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Granites and yet more granites forty years on

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With 1 figure

Zusammenfassung

Das Thema dieser synoptischen Übersicht behandelt das Verhältnis zwischen Ursache, Prozess, Herkunft und dem geologischen Rahmen während der Genese granitischer Gesteine.

Es besteht hier eine enge Beziehung, weil Granite das Endstadium sehr unterschiedlicher Entstehungsprozesse sein können, die verschiedene Ausgangsgesteine einbeziehen und von denen jeder einer speziellen tektonischen Situation entspricht.

Geologisch ausgedrückt kann man die Unterschiede dazu verwenden, eine genetische Klassifikation zu erstellen, um damit den Einfluß basischen Magmas im richtigen Verhältnis zu sehen, die Bedeutung des vulkanisch-plutonischen Grenzbereiches aufzuzeigen, die Wichtigkeit der Textur herauszustreichen und den Typ der Mineralisation vorherzusagen. Auf diese Weise läßt sich das Verständnis für den Modus der Platznahme erzielen und der Einfluß verschiedener Ausgangsgesteine abschätzen.

Abstract

The theme of this synoptic review is the relationship between cause, process, source and the geological context during the genesis of the granitic rocks. A close environmental relationship occurs because granites can arise as the end-stage of several generative processes, involving different source rocks, each appropriate to a particular tectonic situation. Expressed in geological terms the differences can be used to erect a genetic classification, to set in perspective the intervention of basic magma, to reveal the importance of the volcanoplutonic interface, to evaluate the significance of the texture, to predict the type of mineralisation, to understand the mode of emplacement and to determine the contribution of the various source rocks.

Résumé

Cette revue synoptique a pour thème les relations entre la cause, le processus, la source et le contexte géologique au cours de la genèse des roches granitiques. Il existe entre ces facteurs des relations étroites, car les granites peuvent représenter le stade final de plusieurs processus de genèse, impliquant des roches de départ diverses, et appropriés chacun à une situation tectonique particulière.

Exprimées en termes géologiques, les différences peuvent être utilisées en vue d'établir une classification génétique, de mettre en évidence l'intervention du magma basique, d'exprimer l'importance de l'interface volcano-plutonique, d'estimer la signification de la texture de mise en place et de déterminer la contribution des diverses roches de départ.

Краткое содержание

В данной обзорной статье рассматривается взаимосвязь между условиями образования гранитных пород, процессов, ведущих к этому, происхождением этих пород и геологической ситуацией во время горообразовательного процесса. Эта тесная взаимосвязь существует, т. к. граниты являются конечными продуктами многочисленных разнообразных процессов, вовлекающих различные исходные породы, из которых каждая соответствует некой известной тектонической ситуации. Чтобы установить влияние базических магм, показать значение вулкано-плутонической границы, выяснить текстуры и предсказать тип минерализации, необходимо создать генетическую классификацию пород, основываясь на их различиях. Таким образом можно определить месторасположения плутона и оценить влияние различных исходных пород на их образование.

The Read Thesis

In a connected series of famous addresses between 1940 and 1954, H. H. READ (1956) recorded his own evolution as a disputant in the controversy concerning the origin of granites, concluding that there were different kinds of granites as expressed in the pithy title, G r a n i t e s and G r a n i t e s. Influenced by the French and Scandinavian writers Read sought a unity in the plutonic process, envisaging the different kinds of granite as being genetically connected in a G r a n i t e S e r i e s ranging from replacive migmatite to intrusive pluton. Furthermore each of these

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kinds of granite had its own distinctive geological setting, each representing a stage in the development of the orogenic cycle.

Since Read's masterly presentation of the granite problem the advent of the Plate Tectonic Hypothesis has emphasised the relationship between cause, process and the regional geological environment (PITCHER 1982, 1983). We now know that both the plagiogranites and alkaline granites of the intraplate oceanic crust, and the quartz diorites within the volcanic centres of island arcs, are different from the tonalitic suites of the huge, gregarious batholiths that core the marginal continental arcs. Further differences exist between these and the syntectonic to late-tectonic granite series of the continental mobile belts, and also the decidedly post-tectonic group of granodiorites and granites that so often accompany the final phase of faulting and uplift. In even greater contrast are the alkalic granites associated with either the stabilised mobile belts or the intra-continental rifts and swells.

There is also a better understanding of the structural-metamorphic setting of granite plutons, with an appreciation that whilst many granites are essentially magmatic and intrusive others are metamorphic and replacive, the difference being revealed by the degree of structural disharmony engendered. In the event it seems that disharmony is the rule, at least in Phanerozoic mobile belts, indicating that the majority of granite plutons have been mobile to some degree. Futhermore the detailed application of structural analysis to comprehensive field studies (MARRE 1986), coupled with a proper understanding of competence contrasts and guided by the experimental and mathematical modelling of intrusion mechanics (RAMBERG 1981; DIXON 1975; DIXON & SUMMERS 1985), has demonstrated that most granite plutons were mechanically accommodated in the crust.

Such studies, reinforced with a flood of chemical data, provided with an absolute time-scala and supported by increasingly realistic experimental simulations of the granite system, are moving towards a resolution of the debate on the origin of the granitic magmas, not however without the substitution of a new set of questions concerning the nature of the deep sources and the mobilisation and escape of granitic melts.

In what follows I first deal with the possibility of categorizing granites, then explore the reasons for the differences in the light of recent researches on the chemistry and physics of rock melts, all with reference to mode of occurrence, tectonic environment and source composition, concluding with a personal working hypothesis.

The Categories of Granitic Rocks

The mineralogy and mode must remain of first importance in the classification of the granitic rocks. Not only are the minerals easily identified and their proportions simply determined but, more fundamentally, it is the stability of the mineral phases that controls the nature of both partial melting and crystal differentiation. Their composition provides vital clues to the conditions pertaining in natural melts as has been particularly well shown by Japanese workers (e. g. KURODA et al. 1983). We might pause to reflect that stability is so dependent on species composition as to throw doubt on specific applications of the experimental systems precipitating the synthetic analogues.

The mode as rationalized by STRECKEISEN (1976) can effectively chart evolutionary processes, especially when statistically analysed (e.g. WHITTEN 1986). Combined with textural studies modal variation can be vital in identifying consanguineous rock suites (PITCHER 1985, p. 93 et seq.). By itself, however, a quartz-two feldspar mode cannot be expected to underpin a genetic classification, especialy as siliceous liquids originating by mechanisms as diverse as liquid unmixing, fractional melting, fractional crystallisation, and selective metasomatism, may evolve towards similar end-products as expressed in terms of minerals or major elements.

Of more certain genetic significance is the mafic mineral assemblage, whether it be, for example, augite-hornblende-magnetite-sphene, or titaniferous biotite-muscovite-ilmenite-monazite, or fayalite-hedenbergite-arfvedsonite-green biotite-columbite; and here the role of the accessory minerals is important. Even so there are differences of opinion based on the likelihood that one mineral assemblage is convertible into another by mere change of physical conditions in the magma and largely independent of differences in source. In this respect there are particular reservations on the role of muscovite. Nevertheless the mode, mineralogy, relative abundance of the rock species, character of the enclaves, and the nature of the associated dykes and comagmatic volcanic rocks, are clearly interdependent parameters on which a genetic typology of the granitic rocks might be based (CHAPPELL & WHITE 1974; WHITE & CHAPPELL 1983; CAPDEVILA et al. 1970; LAMEYRE 1980, 1984; COLLINS et al. 1982; PITCHER 1983; DIDIER et al. 1982). Again the accessories are useful, e.g. the ilmenite-magnetite pair measures the differences in fO_2 (ISHIHARA 1977; CZAMANSKE et al. 1981), and the crystal habit of the zircon provides a valuable insight into the growth history of the host rock (PUPIN 1980;

CAIRONI 1985). Further there are very significant differences in the mineralisation associated with each of the granite types (TAUSON 1977; ZONENSÃJN et al. 1976; XU KEQIN et al. 1984; MITCHELL and GARSON 1981).

However it is the availability of a great variety of geochemical parameters that has most transformed our views on the typology and origin of the granitic rocks. Taken by themselves the ratios of the major elements can form a powerful tool in establishing consanquinity in rock suites, and displayed in discrimination diagrams they are capable of revealing contrasted magmatic associations (LA ROCHE 1980; DEBON & LE FORT 1982; LAMEYRE & BOWDEN 1982). BOWDEN et al. (1984) offer a guide to the available methods recommending a Q'-ANOR plot devised by STRECKEISEN and LE MAITRE (1979) as adequate to separate these associations. By such a discrimination we are refining Shand's broad division into aluminous, metaluminous and alkaline, but more precisely expressed in plots which highlight specific features such as, for example, the broad spectrum of compositions existing within the aluminous association of the continental crustal environment (LA ROCHE et al. 1980; ANDERSON & ROWLEY 1981).

The addition of trace element data adds to the constraints. Besides more precisely charting the consanquinity of rock suites and providing a tool to distinguish between different generative processes (e.g. CONDIE 1978), those abundance ratios which are largely unaffected by crystal differentiation can be plotted in ingenious ways to discriminate granite compositions in terms of source rock characteristics (ALLÈGRE & BEN OTHMAN 1980; BROWN et al. 1984). The result has been to view granites as »images of their source rocks« (CHAPPELL 1979) so fuelling the present research thrust to determine the nature of the deep crust and upper mantle.

Problems naturally arise in attempting to categorize the granitic rocks because a virtually infinite number of different types might be generated in response to varying physical parameters and source-rock composition. Furthermore the comparative process is itself suspect because the clustering procedures may not identify classes that carry signatures of the relevant petrogenesis (WHITTEN et al. 1986). However the fact that there are several distinct genetic families of granitic rocks has now been widely recognised, with emphasis on the contrast between granite-dominated and tonalite-dominated assemblages, and it is useful to define broad classes when viewing granites within the wider geological frame, and to designate them by appropriate letters such as those introduced by CHAPPELL and WHITE (1974, 1977, 1983, and see BARKER 1984; TISCHENDORF & PÄLCHEN 1985). Furthermore it is my central thesis (PITCHER 1982, 1983) that the classes so revealed broadly correlate with geological environment, a view substantiated by studies of the relationship between trace element abundance patterns and gross tectonic setting (BROWN et al. 1984; PEARCE et al. 1984, THOMPSON et al. 1984, HARRIS et al. 1986). Specifically the use of a Rb-Hf-Ta triangular plot has been successfully used by HARRIS, PEARCE and TINDLE (op. cit.) to distinguish between siliceous magmatism in ocean floor, volcanic arc, within plate and plate collision settings. I conclude that the different tectonic regimes will provide different source rock assemblages and engender different formative processes. Each regime will be characterized by a specific array of tectonic, metamorphic, magmatic and sedimentation features (Fig. 1, p. 70).

