range from 7 to 11%, but the agpaitic index (Na2O+K20/Al2O3 mol%) does not strictly correlate with alkaline character. FeO_{tot}/MgO ratios and HFSE abundances are very high whereas halogen contents are at the lower end of the range displayed by A-type granites. Total REE abundances are variable (830-180 ppm) and correlate fairly well with Y, Nb, and Zr. LREE and HREE fractionation varies within and between each pluton, with an average value of 6 for La/Sm and 1.5 for $(Tb/Yb)_n$. Eu anomaly is also highly variable, ranging from 0.8 to 0.06. The initial Sr isotopic ratio ranges from 0.70506 to 0.71225, the lowest values being displayed by granophyres.

Yemen granites are emplaced in anorogenic settings, and have typical physico-chemical characteristics such as high temperature, high halogen and low water contents, and high HFSE abundances of A-type granites. Basically, three main processes have been proposed to explain the genesis of anorogenic granites: (a) metasomatism of a "normal" granite magma; (b) fractional crystallization from a basaltic magma; (c) partial melting of relatively anhydrous crustal sources.

Yemem granites and granophyres fall well outside VAG and CG fields, indicating that crustal partial melting did not play a leading role in their genesis. Moreover, the ratio of HFSE of basaltic rocks belonging to the Yemen plateau are very clustered with those of the granite. This fact suggests a genetic link between basalts and granites. The highly alkaline granites have higher Nb/Y (≈2), and higher initial Sr ratios (0.70622-0.71225) than the least alkaline granites and granophyres (Nb/Y≈1, initial Sr ratios 0.7046-0.70506). An FC model is supported by the strong depletion in MgO, CaO, Sc, and Sr, whereas the absence of intermediate rocks can be ascribed to the "plagioclase effect". However the variation in radiogenic isotope ratios indicate contamination by more radiogenic crustal material. The absence of crustal xenoliths and magmatic enclaves supports an assimilation plus fractional crystallization (AFC) process, where the heat required for assimilation should be provided by the latent heat of crystallization. Therefore, the genesis of the most and least alkaline granites can be accounted for by a FC (ol+pl+cpx±mt) process from a parental alkali and transitional basalt, respectively, accompanied by different degrees of assimilation. Computations yield a value of residual liquid less than 15% for both types of granite, in agreement with field evidence, but different (rate of assimilation)/(rate of crystallization) of R=0.5 and 0.2.

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

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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 suite of A-type granites and volcanics from the Padthaway Ridge in South Australia. Mineralogical, chemical and isotopic arguments show that the Padthaway Suite evolved from the same basaltic magma that formed contemporaneous gabbrioc plutons which themselves contain A-type granophyres. Olivine, pyroxene and hypersolvus feldspar assemblages in the granites and volcanics document temperatures of 900-1000 ^{o}C and water 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 εNd (+2 to -3) and low initial $^{87}Sr/^{86}Sr$ (0.703 to 0.706) for the whole suite of granites, volcanics, gabbros and granophyres indicates a mantle derived parental magma. Major and trace element modelling confirms that these A-type magmas can be produced by fractionation (ca 90%) of such a magma, though it must be somewhat enriched indicating either a lithospheric mantle source (K-rich layer) or limited crustal contamination. Whilst 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/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?

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Cordierite (and other Al-minerals)-bearing granites occur in batholithic dimensions in some collisional domains. Determining the original I/S character of such granites may on some occasions be controversial. A possible solution may be found if assimilation of the host-rock by the granites is considered. The following points are relevant to such discussion: 1.- Thermal aureoles, with high contents (up to 50%) of prismatic, inclusion-free cordierite have been described on several occasions. 2.- Granites surrounded by thermal aureoles consisting of hornfelses of pyroxene hornfels facies, migmatitic hornfelses, and contact migmatites with elevated content of prismatic cordierite (average contents 15-40%) are known also. 3.- Metamorphism during orogenic stages is of the intermediate P type (postcollisional thermal relaxation). 4.- Very commonly the cordierite-bearing granites are late orogenic, i.e., very late relative to the peak of regional metamorphism. Point 1.- indicates the high capacity of some host-rocks (pelites) to produce cordierite. Point 2.- suggests that high temperatures (close to 700°C) have been reached at low pressure. This resulted from the addition of intrusion heat and crystallization heat input to the already favourable thermal conditions of the host-rocks (induced by the previous regional metamorphism). In this situation, a lowering of pressure is expected to result in fluid-absent reactions in the host as a consequence of magma intrusion (adiabatic decompression as a result of postcollisional uplift). If the metasediments involved have a pelitic composition, the reactions (involving Biot + Musc + Q; Biot + Sill + Q) will result in Cordierite/Garnet + Kid + H_2O or melt. In the first case, subsequent increments of T may result in the equilibrium Q + Ab + Kid + Cord + H_2O = Melt; in the second case, melt is produced directly as a result of the fluid-absent reaction (dehydration melting). The amount of melt generated is small in both cases, but the important point is the generation of an intercrystalline melt in the thermal aureole of an intruding granite magma. Point 3.- implies the possibility of restitic rocks (Al-Fe-Mg rich) being left behind as a result of migration of anatectic melts generated during the peak of regional metamorphism. If any of these rocks is affected also by a lowering of pressure in the thermal aureole, and any restitic phase contains water, reactions transforming the restitic parageneses into lower-P parageneses, with liberation of an intercrystalline fluid (or melt), are to be expected. The interaction (assimilation) of a granite magma with any of these possible rock-types (with original or modified restitic parageneses) developed in its thermal aureole can result in granites with apparent S character, since even small assimilation percentages may drastically modify the original granitic mineralogy and normative corundum contents. The presence of rocks such as andalusite-bearing cordieritites, sillimanite-bearing cordieritites, garnet-bearing cordieritites (cordierite contents up to 60-90%), or other kinds of cordierite-rich rocks in contact with the granites, or as enclaves within them, is an important point that has to be taken into account when considering the significance of some granitic types with more or less typical S-type mineralogy.

