Space and Time in Granite Plutonism

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Space and time in granite plutonism

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Granitic suites formed in the last 2500 Ma are either calc-alkaline or, less commonly, alkalic. The space–time trends of granitoid rocks from modern compressional arcs include variations towards more silicic and potassic products. But even the most 'mature' magmas of these arcs have Fe/Mg ratios near to 1, in contrast with the strongly iron-enriched alkalic suites that characterize zones of crustal extension. Both calc-alkaline and alkalic suites are mainly mantle-derived; they evolved, respectively, from tholeiitic and alkali basalt parental magmas which have been subject, in most examples, to a two-stage fractionation history. Other factors that may influence the evolution of these parental magmas include, first, the addition of variable, but minor, amounts of crustal melt and, secondly, the persistence of refractory mineral phases in the zone of melting. Contributions from subducted continental detritus are thought to be of minor significance.

A long-term trend, over the entire history of the crust from more sodic to more potassic calc-alkaline magmatism may reflect the declining importance of subducted ocean lithosphere in magma generation and the increasing role of the overlying volatile-fluxed mantle wedge. This trend and, in particular, the widespread development of alkalic granite suites in mid-Proterozoic times, may be linked to the declining vigour of tectonic and associated magmatic processes during the Earth's history. These alkalic suites may indicate a period when the continental lithosphere had become stable enough to resist fragmentation, leading to intracontinental 'rift and swell' zones of magmatism. In some cases, new plate cycles, with more normal calc-alkaline igneous rocks, seem to have occurred in the same zones. Although much of the evidence favours the operation of plate tectonic and subduction processes in magma generation during Archaean and early Proterozoic times, this link cannot be taken as proved except for the last *ca.* 1000 Ma.

1. Introduction

One of the most striking features of contemporary research into crustal evolution is the way in which uniformitarian concepts are playing an increasingly important role in the interpretation of past magmatism and tectonics. Several contributors to this meeting have emphasized that ocean–continent magmatic arc models can explain the evolution of Archaean, Proterozoic and Phanerozoic granitic (*s.l.*) rocks (but see Hanson, this symposium, for alternative models). The changes with time in tectonic patterns, magma types and mobility of stable crust can be reconciled with plate models by taking into account the Earth's long-term thermal decay. So, for example, the changes of temperature and rigidity in the subcontinental mantle (Armstrong, this symposium; D. P. McKenzie & F. Richter, personal communication) may help to explain the changes in crustal tectonic patterns, particularly the most widespread and prominent change that occurred near the Archaean–Proterozoic boundary. Later, it will be shown that the trend from sodic to more potassic calc-alkaline magmatism with time (Barker *et al.*, this symposium) may also have a thermal cause, especially if melting of the mantle wedge over subduction zones, rather than ocean crust, has become more important with time (Tarney & Saunders 1979).

2. Granitic rocks of modern magmatic arcs: their geochemistry and origin

The best known Mesozoic/Tertiary granitic batholiths occur along the Cordillera of N and S America and overlie subduction zones. Although each batholith is structurally and chemically complex, there are many gross similarities in their geochemical and isotopic characteristics. These are tonalite-dominated calc-alkaline suites that show a progressive trend from intermediate to acid rocks with *time* (e.g. the Peru coastal batholith rocks ranged from 59 to 67 %† SiO_2, 95 Ma ago, and from 71 to 77 % SiO_2, 33 Ma ago, according to Atherton *et al.* (1979)).

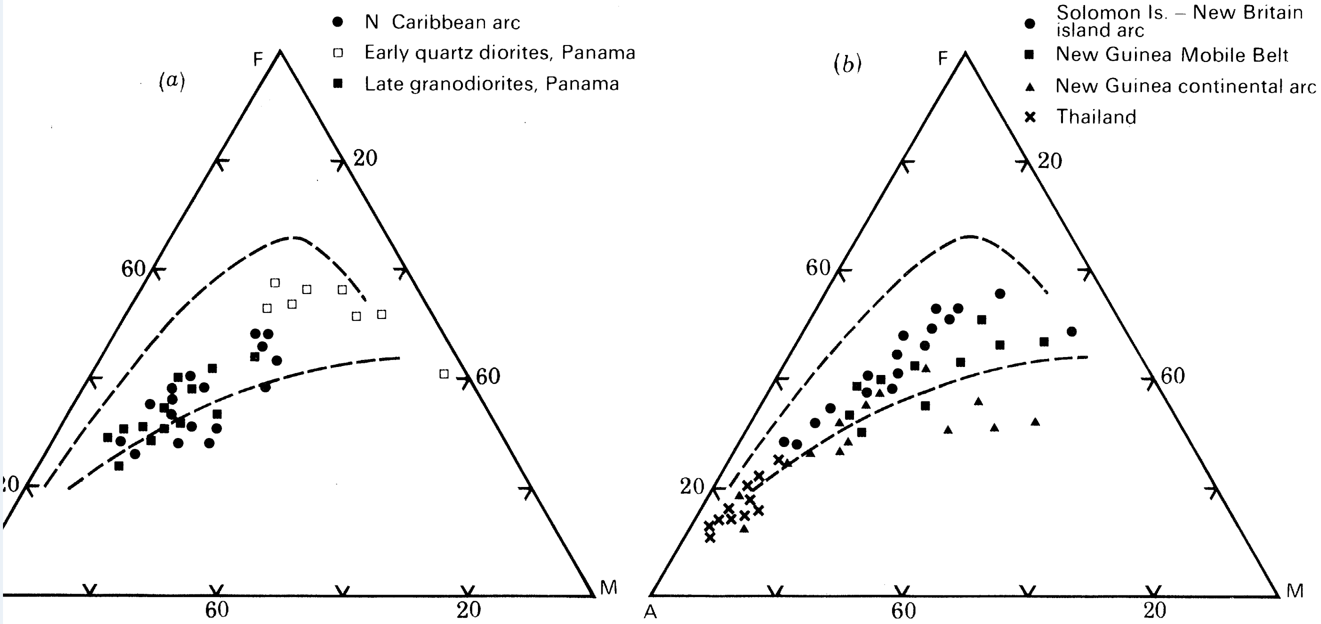

Figure 1. Comparative AFM diagrams for intrusive suites from Mesozoic and Tertiary magmatic arcs: (*a*) Central America and the Caribbean (after: Kesler *et al.* 1975, 1977; Kesler 1978); (*b*) SE Asia and the western Pacific (after: Beckinsale *et al.* 1979; Hine & Mason 1978; Mason & McDonald 1978). – – –, units of AFM variation from volcanic rocks of modern arcs.