Such a relationship has been formalised by TISCHENDORF and PÄLCHEN (1985), and in a survey of granite environments (PITCHER 1982) I concluded that it is possible to define an M-type which includes the strongly calcic and metaluminous gabbro-quartz diorite of stocks within the oceanic island arcs as, for example, those of New Britain and the Aleutians (MASON & MCDONALD 1978; PERFIT et al. 1980). This type is compositionally the end-member of a less calcic, metaluminous I-type represented by the voluminous, gabbro--quartz diorite--tonalite--granodiorite association, dominated by tonalite, and characteristic of the batholiths of the active continental plate-margins, particularly of the western cordilleras of the Americas (eg. PITCHER et al. 1985; BATEMAN 1983). In such an environment when the residence of such magmas moves from new, mantle-derived crust into old continental crust, deep-level contamination can lead to mildly peraluminous variants, providing a compositional transition.

These situations contrast, though less in composition than in geological terms, with another I-type represented by the granodiorite-granite plutons of the post-orogenic, uplift regimes as exemplified by the end-Silurian plutonism of the Scottish and Irish Caledonian (WATSON 1984).

In even sharper contrast are the predominantly peraluminous granite assemblages of the collisional orogenies such as those of the Himalayan (LE FORT 1981; DEBON et al. 1986), and possibly the Hercynian of the Iberian Peninsula (CORRETGÉ 1983). In this environment of the true Granite Series the granites are often recognizably S-type, i.e. ultimately derived from sedimentary lithologies. However there is often a range of composition, as in the European Hercynian (DIDIER & LAMEYRE 1969), which is a natural consequence of the involvement of a heterogeneous crust which becomes increasingly dehydrated and refractory with the continuing extraction of melt (WONES 1984). Furthermore we have to be aware that peraluminicity may result from several generative processes, so that the extension of the S-type terminology from its original definition in the Australian Lachlan Belt requires a proper recognition of all the special features inherent in the original definition (WHITE et al. 1986).

Yet another class of granitic rocks is represented by the unique A-type which includes the peralkaline granites and syenites of the stabilised fold belts and the swells and rifts of the interiors of cratons. Examples are the ring-complexes of Corsica and Nigeria (BONIN 1982; JACOBSON et al. 1958).

In addition to these familiar types of granitic rocks there is the possibility of generating small volumes in the oceanic environment as has been demonstrated for the Kerguelen syenitic-granitic ring complexes (GIRET 1983). Then there are the oceanic plagiogranites, the rather unique characteristics of which have been reviewed by COLEMAN and DONATO (1979). These represent the localised, potassium-poor differentiates of the ophiolite suite, and though they are small in relative volume they may well make a substantial cumulative contribution to the sialic magmatism of plate margins during the subduction of oceanic crust, that is if they are not dragged down into the mantle to be transformed into the remarkable coesite granulites!

Finally we must expect various superpositions of these environments and their attendant magmatisms, as in the Appalachians and the Andes, and not always in the natural order we might expect (PITCHER 1982, 1985).

With this broad geological basis I turn to briefly review the physical chemistry of the granite system, the nature of granite magma, the mode of its intrusion and the problem of relationship to crustal environment.

The Granite System

Experiments in the Making of Granite: Tuttle and Bowen's seminal studies of the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O engendered a plethora of similar researches (LUTH 1976, for review), with the growing realization that experiments carried out in the presence of excess water might bear little relationship to natural processes.

From 1960 onwards a new approach was adopted by WYLLIE and his coworkers (WYLLIE 1983, for review) in melting natural granites under varying P, T and concentrations of water, and so adjusting the conditions as to reproduce the original mineral assemblage in its natural order of crystallisation. The results are of prime importance even though the experiments themselves cannot truly simulate natural conditions in that they represent closed systems starting with entirely liquid melts, and with water the only volatile component. These artificialities are being overcome, with research into the role of other volatiles, though it seems impossible to avoid metastability (JOHANNES 1983).

A most important conclusion of Wyllie and his associates is that most large bodies of granitic magma initially contained less than 2% wt. of water, and that they remained undersaturated throughout much of their evolutionary history.

There are many other valuable deductions. Thus the familiar rock-forming minerals should remain stable at temperatures and pressures to be expected down to the base of the crust, presenting a great simplification in the modelling of magma evolution. Furthermore the phase relationships remain basically similar over a wide range of natural granite compositions, even though the mineral phases vary in accord with the bulk composition, as when the pair muscovite-biotite takes the place of biotite-hornblende in peraluminous granitoids. This latitude in the physical controls goes far to explain why granites of different origin are yet so similar.

Yet another finding by Wyllie et al. is that the granite system consists of two partially independent components. The quartz, orthoclase and the sodic plagioclase melt to produce a eutectic-like granitic liquid that coexists with the more refractory assemblage of calcic plagioclase and mafic minerals with little exchange of components through a wide temperature interval. This is exactly what we observe in rocks, for many granodiorites contain clots of early-formed mafic minerals and plagioclases with calcic cores, together representing this refractory assemblage.

In addition to its master role in determining the form of the granite system and the growth and nature of the mineral phases, water continues to play a vital part in the latter stages of magma evolution and movement as it is concentrated into the residual fluids. Thus the »wetter« the magma the more quickly will it freeze on fall of pressure, possibly explaining why tonalites and granodiorites are more likely than two-mica granites to rise to high levels in the crust (CANN 1970). This cannot, however, be the reason for the preponderance of tonalite at active plate margins because deeper erosion levels only reveal a still greater relative abundance of the latter!

Furthermore granites, even those bearing primary muscovite, do rise to high levels in the crust (discussions in EXLEY et al. 1983, p. 163, and MILLER et al. 1981).

Where granitic magmas have inherited or absorbed water which has then been concentrated during the late stages of crystallisation, enormous energy is released during its final exsolution. BURNHAM (1979) has estimated the great vapour pressures engendered during this second-boiling so that it is no surprise that fractures are formed and hydraulically extended (PHILLIPS 1986, for review), and that brecciation and fluidization are so important at this final stage when crystal fabrics are disrupted and crystal fragments entrained and transported in tuffisitic breccias (see MARSH 1981; also REYNOLDS 1954; BOWES & WRIGHT 1967; PITCHER & BERGER 1972, p. 162; MYERS 1975; PLATTEN 1984).

Melting metamorphic rocks: During the same period that these researches were being carried out in the United States, Winkler and his associates in Germany (WINKLER 1978, for review) found that, in the presence of excess water, granitic partial melts can be generated from a wide range of metasediments, the melt composition depending on that of the source. At first sight such a finding seems consistent with the common occurrence of migmatites in high-grade metamorphic terranes, but because deep-seated metamorphic rocks are likely to be relatively dry it seems that melting cannot proceed far without the release of water combined in the micas and amphiboles. As a consequence the dehydration reactions control the melting process (FYFE 1970, BROWN & FYFE 1972, THOMPSON 1982).

The reaction equilibria involved in partial melting are complex (GRANT 1985, for review), and the reactions slow (TRACY & ROBINSON 1983, p. 172). Nevertheless the restricted compositional range of common pelitic lithologies offers a simplification, so that we can accept the experimental findings that, with water-undersaturated conditions and geologically reasonable pressures, melts appear in volume when muscovite and then biotite become unstable, that is at between 700 and 800°C. But the escape of melt, as represented by the leucosomes of migmatitic gneisses, is not easily realised (ASHWORTH 1985, for review), and it is questionable whether such partial melts commonly coalesce into large bodies of granite. Altough there are some well-authenticated field descriptions of this happening (eg. CURRIE & PAJARI 1981), some kind of contact hiatus is usually discernible between the pluton and its gneissic envelope as is well shown in the Coast Mountains of British Columbia (WOODSWORTH 1979). Thus I am uneasy with any thesis of bulk segregation without account being taken of the ability of the synplutonic deformation to obscure intrusive relationships even in the very root-zones of a diapir. Furthermore the fact that the formation of migmatitic gneisses often proves to be a bulk isochemical process requires that the leucosome has not been drained away. There are problems too in envisaging the physical extraction of small volumes of melt (see MARSH 1981, p. 96). I do not believe this is how granitic plutons are generally formed.

But if not then we need to consider a generative model involving a more wholesale fusion, as envisaged by PRESNALL and BATEMAN (1973), whereby a large batch of magma is produced during a discrete melting event. This model fulfills the requirement that there be sufficient magma to provide the necessary buoyancy for upwelling, and also counters the objection that the order of intrusion is normally the reverse of the order of melting. This new magma, variously loaded with refractory residues, differentiates during its ascent, the precipitated crystals accreting on the walls of the conduits. This is an attractive hypothesis which is in general accord with the experimental works already quoted. There is, however, a severe compositional constraint: using just one of Wyllie's experiments (1977, p. 64) as a guide we learn that the partial melt from a tonalitic gneiss is of granite composition at temperatures around 800°C (at pressures expected in the lower crust), only reaching granodiorite composition above 900°C and tonalite at 1100°C. Whilst there are always reservations on the general application of experiments (see ABBOTT & CLARKE 1979), it does seem unlikely that great volumes of tonalitic and dioritic liquids will be generated during normal crustal processes without a significant contribution of heat from outside the system. It is not therefore surprising that voluminous granites *sensu stricto* are petrologically distinct from voluminous calc-alkaline granitoids, and that the latter are preferentially associated with basic magmas.

Volatiles other than Water in Granitic Magmas: The composition of the earliest of the fluid inclusions in natural granites and their possible source rocks shows that, in addition to water, the magmas contained fluorine, boron, carbon dioxide, and other gases (CHAROY 1979, for review). The relevant experimental work shows that fluorine and boron have an even greater effect than water in depressing the solidus temperatures, even to below 600°C at 1kb (BAILEY 1977, for review, also MANNING & PICHAVANT 1983). Furthermore the phase relationships are sufficiently changed from those of water-bearing melts so as to produce distinctive mineral parageneses within which quartz has a wide temperature interval of crystallisation: moreover, sodium and fluorine are enriched in a late fluid phase (KOVALENKO 1979). On the basis of these experimental findings many of the properties of A-type granites, including their exceptional fluidity and late-stage redistribution of elements, can be explained as due to differentiation of an anhydrous granitic melt enriched in fluorine.

We know that the role of CO_2 is rather different from that of H_2O and other hydrolyzable volatiles in lacking the capacity, at crustal pressures and temperatures, to break up the Si-O-Si bridges. Perhaps the most important consequence of its presence is that it volumetrically enhances the effect of any water present.

The theoretical treatment of the role that these volatiles play in silicate melts has been the main thrust of studies by Burnham, Holloway and their associates (BURNHAM 1979, and HOLLOWAY 1976, for reviews). In the system $NaAlSi_3O_8$ -- H_2O it seems that water functions as a melt component independent of the silicate composition, and the realisation of this enabled Burnham to evolve a general thesis of the evolution of hydrous magmas as water is concentrated in the interstitial melt during crystallisation.