ARCHEAN GRANITOIDS IN THE MURCHISON PROVINCE, WESTERN AUSTRALIA: PETROGENETIC CLASSIFICATION AND RELATIONS TO GOLD MINERALIZATION.

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The Murchison Province is one of the four tectono-stratigraphic provinces comprising the Archaean Yilgarn Block. Granitoid stocks and batholiths in the province can be divided into three major suites on the basis of this study and that of Watkins and Hickman (1990).

Suite 1 comprises homogeneous monzogranites and granodiorites which occur as large composite batholiths. They are distinguished from Suite II granitoids by much higher LILE concentrations and more radiogenic initial Pb and Sr isotopic compositions. These granitoids are best interpreted as being derived from partial melting of underlying tonalitic continental crust consisting of granitoids and gneisses.

Granitoids of Suite II include an early trondhjemite subsuite and a late tonalite subsuite. Geochemical and isotopic (Pb & Sr) characteristics of granitoids from both subsuites indicate that they have been derived from partial melting of subducted/underplated oceanic crust. One of the structurally youngest tonalite plutons was emplaced at 2630, 1±4.3 Ma (2a) based on integration of a whole-rock Pb-Pb isochron and U-Pb in zircon data.

Suite III monzogranites and syenogranites have chemical compositions (Watkins and Hickman, 1990) consistent with A-type granitoid characteristics (e.g. Loiselle and Wones, 19/9; Collins et al., 1982). Combined with their isotopic compositions, they are interpreted to be derived from partial melting of dehydrated silicious continental crust.

It is concluded that three different magma source regions can be inferred in the Archaean Murchison Province. Suite III granitoids clearly belong to the A type granitoid group. However, both Suite 1 and Suite II granitoids can be classified as I-type granitoids according to Chappell and White (1974). It is proposed that granitoids derived from earlier granitoids of gneisses comprising continental crust, such as the Suite I granitoids, should be termed G-type granitoids, and that granitoids derived from a basaltic source, such as the Suite II granitoids, should be termed I-type granitoids.

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

Gold mineralization in the province was associated with late-stage deformation (Grigson *et al.*, 1990; Wang, in prep.) and has been dated at one locality at 2636.8±4.2 Ma(2a) based on a pyrite-titanite Pb Pb isochron. Substantial evidence indicates that gold mineralization, at least in the northeastern part of the Murchison Province, was spatially and temporally related to I-type granitoid magmatism: a genetic relationship is also possible in this particular crustal segment.

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

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The BMR ROCKCHEM data set contains about 800 analyses of Proterozoic rocks from the Arunta Block. Chemical signatures were little disturbed by prograde regional metamorphism. Assessment of these data shows that most of the felsic igneous rocks, using their geochemical signature summarized by multi-element plots, fall into one of three classes, two with the typical Sr-depleted, Y-enriched Proterozoic characteristics, and the third has a *flat profile*, with high Sr and low Y. The Sr-depleted, Y-enriched compositions subdivide into a *normal* Proterozoic type, represented in North Australia by the Kalkadoon-Leichhardt-Ewen association and its correlates, and a high-U type, or *enriched* type. The *normal* and *enriched* types are widely distributed, occuring in all three tectonic zones, the *flat-profile* type occurs mainly in the eastern Central and Southern Provinces.

Both *normal* and *enriched types* have the geochemical characteristics of Sr-depleted felsic magmas, especially the high incompatible elements. Reference envelopes can be used to show the more exaggerated composite profile of the *enriched type* reflecting higher U, Th, K, Rb, REE and Y relative to the *normal* type. High LREE and Th are reflected by allanite or monazite in the mode. Fluorine content may be high enough to give visible fluorite. Relative Rb enrichment leads to lower K/Rb in the *enriched* types. Some chemical characteristics, particularly the high incompatible elements, of the *enriched* granite suites hint at affinities with A-type magmas, "true" examples of which are rare in the Arunta Block, but the *enriched* granites do not have Al/Ga that separates them from the *normal* granites, some have high Ba, not all have high F. The usual perversity of Proterozoic magmas vis-a-vis geochemical models developed from the Phanerzoic is also apparent. Most are "intra-plate", though the *normal* granites may straggle from "intra-plate" to "continental margin" within individual suites.

Distinct suites, delineated within both major types from subtle chemical variations, have a distribution by area with probable time-tectonic significance, if subtle variations that distinguish individual suites reflect different sources. Regional variations amongst *enriched* suites mimic those of the *normal* types in the same areas, suggesting a evolutionary link between the types. As an example, deformed granite and megacrystic orthogneiss in the central Southern Province have chemical signatures typical of *normal* type Proterozoic granites with local characteritics of relatively high Ba, Ga/Al and low Sn. The later Madderns Yard suite, of *enriched* granite and perhaps metavolcanics, similarly has low Sn and high Ba. High REE, Th and U are contained in allanite, monazite is less common.

GRANITES OF EDWARD VII PENINSULA, MARIE BYRD LAND: ANOROGENIC MAGMATISM RELATED TO ANTARCTIC - NEW ZEALAND RIFTING

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Granites outcrop extensively in the Rockefeller and Alexandra Mountains of Edward VII Peninsula, Marie Byrd Land, on the north-eastern margin of the Ross Sea embayment. The granites are of late Cretaceous age (95 - 101 Ma), are undeformed, and occur as small plutons <20km in diameter which have produced contact aureoles in Lower Paleozoic metasediments. The intrusions are coarse grained, leucocratic, subsolvus biotite-granites (syenogranite to monzogranite). Other petrographic features include ubiquitous smoky quartz, the presence of primary fluorite, traces of ilmenite and muscovite, and the red-brown (reduced) colour of biotite. The granites are metaluminous to peraluminous in composition but other than micas, no strongly aluminous minerals are present. Xenoliths and miarolitic cavities are rare.

