

# PETROGENETIC INTERPRETATION OF GRANITOID ROCK SERIES USING MULTICATIONIC PARAMETERS

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## Abstract

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Granitoid rock compositions from a range of tectonic environments are plotted on a multicationic diagram devised by de la Roche and his coworkers. This shows that there is a systematic change through an orogenic cycle which leads progressively to the ultimate development of alkaline magmas. Possible source materials and mechanisms of magma generation are considered from analysis of mineral compositional vectors. These suggest that most granitoid series result from a two-stage process. First, fractional crystallisation of clinopyroxene, olivine and calcic plagioclase from a basic source with tholeiitic affinities produces a magma of intermediate composition. This magma then undergoes periodic mixing with a felsic magma followed by in situ fractionation to generate individual intrusions within granitoid series.

## 1. Introduction

Many major-element studies on granites (s.l.) have made use of bivariate oxide %—silica % plots of Harker (1909), oxide %—Larsen index (Larsen, 1938) or oxide %—differentiation index (Thornton and Tuttle, 1960) to show and to test petrogenetic hypotheses. Alignments or groupings of data points have been variously interpreted as liquid lines of descent (Harker, 1909), proving fractionation trends (Walsh and Clarke, 1982), or to demonstrate bimodality in magmas (Daly, 1933). The inadequacies of oxide % bivariate diagrams and their misinterpretation have been discussed by Chayes (1964) and Pearce (1969). The principal criticism is that wt.% values as oxides do not faithfully represent the cation distribution in the sample. Similar criticisms can be applied to other diagrams which

utilise wt.% oxide values (Figs. 1 and 2).

Petrological and geochemical characteristics have been applied to discriminate between various granite series. The *I* (igneous) and *S* (sedimentary) types for calc-alkaline granitoids, defined by Chappell and White (1974), form a general mineralogical classification which does not satisfactorily discriminate within the variations seen between *I*-type rocks (e.g., Cordilleran granodiorites, Caledonian monzodiorites, Hercynian monzogranites). Didier et al. (1982) improved this classification by differentiating between crustal- and mantle-derived magmas. They proposed *Cs* (crustal sedimentary), *Ci* (crustal igneous) based upon identification of enclaves as either metasedimentary or meta-igneous, and *M* (mantle) types. Collins et al. (1982) identified an alkaline facies within an orogenic sequence which they termed *A*-type (after Loiselle and Wones, 1979). In our opinion

the A-type late-orogenic association of short duration should be distinguished from the alkaline—peralkaline anorogenic suites of episodically emplaced plutons over a long time interval, e.g. Niger—Nigeria (Bowden

and Turner, 1974), because of the contrasting tectonic settings.

An alternative approach to the discrimination of various granitoid series is to use cationic/molecular values, found in French classification schemes which express whole-rock chemistry as cationic parameters in terms of mineralogical components (Fig. 3). This concept has been extensively used by de la Roche (1964, 1978), de la Roche and Leterrier (1973), de la Roche et al. (1980) and more recently by Debon and le Fort (1983), and it has been recommended by Pitcher (1982) (Table I).

In this paper the R1—R2 multicationic scheme (de la Roche et al., 1980) is examined to determine whether petrogenetic models involving fractional crystallisation, partial melting or magma mixing can be readily displayed and identified. The data presented in Fig. 4 were chosen to represent important tectono-magmatic environments as defined by Pitcher (1979, 1982). They are indicated as groups with arbitrarily drawn boundaries. Group 3 (Caledonian granitoids) has been

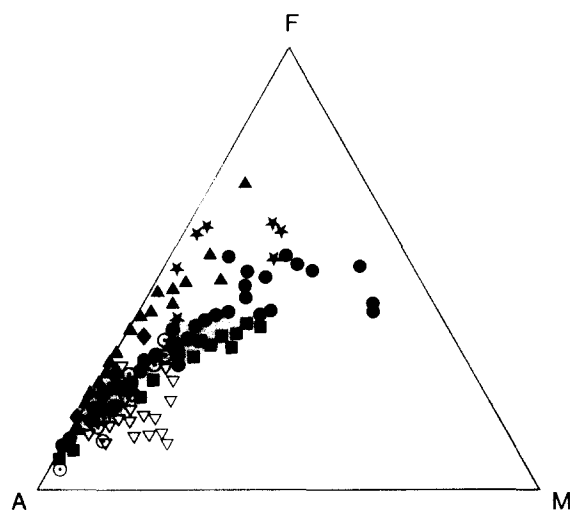


Fig. 1. Triangular variation diagram of wt.%  $(\text{Na}_2\text{O} + \text{K}_2\text{O})-(\text{FeO} + \text{Fe}_2\text{O}_3)-\text{MgO}$ . Symbols as in Fig. 4.