From the work of Taylor and his associates (TAYLOR 1977), utilizing variations in the isotopes of oxygen and hydrogen in rocks, it is possible to conclude that much of the water in granites is derived from crustal rocks, the proportion of meteoric water being greatest in crustal-derived granites. During the intrusion of hot magma a »hydrothermal cycle« operates involving the leaching of the country rock and the absorption of mineralised water into the magma, followed by its expulsion as ore-laden fluid.

By determining whether heat is conducted or convected the hydrothermal circulation controls many granite-associated phenomena, not least the width and form of the metamorphic aureole (PARMENTIER & SCHEDL 1981). Further, such hot water circulations may continue long after the main cooling event, being sustained by the heat generated in granites with higher-than-usual concentrations of radioactive elements, i.e. the High Heat Production Granites (FEHN 1985; PLANT et al. 1985). Such granites ought to be most typical of the encratonic environment, deriving from radiogenic crust, although a contrary view has been expressed by ATHERTON and PLANT (1985).

The Nature of Granite Magma

Whilst there is some considerable understanding of the chemistry of the granite system there is a dearth of new knowledge on the physics of granite melts and we will have to await the results of a new generation of technically difficult experiments dealing with properties of such melts (eg. ARZI 1978; VAN DE MOLEN & PATERSON 1979).

M a g m a R h e o l o g y : Natural granitic magmas, other than those of highly alkalic composition, carry suspended crystals even from the source. Strong evidence of this is provided by the frequency of discrete calcic cores within plagioclase crystals (PIWINSKII 1968; MASON 1985), and also by the presence of ancient zircons, quite apart from the suspicion that many crustal-derived granites carry mafic restite surviving from the zone of melting (WINKLER & BREITBART 1978; CHAPPELL 1984). The implication is that such magmas were at sub-liquidus temperatures for much of their intrusion history, even though temperatures may be held steady by the exothermic nature of the crystallisation of the dark minerals and plagioclase. With a crystallisation interval of several hundred degrees it is likely that a critical crystallinity may be reached whilst the magma is still flowing, when the highly polymerized, crystal-loaded, siliceous melts will assume non-Newtonian, pseudoplastic properties and possess a yield strenght (PITCHER 1979, p. 636; MCBIRNEY & NOYES 1979). Whilst we ought not to neglect the hydrolyzing effect of water in countering this change, this is theoretically of less importance than that of both the rising SiO_2 values and the crystal content of an evolving magma.

Many of the natural features of the granitoids call for non-Newtonian explanations. Examples include the rarity of the gravity settling out of crystals, except where the volatile constituents, such as fluorine, are in high concentration (EMELEUS 1963). The even scattering of phenocrysts and small enclaves, which rarely touch one another even when in dense clusters, suggest that the enclosing magmas had the supportive properties implicit in a yield strength. An alternative is that such suspensions might be maintained by the agitation of localised convection systems (SPARKS 1984, p. 518), but there are yet other features suggesting these special properties. The frequency of localised surge contacts in the interiors of plutons demonstrates considerable differences in mobility between similar magmas with little difference in temperature; also the disruption of synplutonic basic dykes within plutons into globular and angular enclaves evokes the Bingham property of coeval fracture and flow as a function of duration of the application of stress (PITCHER and BUSSEL 1985, p. 107). Flow sorting and particle concentration at contacts, the holding in suspension of small enclaves, and their spacing apart within enclave swarms, are yet other features. Furthermore, because increasing the concentration of xenoliths increases overall viscosity it is not surprising to find that xenolith swarms are so often plastically deformed and streaked out.

If natural granite magmas have these properties then we must expect their effects to vary in degree depending on geological environment, magma source and evolutionary process. At one end of the scale will be the wholly molten melts of the fluxed, alkalic A-type granites representing the nearest approach to true Newtonian fluids. The I-type magmas in the high heat-flow zones of the oceanic and marginal arcs will contain some suspended crystals but are unlikely to approach critical crystallinity till late in their evolution: as a consequence of this and their water undersaturation they are able to rise high up into the base of volcanic centres. On the other hand similar deep-source magmas cooled by penetration along deep-reaching faults in a thick craton are more likely to reach the state of critical crystallinity. In total contrast those magmas arising within encratonic fold belts by the syntectonic melting of crustal rocks are the most likely to be loaded with crystals, of both restitic and intratelluric origin, and these melts are candidates for the pseudoplastic condition. It is particularly in the syntectonic diapirs that such magmas behave, for at least part of their history, like the salts, deforming and flowing in a near solid state.

Clearly it is most necessary to take the ever-changing physical state of a granitic magma into account in modelling differentiation processes.

Magma in Movement: The frozen contents of magma chambers may only represent the residue from the original fill. Moreover these residues necessarily stew for a long time in their own juices so complicating the evidence for the evolution of the magmas. Furthermore the vagaries of erosion rarely enable us to see the filling and the ejecta in the same place. We have to be aware of these and other complications.

Individual granitic plutons can either be remarkably homogeneous or show various degrees of lateral and vertical zoning in texture and composition. A central problem is whether this zoning is produced in situ or is the result of magma pulsing. There are certainly plutons in high-level situations in which the compositional zoning is transitional and in the three-dimensional form of either a closed or open sandwich, and these must represent differentiation in situ (eg. Cañas, Puscao, Peru: TAYLOR 1976, 1985).

However, many plutons lack the evidence provided by the vertical dimension, and whilst in some the form of outcrop has been interpreted as due to the tilting of an originally horizontal compositional layering (eg. New England Batholith, Australia: FLOOD & SHAW 1979), most zoned plutons show only the lateral, centripetal variation approximating to the cross section of a steeply-inclined, zoned cylinder. The peripheral rocks are usually the most basic, with sequences of quartz diorite to monzogranite almost universal, but occasionally the zoning is reversed (eg. FRIDRICH 1983). Such contacts as exist, or even the equivalent zones of rapid transition, are unlikely to represent long time-intervals, though objective time studies are lacking. They can, however, represent a considerable flow-past of magma, sometimes measurable by the magnitude of the compositional hiatus across them (discussion in ATHERTON 1981, p. 348). This happens especially where plutons have been constructed by repeated pulsing of magma, during either the filling above and around the subsiding pistons of cauldron subsidence or the inflation of distension diapirs (discussion in PITCHER 1979, p. 646). The sinking of a block, either of country rock or pluton carapace, into an underlying compositionally and thermally zoned magma chamber provides a ready explanation of the successive pulses of magma, with the additional expectation of commingling, though variously incomplete because of the contrasted viscosities and solidus temperatures of the magmas (MARSHALL & SPARKS 1984). It is not surprising, therefore, that the measurement of modal or chemical variations across inwardly zoned plutons is often discontinuous to some degree, sometimes to the extent that the compositional steps represent wholly separate pulses of internally homogeneous magma, when the differentation process can hardly have operated in situ. The latter process is even more unlikely where the strontium and oxygen isotope compositions of the core rocks differ substantially from those of the rim (eg. HALLIDAY et al., 1980).

In Circum-Pacific batholiths identical rock units appear in the same order in separate and widely spaced plutons (PITCHER et al. 1985, p. 95). This might be due to the differentiation process following a similar evolutionary path after leaving a common cell of parent magma, but I believe that it is more likely that the differentiation largely occurs at depth, the evolving magma cell providing sequential draughts, though the two possibilities are not exclusive.

Remarkably the genesis of particular consanguineous suites of rocks is still a matter of vigorous discussion with crystal differentiation and magma mixing being the more generally favoured alternatives, though unmixing by the fractional melting of the source rocks, or even the separation of immiscible fluids, remain possible mechanisms. Clearly each occurrence needs individual assessment.

A more radical view of magmatic differentiation has been presented by HILDRETH (1981) in a well-documented study of magma evolution during the extrusion of the Bishop Tuff, California. Hildreth argues against adopting any of the conventional mechanisms, especially those involving crystal settling, holding that a compositional gradient existed in the parent magma before the phenocrysts formed, and that this was established in the magma chamber by a diffusion mechanism accelerated by convective transfer of the melt towards the cooling surfaces. This radical hypothesis has not found general favour (e.g. MICHAEL 1983), probably because the evolution of magma suites can be so elegantly modelled by linear programming on the basis of the differential removal of crystal crops (WRIGHT & DOHERTY 1970; BANKS 1979). This approach, embellished by the use of trace element studies to trace the paths of fractional crystallisation (ARTH 1976; MCCARTHY & HASTY 1976), has so confirmed this fractionation thesis that few workers question the accepted values for distribution coefficients, particulary for the accessories, in the crystalline granite system.

In discussing the possible forms of convective systems in magma chambers SPARKS and his coworkers (1984) also agree that the gravity-aided settling of crystals is an inadequate and improbable mechanism for explaining differentiation. Instead they argue for convective fractionation. From their modelling of the dynamics of magma-chamber processes, they find that the compositional variation consequent on fractional crystallisation reduces the density of the residual melts sufficiently for them to rise away from the sites of crystallisation. Such a localised but cumulatively effective separation of liquid from crystals causes compositional differentiation during inward crystallisation from a side wall and upwards from a floor. This permits continuous exchange of elements across the boundary layer between the intercumulus pore fluid and the main body of magma (SPARKS et al. loc. cit. p. 530). Moreover such an exchange is more effective in transfer than the diffusion mechanisms previously suggested (SHAW 1974). Here then is an adequate explanation of vertical zonation without resorting to large-scale crystal settling, or even major convective overturn in what is probably a system of convecting layers.

The laboratory experiments of Sparks and his colleagues also show how complex are the convection dynamics of a multi-component system involving saturated aqueous solutions of salts, and we can hardly guess how much more or less complicated are siliceous melts, especially those loaded with crystals and possessing a yield strength. Nevertheless it is possible to deduce from these experiments that highly fractionated fluids are formed and moved to the top of a chamber by the type of convective fractionation described above and without having to invoke a heavy precipitation of crystals. In such a model it is also possible to simulate compositional layering so that adequate physical explanations are now forthcoming for many of the features of zoned plutons.

All this is consonant with the lack of unequivocal evidence in the outcrop of convective flow as recorded in the fabric of granite plutons. Generally mineral foliations are simple in form, conforming to the external contacts yet often independent of internal contacts, so that I have argued that they are largely the result of syn-intrusion, ductile deformation, and not true flow (cf. MARRE 1986, p. 86). However I accept that flow might pass imperceptibly into ductile deformation in the solid state (compare BATEMAN 1983, p. 248, with PITCHER and BERGER 1972, p. 333). Sometimes evidence of flow-layering exists in the form of biotitic schlieren graded inwards into a pluton as if representing a tube-like magma vortex (BARRIÈRE 1977). Turbulent flow is also represented by the swirls picked out by the K-feldspar megacrysts in some plutons particulary in crustal-derived S-type granites, presumably because the inherited seed-crystals in such magmas record the early flow regimes. Such structures are clearly to be associated with the intrusion of the magma, but my experience is that the more general biotite alignments are commonly superposed on such schlieren indicating that flowage has yielded to plastic deformation.