Often the batholiths intrude older 'andesitic' volcanic rocks and, although there is much geochemical and isotopic evidence of possible magmagenetic links between intrusive and extrusive suites of similar age (see, for example: Myers 1975; Thorpe & Francis 1979), direct field evidence for connections between the two has remained elusive. However, the evidence from Central America (Kesler 1978) indicates that the granitoid rocks of this region are subvolcanic, for they are exposed only towards the southern, more deeply dissected part of the area, where volcanic cones have been eroded.

The Central American – Caribbean area contains some of the youngest (< 70 Ma) arcs with unroofed intrusive rocks. The entire region is founded on *ocean crust* (Case 1974): the North American continental basement terminates in Nicaragua to the north (Kesler 1978) and, to the south, older continental crust commences again in the Colombia–Ecuador region (Thorpe *et al.*, this symposium). No continental rocks can have been involved in the genesis of the earliest intrusive rocks of Panama which are quartz diorites with iron-enriched tholeiitic affinities

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† Percentage compositions in this paper are by mass unless otherwise stated.

(figure 1*a*). Later intrusive suites in the same area (5–50 Ma in age) are calc-alkaline diorites and K-rich granodiorites. Similarly, the granitoid rocks exposed in the N Caribbean area follow an overall trend towards more potash- (and silica-) rich intrusions with *time* (figure 1*a*; data from Kesler *et al.* (1975, 1977)). This is thought to reflect the increasing growth in crustal thickness and maturity of each arc.

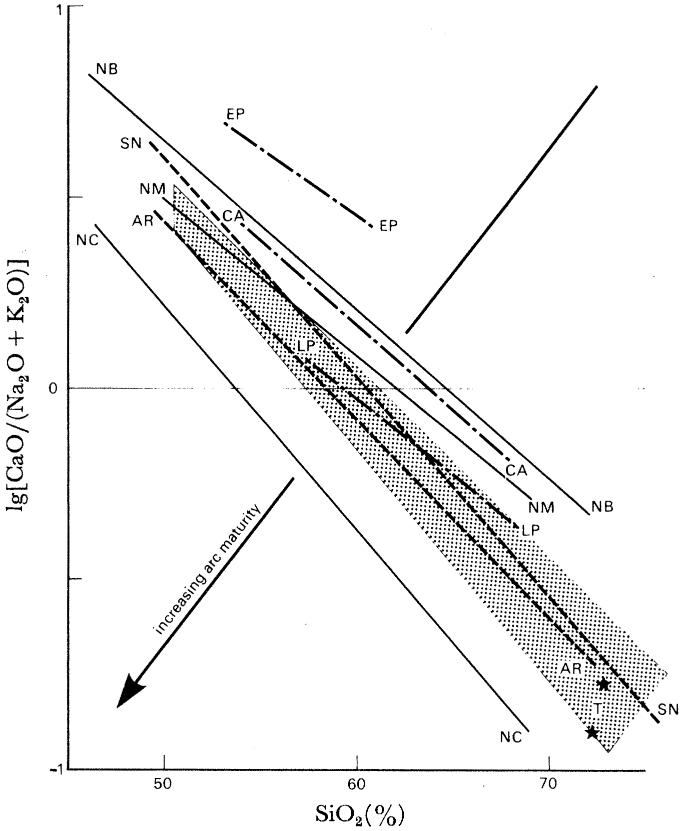

FIGURE 2. Calc-alkali ratio – silica trends for intrusive suites from some Mesozoic and Tertiary magmatic arcs compared with the range (shaded) of volcanic rocks from the same arcs (data sources in addition to those of figure 1 are: Bateman & Dodge (1970); Richter *et al.* (1975)). ——: New Britain – New Guinea arc, NB; New Guinea mobile belt, NM; New Guinea continental arc, NC. — · —: Early Panama diorites, EP; north Caribbean arc, CA; Late Panama granodiorites, LP. – – – –: Sierra Nevada batholith, SN; Alaska Range batholith, AR. The two stars, labelled T, are average Thailand collision zone granites.

Magmatism in the Central American and Caribbean areas is closely confined to a narrow zone parallel to the trench. A better opportunity for examining the *spatial* variations in magma types normal to a subduction margin occurs in the western Pacific region, where young (< 20 Ma old) intrusive rocks are exposed intermittently across the New Britain – New Guinea arc. There are three overlapping tectonic and geochemical zones (figure 1*b*; data from Mason & McDonald (1978) and Hine & Mason (1978)):

(i) the north 'New Britain – New Guinea arc', founded on Pacific ocean crust, which contains young diorites and low-K granodiorites that are quite iron-enriched;

(ii) the so-called New Guinea mobile belt, an elongate thrust zone with quartz diorite/granodiorite intrusive rocks that follow more closely the calc-alkaline trend of the western American batholiths (figure 1*b*);

(iii) the south 'New Guinea continental arc', where a high-K *series* of granitoid rocks intrudes the Palaeozoic crystalline basement extension of the Australian Block.

The New Guinea rocks exemplify magmatic variations in space at a given time; similar spatial trends have been noted in the great western American batholiths (Bateman & Dodge 1970; Pitcher 1978), where eastwards increases in the K_2O/Na_2O ratio, in particular, gave rise to the 'quartz diorite line' concept of Moore (1959). For example, the Eastern Cordilleran 'tin belt' of Bolivia contains a high-K intrusive suite not unlike that of southern New Guinea (Evernden *et al.* 1977). Earlier, evidence from Peru and Central America was cited to show that similar changes take place with time in a given location. *It follows that the spatial petrochemical trends normal to a modern arc at a given time (figure* 1*b*) *are comparable with the temporal trends in a given location (figure* 1*a*).