Granite compositions are highly fractionated with SiO_2 = 73 - 78%, FeO* = 2.1 - 0.7% and low Ba and Sr. Concentrations of Rb, Th, Ga, Y and REE are high and proportional to F content which reaches >6000 ppm in the more evolved rocks. REE patterns vary from LREE enriched in the least fractionated granites (Ce_N/Yb_N = 8.3, Eu/Eu* = 0.76) to flat patterns with large negative Eu anomalies in the most evolved rocks (Ce_N/Yb_N = 1.1, Eu/Eu* = 0.07). Initial $^{87}Sr/^{86}Sr$ ratios are in the range 0.7177 -0.7128 and epsilon Nd values are -5.6 to -7.7.

The highly fractionated compositions of the Edward VII Peninsula granites makes classification in terms of granite-type difficult. Most samples plot as A-types in published discrimination diagrams. Y/Nb ratios (2 - 4.5) suggest subduction-related source characteristics. Melting of subduction-related I-type Devono-Carboniferous granodiorites which occur extensively along the Marie Byrd Land coast and may underlie Edward VII Peninsula satisfies the isotopic constraints; melting of Lower Paleozoic metasediments does not. The age of the Edward VII Peninsula granitoids corresponds to a period of extensional faulting and crustal thinning that was the precursor to the continental separation of Marie Byrd Land and New Zealand. The timing of this episode is closely constrained by subsidence curves from hydrocarbon wells on the continental shelf south-east of New Zealand.

A GRANITE GEOCHEMICAL AND ISOTOPIC TRANSECT OF THE SOUTHERN CANADIAN APPALACHIAN OROGEN: PETROGENETIC AND TECTONIC IMPLICATIONS.

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From west to east, the four major Appalachian tectonostratographic zones (after Williams, 1978; 1979) are: (1) Humber (HZ), western margin of the Iapetus ocean developed on Grenville craton; (2) Dunnage (DZ), allochthonous remnants of Iapetus arc and back-arc sequences; (3) Gander (GZ), eastern continental margin of Iapetus; and (4) Avalon (AZ), a Late Precambrian terrane which formed a stable platform during the early Paleozoic. Recent deep seismic reflection studies (Keen et al., 1986; Marillier et al., 1989) have defined three main lower crustal blocks (LCB's) 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. Granite suites in each zone exhibit features indicative of comingling of felsic and mafic magmas. Within HZ and DZ, proportions of intermediate to felsic, amphibole-bearing plutonic rocks are about equal, whereas in GZ and AZ, felsic biotite granites (senso stricto) vastly predominate. Based on Na_2O and Al index values (generally >3.2 wt% and <1.1) and elevated high-field strength element contents, most granites can be characterized as I-types with some "A-type affinities".

ε_{Nd} data map three contrasting groups of granites: HZ+DZ (+3.4±1.5), GZ (-1.8±1.6) and AZ (+1.8±1.8). $^{207}Pb/^{204}Pb$ and $\delta^{18}O$ values for these groups are: HZ+DZ (15.565±0.024; 7.0±0.9), GZ (15.676±0.022; 9.2±0.7) and AZ (15.674±0.036; 8.5±0.5). Positive ε_{Nd} values for HZ, DZ and AZ granites indicate melting of predominately juvenile sources. The 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 ε_{Nd} and elevated $^{207}Pb/^{204}Pb$ values for GZ granites are consistent with reworking of older (1.1-1.8 Ga) crust. Elevated $\delta^{18}O$ values from GZ granites indicate a significant supercrustal component in their source.

The granite data suggests that different protoliths are juxaposed at the DZ-GZ and GZ-AZ boundaries. Contrary to expectations, the Nd data effectively rules out Grenville basement as a source for HZ+DZ granites. This raises the possibility that the seismically defined Grenville LCB may not be 'Grenville-like' compositionally and/or it is composite. The geochemical and isotopic similarity between Orodovician 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. Conrasting ε_{Nd} signatures from AZ and GZ granites helps substantiate the seismic interpretation that GZ and AZ are underlain by different crustal blocks; ie. Precambrian Avalon basement is not a suitable protolith for GZ granites.

The heat source for the major Ordovician and Siluro-Devonian plutonic events is problematical. Our prefered model (after Sacks and Secor, 1990) assumes that, during Iapetus closure, two separate collisional events were accompanied by oceanic lithosphere delamination, juxtaposing hot asthenosphere and continental crust, producing synorogenic metamorphism and melting. Based on this model, HZ+GZ granites fail to image the Grenville LCB because they were derived by melting of underlying metasomatised mantle. In contrast, GZ and AZ granites represent more complex crust-mantle mixtures. These granites are not simply probes of the lower crust; rather they record different histories of mantle-crust interaction beneath different segments of the orogen.

Field and Petrographic Relationships of S- and I-type Granites in the Lachlan Fold Belt

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S- and I-type granites are almost equally abundant in the Lachlan Fold Belt (LFB), although the former are more restricted in their distribution. Both types occur as plutons with average outcrop areas of about 50 km^2, surrounded by contact aureoles about 1 km wide. Biotite-rich cordierite granodiorites rarely with garnet (S-types), and hornblende granodiorites (I-types), may occur with volcanics of the same composition and such granites commonly have miarolitic cavities, graphic intergrowths of feldspar and quartz, and porphyritic fabrics typical of near-surface intrusions. Some are pressure quenched. These, and other data (experimental and theoretical), indicate that the amount of H_2O is much the same in the melt component of the both magma types (3-4 wt%).

All S-type granites are peraluminous, normally with alumina saturation indices, ASI > 1.1 [ASI = mol. Al_2O_3 / (Na_2O + K_2O + CaO)]. This chemical feature is directly inherited from the source. The strongly peraluminous chemistry when coupled with a low H_2O content, produces the assemblage biotite + cordierite ± garnet. Biotite in the more mafic S-type granites is so abundant that the amount of K-feldspar may be low enough to classify the rock as tonalite despite the high K/Na. The majority of the S-type granites in the LFB are reduced so that the biotites have a foxy red-brown colour and the opaque mineral is ilmenite; magnetite is rare and confined to only a few suites (eg Dalgety). Calcic plagioclase cores, more commonly seen in mafic rocks, have a composition characteristic of the particular S-type suite, e.g. An_{55} (Bullenbalong), An_{60} (Dalgety) and An_{80} (Cootralantra).