Thus I am not persuaded that the common foliation patterns of plutons represent the palimpsest of large-scale convective overturns (cf. PHILLIPS et al. 1981, and discussion in HOLDER 1983).

In relation to the overall thesis relating physical process to granite type and environment it has been pointed out (see WHITE et al. 1977, p. 74) that there is a more limited composition range within individual S-type plutonic complexes than within those of I-type granitoids, especially when expressed in terms of total SiO_2 content. Furthermore, where there are different rock units of S-type these are commonly in the form of separate intrusions. True zoning, especially when gradational, and originating in situ, is almost a prerogative of I-type rock sequences, with volumetrically the widest spectrum of rock units in those plutons of the continental margin arcs, and the most significant inward changes in isotopic composition occurring within the I-type plutons of the fault-block regime. A-type granites are the most distinctly multi-pulse, with contrasted rock units often representing quite separate magmas.

Comments on the intrusion process

Intrusion mechanics: The causes of magma upwelling have long been discussed with the identification of buoyancy as the potential driving force, variously coupled with the volume expansion on remelting, tectonic squeezing, seismic pumping and, at high levels in crust, the vapour pressure. Evaluation of these processes is difficult because the study of the fluid dynamics and heat flow properties of mobile magma is in its infancy, and also because the viscous forces which act to impede melt segregation and flow depend greatly on the degree of crystallisation.

A theoretical treatment of the flow of magma is provided by MARSH and KANTHA (1978), MARSH (1982) and SPERA (1980), and these works illustrate well the complexities which are probably more easily resolved for basic magmas than their granitic analogues. Whilst it seems possible to estimate the forces of buoyancy, the viscous forces are more intractable depending on the ductility contrast between the magma and its host, itself dependent on crustal depth, time of intrusion in relation to regional deformation, availability of water derived by the dehydration of the aureole rocks and, not least, the lithology and fluid permeability of the host rocks. Such controls are not easy to quantify, but considerations of pluton-spacing geometry (RICKARD & WARD 1981), and simple parameters based on mineral stabilities within both the granite and aureole, can be used to place constraints on the depth of both the source and the arrival of granite magma, though the application of the experimentally determined stability curves demands caution (e.g. D'AMICO et al. 1981; MILLER et al. 1981). Using such procedures HYNDMAN (1981) determines that in those plutons emplaced at mid-crustal levels the magmas were probably relatively hydrous and generated by the partial melting of crustal rocks, whilst those emplaced at shallow levels were probably generated at deep crustal or mantle depths, two situations applying to the S- and I-types respectively.

Be that as it may it is fortunate that contrasts in ductility are readily appreciated in the field where they can be measured by comparing the strain components. They are presumed to be least when the internal and external fabrics of plutons conform, when the enveloping rocks concordantly wrap around the pluton (BERGER & PITCHER 1970).

Where there is conformity, then by analogy with laboratory experiments and comparison with salt diapirs, the upwelling of granite magma has often been envisaged as starting with the initiation of a dome, continuing with a steepening of the flanks and eventually forming a waist, at which point the diapir ascends most rapidly, developing a tail due to the sinking of the enveloping rocks into the trunk of the diapir, and finally mushrooming out at some limiting height in the crust (RAMBERG 1981, for review; BERNER et al. 1972; SORGENFREI 1971). It is easy to conceive of such an evolutionary series starting within the ductile lower levels of the crust, though needing the trigger of deformation to set it in train. Indeed the role of syn-kinematic deformation in reactivating granitic material in the deep-seated environment of gneiss domes is indisputable, though the relative importance of tectonic squeezing vis-a-vis buoyancy has invited some discussion (PLATT 1980; SCHWERDTNER 1981; also BRUN 1980; SCHWERDTNER et al. 1983; MILLER 1983).

We might suppose that a growing, buoyant blob of magma could only begin to rise when the theoretical ascent rate for the blob exceeds its growth rate. This is consonant with the finding that natural magmas are indeed intruded periodically, the separate pulses also having the size limitations suggestive of the need to accumulate a critical volume before magma escape (FYFE 1970, p. 231; PITCHER 1979, p. 628). That this particular volume of magma has to be scavenged from a specific radius of the source zone might ensure a particular spacing of plutonic centres (see RICKARD and WARD 1981).

The problem then arises as to how a magma blob can continue to rise within the relatively cool higher levels of the crust. MARSH and KANTHA (1978) envisage the formation of a thin rind of nearly-melted wall-rock which effectively lowers the viscosity contrast (see also HODGE 1974), and it is true that some »mesozonal« plutons are coated with a thin skin of plastically deformed hornfelses (e.g. Thorr, Donegal: PITCHER 1953).

However the concept of a rising blob is not in accord with the structures observed in association with many so-called diapiric plutons where piercement is less of a mechanism than a ballooning distension accomplished by replenishment by new magma into the hot interiors of plutons: a replenishment that may be from depth, or otherwise represent the continuing upwelling of the still mobile and buoyant core when the column of magma withdraws upwards as it mushrooms into the upper crust.

The Papoose Flat Pluton in California (SYLVESTER et al. 1978) provides an excellent example of magma injecting into a fault zone and expanding into a blister by multipulse filling. A similar distension diapir is that of Ardara, in Donegal (HOLDER 1979), where the degree of inflation has been calculated by the measurement of the incremental strains recorded in both the periphery of the pluton and in its envelope. And still in Ireland, the Leinster Batholith illustrates the assembly of an array of distensional plutons into a »diapir batholith« rising into a ductile shear-zone of regional extent (COOPER & BRÜCK 1983), whilst the Main Donegal Granite pluton consists of great confluent sheets of granite wedging up into a contemporaneous shear zone. Within the latter the creation of a zone of finite volume-gain caused the magma to be sucked up into the upper crust (HUTTON 1982). A further and highly illustrative example of this process is provided by the intrusion history of the Extramadura batholith of central Spain where CASTRO (1985) has developed a model, based on his own studies and those of GARCIA DE FIGUEROLA et al. (1983), whereby regional compression first produced deep-seated fractures which admitted hot, basic magmas into the lower crust; these contributed to the thermal event that gave rise to the granodiorites which were themselves admitted into higher levels during a later phase of regional shearing.

That the combination of controls of the mechanism of emplacement is dominated by structural and lithological factors is shown by finding that both brittle and ductile mechanisms can operate at a single level in the crust (e.g. Donegal: PITCHER & BERGER 1972; Saudi Arabia: DAVIES 1982, AGAR 1986; Greenland: BECKER & BROWN 1985).

In summary there is a range of possible mechanisms, including sheets sucked into movement zones, simple magma blobs piercing a ductile crust yet mushrooming out at high level, and plutons ballooning from a fault plane as the result of the continuous replenishment of magma seismically pumped through this feeder conduit. Possibly the hotter and drier the magma the more likely it is to be rapidly pumped into cracks and potential voids, in contrast to a cooler and wetter magma which early becomes loaded with crystals and increasingly viscous as it is tectonically squeezed up into the crust by forcibly shouldering it aside. Thus we might expect true diapirism to be more a feature of the crustal-derived granites of the orogenic belts than those of the I-types of the true arcs.

A structural control is evident at all stages of magma emplacement and wholly predictable from theory and experiment RAMBERG 1981, p. 339). Pre-existing and magma-propagated fractures locate intrusions on all scales and in regional structural contexts as different as those of the ductile shear zones of Brittany (STRONG & HANMER 1981), and the deep-reaching, fundamental faults of the Peruvian Andes (BUSSELL & PITCHER in PITCHER et al. 1985; DAMM & PICHOWIAK 1981), where pluton emplacement plays no small part in finally welding together the opposing blocks. The regional siting of plutons in relation to block-faulting has been commented on by LEAKE (1978) and is reported by many workers (e.g. XU KEGIN et al. 1984, p. 28).

Furthermore the detailed control of pluton contacts is commonplace (eg. PITCHER 1953; BUSSELL 1976; AGAR 1986). It is particularly evident at high crustal levels where fracture systems are propagated by the large effective stresses created by the prevailing high vapour pressures, the crack-penetrating vapours brecciating, entraining and intruding the country rocks in the form of tuffisites. This is especially so within the sub-volcanic regime of nested plutons and ring-dykes where the interplay of regional and pluton-activated stresses locate and orient the bounding fractures of subsidence cauldrons and their associated dykes and sheets (e.g. MYERS 1975; CASTRO 1984).

At such high crustal levels major stoping operates and, coupled with updoming, forms an effective mechanism for magma emplacement whereby cylindrical, piston-like blocks are stoped from brittle crust. Whilst the sinking of blocks is the expectation, the high viscosity of some quasi-solid diapirs might lead to an upward punching emporte pièce through a resurgent dome (BARRIÈRE 1977; RAMBERG 1981, p. 343).

The blocks must often be broken up, but the larger the sinking fragment the less the cooling effect it has on the invading magma (see OXBURGH & MCRAE 1984), which may partly explain why major stoping takes the form of of great flat-topped pistons (MYERS 1975; PITCHER 1978), and why we rarely see a jumble of smaller blocks in deeply eroded plutons. I envisage some multiple batholiths, like those of the Andean margins, as constructed from a stack of such cauldrons arising from the base of the crust as a system of interconnecting magma chambers.

What then is the connexion between such mechanisms as apparently diverse as cauldron subsidence and diapirism? GASTIL et al. (1975, p. 39) explain the circular outcrops and similar diameters of associated diapirs and cauldrons on the basis that it is the rising diapir, or more specifically its mushroomed capping, that measures the doming and the consequent arcuate fracture that locates the cauldron (RICKARD & WARD 1981, p. 28). There are indeed examples of such a connected mechanism in the form of fracture-controlled intrusions lying within steep domal structures (e.g. Arran, Scotland: BELL 1982, p. 432, and PITCHER, personal observation), but I suspect that, more generally, the tectonic environment determines the dominant form of the intrusion.

Thus, as hinted above, I envisage true piercement diapirs, involving anatectic melts, as being squeezed up from the metamorphic cores of collisional fold belts, both along and through the developing thrusts which they may well rivet and lock by their consolidation. The distension diapirs form blisters within the master fractures of block-faulted continental regimes. Cauldrons form by block-subsidence particularly when mantle-derived magmas are released during crustal extension, either at active plate margins or in encratonic rift zones.

Lastly, with the reservation that we need a greater input from geophysical studies, particularly seismic reflection surveys, I believe that detailed mapping, coupled with structural analysis of both pluton and aureole, can provide sufficient data to model emplacement mechanics of individual intrusions (e.g. HUTTON 1982; CASTRO 1984; BATEMAN 1985). But whilst the arrival room problem can be solved it is the rooting of plutons and batholiths that remains enigmatic. Conventional gravity surveys very often reveal steep-walled and deep-rooted bodies the large volumes of which seem inconsistent with anatexis within the immediately available crust (e.g. BROWN 1981). This is further evidence for the deep-seated origin of melt from a wide zone of the crust-mantle interface. Certainly I remain sceptical of any general model of thin batholiths (cf. HAMILTON & MYERS 1967). However I am puzzled by the reports of flatlying reflectors (LYNN et al. 1981), and it is possible that the great I-type batholiths of the American cordilleras represent, in the most general terms, a silicic layer capping the basic parent. In contrast I envisage the crustal-derived granites as being essentially rootless.