These features are summarized in a single diagram (figure 2) which plots the ratio $CaO/(Na_2O+K_2O)$ against silica content for batholith rocks. Peacock (1931) defined as calc-alkaline those magmatic suites for which CaO becomes equal to Na_2O+K_2O between 56 and 61% silica. Data from two typical western American batholiths and from circum-Pacific andesites (shaded) fall into this category. But data for the early intrusive rocks of Central America, the Caribbean, and the New Britain – New Guinea arc cross the SiO_2 axis at values in excess of 61% SiO_2 and are *calcic* (with tholeiitic iron enrichment trends in figure 1). With time, the later intrusions of Panama became calc-alkaline, as did the intrusive suites more remote from the New Guinea margin, but the 'continental arc' rocks from the latter region are distinctly more alkaline than most batholiths. (Strictly, they are defined as alkali-calcic with a cross-over between 51 and 56% SiO_2 (figure 2); truly alkalic suites have alkali oxides > CaO still at 51% SiO_2 (Peacock 1931).) This diagram provides a useful index of the *maturity* of a magmatic arc. Primitive island-arc plutons are calcic diorites and monzonites (some have Na-rich, trondhjemitic chemistry) and, as arcs thicken with time, they become characterized by calc-alkaline tonalites and granodiorites. Where an arc is developed along a continental margin, analogous trends towards increasingly 'mature', alkali-rich rocks are found away from the trench zone. Other parallel and distinctive geochemical changes that take place with increasing arc maturity are towards increased Rb/Sr ratios and abundances of many incompatible elements and towards decreased K/Rb and Zr/Nb ratios and abundances of ferromagnesian elements. These features may all be related simply to the processes of melting and crystal fractionation that take place over variable ascent rates and distances through enriched mantle and crustal columns (Tarney & Saunders 1979; Saunders *et al.* 1980; Thorpe *et al.*, this symposium; and below).

A final stage in the petrochemical evolution of intrusive rocks from zones of plate convergence is found in arc–continent or continent–continent collision zones. The best known, geologically recent, examples occur in the Himalayas, Malaysia and Thailand, from which alkali-rich two-mica leucogranites (*s.s.*) have been described (see, for example: Le Fort 1975; Beckinsale *et al.* 1979). Geochemical data for the Thailand granite suite (figures 1*b*, 2) show little variation that would allow these rocks to be classified in terms of silica saturation: they are alkali-rich, but usually lie in the calc-alkaline field. It is emphasized that the narrow range of silica variation in modern collision-zone granites is distinctive and allows them to be distinguished from the K-rich diorite–syenite–granite suites that occur behind calc-alkaline magmatic arcs (e.g. the New Guinea continental arc and the Bolivian 'tin belt' granites). However, there is a need for caution in using this observation to interpret ancient granitic rocks at deeper crustal erosion levels because the extent of geochemical variation with depth in collision-zone granites is unknown.

Most attempts to account for the origin of granite magmas have attributed collision-zone granites to crustal anatexis because there is abundant geological evidence of sialic overthrusting, which favours abnormally high crustal temperatures. There has been less agreement about the source of granite magmas over subduction zones, and much use has been made of isotope ratios in attempting to discriminate between the alternative theories of magma genesis. Strontium isotope data for many examples of batholiths from known tectonic environments are summarized in figure 3. The high initial ratios (0.71–0.74) of collision-zone granites from Nepal and Thailand are consistent with a crustal source; the Lower Cretaceous rocks of Thailand may be exceptional in this context in possibly representing a short period of renewed subduction beneath the Triassic arc–continent suture (Beckinsale *et al.* 1979). All the other intrusive rocks in figure 3 represent ocean–continent convergence zones and have initial ratios in the range 0.703–0.712, which, in some areas, increase through this range with time and geochemical maturity (e.g. N Chile (McNutt *et al.* 1975)). Although these ratios are close to those of the modern mantle, clearly, a simple mantle source is unable to account for most of the observed isotopic range. Equally, these rocks cannot have been derived from a source enriched in radio-elements like that which produced the collision-zone granites. In such circumstances, a single 'depleted lower crust' source is frequently invoked in the literature (see also Hanson, this symposium), but I maintain that there are sound isotopic and volumetric arguments against major batholiths being melted from such depleted source regions (see also Leake *et al.* 1980). The strontium isotope variations of batholiths are much more likely to reflect a mixing between mantle-derived and crustal magmas, with the latter being relatively minor.

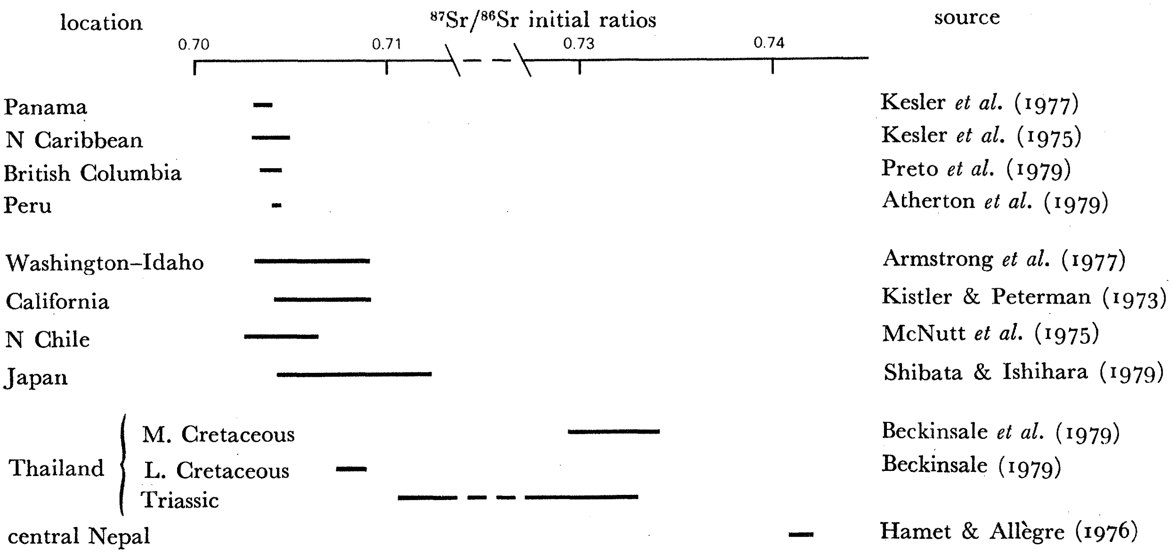

FIGURE 3. The ranges of initial strontium isotope ratios for intrusive rocks from Mesozoic and Tertiary magmatic arcs (see text for further discussion).