Fractionation of S-type magmas results in their becoming more strongly peraluminous and causes an increase of H_2O in the melt, allowing muscovite to crystallize in more deep-seated intrusions and causing a reaction relationship between early cordierite and melt to form muscovite. Fractionation also increases F in the melt phase, which may result in abundant topaz as the aluminous phase in S-type granites crystallizing near the surface.

Mafic hornblende-bearing I-type granites are metaluminous and, if oxidized, hornblende is accompanied by chocolate-brown biotite and the accessory minerals magnetite ± titanite ± allanite. However, more felsic I-type granites, even of the same suite, may have biotite as the only major mafic mineral. These rocks are weakly peraluminous. Titanite ± allanite may still be present in these felsic rocks in spite of their weak peraluminous nature; when titanite and allanite are absent, monazite occurs to accomodate the REEs. The melt phase of I-type magmas is so close to the peraluminous--metaluminous boundary that the presence of hornblende as a residual phase, or its removal from the magma by fractionation, will render the melt phase slightly peraluminous. Reduced I-type granites contain red-brown biotite + ilmenite and white or colourless K-feldspar. Calcic cores with a composition characteristic of the suite are also seen in many I-type granites, particularly those that are relatively mafic.

Very felsic fractionated I-type granites may be sufficiently peraluminous, but still with ASI <1.1, for an aluminosilicate to crystallize along with biotite. This is normally garnet, andalusite, late muscovite, or topaz if F has been concentrated in the melt phase during fractionation.

INHERITED AND DETRITAL ZIRCONS—VITAL CLUES TO THE GRANITE PROTOLITHS AND EARLY IGNEOUS HISTORY OF SOUTHEASTERN AUSTRALIA

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Many of the principal periods of granite plutonism throughout the Earth's history are distinctive in their particular range of magma compositions and intrusive styles. The major feature of the great mid-Palaeozoic 'Caledonian' magmatic episode is that worldwide, broad belts of the Earth's crust were melted on a massive scale.

In Australia, Caledonian granites occur the length of the eastern coast, a distance of over 3000 km. They in turn are only part of a plutonic belt that extends southwards into the Trans-Antarctic Mountains and northwards into east Asia. It is in the Lachlan Fold Belt, in southeastern Australia, that most geological and geochemical work on the granites has been concentrated.

Because the granite magmas, particularly the more mafic ones, commonly carried with them unmelted source material (restite), their chemical and isotopic compositions reflect those of their source rocks. From those compositions it is therefore possible to infer not only the rock types which might have comprised their protoliths, but also the protoliths' ages.

Isotopic data from the Kosciusko, Berridale and Bega batholiths, near the southern end of the Lachlan Fold Belt, consistently point to the granites' source rocks being dominated by isotopic systems as old as mid to late Proterozoic. The S-type granites (with dominantly sedimentary precursors) are rich in inherited zircon with mean U-Pb ages between 1950 and 1350 Ma, the source-rock Rb-Sr isochron for some of the I-type granites (with dominantly igneous precursors) suggests a mean source age of about 1100 Ma (Compston and Chappell, 1979) and the Nd_{DM} model ages for both granite types range up to about 1500 Ma (McCulloch and Chappell, 1982). With none of these techniques can the ages of individual components within the source rocks be resolved; that can only be done by dating a restite component, such as the inherited zircon, directly.

Inherited zircon is present in most of the granites as small, commonly indistinguishable, cores within zircons precipitated from the magma. Using the SHRIMP ion microprobe, it has been possible to measure the U-Th-Pb isotopic composition of over 1000 zircons from more than 20 plutons and enclaves and so begin to establish the ages of the principal components in the granites' sources and how those components, and their relative abundances, might differ geographically.

The granites range in age from 440 to 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. To date the cores assumptions must be made about their Pb-loss histories, but a self-consistent pattern of ages is emerging nevertheless. In most granites, most of the cores are 650 to 450 Ma old, there is a lesser group 1075 to 800 Ma old, and a lesser group again with ages up to 3350 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 quartz dioritic enclaves. There is little difference between the I- and S-type granites in the relative abundances of cores of different ages, except possibly in the Archaean components. The inherited zircon becomes older and more abundant westwards across the I-type Bega Batholith.

Zircons from four Ordovician sandy mudstones, country rock to the Bega Batholith, show the same age groups as the inherited zircons in the granites. The relative proportions of those groups differ widely from one mudstone to the next, but on average the 650-450 Ma age group is significantly less abundant in the sediments than in the granites.

The inherited zircons in the granites are unlikely to be derived directly from the Ordovician country rock. Rather, it appears that 1075 to 800 Ma ago, and again 650 to 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 sources for the S-type granites. Recycling of those sediments produced much of the early Palaeozoic flysch. The presence of 1100 to 3350 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.

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The Relationship Between Crustal Magmatic Underplating and Granite Genesis: An Example from the Velay Granite Complex, Massif Central, France.

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Abstract

The Velay granite pluton (Massif Central, France) is the youngest (304±5 Ma) and largest (~6900 km^2) of the major Massif Central monzogranites/granodiorites and was formed nearly 50 Ma after the cessation of Hercynian continental collision (Pin and Duthou, 1990). It is a highly heterogeneous pluton consisting of I-type, high Sr granites (Sr = 500-900 ppm) with low $\varepsilon Sr_{(304)}$ (+35 to +41) and high $\varepsilon Nd_{(304)}$ (-3 to -5), at its centre, grading into S-type and mixed I-S-type heterogeneous granites of more normal Sr content (100-420 ppm) and higher $\varepsilon Sr_{(304)}$ (+60 to +210) and lower $\varepsilon Nd_{(304)}$ (-3.8 to -7.3) at its margins.