Concerning Granite Texture

Turning to the crystallisation of the granitic magmas we remain largely ignorant of the kinetics of crystallisation not only because the reproduction of real granites still remains elusive but also because the interpretation of grain-contact patterns is in its infancy. Although there is a substantial theoretical backcloth on which to view the possibilities (DOWTY 1980 & LOFGREN 1980 for reviews), and laudable attemps to utilise the experimentally determined phase diagrams, we await the experimental duplication of even the simplest granite texture in its entirety.

However the work of LOFGREN (1980), FENN (1977) and SWANSON (1977) on nucleation and growth in hydrous granitic melts marks a start revealing, for example, that the growth rate of feldspar crystals exceeds the rate of nucleation, providing an explanation of the common coarseness of grain. Furthermore the growth of phenocrysts is a usual product of single stage cooling of totally liquid melts. Phenocrysts are indeed a feature of some plutons, as for example in the Sierra Nevada (BATEMAN & CHAPPELL 1979), where it is usual for the K-feldspar megacrysts to diminish in size and abundance away from a contact, apparently conforming to Swanson's experimental finding that the growth rate is at its optimum at the beginning of nucleation, logically within the contact zone. More often, however, granitic rocks are remarkably uniform in grain size and grain distribution within the separate pulses, with these two parameters being highly specific to each pulse. This may be because most granitic magmas carry seed crystals in suspension thus avoiding the phase of slow nucleation and enjoying unihibited growth. As a result the plagioclase and mafic minerals grow evenly from existing, randomly distributed nuclei to produce the characteristic even-grain (RODGERS & BOGY 1958).

It is less easy to explain why S-type granites of crustal origin are the most commonly K-feldspar megacrystic, when these are the very magmas that would be most likely to be crystal-seed bearing. Perhaps they are only so by reason of extended growth in the solid state, a matter I return to below.

Concerning the most characteristic textural feature of granites, wherein K-feldspar and quartz lie interstitial to the dark minerals and zoned plagioclase, this is in accord with the experimental finding that the latter mineral phases exist in equilibrium with felsic melt over a wide temperature interval. It follows that the two feldspars can hardly be interpreted as a tied pair and that their use in granite geothermometry must be suspect (see BROWN & PARSONS 1981).

Though in its infancy the experimental study of texture is important in stimulating a fresh approach to the morphological petrography of real granites. This must involve the statistically controlled examination of grain shape, size and distribution (e.g. VISTELIUS 1972; WHITTEN & DARCEY 1974; MCLELLAN 1983; ASHWORTH & MCLELLAN 1985). Of course petrologists are well aware of the need to systematically record textures at pluton scale but the labour involved is immense (e.g. HUTCHINSON 1982, p. 57 et seq.).

There are particular complications to be addressed in morphological textural studies. First, the textures of granitic rocks are variously metamorphic in character as is well illustrated by many of the plates in Augustithis' Atlas of Textural Patterns (1973). Unlike the transformists I do not regard this as evidence of the primary metamorphic origin of granite, but more usually of sub-solidus grain interaction during either synplutonic deformation, or cooling in the presence of those circulating fluids which become available at various stages during magma evolution. A great range of textural reconstitutions and regrowth chronologies is involved, a familiar example being the continuing growth of K-feldspar from magmatic seed to metasomatic overgrowth as granite enters the late, incipient pegmatitic stage of its evolution (discussions in SCHERMERHORN 1956; BATEMAN et al. 1963; EXLEY et al. 1983, p. 163; MENHERT & BÜSCH 1981, 1985). More severe modifications are produced by the late-stage fluids deriving from highly evolved magmas and which are retained within thick-skin carapaces of plutons at high levels in the crust, and MARTIN and BONIN (1976) consider that such a late-stage influx of water may induce a near complete refusion. Whatever their origin such textures often prelude mineralisation.

Each of the special textures of granitic rocks has its own physical message. Local changes in water saturation form the basis of explanations for the preferred growth of primary K-feldspar megacrysts (HIGGINS & KAWACHI 1977), and for the formation of comb layering and the related orbicular structure (VERNON 1985). A similar explanation also applies for rapakivi mantling (CHERRY & TREMBATH 1978), the more credible now that the type rapakivi granites are known to occur in very high-level, post-orogenic cauldrons (BERGMAN 1986), an environment consonant with the rapid release of volatiles. Clearly explanations exist for many textures and growth orders, but as yet little account is taken of the possible effect of the different volatile species (RANKIN & ALDERTON 1985, p. 298).

In view of these controls on texture it is not surprising to find that the granitoids of the volcanic arcs show the most pristine of melt-crystallisation textures, approaching the tabular and adcumulate, whilst those of the collisional belts show blastic textures of a degree varying from relatively simple grain enlargement and inter-grain reaction in many post-tectonic plutons to wholesale recrystallisation in syntectonic diapirs. But the most through-going reconstruction occurs in the A-type, alkalic granites where the concentration of the non-hydrous volatiles ensures a maximum of sub-solidus reaction and recrystallisation.

A further factor is not so much a complication as the recognition that detailed examination of textures, especially those of high-level granites, often reveals heterogeneities of grain size and the corrosion and fracture of crystals which are not the result of imposed cataclasis but some kind of reaction between the matrix and the larger, earlier-formed crystals. Such features were first meaningfully commented on by REYNOLDS (1954), with the explanation that they may sometimes result from the comminution and entrainment of crystals within a gas-charged magma. The possibility of late-stage refusion has already been mentioned, and the report by COBBING et al. (1986, p. 538) that two-phase textures are ubiquitous in the granites of western Malaysia requires a fresh approach to textural studies of real granites.

Process Time

We know very little about the times required to melt, segregate, differentiate, intrude and cool granite magmas. Estimates are of little value when the times involved must surely differ according to the geological environment (PITCHER 1979, p. 640; SPERA 1980). Certainly very long periods are involved in the assembly of plate-edge batholiths, e.g. 70Ma for the Coastal Batholith of Peru (PITCHER et al. 1985), and two periods of 50Ma each for the Sierra Nevada Batholith of California (BATEMAN 1983), but in this same environment the narrow spreads of ages recorded from individual rock suites allow only a very few millions of years for their entire evolutionary histories (e.g. BATEMAN 1983, p. 250).

Such relatively short periods seem also to hold for the evolution of granitic suites in general. Thus within the fault-block uplift environment of the Late Caledonian plutons of the British Isles a single complex such as that of Donegal may span 13Ma, yet it is still resolvable into two close-knit groups of intrusions dating at 418Ma and 405Ma (O'CONNOR et al. 1982). In the rather different post-tectonic context of the Appalachians the South Mountain Batholith divides into three separate, though cogenetic, groups spanning 9Ma (CLARK & HALLIDAY 1980). We need to know from many more examples, and more exactly, the periods of assembly, but there is the difficulty that, at this level of refinement, secondary effects masks the separation intervals. Nervertheless the indications are that such intrusive events are relatively short-lived. They may be repetitive and episodic as viewed from within any one segment of a mobile belt, but seemingly more continuous on a regional scale.

It is tempting to connect such episodicity with tectonic events, and this has led to elaborate magma-tectonic schemes being proposed for many mobile belts. In what might be supposed to be a relatively straightforward case of plate interaction, that of the Mesozoic Andes, this connexion seems to be real (AGUIRRE et al. 1974; BUSSELL 1983; MOORE 1984), the intrusion of the magmas being responsive to episodic compression-relaxation rhythms and the connected resurgence of movement on faults. However it is difficult to see any more than a very gross connexion with global tectonic processes such as sea-floor spreading, and detailed correlations as proposed by NOBLE et al. (1974) and FRUTOS (1981) fail on the point of marked local differences in the sequence of the arrival times of magmatic suites (BECKINSALE in PITCHER et al. 1985).

Such time-oriented studies are clearly in their infancy and we need much more volumetric data concerning the rates of magma production (e.g. FRANCIS & RUNDLE 1976). However I suspect that the assembly histories of batholiths will be found to be longest, though single pluton assembly shortest, in relation to ocean-continent subduction; the histories much shorter, but the assembly time much the same, in relation to fault-block uplift; whilst long-duration, »granite series« magmatism, with long-time pluton arrival in the early stages, will be found to characterize the collision belts.

The Basic Rock Association

Granitoids are commonly associated in time and place with intrusive basic rocks, though in different relative volumes in accord with the geological environment, i.e. the basic rocks are least in association with the crustally-derived granite series, greatest in association with the granitoids of the volcanic arcs. Thus gabbros form an integral and synchrononous part of those plutonic centres cored by quartz-diorites within the island arcs (e.g. FIJI: GILL & STORK 1979, Aleutians: PERFIT 1980, New Britain: MASON & MCDONALD 1978); they occur as independent, precursor intrusions forming an important component of the tonalite batholiths that intrude the marginal continental arcs (e.g. Peru: REGAN: in PITCHER et al. 1985; California: WALAWENDER & SMITH 1980). In contrast cogenetic basic rocks are either lacking or are of small volume in association with those early manifestations of granite plutonism characteristic of collisional orogenies. However hornblende gabbros and associated appinitic diorites commonly accompany the granodiorites and granites of the waning, uplift stage of such an environment, forming clusters of relatively small satellitic bodies (e.g. Donegal: FRENCH 1966; HALL 1967; Bohemia: PATIVCOVA 1984; Sardinia: SIMPLICIO et al. 1975; Pyrenees: ENRIQUE 1983).

All such granite-associated basic rocks are characteristically hornblende-bearing and subject to hybridisation (e.g. PALIVCOVA 1982; BISHOP & KEY 1983). This is particularly so in the case of the appinites, where extreme variations in the mode, cored hornblendes, disequilibrium in mineral growth as illustrated by the late-stage overgrowth on the amphiboles, and the association with fluidised breccias, provide evidence for high fluid pressures in the magmas (WRIGHT & BOWES 1979, PITCHER & BERGER 1972, MULLAN & BUSSELL 1977). The influence of high water-pressures on viscosity, crystal differentiation and accumulation, ensures that the appinites are chemically distinct from the basic rocks of stratiform and alpine associations (HALL 1967, p. 163). This relative water-enrichment is also suggestive of a connexion with crustal remelting in which the basic magmas played an important role.

Although basic rocks are not generally abundant in the anorogenic alkali-granite ring complexes, this is probably a consequence of crustal level because positive gravity anomalies often reveal the presence of deep-seated basic magma reservoirs (WALKER 1975). Furthermore the low abundance belies the clear evidence of the coexistence and mixing of acid and basic magmas in such sub-volcanic complexes (BLAKE et al. 1965), as is apparent in examples as far apart as Maine (CHAPMAN 1968), Nigeria (BOWDEN & KINNAIRD 1984), and Corsica (BONIN 1982).