Then there is the problem of whether the crustal contribution is due to subduction of clastic debris (compare: Fyfe 1979; Armstrong, this symposium; Karig & Kay, this symposium) or to melting within the crust and mixing during the ascent of mantle-derived magmas (Brown &

Hennessy 1978; Eichelberger 1978). It will be argued later (§4) that crustal scavenging during magma ascent is the most likely process. Together with associated changes in fractionating mineral phases, this process can account for the correlated isotopic and geochemical space–time trends in the Mesozoic and Tertiary batholiths of California and N Chile, for example. Sometimes, isotope ratios are decoupled from the overall geochemical trends and so, for example, the geochemical maturity of the late Panamanian rocks (figure 1*a*) is not reflected in their isotopic characteristics (figure 3). This does not necessarily imply that there are no fusible rocks in the young crust of Panama, but merely that there is no radioelement-enriched basement. The lack of maturing isotopic ratios with time in Peru and British Columbia may be explained in an analogous way (§4).

This survey of important space–time changes in the major granite-bearing suites of recent geological time provides a basis for comparison with similar evidence from selected suites of Proterozoic and early Phanerozoic age.

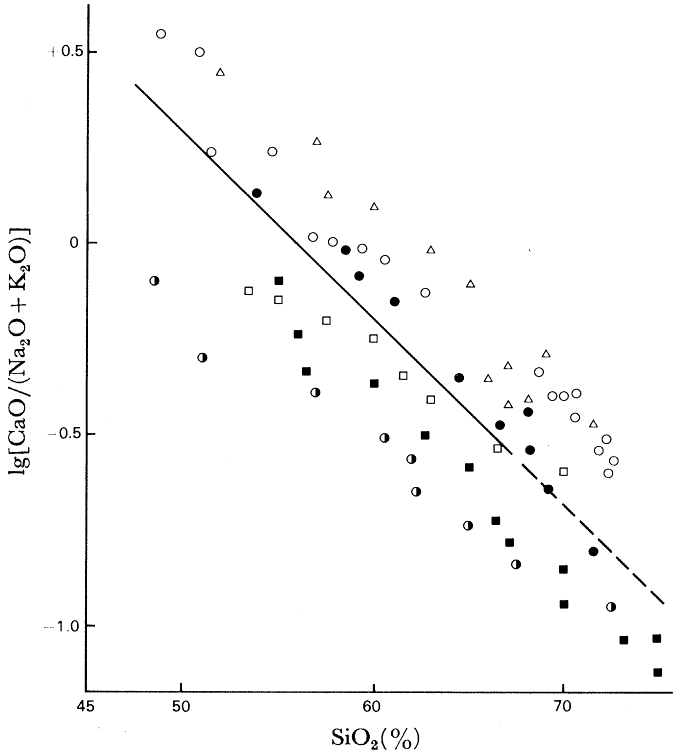

Figure 4. Calc-alkali ratio – silica trends for some Proterozoic and Phanerozoic intrusive suites. The solid line represents the division between suites classified as calc-alkaline (above) and alkali-calcic (below). Symbols and data sources are: ○, SW Finland trondhjemites (Arth *et al.* 1978); △, Ben Ghnema batholith, Libya (Ghuma & Rogers 1978); ●, British Caledonides, S Scotland (Brown *et al.* 1979); ◑, Pikes Peak batholith, Colorado (Barker *et al.* 1975); □, Fennoscandian rapakivi granites (Vorma 1971); ■, Nigerian younger granites (Jacobson *et al.* 1958).

3. Proterozoic and early Phanerozoic granites

Much has been written elsewhere in this meeting report about granite generation early in the Earth's history. There is good agreement that most of the K-poor Archaean suites that characterize the high-grade domes are similar in many ways to those of modern primitive arcs

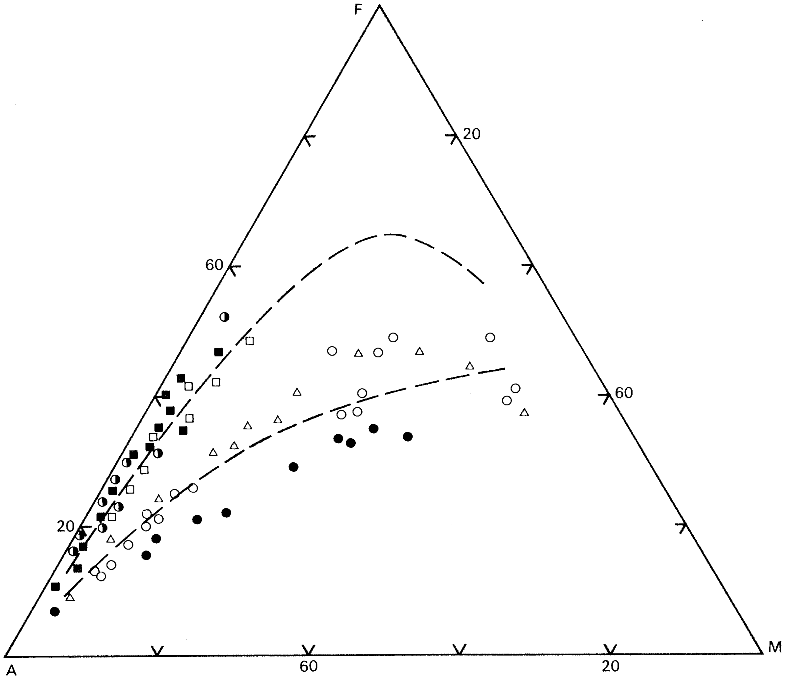

Figure 5. AFM diagram for some Proterozoic and Phanerozoic intrusive suites (symbols and data sources are as for figure 4); – – –, limits of AFM variation from volcanic rocks of modern arcs (cf. figure 1).