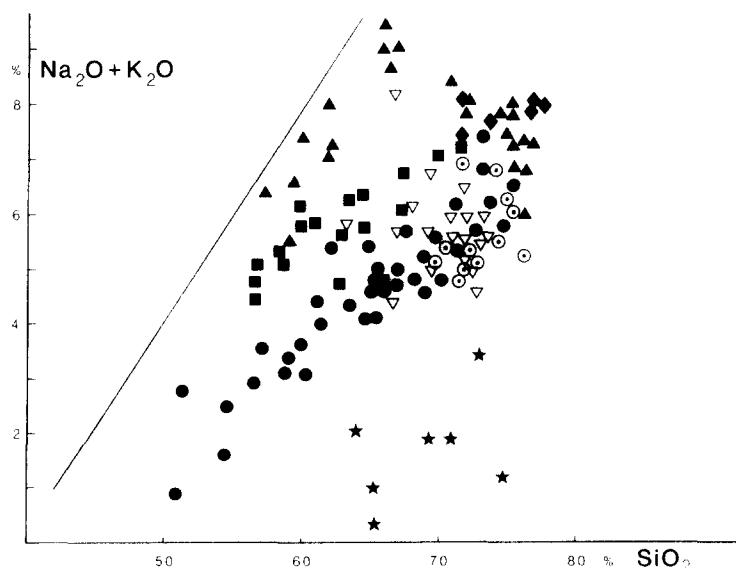


Fig. 2. Bivariate diagram of wt.%  $(\text{Na}_2\text{O} + \text{K}_2\text{O})-\text{SiO}_2$  (after Cox et al., 1979). Symbols as in Fig. 4. Oblique line divides alkaline (above) from tholeiitic (below) affinities, Hawaii (Macdonald and Katsura, 1964).

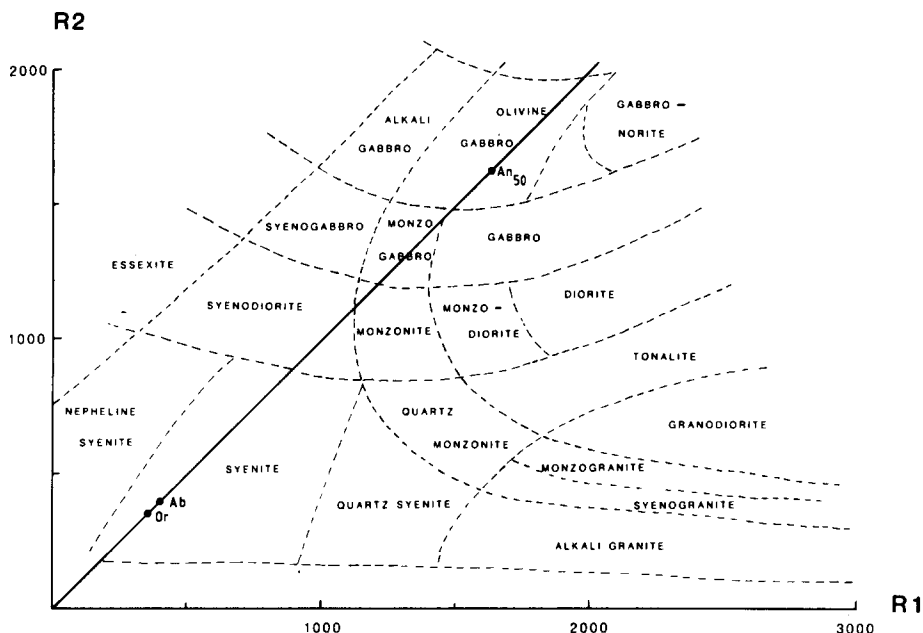


Fig. 3. The de la Roche R1—R2 diagram showing petrographic divisions (Ab = albite; An<sub>50</sub> = plagioclase An<sub>50</sub>; Or = orthoclase). (After de la Roche et al., 1980.)