In each of these environments the basic rocks are often the precursors of the main granitoid event, albeit overlapping to the extent of coexistence. Usually there is a degree of separateness, and a compositional hiatus is general even in the island-arc association where an approach to total consanguineity might have been expected (e.g. Fiji: GILL & STORK 1979), though this hiatus is most obvious in the A-type assemblages. This lack of transition is well expressed in a comparison of the abundance of light and heavy REEs in granitoids and cogenetic basic rocks, as exemplified by the late-tectonic Hercynian granites of the Pyrenees and Brittany (FOURCADE & ALLÈGRE 1981). Furthermore the correlation of the oxygen and strontium isotopes is not in accord with a direct derivation of granitoids from mantle-type rocks (MCCULLOCH & CHAPPEL 1982). Thus although coexistence proves that they are expressions of the same melting process it seems that basic and acid magmas are separately produced, even derived from different sources.

The separation of two immiscible liquids, felsic and mafic, remains a theoretical possibility and is invoked by BENDER et al. (1982) in their study of the Cortlandt complex, on the basis of the discovery of coexisting, cogenetic melts in lunar rocks. However even at Cortlandt the precursor nature of basic intrusives suggests otherwise: that the basic rocks represent the remelting agents, the transporters of the necessary heat and volatiles for the remelting of an existing source rock.

Howsoever the two magmas are produced mixing is always a possibility and is a favoured hypothesis in innumerable studies (discussion in VERNON 1983). Thus in the continuing study of the granites of southeastern Australia, and somewhat in contradiction to opinions expressed above, GRAY (1984) has found such an excellent hyperbolic correlation of Nd and Sr isotope ratios that he models the origin of all the rock species and types as a single broad family resulting from a mix of sedimentary-derived and basaltic magmas : the simplest thesis of them all! Further, mixing is an observable process in volcanic regimes (discussion in CANTAGREL et al., 1984), and is particularly evident in sub-volcanic centred complexes (discussion in BLAKE et al., 1965). The ubiquity of microdiorite xenoliths in granitoids in general suggests that it is also important in plutonic rock suites.

These microdiorite inclusions continue to be variously interpreted (discussions in DIDIER et al. 1982, LORENC 1984), with a consensus view that they represent basic magma intruded into a reservoir of cooler and more viscous magma. The synplutonic dyke phenomenon is just one example of such relationships (PITCHER & BUSSELL 1985, p. 107), the feasiblity of which is demonstrated by the melt experiments of BÜSCH & OTTO (1980). But we cannot expect that a single model will suffice when comagmatic inclusions cover the whole range of source restite, disrupted wall-accumulations of crystals or earlier quasi-solid phases, disrupted synplutonic dykes, and even engulfed wall-rocks of comagmatic volcanic material.

There is variety, too, in the ductility contrast between enclave and host (e.g. CORRETGÉ et al. 1984), from the fluidal form assumed by the basic globules in composite ring-dykes to the sub-angular fragments which are thermally spalled from gabbroic walls, then shattered, spalled and corroded. Within sizeable plutons such small enclaves, garnered from various sources, reciprocally interchange materials and equilibriate with the host, precipitate the same crystal phases, and are eventually cannibalised: a process seen frozen within many granite outcrops. Whether the mixing is considered to be between liquids, or liquid and disrupted solid becomes a matter of semantics.

Attempts to discover the separate contributions of magma mixing, xenolith assimilation and crystal differentiation are often defeated when the materials involved are co-genetic as is the case in many arc-type situations. For example in a carefully controlled study by TAYLOR (1976) the interspacing of a dense layer of andesitic xenoliths makes little impression on the form of the compositional isopleths established within a single granite pluton. However where the country rocks are continental clastics the contamination is easier to recognise and a quantitive study by WHITTEN (1961) of the flooding of the periphery of a granodiorite pluton by metasedimentary xenoliths showed how the contamination can be mapped. On the basis of trend surface analysis the dominant process, presumably crystal differentiation, can be related to a simple variation law, the residuals being assigned to the effect of contamination.

In recent years a considerable literature has accrued based an the use of the Rare Earth Elements to discriminate between the several possible processes (HART & ALLÈGRE 1980, p. 135 et seq.). As an example the variations in the light versus heavy REE can theoretically distinguish mixing and feldspar-dominated fractional crystallisation. Each plutonic complex requires assessment on the basis of field and chemical data (and REE budget accessories!), but the equivocal results generally obtained probably reflect a multifactoral process, best modelled by combination of liquid mixing and subsequent fractional crystal differentiation (VERNON 1983 for discussion), though restite unmixing or assimilation are more likely to be involved in the genesis of crustal granites.

I do not subscribe to the rather extreme view that crustal magmatism is fundamentally basaltic. In fact, as pointed out by NOZAWA (1983, p. 121), throughout a wide area of the Asiatic continental margin, from Japan to mainland China, basic rocks are poorly represented amongst a vast volume of felsic plutonic rocks. Rather it is the influx of basic magmas at depth that triggers the melting that gives rise to the granitoid magmas. Their influence is most obvious where there is continuous high heat flux below relatively thin crust, less so under the fault-blocks within the thick continental crust where adiabatic heat production is short-lived and insulated, and least at the early stages of melting within the metamorphic cores of compressional, collision belts.

The Volcanic-Plutonic Interface

Because the intrusion of granite, uplift and erosion are connected processes (GANSSER 1982), the higher levels of plutons tend to be removed. It follows that any upward passage from granite to rhyolite will rarely survive and furthermore there will be a severe underestimate of the volumes of silicic magma actually erupted. Nevertheless examples exist of upward transitions from coarse granite to a more siliceous cap of granophyre or aplogranite representing a quenched hypabyssal facies (e.g. Peru: BUSSELL in PITCHER et al. 1985, p. 153; Japan: ARAMAKI et al., quoted in NOZAWA 1983, p. 112). The volcano-plutonic interface is also represented by nested granite plutons capped by a granophyric and tuffisitic ring-dyke complex and leading up into an ignimbrite-filled caldera. Furthermore the plutons often intrude the comagmatic lava infill.

This volcano-plutonic connexion can be observed in almost all the global plutonic environments (BONIN 1982), ranging from the anorogenic, alkalic ring-complexes (Nigeria: BOWDEN & KINNAIRD 1984), the post-collisional granitic plutons (e.g. Scotland, Argyll: PANKHURST & SUTHERLAND 1982, p. 163), the batholiths of the marginal continental arcs (Peru: BUSSELL PITCHER & WILSON 1976; California: FISKE et al. 1977), and the volcanic centres of the mature oceanic arcs and oceanic islands (Aleutians: PERFIT et al 1980; Kerguelen: GIRET 1983).

Differences exist in style and relative abundances, the volcanic association being at its optimum in subduction-related environments and least in evidence in association with the syntectonic, S-type granite series of the collisional orogenies, and this is surely a reflexion of the expected differences in the rheological character of the magmas. However a reservation is introduced here by the existence of S-type lavas even in the Lachlan Belt of southeastern Australia (WYBORN et al. 1981), and thorough-going S-type granites in the centred complexes of southwestern Japan (OBA 1977)!

The fallacy that silicic magmas seldom erupt was laid to rest by SMITH'S (1960) review of ash flows. Provided that they are dry enough granitic magmas can rise high in the crust and vent, sometimes directly in the form of rhyolite and dacite, but more often as fluidized material, entrained and intruded as tuffisites and extruded as ignimbrites. But, as already mentioned, the compositional connexion has been highlighted by HILDRETH (1981, p. 10181) in questioning whether the zonation revealed in voluminous pyroclastic eruptions is reflected in the present fill of the parent plutons. Following eruption the continuing evolution of the residual magma, along with post-consolidation changes, is likely to result in a compositional mismatch of even cogenetic eruptive and plutonic rocks.

However, as already noted, there are examples of silicic-topped plutons in accord with the expectation that they represent the potential supply magma chambers of silicic volcanic rocks (e.g. Puscao pluton, Peru: BUSSELL, in PITCHER et al. 1985; TAYLOR 1976; Quartz Hill and Divide Stock, Alaska: HUDSON et al. 1979; Okueyama pluton, Japan: ARAMAKI et al., op.cit.). On the other hand the bulk of coeval basic lavas is more often vented by way of fissures, even during the plutonic phase, being represented by the ubiquitious, synplutonic dykes that swarm onto the plutonic centres. A good case of this duality is provided by the deeply eroded caldera of Glen Coe, Scotland, where a plateau of fissure-erupted, basaltic lavas is intercalated with ignimbrite flows which thicken towards the parent caldera (ROBERTS 1966). Thus we must accept that even closely related volcanic and plutonic magmas may have different sources.

Metallogenesis and Granite Type

Much has been written about the association between metallisation and silicic magmatism with particular reference to its typicality (e.g. ZONENSAJN 1976; TAUSON 1977; MICHELL & GARSON 1981). Even in touching briefly on the subject it is important to distinguish between metalliferous and mineralized granites (PLANT et al. (1985), and to recall that the acquisition of the ore-forming elements by granite magma and their subsequent history of hosting and final release is very complex (EUGSTER 1985, for review). The metals are not easily concentrated without the scavenging role of the volatiles and brines derived as end-products of the more highly evolved magma systems. Furthermore modern studies are tending to loosen the connexion between magmatism and metallisation by finding a hiatus in time and a particular localization of the circulation systems which are contrary to hypotheses involving direct parentage (e.g. SHEPHERD et al. 1985, p. 362; STONE & EXLEY 1985, p. B 34).

Nevertheless there are some well-established, general associations. The porphyry-Cu deposits are very closely related to arc magmatism with its magnetite-bearing I-type tonalites and granodiorites (SILLITOE 1981), with gold as a frequent accessory, accompanied by molybdenum in continental marginal arcs. However even here the association with the granitoids is indirect, representing a complex recycling and concentraion of the metals derived first from existing exhalative deposits within the volcaniclastic host (VIDAL, also PITCHER & COBBING, in PITCHER et al. 1985, pp. 249 and 289).

The relationship between granitic magmatism and tin and tungsten deposits has been exhaustively studied and the current model for the origin of their origin, particularly within the tin girdle of S. E. Asia, is again that the metals were originally garnered from metasediments, this time during a cycle of partial melting and fractional crystallisation that produced the ilmenite-bearing S-type granites (HUTCHISON & CHAKRABORTY 1979; BECKINSALE 1979; contributions in XU KEGIN & TU GUANGCHI, 1984). Concentration was enhanced in those magmas differentiating an alkaline residuum (cf. ŠTEMPROK 1982). Although the nature of the global tectonic environment of these tin-granites of S.W. Asia has been much debated a continental collision model is favoured.