The age of intrusion of the Velay granite is similar to that of underplating/intrusion by basic mantle-derived magmas of the metasedimentary lower crust (360-305 Ma). Further underplating led to partial melting and granulite facies metamorphism (300-280 Ma, Downes *et al.*, 1991) of the underplated material (represented by acid and basic meta-igneous lower crustal xenoliths, $\varepsilon Sr_{(304)}$ = -11 to +112, $\varepsilon Nd_{(304)}$ = +2.2 to -5.5, Downes *et al.*, 1990). The partial melts assimilated mainly schist but also acid gneiss and older granite country rock material ($\varepsilon Sr_{(304)}$ = +200 to +300, $\varepsilon Nd_{(304)}$ = -4 to -9) to produce the heterogeneous granites. Plagioclase and biotite were accumulated at the base of the intrusion which was intruded to high levels to form the high Sr granites.

A Pb Isotopic Paradox for Granitoids: Low-Mu Rocks from High-Mu Sources

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Granitoid rocks from Montana and Wyoming in the northern part of the Archean Wyoming province and from southeastern California and western Arizona in the southwestern U.S. Proterozoic crustal province have been the subjects of extensive geochemical and Pb isotopic studies. Granitoids in the northern Wyoming province are dominated volumetrically by Late Archean suites that intruded Middle and Early Archean crust. The Late Archean granitoids are extremely variable in composition ranging from dioritic to granitic and encompassing calalkaline, tholeiitic, and sodic and trondhjemitic suites. Pb, Sr, and Nd isotopic studies indicate that all these rocks were derived from sources with higher than average, long-term U/Pb, Rb/Sr, and Nd/Sm ratios. Mu (238U/204Pb) values for these granitoids vary (1-12) but are dominated by remarkably low values between 2 and 6. Th/U ratios vary from 2-26 and are generally very high, and 232Th/204Pb ratios range from 12-220 with most greater than the crustal average of 34. These data indicate an absolute enrichment of Th and an absolute depletion of U.

In the Mojave crustal province of southeastern California and western Arizona 1.4 to 1.75 Ga granitoids intrude gneisses with 207Pb/206Pb zircon ages from 1.8 to 2.3 Ga. These granitoids do not have inherited zircons but do have depleted-mantle Nd model ages of 2.0 to 2.3 Ga, and Pb isotopic data that require sources with mu greater than the Stacey-Kramers' 2-stage model. The granitoids are mostly alkali-calcic but minor calcalkaline and sodic suite compositions also occur. Mu values for these granitoids average about 7, but in some plutonic suites range only from 1-3 or 3-6. Th/U ratios range from 4-30 and values over 10 are common. 232Th/204Pb values vary from 3-160. As in the Wyoming province these data indicate that the granitoids have an absolute enrichment of Th and depletion in U.

The granitoids of the Mojave and Wyoming crustal provinces are not similar in composition. Their U-Th-Pb geochemistry and isotopic history, however, are very similar. The reservoirs from which crust was produced in each case had early histories during which *U/Pb and Th/Pb were modestly higher than, but Th/U close to, that of the Stacey-Kramers' average crust model.* Major crust formation cycles affecting each craton 0.3 - 1.0 Ga after original formation produced large volumes of crust with *Th concentrations and Th/Pb much higher, and U concentrations and mu much lower, than the crustal average.* The process that produced this strong fractionation between Th and U was not specific to a particular compositional suite. While some other trace element abundances can be correlated with Th (eg. La, Zr, Sr) in each crustal province, they are not the same correlations and are not consistent for all compositional types. These observations are strongly indicative of a fluid or melt with a high Th/U ratio, high Th, and low U and Pb concentrations, but variable concentrations of other trace elements, being introduced into the source regions. Th behaves more incompatibly than U in the mantle but melt/solid partitioning involving the major silicate phases in the mantle would not provide the strong fractionation required in this case. Such strong fractionation is unexpected unless Th and U abundances are controlled by accessory minerals (such as zircon, low Th/U, and monazite, high Th/U, in crustal environments) or by special oxidation-reduction conditions that reduce the solubility of U (opposite the usual conditions in the upper crust where oxidizing conditions allow U to be mobile and Th immobile). In the Mojave crustal province physical evidence for a mantle derived melt with the required Th, U, Pb geochemistry is provided by 1.4 Ga alkalic plutonic rocks whose source is best modelled as an hydrous, metasomatized upper mantle. Similar conclusions were reached for sources of Late Archean, trace element enriched, andesitic rocks in the Wyoming province.

The volume of upper and middle crust represented by these granitoids in the two provinces is considerable. The mass of these reservoirs is even larger if it is assumed that this crust is also representative of the associated lower crust and upper mantle which are required as first and second stage sources for these intermediate to silicic rocks. Taken as combined crust and mantle volumes, these two lithospheric provinces represent important reservoirs with high Th concentrations and high Th/U ratios. A careful evaluation of these reservoirs is critical for general models of crustal growth and for mass balance arguments based on the mechanisms and extent of transfer of Th and U from the mantle into the crust and from depleted asthenospheric mantle to enriched lithospheric mantle.

Enclaves in the S-type Cowra Granodiorite.

by D. Wyborn, AJR. White, and BW. Chappell.

The Cowra Granodiorite is an elongate, high level, mafic, cordierite granodiorite of about 95 km^2, from the north-western side of the Wyangala Batholith in the Lachlan Fold Belt in New South Wales. The pluton is one of the most mafic S-types from the Lachlan Fold Belt, averaging 67.5% SiO_2, 2.0% MgO and 4.5% total FeO. Despite its mafic character, contact metamorphic affects are only discernible within about 1m of its contact.

The Cowra Granodiorite contains an abundant assemblage of enclaves which have been previously divided into 5 main types: 1)pelitic 2)psammmitic 3)calcareous 4)igneous and 5)granitized. Vein quartz is also a common enclave type.