Table 1. Ages and initial ^{87}Sr/^{86}Sr ratios of some major Proterozoic and early Phanerozoic calc-alkaline and alkalic granite suites

	age/Ma	initial $^{87}Sr/^{86}Sr$	source
	calc-alkaline group		
SW Finland	*ca.* 1900	0.7021–0.7022	Arth *et al.* (1978)
S Greenland (Ketilidian)	*ca.* 1900	0.7022–0.7036	Van Breemen *et al.* (1974)
New Mexico			
high Ca	*ca.* 1800	0.7020–0.7050	Condie (1978)
high K	*ca.* 1400		
Arabian Pan-African	960	0.7029	Greenwood *et al.* (1976)
	ca. 780	0.7028–0.7035	
	560	0.7032–0.7093	
Egyptian younger granites	580	0.7016–0.7061	Fullager (1981)
Libya (Ben Ghnema)	550	0.7052–0.7065	Pegram *et al.* (1976)
British Caledonides	> 450	0.707 –0.720	Pankhurst (1979)
	390–450	0.704 –0.709	
	alkalic group		
S Greenland (rapakivi suite)	1786	0.7032–0.7036	Van Breemen *et al.* (1974)
Scandinavia (rapakivi suite)	*ca.* 1700	0.704 –0.712	Versteeve (1975)
SW Greenland (Gardar granites)	1180	0.698 –0.702	Van Breemen & Upton (1972)
N America			
Wolf River, Wisconsin	*ca.* 1500	0.7048	Van Schmus *et al.* (1976)
Pikes Peak, Colorado	*ca.* 1030	0.7040–0.7011	Barker *et al.* (1976*b*)
Nigerian younger granites	154–175	0.706 –0.729	Van Breemen *et al.* (1975)

(see, for example: Barker *et al.*, this symposium; Windley & Smith 1976) and may have been generated by analogous processes (Tarney 1976). They share their dominantly mantle-type isotopic signature with modern batholiths (Moorbath 1978) but contrast in having lower concentrations of heavy rare-earth elements (r.e.es) and positive Eu anomalies. These features indicate garnet or hornblende crystal fractionation (Arth & Barker 1976) or the persistence of these mineral phases as melt-zone residua (Tarney *et al.* 1979).

This section examines the geochemical and isotopic characteristics of some granite-bearing suites from the intervening period (between the Archaean and the present day). Interpretations of early Proterozoic geology indicate the advent of the first, large ($> 10^3$ km in size) continental masses, traversed by linear mobile belts of intensely deformed clastic sediments, supposedly the high-grade equivalents of those forming today in back-arc basins and closing oceans (Tarney & Windley, this symposium). However, it is not known whether these belts do represent the sites of former accretion and ocean closure or whether they are ensialic developments associated with rift zones (see Windley (1977) and Kröner (1979) for contrasting views). Some examples of calc-alkaline granite magmatism associated with Proterozoic mobile belts and known continental margins are thought to support the former, rather than the latter, view.

In addition to this calc-alkaline magmatism, the Proterozoic continents were also characterized by important intrusive suites of sodic anorthosites, syenites and potassic rapakivi granites that may, in some cases, be attributed to post-tectonic activity on mobile belts. Major-element (figures 4, 5) and isotopic (table 1) geochemistry of examples of both granite associations are considered below.

Calc-alkaline suites

Several examples of early Proterozoic calc-alkaline intrusive suites have received considerable attention in the recent literature: these occur in SW Finland (Hietanen 1975; Arth *et al.* 1978), S Greenland (Van Breemen *et al.* 1974) and the Colorado – New Mexico area (Barker *et al.* 1976*b*; Condie 1978).

Perhaps the best known, classic complex is that of SW Finland, where an 1850–2100 Ma old gabbro–tonalite–trondhjemite series of differentiated rocks, metamorphosed to granulite grade, is cross-cut by later (*ca.* 1700 Ma B.P.), massive intrusions of rapakivi granite (see below). The geochemistry of the older suite is calc-alkaline with a silica range from 41–73 % (figure 4). Like many Archaean tonalite–trondhjemite suites, the Finnish rocks have highly fractionated r.e.e. patterns, with positive Eu anomalies, suggesting an origin from basic liquid with hornblende-controlled fractionation (Arth *et al.* 1978). The K_2O content of the suite is low (ubiquitously < 2.5 %) but Hietanen (1975) claims there is evidence for a northerly increase of K_2O (at constant silica concentration) and a decrease in age reminiscent of similar trends across the California batholiths.

In the Colorado – northern New Mexico area, Proterozoic activity produced older trondhjemites and 'high-Ca' granodiorites in the north and younger 'high-Si' and 'high-K' granites in the south. There has been some debate about the origin of these rocks (Barker *et al.* 1976*a*; Condie 1978), though their isotope ratios (table 1) suggest a mantle derivation. Possible subduction-related magma genesis is difficult to equate, however, with the large north–south distance (*ca.* 1000 km) over which variation from primitive to mature arc magmas is implied. A more convincing case for Proterozoic subduction zones was made by Bridgewater *et al.* (1973) for the *ca.* 1800 Ma old Ketilidian mobile belt of S Greenland, which contains prominent granodiorite intrusives such as that at Julianehaab (discussion by Van Breemen *et al.* (1974)).

The Grenville belt of E Canada contains another extensive calc-alkaline granite–andesite suite reminiscent of those in modern circum-Pacific arcs (Irving & McGlynn 1976). The localities discussed above may have been sites of magmatism along former Proterozoic continental margins before suturing events took place.

In contrast with the evidence (just discussed) from the North Atlantic province, some students of *African* geology would still interpret the early to middle Proterozoic mobile belts as 'ensialic'. A key example is the late Proterozoic Mozambique belt, which is deeply eroded in the south (appearing ensialic) yet carries andesite lavas, ophiolites and other evidence of suturing and subduction in NE Africa and Arabia. Greenwood *et al.* (1976) described three important episodes of magmatism in Arabia (table 1) with evolution from diorites to granodiorites to quartz monzonites, all with low initial strontium isotope ratios and all showing modern arc-type geochemistry (Gass 1977; Brown 1980). Gass (1981) has developed a multiple-arc accretion model that accounts for the progressive cratonization of this continental area during the Pan-African (*ca.* 960–560 Ma) period. All the arcs were developed on former ocean crust and there is no need for and, as yet, no evidence for a pre-1000 Ma basement in the Arabian Shield. The accretion process in Arabia terminated with *ca.* 600 Ma B.P. alkalic granites (Gass 1981), similar in their geochemistry to those of modern collision zones.