However, this is not the only environment of tin deposits, another being in association with the alkali granites of the anorogenic ring complexes, with their highly evolved magmas and exceptional concentration of Nb. These are well-exemplified in Nigeria where a Sn-Zn-Nb assemblage is related to a complex alkali-fluorine metasomatism (BOWDEN 1982).

Remarkably those I-type granites and granodiorites that characterise the post-tectonic fault regimes seem less likely to be highly mineralized. It seems that this is not because they are non-metalliferous but because they fail to maintain a sufficiently high heat flow to sustain late stage fluid circulation (discussion in PLANT et al. 1985). Perhaps this is on account of the paucity of radiogenic minerals in such primarily mantle-derived magmas, and the fact that they are divorced from the high heat flows associated with subduction processes. In contrast it is predictable that the radiogenic continental crust will provide the S-type granites with a sufficiency of the heat-producing elements and the necessary water to provide the conditions for long-standing fluid circulation.

Magma Sources

The Peraluminicity Problem: Peraluminous granites can be generated by a number of diverse mechanisms (CLARKE 1981, and HALLIDAY et al. 1981, for discussions). Leaving aside the mildly peraluminous, biotite-bearing granites of the peralkaline complexes, which suffer a removal of alkalis during the subsolidus cooling history (MARTIN & BOWDEN 1981), the possibilities range from a particular type of crystal differentiation to the deep-level assimilation or anatexis of pelitic material.

It seems that amphibole extraction during differentiation is capable of producing peraluminous trends in the composition of the liquid even in calc-alkaline magmas (CAWTHORN et al. 1976; ABBOTT 1981), so that highly evolved fractions of calc-alkaline granite suites may sometimes evolve to peraluminous compositions from which a primary muscovite is precipitated.

However this is unlikely to be the origin of those more strongly peraluminous rocks which bear primary garnet, cordierite and andalusite as well as muscovite. There is nothing suspect about the precipitation of these minerals as primary phases: the appropriate experimental systems have been synthesised with the finding that the oxygen fugacity is a critical factor (CLEMENS & WALL 1981). In natural rocks of this kind the associated high $\delta^{18}O$ and high Sr_i values so closely approach those of meta-pelites that a substantial contribution from such material is very likely (e.g. HALLIDAY et al. 1980), and is often the expectation from the field evidence.

The anatexitic generation of a melt in which is retained a residuum of refractory materials (the restite) is enshrined in the »restite hypothesis« of CHAPPELL and WHITE (1974; CHAPPELL 1984). There has been much debate concerning this hypothesis (e.g. CLARKE & MUECHE 1985, mainly because of the difficulty in identifying restite, for it is evident that any solid material that has been long-suspended in magma, whether it be of endogenic or exogenic origin, will be continuously re-equilibriated and recrystallised. The challenge is to distinguish between mineral clots of different origin, and here the immobile trace elements may provide the clue. Whatever the reservations the hypothesis provides a nice model of unmixing, and certainly there are granitoids full of dark-mineral aggregates and with a colour index independent of a consistently high silica value. To generate such rocks it is envisaged that batch melting reaches the point of the disruption of the rigid framework of solid material when the solid residuum (restite) is entrained in the mobile partial melt. Depending on the water content the viscosity and yield strength may be sufficiently high to inhibit the separation of the restite, and Chappell argues that this is why S-type granites do not have minimum melt compositions. Although there are justifiable reservations on extending the S-type designation from the type area of Lachlan (e.g. ANDERSON & ROWLEY 1981; WHITE et al. 1986), there are already sufficient reports of such similar rocks (e.g. South Carolina: SPEER 1981; Moravia: D'AMICO et al. 1981; Calabria: D'AMICO et al. 1981; Southwest Japan: MURATA 1983), all involving emplacement into slate belts, that I accept the greater generality of this »end-member« type and also the restite model for its origin. Of particular interest is whether the relatively »dry« S-type of Lachlan can evolve into the »wet« peraluminous granites of wider distribution.

A third and related possibility involves the all-important metasomatic transfer of water from country rock to magma, when mineral precipitation will be drastically affected in the consequent reducing environment: e.g. hornblende will not be precipitated, ilmenite will appear in the place of magnetite and red Ti-rich biotite in place of green biotite, all changes characteristic of an S-type granite. An example of such a transition of I to S-type character has been documented in a contact zone of the Thorr Pluton, Donegal by Oglethorpe and Atherton (in press). A similar interaction between circulating waters and consolidating granite is thought to have transformed the mineralogy, trace-element chemistry and the isotopic systems in the Cornubian Batholith of southwest England (SIMPSON et al. 1982). Such a process provides a likely explanation of those occurrences of S and I-type granites within a single unit and, more fundamentally, the connexion between slate-belts, S-type granites and mineralization (PITCHER 1982).

The fact that metaluminous I-type granites are abundant in arcs, often to the virtual exclusion of the strongly aluminous S-types, whilst the latter feature predominantly in continental fold belts, suggests that either the sources of peraluminous magmas were largely crustal, or that the longer residence of more primitive magmas in thick crustal zones enabled fluid exchange to produce fundamental changes in their evolution.

The Possible Sources of Granite: The main thrust of recent research is aimed at discovering the sources of granite magmas in order to determine the composition of the crust (see MOORBATH, THOMSON & OXBURGH 1984). These sources have often been simply modelled as upper and lower continental crust, oceanic crust, or mantle, but each of these has its own regional variations and, furthermore, there are various derivatives such as the so-called »enriched lithosperic mantle«, and the new crust generated at plate boundaries. But at least it seems that granitic melts cannot have been derived directly from mantle peridotite (WYLLIE 1983), so that we need to envisage more complex models.

For the primitive magmas associated with active ocean-continent plate margins, it is possible that some kind of crust-mantle interaction is involved, whereby basaltic andesite magma is scavenged, segregated and ponded at the base of the crust, eventually providing the source of the tonalitic magmas (THORPE et al. 1982; DEPAOLO 1981, TINDLE & PEARCE 1981). The composition of other magmas, especially those produced in continent-continent collision zones, suggests that they originate mainly by the melting of recycled crustal rocks, as a result either of the heat generated by tectonic thickening of the radiogenic upper crust, or by hot, basic magmas seismically pumped into fundamental faults. There are clearly many variations on these simple scenarios.

Studies involving trace element compositions and utilizing ratios of those elements with process-independent characteristics have given a new direction to the search for sources (reviews in KAY 1984, TAYLOR et al. 1984). But this search cannot be straightforward when source heterogeneity is so little understood. Not only are mixed sources likely but the source rocks may themselves change in composition with increasing maturity of the arc or the orgenic belt (BROWN et al. 1984; WONES 1984). Furthermore the specificity of the geochemical signatures tends to be lost as granite magmas evolve, the compositions converging to the point of overlap. Despite these reservations such studies have already moved on to identify the different source components of particular granites and to estimate the relative quantities involved. Reference to a few examples will suffice to set the scene.

The study of the compositional and isotopic systematics of the Caledonian intrusions of Scotland and Northern England provides an instructive example (e.g. HARMON et al. 1984; HALLIDAY & STEPHENS 1984). The data indicate that an early group of granites, emplaced during the later phases of the Caledonian orogeny proper, were the products of various anatectic meltings of late-Proterozoic metasediments within the upper crust, an interpretation wholly in accord with the geological history. On the other hand a much later group of granites, clearly post-closure and post-tectonic, have a more complex, multiple source variously involving four different types of crust (depending on location within a plate complex), together with a substantial contribution from the uppermost mantle. The latter presumably supplied basic magmas which might well have brought in the heat required for local crustal melting and assimilation. Harmon and his colleagues make the important point that this type of plutonism, being dominated by the recycling of continental crust, does not represent a major crust-forming process.

In a parallel study HALLIDAY and STEPHENS (1984) refine this model arguing for an important contribution from an old crustal basement with additions from the metasedimentary cover. They discuss at length the problem of deciding what geochemical features are best explained as a result of differences in either process or source, placing emphasis on the latter and concluding that the overall geochemical signature of the Caledonian granites of the British Isles reflects a long-established geochemical provincialism in crustal and mantle composition.

In another geographically oriented study in the western United States, DEPAOLO and FARMER (1984) were similarly able to model the several magma sources by utilising the systematic variability of Nd isotope compositions. These were identified as various age-groupings of old crustal rocks, a lithosperic mantle, and the mantle-derived material involved in the formation of marginal arcs. The latter situation is also well-exemplified by the Coastal Batholith of Peru (PITCHER et al. 1985), the granitoids of which have primitive mantle-like characteristics largely uncontaminated by the old crust that had been split apart to accept them (MUKASA & TILTON, in PITCHER 1985, p. 135). In both the Sierra Nevada and the Andes the voluminous intrusions make a notable contribution to the formation of new crust.

Perhaps the most important conclusion of such studies is that the presence of old crust is not a prerequisite for the production of granitoids. Further, it seems that a more vital factor than the composition of the crust is its thickness, because this provides the necessary space, pressure and thermal conditions, and residence time, to evolve siliceous liquids from the ponded magmas.

In yet another study the various isotopic ratios have been adroitly used by TAYLOR et al. (1984) in their dissection of the Precambrian granitoids of West Greenland. Here the initial Sr_i values identify the various contributions as derived from deep (low Rb/Sr) or upper (high Rb/Sr) crust. $Pb\mu_i$ data permit a similar identification, whilst Sr and Nd data signal the contribution of the mantle. The authors also show how the Sm-Nd model ages of the source rocks in this part of Greenland greatly exceed the ages of intrusion of the melts; a general finding in continental granitic terranes. Such a determination of the age of source rocks has also been attempted by COMPSTON and CHAPPELL (1979) who, by assuming a restite model, devise a method for calculating not only model ages but the source-rock compositions of the Lachlan Belt of S.E. Australia.

Thus we are now provided with procedures, including the established use of inherited zircons (PIGEON and AFTALION 1978), which allow a determination of the nature and age of a model »protolith« for a specific granitoid. But discussion of the role of the lower crust vis-a-vis the mantle will long continue (e.g. LEAKE, BROWN & HALLIDAY 1980), with focus on the mysterious lower crust--mantle interface, ie. the »transitional crust« of Chinese workers (XU KEGIN et al. 1984).

A general Thesis

I believe that we can look forward to a general unifying thesis concerning the production of granitic rocks. The basis of such a thesis must be that magmas reflect differences in source and process in response to changing geological environment.

I start by referring to the occurrence of abundant metamorphosed basic igneous rocks in the lower crust of island arcs (sampled as xenoliths), which have indicated to KAY (1984, p. 544) that the remelting of lower crustal igneous rocks is a likely process for the origin of the M-type granitoids of convergent plate margins. However in such a situation the near contemporaneity of generation and intrusion must make it difficult to geochemically distinguish between the products of a melting process and those of a closed system fractionation of basalt.