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

TABLE I

Calculation of R1—R2 parameters

	Weight percent oxide	Molecular weight, M.W.	Number of cations	Cationic proportions	Millications per 100 g
SiO <sub>2</sub>	73.60	60.09	×1	1.225	1,225
TiO <sub>2</sub>	0.10	79.90	×1	0.001	1
Al <sub>2</sub> O <sub>3</sub>	13.17	101.96	×2	0.258	258
Fe <sub>2</sub> O <sub>3</sub>	0.99	159.69	×2	0.012	12
FeO	1.61	71.85	×1	0.022	22
MgO	0.06	40.30	×1	0.001	1
CaO	0.70	56.08	×1	0.012	12
Na <sub>2</sub> O	3.69	61.98	×2	0.119	119
K <sub>2</sub> O	5.38	94.20	×2	0.114	114

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$= 4900 - 11(233) - 2(12 + 22 + 1) = 2267$$

$$R2 = 6Ca + 2Mg + Al$$

$$= 72 + 2 + 258 = 332$$

defined on the basis of distinctive petrographic characteristics of its neighbouring groups (2 and 4), since "Caledonian" represents a temporal event and not a simple

tectonic association. This may explain the spread of group-3 sample points (filled squares).

The main feature of this diagram (see Fig.

10) is the progression of compositions through an orogenic cycle, starting at group 2 (pre-plate collision, subduction regime) through uplift (post-plate collision, group 3) to late-orogenic plutons (group 4). This progressive change in compositions from group 2 to group 4 reflects a general and consistent increase in K and Na, and could be related to a common source. This inferred trend will be termed the *source trend*. The variation in composition within each group perpendicular to the source trend will be

referred to as the *series trend*.

Group 5 represents post-orogenic or anorogenic magmatism.

The syn-collision group (6) reflects the restricted range of "S-type" granites (Chappell and White, 1974) and anatectic granites. The overlap around this area is inevitable since all granitoids evolve towards minimum melting compositions (Tuttle and Bowen, 1958). In time terms it represents the span through a plate collision event (groups 3 and 4).

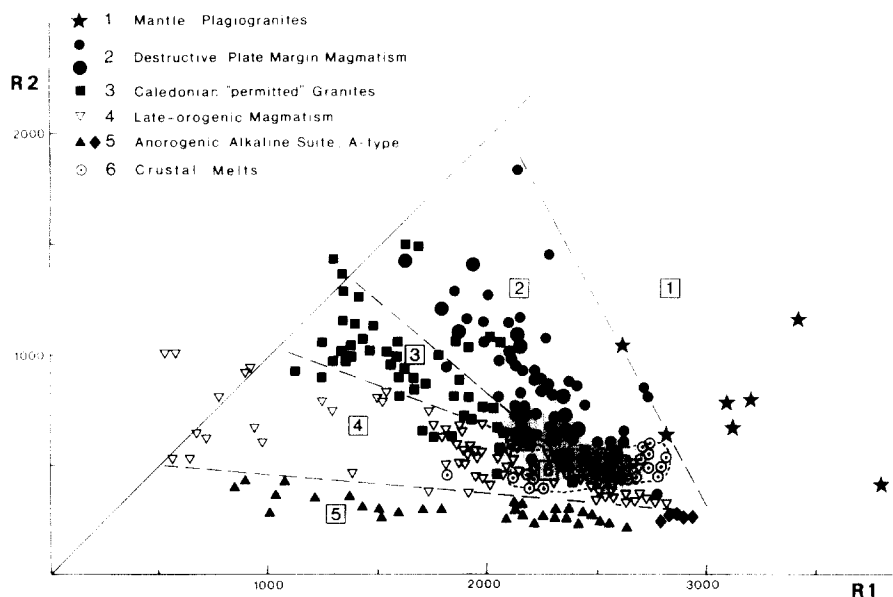


Fig. 4. A display of selected granitoid compositions on the de la Roche R1–R2 multicatic diagram. The numbered groups 1–4 relate to the tectonomagmatic divisions postulated by Pitcher (1979, 1982).

Group 1: *Mantle plagiogranite* (Oman and Cyprus — Coleman and Donato, 1979).