Elsewhere in North Africa, similar observations have been made concerning the origin of the late Pan-African granites of NE Sudan (Neary *et al.* 1976), Egypt (Fullager 1981) and Libya (Pegram *et al.* 1976). A detailed petrochemical study of the Ben Ghnema batholith (see figures 4 and 5) by Ghuma & Rogers (1978) revealed significant east–west variation across the complex. They postulated a juvenile magma source related to the subduction of ocean crust from the east beneath the massif, though the position of such a suture has not been identified in Libya. The case for plate-type motions in the late Precambrian of North Africa has been strengthened by Black *et al.* (1979), who reported structural and magmatic evidence for 600–800 Ma B.P. rifting and suturing along the eastern margin of the West African craton in Mali. In Nigeria, calc-alkaline volcanic rocks of late Pan-African age have been related to a similar suturing event (McCurry & Wright 1977).

A final example of a calc-alkaline granite-bearing 'mobile belt' or 'plate collision zone' is the Caledonian–Appalachian orogen, whose rocks are exposed in most countries bordering the North Atlantic. Studies of important intrusive suites in northern Britain (reviews by: Simpson *et al.* 1979; Brown *et al.* 1980; Pankhurst & Sutherland 1981) have identified early Palaeozoic calc-alkaline igneous rocks (e.g. figure 4 and table 1). The timing of events in the British Caledonides is complex because intrusive rocks with the strongest inherited crustal isotopic signatures (table 1; Pidgeon & Aftalion 1978) are older than a typical 'plate margin' batholith suite, which bears a stronger mantle imprint (see, for example, Harmon & Halliday 1980). But, like modern batholiths, these intrusions have fractionated r.e.es and *negative* Eu anomalies, indicating plagioclase + pyroxene, rather than hornblende fractionation. A model for the evolution of the late Caledonian granite suite in post-collisional (tensional) conditions has been proposed by Simpson *et al.* (1979) and may have widespread applicability.

In summary, calc-alkaline magmas with geochemistry similar to those found at modern ocean–continent boundaries persisted throughout Proterozoic and early Phanerozoic times. Good independent geological evidence for such plate-like processes only becomes available, however, during the last *ca.* 1000 Ma. The major geochemical changes that have taken place are from more sodic to more potassic magmatism with time and from r.e.e. evidence of hornblende to plagioclase–clinopyroxene fractionation with time. There is every reason to suppose that fractionating (or residual) phases were determined by pH_2O in the source region (high for hornblende, low for plagioclase and pyroxene). It may also follow that the change with time from more sodic to more potassic magmatism was determined by the fractionating phase, for hornblende retains more potassium whereas plagioclase retains more sodium. Changes in the influence of subducted basaltic ocean crust may also be important (Tarney & Saunders 1979). These points are developed in §4.

Potassic (alkalic) granite suites

There are many notable occurrences of chemically distinct potassic granites, often with rapakivi textures (potash feldspar mantled by plagioclase) in the late history of the Proterozoic mobile belts. Emslie (1978) identified three important age groupings in the North Atlantic area; in each group there is often a close spatial association between potassic granites and major occurrences of sodic anorthosites with norites. The geochemistry of the anorthosite–norite suites appears to complement that of the granites (e.g. members of the Rogoland province, southern Norway (Duchesne & Demaiffe 1978)). Similarly, Bridgewater *et al.* (1974) proposed that sodic anorthosites (low r.e.e. abundances and positive Eu anomalies) are cumulates from parental magmas whose residual liquids evolved towards potassic granites (high r.e.e. and incompatible element abundances and negative Eu anomalies).

The acknowledged type area for rapakivi granites is in the Wiborg and Loos-Hamra areas of S. Finland, where the 1900 Ma calc-alkaline suites were re-invaded 1700 Ma ago by rapakivi granites, but similar granites are found throughout the Baltic and Ukranian shields. Emslie (1978) pointed out that the closely similar age and quite linear distribution pattern of the *ca.* 1700 Ma anorthosite–potassic granite suites of Europe, Scandinavia and Greenland implies a common tectonic control on their magma genesis at depth and their consequent emplacement mechanisms. Major-element chemical data (figure 4) for the Fennoscandian rapakivi suite show *alkalic* affinities over a wide range of silica contents, comparable with the data for the modern New Guinea continental arc but in contrast with those for the Thailand collision zone (figure 2).

Younger Proterozoic potassic intrusions occur throughout the continent of North America (age range 1000–1400 Ma (table 1)) and in the Gardar province of SW Greenland. Data for the Pikes Peak batholith (Southern Front Range, Colorado) overlap with the earlier Fennoscandian trend in figure 4; such observations led Barker *et al.* (1975) to conclude that 'the Pikes Peak intrusives are similar in mode of emplacement, composition and probable genesis to the rapakivi intrusives of Finland' etc. Alkali and iron-rich crystalline phases are another characteristic of these suites and, at Pikes Peak, rocks ranging from quartz syenite to fayalite granite to riebeckite granite are intimately associated in a 50 km × 20 km outcrop. Returning to their geochemistry, strong iron (F) and alkali-element (A) enrichments coupled with low MgO (M) contents, result in a strikingly distinctive trend on the AFM plot (figure 5). This leads to a most important point: although these Proterozoic K- and Fe-rich, often rapakivi, suites appear to occupy a 'mature arc' position in figure 4, they are distinguished from arc-type suites once their ferromagnesian constituents are taken into account. They are dissimilar, even, to the known examples of collision-zone granites (reviewed in §2) and must have a quite separate origin, which is considered below.

In searching for more recent examples of alkalic granites that might help to solve questions of their origin, several authors have drawn comparisons with the younger (Jurassic) fayalite–riebeckite granites of Nigeria and the Hebridean Tertiary granites of Scotland (see, for example, Emslie's (1978) review). These are also alkali-calcic to alkalic granites (figure 4) and the Nigerian suite, in particular, has an AFM trend analogous to that of the Proterozoic intrusions (figure 5). It is highly significant that the tectonic environment of both these younger alkalic suites is likely to be *extensional* and associated with crustal swells or rifts (Le Bas 1971). The Nigerian suite lies on a possible extension of the Mesozoic rift that opened the Atlantic (MacLeod *et al.* 1971) and the British Tertiary suite is well known to be associated in time and space with North Atlantic rifting. Petro *et al.* (1979) have taken these comparisons further: they showed that acid rocks from the entire North Atlantic Tertiary province, including East Greenland, Iceland and Skye, all have similar alkali, iron-rich, magnesium-poor geochemistry, which they consider distinctive of *extensional magmatic suites*. They also classified as *compressional suites* those calc-alkaline intrusives known to occur above modern destructive plate boundaries.