Of particular interest are the "igneous-looking" microgranular enclave types with the assemblage plagioclase-quartz-orthopyroxene-biotite-apatite-ilmenite. Biotite replaces orthopyroxene in a well-defined reaction rim 1-2cm. thick around the enclave. Plagioclase (40-45%) and quartz (25-30%) are the most abundant minerals, the quartz occurring as equant grains with inclusions of all other minerals. Apatite forms needle-like inclusions in the quartz. The resulting texture is pseudo-doleritic, but the composition does not fit with any known igneous rock. Plagioclase is extremely calcic, up to An94 in some enclaves, reaching a maximum in euhedral grains with abundant optically continuous quartz inclusions. The enclaves are weakly peraluminous and there is an antithetic relationship between normative anorthite content (range An90-60) and A/CNK. Enclaves with the highest values of A/CNK contain minor cordierite and have the most abundant apatite needles. Europium anomalies are small and range from negative in rocks with the most anorthitic plagioclase to positive in rocks with the least anorthitic plagioclase. The best explanation for these enclaves is that they are migmatitic residues from partial melting of feldspathic sandstones in the source of the granodiorite. They would have formed just prior to mobilization of the source region at the rheologically critical melt percentage (RCMP). Their formation relates to melt production during the breakdown of biotite into orthopyroxene and K-feldspar at the amphibolite-granulite transition (800-850°C). The extreme anorthitic composition of the residual plagioclase is conformation of the flattening of the plagioclase melting loop shown by Johannes (1980, 1984) for the five phase granite system. The range of A/CNK and P_2O_5 content shown by the enclaves relates to the proportion of pelitic material in the feldspathic sandstone source. Only a small proportion of the Cowra Granodiorite source was refractorary enough to form these residues, most of the source melted to the RCMP and disaggregated into melt plus restite crystals including plagioclase of An55. Onced formed the migmatitic residues became refractory material incapable of further melt extraction and are carried up with the bulk magma as enclaves.

Microgranular enclaves with similar textures including plagioclase, clinopyroxene and apatite needles in K-feldspar or quartz are widespread in many I-type granites, and have been widely cited as mingled blobs of mafic magma intruded into the magma chamber, and constituting a suitable heat source for the melting event. The texturally similar enclaves in the S-type Cowra Granodiorite imply that an igneous origin for the I-type enclaves is not necessarily correct. The texture of these microgranular enclaves is so characteristic in both S- and I-type granites that the name "enclave texture" might be appropriate.

AUSTRALIAN PROTEROZOIC GRANITES: IMPORTANT INDICATORS OF CRUSTAL EVOLUTION.

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Granites in the Proterozoic of Australia were emplaced within distinct time groups. The granite episodes were at 1870-1820 Ma, 1820-1760 Ma, 1670-1600 Ma, and 1550-1450 Ma, 1100 and around 700 Ma. Felsic melts aged 1100ma (Grenville) and 600-700 Ma (Pan-African) are not as extensive as in other continents, although the granites of some Australian Proterozoic provinces have not been fully documented.

The period 1870 Ma to 1820 Ma was dominated by a continent wide felsic volcanic and granite event in which rocks of mafic or intermediate composition are rare. The alignment of the batholiths of this age into a polygonal array around known or postulated Archaean nuclei of about 700 km radius suggests that the source of these magmas was derived by small scale mantle convection.

1820 Ma marks the transition to quite distinctive felsic magma types which are found in almost all Proterozoic provinces. These granites form the typical Proterozoic anorogenic suites, many of which are characterised by rapakivi textures. Most post-1820 Ma felsic magmas are considerably enriched in elements such as K, Th, U, Zr, Nb, and F relative to the older Proterozoic granite suites. Geologically they are coeval with, but spatially separated from major extensional sedimentary sequences, as is predicted by the assymetric detachment model of continental extension.

The majority of Australian Proterozoic felsic igneous rocks are enriched in K, Rb, Th, U when compared with Phanerozoic granites (particularly those derived in island arcs or continental margins) and early Archaean tonalites. However spidergrams of Proterozoic granites closely resemble those of early Palaeozoic granites: both groups are dominated by a Sr-depleted, Y-nondepleted signature inferring derivation from sources with residual plagioclase, but not garnet. In contrast, early Archaean and late Palaeozoic to Cenozoic granites are dominated by Sr-undepleted, Y-depleted granites implying derivation from a source which has residual garnet but not plagioclase. This signature is present in only a few rare Proterozoic granites: in Cenozoic granites, this signature is regarded as synonymous with subduction.

Isotopic data indicate that although the majority of Australian Proterozoic granites have a recognisable crustal prehistory, they are not derived from Archaean crust or Archaean-derived sediments. Their chemistry also precludes a direct derivation from the mantle. The preferred model is that most Proterozoic granites are sourced from fractionated mantle derived mafic underplates that are successively added to the base of the crust during major Proterozoic tectonothermal events. Evidence for this vertical accretion model comes from seismic refraction data which shows a high velocity layer characterised by seismic velocities of 7.4 to 7.6 km/s underneath Proterozoic and Palaeozoic Provinces. This layer, which is up to 15 km thick, is made up of at least 45% mafic granulite and is only apparent in provinces where the granites are characterised by plagioclase stable source regions. This high velocity layer is not found beneath island arc or continental margin environments, nor is it present in Archaean terranes.

Thus Australian Proterozoic granites are similar to early Palaeozoic granites but differ markedly from Archaean or modern subduction equivalents. Although actualistic processes are used to derive both the granites and their sources, they point to a time in crustal evolution when vertical accretionary processes dominated.