Group 2: *Destructive active plate margin (pre-plate collision)* (Mt. Given, Sierra Nevada, California — small solid circles; Bateman et al., 1963), (trondhjemites, Finland — large solid circles; Arth et al., 1978).

Group 3: *Caledonian "permitted" plutons (post-collision uplift)* (Ben Nevis, Scotland — Haslam, 1968), (Balachulish, Scotland — Bailey et al., 1960; Clarke, 1982), (Etive "Cruachan" — R.A. Batchelor, unpublished data, 1983), (Rannoch Moor, Scotland — P. Leighton, unpublished data, 1983).

Group 4: *Sub-alkaline plutons (late orogenic)* (Ploumanac'h, Brittany — Barriere, 1977), (Etive "Starav", Scotland — R.A. Batchelor, unpublished data, 1983), (Ardara, Donegal — Pitcher and Berger, 1972), (leucogranites, Massif Central, France — Lameyre, 1966), (late-orogenic granites, Ahaggar, N. Africa — Boissonnas, 1973).

Group 5: *Alkaline/peralkaline magmatism (post-orogenic)* (Nigeria–Niger alkaline province — P. Bowden, unpublished data, 1981).

Group 6: *Anatectic magmatism (syn-orogenic)* (Moy, Grantown and Ardlach granites, Aberdeenshire — Zaleski, 1982), (cordierite granites, Strathbogie, Australia — Phillips et al., 1981), (cordierite granites, Massif Central, France — Lameyre, 1966).

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

## 2. Mechanisms for magma formation

### 2.1. Partial melting

The first liquids to separate from the fusion of a felsic crustal source (gneiss, meta-pelite, intermediate meta-igneous rocks) will have compositions equivalent to alkali feldspar and quartz  $\pm$  sodic plagioclase. The anorthite content increases with temperature (and with the availability of Ca) (Winkler, 1979).

If a felsic melt is completely mobilised in the crust and emplaced at a higher level, then its composition will be equivalent to a syenogranite or monzogranite. The melting vector will follow *PM*—*C* on Fig. 5, since it lies on the quartz—orthoclase tie line. Only as the anorthite component increases does the vector curve upward. If variable amounts of mafic restite material (biotite, amphibole, pyroxene) are included, then the bulk composition will lie on mixing lines joining the

zone of melting (designated *PM*) with the restite minerals composition pole (Fig. 5).

The compositional trend *A*—*B*—*C* which progresses through an orogenic cycle (Fig. 4) could be explained by:

(1) Contamination of basaltic magma by K- and Al-rich phases.

(2) Discrete bulk crust compositions which consistently vary from *A* to *B* to *C*.

(3) Fractional crystallisation (see Section 2.2).

If basaltic material were selectively contaminated, Fig. 5 requires that the contaminants be orthoclase, albite, biotite, or any combination of these (see Fig. 8 for comprehensive mineral pole positions). However, the progression found in orogenic suites (Fig. 4) would require this contamination to follow a regular pre-determined pattern.

If it were assumed that lower crustal sources had compositions represented by *A*, *B* and *C* (Fig. 5), then increasing degrees of