In the light of the association between alkali granites and rift environments there are two other points to consider: the generation of their magmas and the indications that they may have been more extensively developed in Proterozoic times. Any question that the Proterozoic magmas had crustal sources that contrast with the young rift zone examples just considered is ruled out by isotopic data (table 1), although some suites do have initial strontium isotope ratios that rise above the mantle value. Some crustal contamination of a mantle source is implied and, for the latter, an alkali olivine basalt liquid is preferred (see: Barker *et al.* 1975; Duchesne & Demaiffe 1978; Brown 1979; Petro *et al.* 1979). Such liquids are thought to form by limited fusion at mantle depths greater than for tholeiitic magmas (Ringwood 1975), and have been invoked as the ultimate source of rift-zone magmatism (see, for example, Gass *et al.* 1978). High-pressure fractionation of magnesium-rich phases (orthopyroxene and olivine) will enhance the natural iron and alkali-element enrichments of such magmas, and subsequent low-pressure fractionation of plagioclase may by necessary to produce the observed variety of acid rocks and the associated anorthosite–granite suites.

It is proposed that the alkalic granite suites that are so well developed in mid-Proterozoic mobile belts are indicative of important extensional rift tectonics (Emslie 1978). Frequently, these rocks were emplaced some time after a more normal compressional cycle of calc-alkaline magmatism (table 1 and earlier discussion). They may variously reflect the existence of abortive and successful rifts along weak zones of earlier continental collision, the mobile belts, and the development of potential new ocean basins.

4. Summary of granite magmatism and crustal evolution

First, the main conclusions are summarized, leading to a discussion of magma genesis and the contribution of granitic rocks to crustal growth in general. This paper has shown that both the major compressional calc-alkaline and minor extensional alkalic suites of intrusive rocks have characterized the Proterozoic and Phanerozoic crustal history of the Earth. It is difficult to estimate the relative volumes of these two suites because of the two-dimensional aspect of the crust but, from maps, it appears to be a maximum at about 3:1 in mid-Proterozoic crust and about 20:1 (or more) today, both in favour of the calc-alkaline suites. Superimposed on the long-term (4×10^9 a) trend towards less sodic and more potassic calc-alkaline magmatism are short-term (10^8 a) space–time trends in most arcs (ancient and modern) towards more mature silicic and potassic products (seen particularly in collision zones). The most mature ocean–continent arcs carry high-K, alkali-calcic intrusives that, nevertheless, have Fe/Mg ratios close to unity. In this way they contrast with the iron-enriched alkalic extensional suites that are found in Proterozoic mobile belts. These are thought to indicate episodic thermal and magmatic reactivation along former sutures before they finally became quiescent. It is possible that examples of mid-Proterozoic alkalic rift magmatism may have recorded abortive rifts, suggesting that the ease with which the Archaean crustal rafts had been jostled and fragmented was changing to a style of crustal tectonics where fragmentation forces could be resisted.

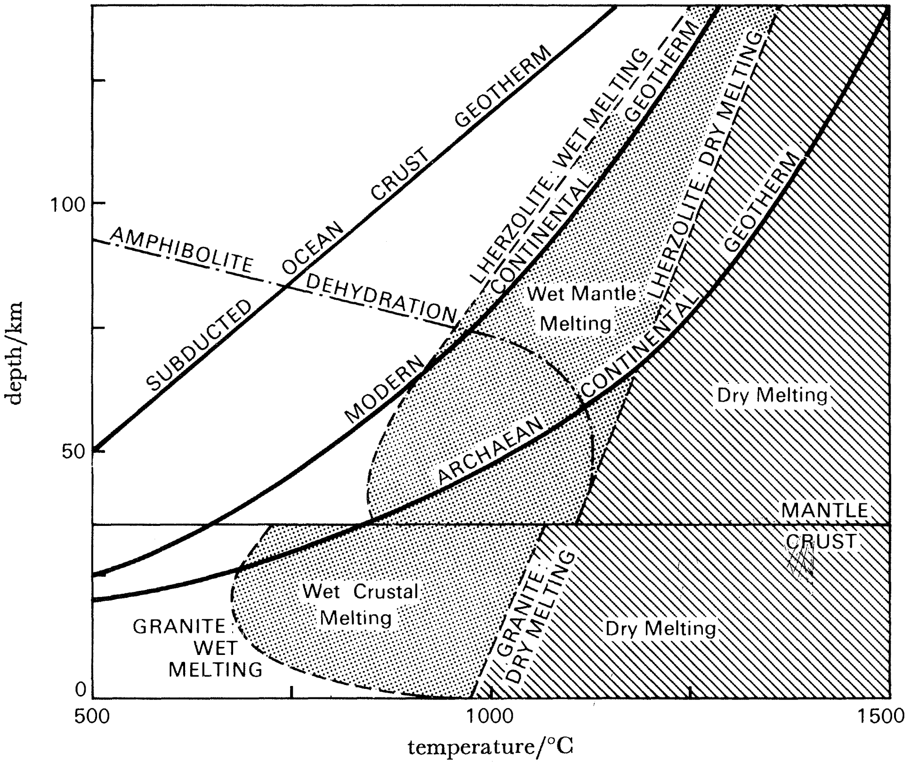

Figure 6. Schematic pressure–temperature diagram to show the approximate conditions of wet (stippled) and dry (ruled) melting in a 35 km thick crust and the top 100 km of the underlying mantle. Also shown are the amphibolite dehydration curve (– • –) and several (labelled) geotherms. (Data from Brown & Hennessy (1978), Fyfe & Brown (1973) and Ringwood (1975).)

From isotopic data (figure 3; table 1) both types of granite are thought to have evolved mainly from parental mantle-derived magmas. The differences between the two suites arises from the parental magma types: *alkali olivine basalt liquids* generated by restricted partial melting in relatively deep mantle zones evolve to alkalic suites whereas relatively shallow, *tholeiitic parental magmas evolve to produce the calc-alkaline suites.* However, in both cases, two stages (high and low pressure) of fractionation are necessary features of magmatic evolution. High-pressure fractionation of olivine and/or orthopyroxene, leading to iron enrichment (figures 1, 5), is most important in the alkalic suites and contributes, with decreasing importance, to the evolution of tholeiitic and calc-alkaline magmas as arcs mature and thicken. Low-pressure fractionation of plagioclase (with clinopyroxene) is necessary to explain the remaining stages in the evolution of both suites, and crustal contamination of the residual liquids is also a distinct possibility. While there is good evidence for the low-pressure process, in the form of sodic anorthosites and

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norites from Proterozoic alkali granite terrain, the association of calcic anorthosites with calc-alkaline granites is less well documented and is often elusive. Although the evolved members of these suites do carry r.e.e. evidence of low-pressure fractionation, this evidence might equally imply that the appropriate minerals are refractory phases in the melt zone.