RESTITE-MELT AND BASIC-ACID MAGMA MIXING(-MINGLING) IN ALMANDINE-BEARING BIOTITE-CORDIERITE-LABRADORITE DACITE, CERRO DEL HOYAZO, SE SPAIN

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The Hoyazo dacite in SE Spain is part of the 15-7 Ma old volcanic province in SE Spain postdating the Alpine nappe emplacement in the Betic-Rif-Maghrebian orocline which forms the western termination of the Alpine orogenic belt in Europe/Africa. The rock consists of a glass base containing crystallization products of the magmatic melt (biotite, cordierite and plagioclase) and a range of rock inclusions and monocrystal inclusions derived therefrom. The rock inclusions (1.4 ± 0.3, 2σ, vol%, Ø>1cm) comprise:
1) cordierite-biotite quartz-diorite formed from the dacite magma at depth,
2) syngenetic, Al-rich restite material (c.60% of the rock inclusions, Ø>1cm),
3) basaltoid and quartz-gabbroic material in part mingled into the dacitic magma (c.40%, Ø>1cm),
4) accidental inclusions (schists, quartzites, amphibolites).

About 10-15% of the dacitic rock consists of **Al-rich restite material**: foliated almandine-biotite-fibrolite-plagioclase rock, quartz-cordierite rock and spinel-cordierite hornfels, and monocrystal inclusions derived therefrom. The spinel-cordierite hornfels represents deep-seated recrystallization products of the foliated almandine-biotite-fibrolite-plagioclase rocks, the major restite material. The restite material and the dacite melt were derived syngenetically from a (semi-)pelitic rock sequence by means of anatexis; critical features are the restite texture, mineralogy and Al-rich composition (Al_2O_3=20-45 wt%), the high and similar $\delta^{18}O$ values (12-16 per mil) in the dacite and restite rock inclusions, and the perfect eutectic split in (a) plagioclase-bearing restite without a trace of quartz or K-feldspar and (b) quartz-bearing restite without plagioclase or K-feldspar. Striking mono-crystal restite inclusions in the dacitic rock are a few hundred mμ large graphite crystals and 2-6 mm large, bright red garnet crystals, the latter forming 1.1 ± 0.2% of the dacitic rock. The garnet crystals are often perfectly euhedral and have (therefore) been interpreted by some authors as crystallization products of the melt. However, this interpretation is untenable as these crystals are in every respect identical to the crystals found in the Al-rich restite rock inclusions; size, colour, inclusions (fibrolite felt), refringence, chemical composition and zoning ($Alm_{70-82}Py_{7-13}Gr_{15-2}Sp_{10-1}$, core to rim) are identical.

The **basaltoid and quartz-gabbroic rock inclusions** have a rounded form, vary in size from c. 1 mm to c. 60 cm, and most of them contain some inclusions identical to the Al-rich restite material found in the dacite glass base. Most basaltoid rock inclusions show well developed chilled borders. Their petrography, chemistry and O and Sr isotope relations suggest that these inclusions represent an anatectic magma derived from a more basic crustal section, or a mantle-derived magma, contaminated by the dacitic magma it was incorporated in, or by similar crustal material.

The processes of anatexis and magma mixing/mingling giving rise to the Hoyazo dacite may be related to regional mantle diapirism employed in current orogenic models for the Betic-Rif-Maghrebian belt to explain nappe emplacement during the final stage of the Alpine orogeny by extensional collapse tectonics. High rates of uplift and denudation (5-10 km/Ma) and cooling (250-350°C/Ma) support such models.

Modelling the Genesis of Late Cretaceous Granitic Rocks in SW Montana, U.S.A.

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The major-element chemistry of crustally-derived granitic rocks reflects the chemical (e.g. peraluminous) or even the petrogenetic (e.g. pelitic sedimentary) nature of the source rock; their isotopic geochemistry (e.g. Pb, Nd/Sm, and initial Sr ratio iSr) constrains the crustal residence time of the source rock and possibly even its terrane affinity. However, these data yield no information on the physical nature of the source terrane. The heat productivity Q_g of the granite should reasonably image that of the source, Q_s, because K is heavily partitioned into the melt and U and Th may dissolve in the melt or enter the magma in restite minerals. Q_s in turn affects the thermal state of the crust leading up to melting.

These considerations are applied to the Late Cretaceous calcalkalic batholiths of southwestern Montana, especially the Pioneer batholith (area ca. 1000 km^2) that intruded at high level (ca. 3-8 km) into the Archaean craton about 300 km from the accreting plate margin. The iSr values range from 0.7113 to 0.7160, indicating an old crustal source; the Pb isotopes suggest a 2 Ga source age. Rocks of this batholith mostly contain biotite-hornblende, show no evidence of an aqueous vapour phase except during final solidification, and is never strongly peraluminous. Thus during anatexis the solidus must have been much hotter than for H_2O-saturated peraluminous melts and energy for melting could not have been significantly delivered by an aqueous fluid. Because the thermal efficiency of melting in a conductive regime is low, very powerful heat sources lasting tens of millions of years are needed to produce the magmas.

One-dimensional thermal modelling for the genesis of this batholith used field-based constraints. Based on discordant biotite and hornblende $^{39}Ar/^{40}Ar$ cooling ages, intrusion was at about 8 km depth in the west Pioneers (WP) but was at about 3 km depth in the east Pioneers (EP). The two parts were separately modelled, but were linked by the timing of the shared igneous and tectonic events. Other field-based inputs include the number and thickness of thrust sheets (6 km lower and 10 km upper sheet, WP; lower sheet only, EP); age span from end of sedimentation by thrust sheet arrival to igneous intrusion (mid-Campanian to early Maastrichtian, 5-10 m.y., based on palynomorphs and geochronology); uplift rates (0.2 km/m.y., WP; 0.1 km/m.y., EP); Q_g (about 2 uW/m^3) and inferred Q_s (1 uW/m^3); and ambient temperature away from intrusions at the model depths (350°C, WP; 150°C, based on presence of smectite, EP).