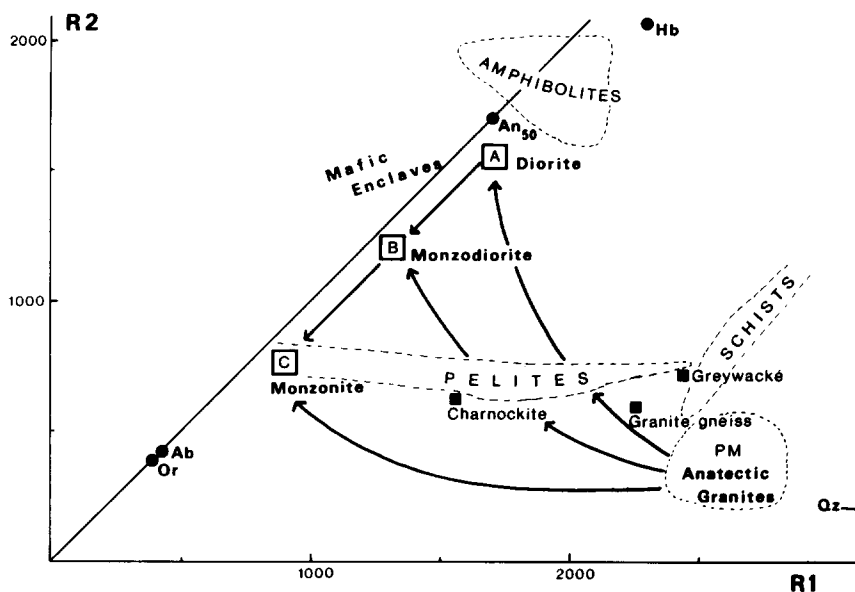


Fig. 5. Partial melting vectors and metasedimentary sources. *PM* represents the zone of anatectic melts. The vectors *PM*—*A*, *PM*—*B* and *PM*—*C* indicate the change in melt composition under progressive equilibrium partial melting of rocks of dioritic, monzodioritic or monzogranitic bulk composition, respectively (Hb = hornblende; An<sub>50</sub> = plagioclase (An<sub>50</sub>); Ab = albite; Or = orthoclase; Qz = quartz). Metasediment compositions were obtained from Mason (1978).

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

equilibrium partial melting would generate compositions whose vectors could be represented by  $PM-A$ ,  $PM-B$  and  $PM-C$ , respectively. Sequential intrusions within an igneous complex trend towards more silicic and alkaline compositions with time (source trend). This is demonstrated by the Ben Nevis in-

trusion (Haslam, 1968) (Fig. 6) and the Etive granitoid complex, Argyll (R.A. Batchelor, unpublished data, 1983) (Fig. 7).

The metasediment compositions plotted on Fig. 5 do not equate with the compositions of A and B which are the starting compositions inferred from the R1-R2 diagram for

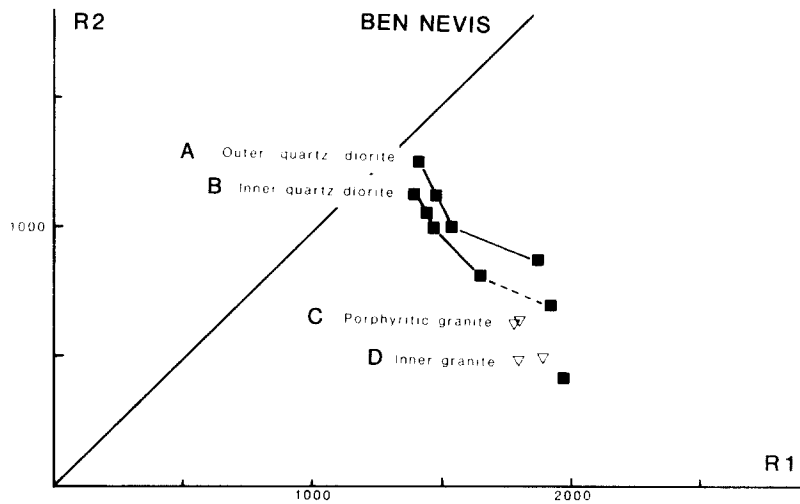


Fig. 6. Data for granitoid rocks from Ben Nevis, Scotland (Haslam, 1968). (A-B-C-D indicates the order of intrusion.)

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

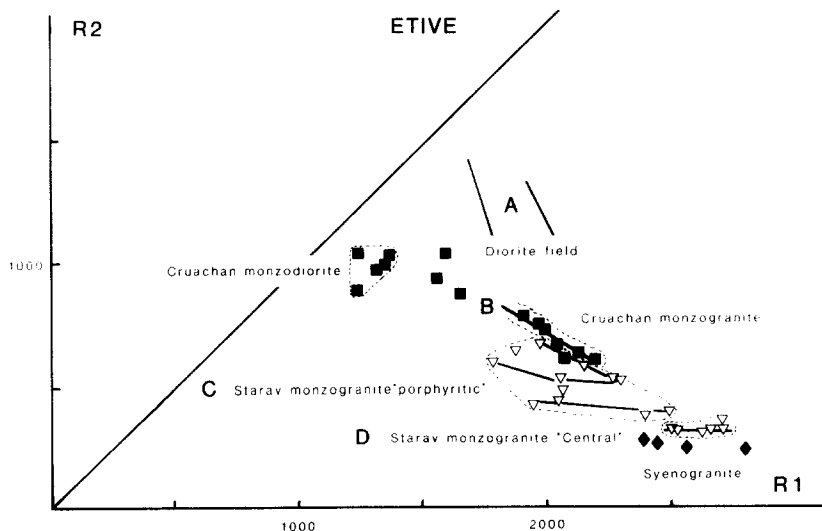


Fig. 7. Data for granitoid rocks from Etive complex, Scotland (R.A. Batchelor, unpublished data, 1983). (A-B-C-D indicate the order of intrusion.)