Figure 6 focuses attention on the origin and evolution of calc-alkaline magmas above subduction zones (see also: Fyfe & Brown 1973; Brown & Hennessy 1978). It is generally agreed that subducted basaltic crust passes through amphibolite facies metamorphism *en route* to eclogite (Ringwood 1975). Figure 6 shows that a typical geotherm for subducted ocean crust is unlikely to intersect the wet melting curve until well after amphibolite has released its water in the production of eclogite. Water and other volatiles carrying incompatible elements such as potassium stream off the subducting slab and encounter warmer, but dehydrated, mantle, where pressure–temperature conditions (close to the modern continental geotherm) lie within the field for wet melting. Here, within volatile-fluxed upper mantle, lies the most likely source for tholeiitic basalt – basaltic andesite melt (as postulated in the review by Thorpe *et al.* (this symposium)). This melt rises and passes through the lower regions of progressively thickened crust, where resulting temperatures exceed that of the modern continental geotherm, and so reach the field of wet crustal melting (figure 6). The rising magma may, therefore, not only fractionate, but also may mix with crustal melts produced near the granite minimum. Melting of both the crust and mantle will leave high-temperature feldspar mineral residua in the melt zone, so generating a fractionated r.e.e. profile in the residual liquids. Fractional melting may, therefore, explain why large volumes of cumulate rocks, which ought to be present if extensive crystal fractionation has occurred, are not found in deeply eroded parts of calc-alkaline batholiths (Tarney & Windley 1977).

If mantle temperatures were some 200–300 K higher in Archaean times than at present, then the Archaean continental geotherm would have reached the dry-mantle solidus at about 50–75 km depth, rather than near 200 km as today. If subducted crust was also at a higher temperature than today, then amphibolite would have persisted into the wet melting field. Hence, ocean crust itself would be more likely to melt directly to give tholeiitic magma, which would reflect its lower K/Na ratios compared with magmas produced in volatile (and K) fluxed mantle zones (Saunders *et al.* 1980). The long-term chemical change in calc-alkaline magmatism may, therefore, also directly reflect the decreasing contribution of subduction-zone melting with time. This conclusion was also reached by Tarney & Saunders (1979), who argued that high $p\text{H}_2\text{O}$ must have persisted in the melt zone to explain the tendency for Archaean and early Proterozoic calc-alkaline magmas to have positive Eu anomalies, indicating residual hornblende. Indeed, melting may have commenced in the subduction zone, not at amphibole-dehydration conditions, but in the presence of stable amphibole! In passing, it is worth noting from figure 6 that, for a given crustal thickness, the Archaean/early Proterozoic crust would have been more easily melted than that of today on thermal grounds (cf. O'Nions & Hamilton, this symposium).

Confirmation of a mantle (dominant) – crust (minor) magma mixing model for modern calc-alkaline magmatism is derived from isotopic data (figure 3). Here we find that only intrusive rocks that have risen through ancient continental basement have initial ratios well above mantle values. The apparent exceptions to this were, until recently, data for the Peru coastal batholith, where it has now been shown (Thorpe *et al.*, this symposium) that ancient basement is not likely to be present. Moreover, Armstrong *et al.* (1977) showed that initial strontium isotope ratios are low in the western part of the Washington–Idaho batholith but increase in the east, where independent geological evidence favours the presence of ancient basement in batholith root zones. It is noted that if subducted sediments were a major factor in determining the 'continental' input to batholiths (as argued elsewhere in this volume) then a correlation between initial ratio and amount of sediment on the adjacent ocean crust would be expected. If the 'continental' strontium contribution came from hydrothermally altered, subducted ocean crust then similar ratios should occur everywhere, which is also not the case. The observed correlation between initial ratios and known (or inferred) ancient basement is taken to indicate that the crust itself is involved in magma genesis.

Of course, this evidence does not prove the case against major sediment subduction, but it does indicate that a sediment source is not seen in calc-alkaline magmas. Therefore, the crust may still be growing at an appreciable rate through arc magmatism and by the erosion and accretion of continental detritus along active margins. However, the volumetric differences between postulated growth and, even, shrinkage models (Fyfe 1978; Brown 1979) are so small in comparison with the overall size of the *modern* continents that the matter becomes a non-issue, except for understanding the early history of the Earth's crust. In that context, it is noted (see, for example, Moorbath 1978) that each new batch of calc-alkaline magma seems to represent new crust, and the data for the Proterozoic and Phanerozoic suites reviewed here (table 1; figure 3) are reasonably consistent with this view.

In conclusion, there is a gross similarity about the likely mechanism of granite magma generation for all geological ages. The geochemical, temporal and spatial trends in magma type are consistent with the gradual cooling of near-surface layers and the thickening of the continental lithosphere with time. This process of lithosphere stabilization may be responsible for the accumulation of Archaean 'micro-continents' into Proterozoic stable blocks (see Armstrong, this symposium). Calc-alkaline intrusions along Proterozoic mobile belts and around known continental margins with multiple arcs are similar, geochemically, to modern arc batholiths, and many indicate considerable continental mobility in Proterozoic times. But the prominence of alkalic suites along the same belts may indicate episodes of rapid thermal and magmatic 'rejuvenation', possibly along old sutures; in some cases this may have initiated new plate cycles. It might be postulated that this mid-Proterozoic period, with its widespread alkalic magmatism, was a transitional stage in the progressive growth and stabilization of large Phanerozoic continental masses from small Archaean crustal rafts. Bickle (1978) has emphasized that there is good reason to suppose that the *rates* of magmatic processes and associated oceanic lithosphere movements have declined progressively in response to the declining production of radiogenic heat in the Earth. By implication, this must mean that the continents have become more stable. The present may be the best key to the past, but there are still many speculations and hidden facts: despite many favourable indications, it still remains to be proved (cf. Bird 1979) that the geochemical similarities of granites of all ages, particularly > 1000 Ma, *necessarily* require modern subduction processes.

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