In the extensional regime of the marginal continental arcs, such as those of the southeastern Pacific margin, the batholiths also bear evidence of their basic progenitor in the form of precursor gabbro intrusions, basic xenoliths, syn-plutonic dykes and the contents of intersecting volcanic pipes (BATEMAN 1983, p. 250, PITCHER 1985, p. 288). This is best modelled in the Peruvian Andes as new crust segregated from the mantle wedge above a subduction zone; a source repeatedly remobilised in the form of the Ca-rich, but K-poor, I-type granitoids which rose up along the deep-reaching faults. In such a zone of extension the source of heat must lie in the mantle and it is there that the sequence of melting is initiated. Appropriately, in the Andes and elsewhere, the lithosperic mantle wedge might have been enriched by material released from subducted oceanic material.

Within such marginal-arcs where the granitoid production reached eastward into the lip of the continental crust the primitive magmas were variously contaminated. There is also the problem of the origin of certain discrete, high-K rock suites that sporadically accompany the more usual calc-alkaline granitoids (GULSON et al. 1972; AGAR & LE BEL, in PITCHER et al. 1985). Whatever the final solution the enrichment in potassium is not to be sought in the continental crust but in the zone of initial generation of the magmas which lay, perhaps, at a greater depth than that of their low-K analogues (DICKINSON 1980, p. 353).

In contrast to the arc environment that of the Ca-poor and relatively K-rich, I-type granites and granodiorites, as exemplified by the end-Silurian, short-lived plutonic event of the British Isles, is one of block-faulting and uplift and, as already mentioned, wholly post-collision in time and unrelated to any subduction process (LEAKE 1978, p. 237; PITCHER

1982, p. 30; WATSON 1984, p. 210; JIAXIN ZHOU 1985). Such a situation is also represented by the plutonic events in the early Devonian plutonism of the Lachlan Belt of S.E. Australia (CHAPPELL 1984), the Variscan plutonism of Sardinia (SIMPLICIO et al. 1975) and, as a more exotic example, the Permo-Trias of Peru (PITCHER 1985 et al., p. 21; KONTAK et al., in PITCHER et al. 1985), so that it is clear that this variant of I-type granitic magmatism can exist outside of subduction regimes.

Thus we have to find a source of energy alternative to subduction to fuel these relatively short-lived melt episodes so closely associated with faulting, rapid uplift and erosion. Theoretically, in a thick crust a relatively steep geotherm could intersect a crustal solidus and produce localised melting near the base of the lower crust, yet still not reach the mantle solidus until deeper levels (discussion in HARMON et al. 1984, p. 738). Alternatively melting may be induced by the adiabatic decompression associated with uplift, when the rate of that uplift will be critical (HARRIS et al. 1986, p. 77). Leake (op. cit.) considers that major deep faulting will serve to promote such partial melting of the lower crust by raising hot segments into zones of lower pressure and into juxtaposition with cooler zones. Such faulting will also facilitate magma collection, its funnelling into the upper crust and its interaction and hybridization.

Turning to those granites of predominantly S-type that characterise the collisional orogens, we can reasonably expect that crustal sources will predominate. Repeated episodes of partial melting, resulting from the progressive thrust-thickening of radiogenic crust, will provide all the terms of a granite series. Possibly the complexities of the Upper Palaeozoic Iberian granites can be interpreted on the basis of such a continuum involving a close-knit series of the syntectonic to late-tectonic, two-mica granites of probable palingenetic origin (CORRETGÉ 1983, for synopsis), and it cannot be by chance that the latter were generated within a great pile of nappes within a major slate belt. Thrust thickening combined with shear-heating and an increased circulation or volatiles will lead to widespread crustal melting without involvement of material from the mantle (ENGLAND & THOMPSON 1986). The obvious heterogeneity of the crust in such thrust zones will ensure a range of composition amongst the derived granites, so that it is not surprising to find both the K-rich I-type, and S-type granitoids in such a tectonic environment. Further, as previously mentioned, we can expect a gradual change in source composition as melts are progressively extracted and refined during each tectonic phase of the orogenic cycle.

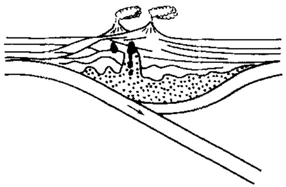
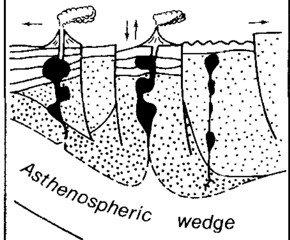
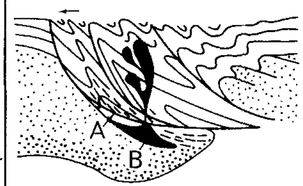
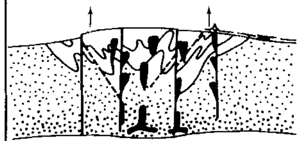
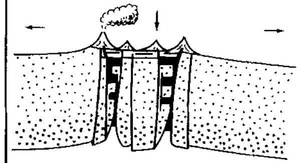
Different again is the setting of those alkalic granites located either within the interiors of cratons and often in association with rifting, or on the sites of stabilized mobile belts. Their magmas may represent the manifestations of a relatively low degree of partial melting under anhydrous conditions deep in a thick crust (COLLINS et al. 1982). The special concentrations of fluorine and boron may result from the magmas being long trapped under a thick lithospheric blanket until released by the rupture of rifting (BONIN 1982, p. 146). The isotopic evidence for source is often masked by the fluid-induced metasomatism associated with the subsolvus recrystallisation, but the favoured candidate is the mantle, albeit with crustal contributions caried in by diffusion or fluid transport (BONIN 1982, p. 162).

Source and geological context are clearly inextricably combined in relation to the different granite types so that I draw all the threads of this essay together into the overall model displayed in Figure 1.

Typology and Time

Finally, the thesis that the type of granite plutonism depends on the geological context is largely based on a survey of Phanerozoic examples, so that we might enquire how far back in time this relationship extends, and whether there is any fundamental change in the character of granitic magmatism back into the Archaean. Comparisons have certainly been made between young and old orogenic belts and their magmatism (references in PITCHER 1982, p. 35), particularly in attemps to identify cordilleran, plate-edge type phenomena in ancient terranes. It seems that we may expect a relative uniformitarianism well back into the Proterozoic: thus both I and S-type granitoids have been identified within the Early Proterozoic (Sweden: WILSON 1980), and S-types in the younger Archaean (Brazil: HOFFMANN 1983), and in their appropriate tectonic environments.

There is, however, a view that the proportion of primitive tonalitic rocks increases into the Archaean. Apparently this ancient tonalite-trondhjemite association can be compositionally contrasted with the tonalite--granodiorite association of the Phanerozoic. In general terms the ancient tonalites differ from those of cordilleran batholiths by having a higher Na/K ratio, moderate to extreme heavy REE depletion, and a tendency to develop positive Eu anomalies in the residual fluids (e.g. TARNEY & SAUNDERS 1979). This suggests that the conditions or mechanisms of magma generation were different in the Archaean. ALLÈGRE and BEN OTHMAN (1980) contend

OROGENIC				ANOROGENIC
IOK	IMT	Ss Si	IKK	IMA
W. Pacific-type	**Andinotype**	**Hercynotype**	**Caledonian-type**	**Nigeria-type**
Oceanic Island Arc	Continental-lip arc, liminal basin	Oblique continental collision	Post-closure uplift	Major rifting
		 'A' anatexite, 'B' batch-melt		
Volcanic and volcaniclastic aprons	Sedimentation in fault margined furrows and marginal basins	Sedimentation in fore-thrust and pull-apart basins	Erosion: flanking molasse basins	Rift infills
Basalts	Andesites in great volume	Rarely silicic lavas	Plateau-type basaltic volcanicity	Alkali lavas, tuffs, as caldera infill
Burial metamorphism	Burial metamorphism	Regional, low-pressure metamorphism	Strongly discordant aureoles	
Gabbro, M-type granitoids in mature arcs	I-type tonalite, granodiorite, with gabbro	Migmatites, reworked as S-type granites	Biotite granite, appinitic diorite and gabbro	Biotite granite, alkali granite and syenite
Small zoned plutons	Disharmonious (Daly), linear, cauldron batholiths feeding volcanoes	Harmonious (Suess) diapir batholiths in early phases	Discordant plutons and distension diapirs	Resurgent subsidence cauldrons
Open folding	Spreading-Minimal shortening	Shortening and thickening	Tensional faulting, uplift	Rifting
Ocean-ocean subduction	Ocean-continental subduction	Continent-continent "subduction"	Rapid, post-closure uplift	Encratonic or post-orogenic rifting
Short-lived	Long-lived	Episodic recycling	Relatively short-lived	Relately short-lived
Partial melting of mantle-derived, metamorphosed underplate	Partial melting of mantle-derived underplate: crustal contribution within continental lip	Partial melting of recycled crustal material by metamorphic anatexis: reworking as batch-melts	Partial melting of old, tonalitic lower crust plus mantle contribution	Partial melting of old mantle, or exhausted lower crust, under anhydrous but F,B-rich conditions
Hot, ?"dry," quartz-diorite magma	Hot, "dry" tonalitic magma rising high into the crust	Relatively warm, "wet," granitic mush freezing at depth, with autometamorphic recrystallization	Moderately hot and "dry," evolved, crystal-bearing magma rising to various levels	Relatively cool, fluidal magma, rising to near surface with sub-solidus crystallization
Subduction energy - transfer of heat by basic magmas		Blanketing by tectonic thickening of radiogenic crust	Adiabatic decompression, heat transfer by basic magma	Decompression on release from deep crustal trap

that this is because the ancient tonalites represent only juvenile mantle extracts. However TAYLOR et al. (1984, p. 606) reject this latter explanation on the grounds that granites of any age may include a proportion of crustal components, and equally tonalites of any age may be predominantly derived from mantle sources. They also contend that the initial Sr, Nd and Pb isotopic character of granitoid rocks is not related to their age but to their petrogenesis, which is itself closely dependent on the presence or absence of the available continental crust. I would add that it is the thickness of the latter which is the critical factor. Nevertheless, it must be admitted that volcanic and volcaniclastic rocks of primitive character are likely to have been the predominant sources in the early crust, and the melting process more vigorous, so that I would expect a crude change in the proportion of the granite types with decreasing age in tandem with the development of a sialic crust.

Finale

Though much of the above typology may turn out to be a philosophical abstraction it does provide a framework and a direction in dealing with a great volume of geological, geochemical and geophysical research. I can hardly be accused of not dealing in detail with individual plutons in my own work, but from time to time we need to stand back from specialisation in order to understand the separate geneses of the types of granite, the relation between these and the different metal concentrations, the changing role of granite types in earth history and, not least, the nature of the continental lower crust. In conclusion I would assert that granites are not simply chemical numbers but representative of central geological processes.

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◄ Fig. 1. Highly schematic representation of the different geological settings of the granitic rocks. Sub-nomenclature letter classification due to TISCHENDORF and PÄLCHEN (1985). Crust is stippled, lower crust more densely, whilst granitic rocks are depicted in black.

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