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

granitoid groups 2 and 3. The exception is the coincidence of monzonite with certain pelites.

According to Wyllie (1977) tonalites and diorites (represented by A in Fig. 5) may represent crustal melts from which most of the alkali feldspar component has been lost by upward migration. On the other hand diorite (A) could reflect the accumulation of residual refractory phases in the source area. This theory requires a source melt of monzonitic composition which through progressive loss of alkali feldspar component by external heat and pressure would cause compositions to change C—B—A. This is contrary to the source trend defined earlier. Complete melting of pelite which was mobilised and then underwent crystallisation of plagioclase and alkali feldspar could produce melts of monzonitic composition.

In general, low degrees of partial melting of crustal rocks can produce felsic liquids which if mobilised in the crust may either form plutons of leucocratic "S-type" granites or mix with more mafic material to form magmas of intermediate composition.

The constraints imposed by the de la Roche R1—R2 diagram suggest that partial melting alone would seem unable to explain all the variations seen in most granitoid rocks.

## 2.2. Fractional crystallisation

Theoretical removal of individual phases of rock-forming minerals from basaltic compositions is displayed in Fig. 8. The trends obtained show the calculated maximum limit of fractionation (when any one major-oxide component is completely removed). The numerical values are only a guide since in

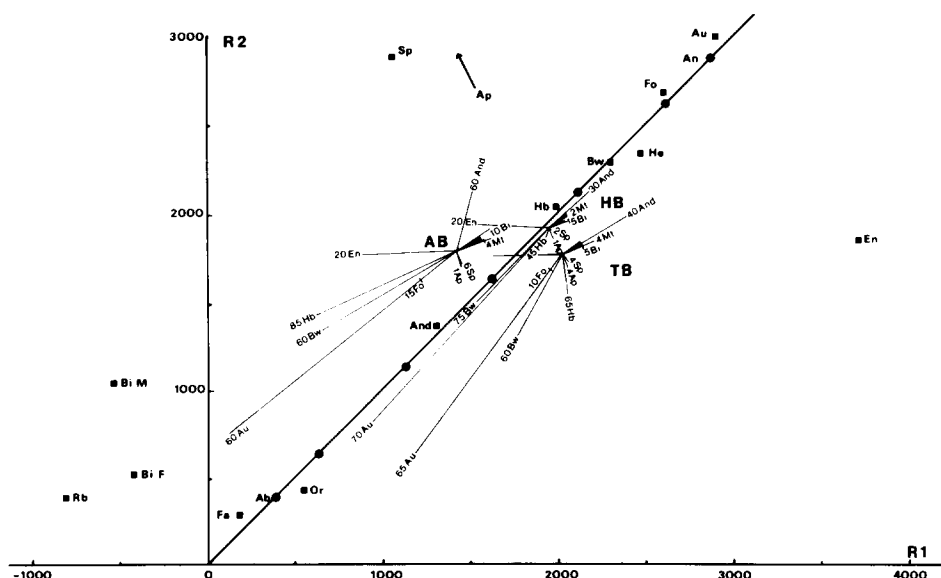


Fig. 8. Fractional crystallisation vectors. (Ab = albite; And = andesine; An = anorthite; Ap = apatite; Au = augite; Bi F = ferroan biotite; Bi M = magnesian biotite; En = enstatite; Fa = fayalite; Fo = forsterite; Hb = hornblende; He = hedenbergite; Or = orthoclase; Rb = riebeckite; HB = high-alumina basalt; TB = tholeiitic basalt; AB = alkali basalt; solid squares represent natural compositions; solid circles represent theoretical compositions).