The modelling results suggest that for significant melting to occur, the heat source must have been no deeper than 15 km below the original base of the 30-km thick sialic crust even for heat flux of 75 mW/m^2 lasting as long as 30 m.y. Neither thickening by thrusting nor subduction of oceanic material can cause the volume of magma observed. Geologic history precludes crustal thinning as a significant factor for this time and place; the high iSr values preclude much direct mixing of mantle magma. By elimination, deep subcrustal upwelling, possibly a hotspot, is inferred to be the principal heat source. In contrast, the nearby, coeval, petrographically and chemically similar, and tectonically aligned Boulder batholith, having the same Pb isotope model age but iSr between 0.706 and 0.709, could allow some mixing of mantle material, helping to explain its larger size. East of both is the small coeval Tobacco Roots batholith, having iSr of 0.704; its isolated presence might be due entirely to efficient heat transfer through mixing of mantle material.

GEOCHEMICAL AND ISOTOPIC STUDIES OF GRANITES FROM THE PROTEROZOIC ARUNTA BLOCK, CENTRAL AUSTRALIA: EVIDENCE FOR TRANSITIONAL TECTONIC REGIMES

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The Arunta Block, the largest Proterozoic block of central Australia (~200,000 km^2), is situated on the southern margin of the early Proterozoic Northern Australian Orogenic Province. The north-dipping Redbank Deformed Zone, which separates a narrow, approximately linear zone in the south from the main portion of the Arunta Block, is the thick-skinned mantle-deep thrust zone forming a major crustal discontinuity. Reconnaissance major and trace element analyses of granites collected mainly from the eastern and central portion of the Arunta Block have been undertaken in conjunction with isotopic studies. These data, combined with previous work (e.g. Foden et al. 1988), allow geochemical comparison and interpretations to be made in terms of Proterozoic tectonics and crustal evolution.

Three geochemically distinctive suites, a 'normal' suite, a high heat production suite (HHP), and a calcalkaline-trondhjemitic suite (CAT), are identified in the Arunta Block. The HHP suite is confined mainly within the inland section of the Arunta Block. It occurs either as major separate plutons or as microgranite minor phases of the normal granite suites. Both types of HHP granites intrude coexisting normal granites. Geochemically, the HHP suite is exceptionally enriched in Th, U, K, Rb, Pb and LREE and depleted in MgO, CaO, Ba, and Sr. Elemental ratios such as La/Nb, Ce/Y, Rb/Sr, Ca/Sr, K/Ba and Rb/Zr are higher and Na/K, Ba/Rb and K/Rb lower relative to the normal granites. Steep LREE-enriched patterns with large negative Eu anomalies are also characteristic. Both the HHP and normal suites yield similar ranges of Nd model ages (2.0-2.3 Ga). Although analogous to the A-type granites in having elevated levels of Zr, Nb, Y, REE, the HHP suite differs from the A-type granites in two main respects: (1) Ga abundances (17 ppm) and Ga/Al ratios (2.37) are identical to the normal suite (17 ppm; 2.33), in contrast to A-type granites which have much higher Ga (21 ppm) and Ga/Al (3.12) than the I-type granites (17 ppm; 2.24); (2) La/Nb, Ce/Y and Rb/Zr ratios (5.67; 3.39; 1.52) are higher than in the normal suite (3.92; 2.43; 1.00) whilst in A-type granites (2.50; 1.76; 0.58), reverse trends are normally observed if compared with I-type granites (2.82; 2.16; 1.06). It therefore follows that the genetic models formulated for the A-type granites are not directly applicable to the genesis of the HHP suite in the Arunta Block. The normal suite could have been derived by partial melting of a mantle-derived underplate formed during an earlier crustal extension episode (e.g. Wyborn 1988), whereas the HHP suite could represent products of partial melting/remelting of recycled crustal materials or the normal granites having similar ranges of Nd model ages.

The second main group is the calcalkaline-trondhjemitic suite (CAT) which is confined exclusively within the S and SE margin of the Arunta Block. This suite consists of two main subgroups with different rock assemblages, a gabbro-diorite-tonalite-trondhjemite (granodiorite) group (GDTT) broadly analogous to the modern calcalkaline intrusions, and a more felsic tonalite-trondhjemite-granodiorite (TTG) group identical to the ubiquitous Archean TTG suites. The GDTT group shows a typical calcalkaline trend on a number of discrimination diagrams except for pronounced trondhjemitic-type depletion in K and Rb, which could be related to retention of these elements by phlogopite in the source region. The absence of Eu anomalies in the felsic components also distinguishes it from the modern calcalkaline analogues, in which negative Eu anomalies tend to be developed in the felsic components. The TTG group is characterised by high Al_2O_3 (>15%), Sr (>500 ppm), Na/K, La/Yb and Sr/Y, low Rb and Rb/Sr, and strongly fractionated REE patterns with HREE depletion and possible positive Eu anomalies, indicating garnet/hornblende-controlled petrogenesis (either by partial melting or by crystal fractionation processes). Both types of the CAT suite are considered to be formed under subduction-related environments. Partial melting of the mantle wedge metasomatised by slab-derived fluids/melts would have produced the parental magmas of the GDTT group, whilst partial melting of the subducted slab under P-T conditions within hornblende/garnet stability field would have generated the TTG-type magmas. An intermediate geothermal gradients prevailing during the Proterozoic would have optimised the situations for productions of both types of magmas. A wide range of Nd model ages (1.9-2.3 Ga), all being older than corresponding U-Pb zircon ages (1.75-1.88 Ga), suggests variable proportions of recycled older crustal components may have been incorporated into these parental magmas.

The above geochemical observations are interpretable using a tectonic model in which the S and SE margin of the Arunta Block represented a subduction-related active continental margin, analogous to modern Cordillera. Subduction of oceanic crust around a Proterozoic continental margin could have provided an additional driving force to facilitate thermal subsidence induced crust-mantle delamination and A-type subduction proposed for the tectonic evolution of the inland section of central Australia (Etheridge et al. 1987). Further understanding of the geochemical evolution of these granites would require the clarification of their age relationships. Such work is in progress.