The trends were constructed by removing two compositions of plagioclase feldspar ( $An_{80}$  and  $An_{30}$ ), olivine ( $For_{90}$ ), augite, hornblende, biotite, apatite, spinel, magnetite and enstatite (data from Deer et al., 1966; Cox et al., 1979) from alkali, tholeiitic and high-alumina basalt compositions (de la Roche et al., 1980). The computed compositions of the liquid fractions caused by fractional removal of crystals are plotted on the R1—R2 diagram.

$$R1 = 4Si - 11(Na + K) - 2Fe + Ti$$

$$R2 = 6Ca + 2Mg + Al$$

natural situations the depletion of certain elements in the melt by a crystallising phase would form a zoned mineral and not necessarily arrest its formation. These vectors are unique for the given initial composition.

**2.2.1. Alkali basalt fractionation.** Some oversaturated trachytes may only be produced by crossing over the silica saturation plane, which could only happen if biotite or alkali pyroxene/amphibole, followed by alkali feldspar played an important role in a fractionating system. The role of these minerals is inferred from their relative position on the R1–R2 diagram (Fig. 8).

**2.2.2. High-alumina basalt.** The vectors shown in Fig. 8 parallel the plane of silica saturation on the quartz-rich side. Clinopyroxene + olivine + calcic plagioclase could generate liquid compositions by crystal fractionation which represent the intermediate (starting) compositions for the genesis of some granitoid series. The most mafic members of the granitoid series plot along a line close to and parallel to the clinopyroxene vector. Work on the Santorini, Greece, lavas has shown that calc-alkaline lava series can be generated directly from a basalt by fractional crystallisation. A two-stage model can explain the sequence high-alumina basalt to andesite (by clinopyroxene + olivine + plagioclase removal) and andesite to rhyodacite (by plagioclase + clinopyroxene + orthopyroxene + accessories) (Mann, 1983). However, these acid lavas are volumetrically small and cannot be considered as sources for the large calc-alkaline batholiths represented by group 2 (Fig. 4).

**2.2.3. Tholeiitic basalt fractionation.** The vectors are more wide-reaching than those originating from a high-alumina basalt, and could yield compositions suitable as starting materials for the derivation of K-poor calc-alkaline granitoids (group 2, Fig. 4). Removal of calcic plagioclase and amphibole could directly generate “tholeiitic” or plagiogranite

melts associated with oceanic environments (group 1, Fig. 4).

The fact that the origin of each granitoid suite (Fig. 4) follows a trend close to and parallel to the high-alumina basalt clinopyroxene vector may point to the nature of a source magma (source trend). However, each granitoid series on the R1–R2 diagram defines a trend which moves away perpendicular to the source trend. This suggests that each granitoid series may be related to a fractionating mafic source, but once mobilised into the crust, can undergo a variety of changes, either by continued limited fractionation, or by mixing with felsic melts. The direction of the granitoid series suggests that plagioclase ( $An_{30}$ – $An_{60}$ )  $\pm$  biotite or orthoclase would be the important fractionating phases.

Calculations involving a single phase are displayed as linear vectors. If one mineral becomes zoned, or if a combination of minerals are involved whose proportions vary with time, then the resultant vectors on the R1–R2 diagram will be curvilinear. If mixing dominates the series, the series trends will be strictly rectilinear.

### 2.3. Magma mixing

The marscoite suite from the Isle of Skye, Scotland, provides an example for demonstrating the mixing model. Analytical data for the Skye Tertiary Igneous centre have been recalculated as cationic proportions and are presented in Fig. 9. Included in the diagram are the compositional variations for the series of alkaline lavas found in the northern part of the island, as well as the data points for the granitic rocks of the Red Hills. Also included are rock types of known mixed parentage (marscoite and glamaigite) as well as ferrodiorite which represents a more mafic marginal facies of the marscoite suite.

It can be seen that:

(a) There are two distinct mafic trends leading to contrasting fractionated composi-



tions. One, shown by the curvilinear vector in Fig. 9, demonstrates variations from alkali olivine basalt through hawaiite, mugearite to trachyte. The tholeiitic trend, in contrast, terminates at ferrodiorite composition.

(b) Epigranites form a distinct cluster on the R1–R2 diagram situated beyond the projection of the curvilinear alkaline trend. These can be interpreted either as products of prolonged fractionation along the alkaline trend or of partial melting of crustal rocks.

(c) The felsite sample plots at the silicic end of the inferred mixing line, suggesting that marscoite and glamaigite could be generated by mixing of felsic magma with either fractionated tholeiitic melts of ferrodiorite composition, or with fractionated alkali olivine basalt magma of hawaiite composition.

The proportions of mafic to acid magma required to generate marscoite can be calculated from the mixing line in Fig. 9 as 55% hawaiite and 45% felsite, or 80% ferrodiorite and 20% felsite. Wager et al. (1965) estimated 60% hawaiite and 40% felsite, or 65% ferro-

diorite and 35% felsite. Recent work by Bell (1983) using trace-element data for these Skye rocks has shown that marscoite resulted from mixing 73.8% ferrodiorite with 26.2% felsite.

If these data represent a mixing regime, then the inference is that both mafic and acid melts must have coexisted in order to generate intermediate compositions and must have had independent origins.

### 3. Discussion

Using the de la Roche R1–R2 multicationic diagram the following interpretations can be made:

(1) The partial-melting diagram indicates that large-scale melting of felsic crust is unable to explain the development of most granitoid series because the sense of direction for successive melting vectors contradicts the observation that most polyphase granitoid complexes trend to more silicic compositions with time. It is clear that large volumes of felsic liquids can be gener-

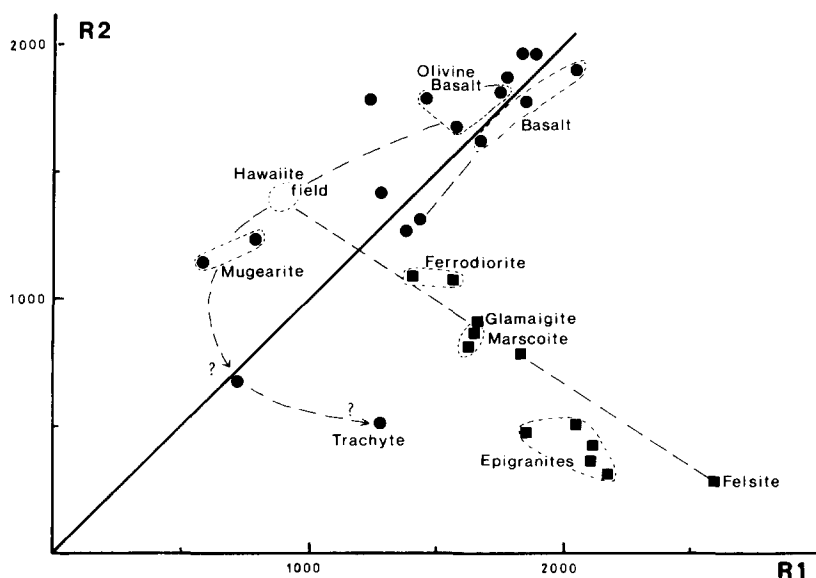


Fig. 9. Magma mixing vectors. Data for the Skye Tertiary Igneous centre were taken from Wager et al. (1965) and Anderson and Dunham (1966).

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

ated by low degrees of partial melting of felsic crust which may form large batholiths of anatectic leucocratic granites. However, this process cannot explain the source trend. Fractionation of relatively large amounts (70%) of clinopyroxene + calcic plagioclase + olivine from a high-alumina basalt parent magma could generate source magmas for each granitoid series. On the other hand, it is then difficult to explain the variability in compositions found within any one granitoid series. Removal of an unacceptably large volume of intermediate plagioclase, biotite, hornblende and accessories is necessary in order to generate, for example, a syenogranite from a monzonite or monzodiorite. It is, however, feasible to generate a mafic-intermediate parental melt, whose composition "evolves" along the source trend. The notion of a parental magma of intermediate composition as the source for calc-alkaline granite batho-

liths is expressed by Presnall and Bateman (1973) and Presnall (1979). These authors do not consider it feasible to generate sufficient felsic liquid from a basaltic source by fractional crystallisation to produce the large batholiths of the Sierra Nevada, California. The source trend, which appears to correlate with known compositional variations through an orogenic cycle, moves compositions from top-right to bottom-left of the diagram (Fig. 10). The composition of the source will be a function of the  $P$ - $T$  conditions prevailing at depth, linked to the rate of crustal thickening. It is also possible to generate felsic liquids by anatexis of some crustal rocks. The mixing of these two components can form melts of intermediate composition. Once such a "cocktail" has homogenised and intruded to higher crustal levels, it may then undergo limited *in situ* fractionation to produce a zoned pluton. Mixing of variable proportions

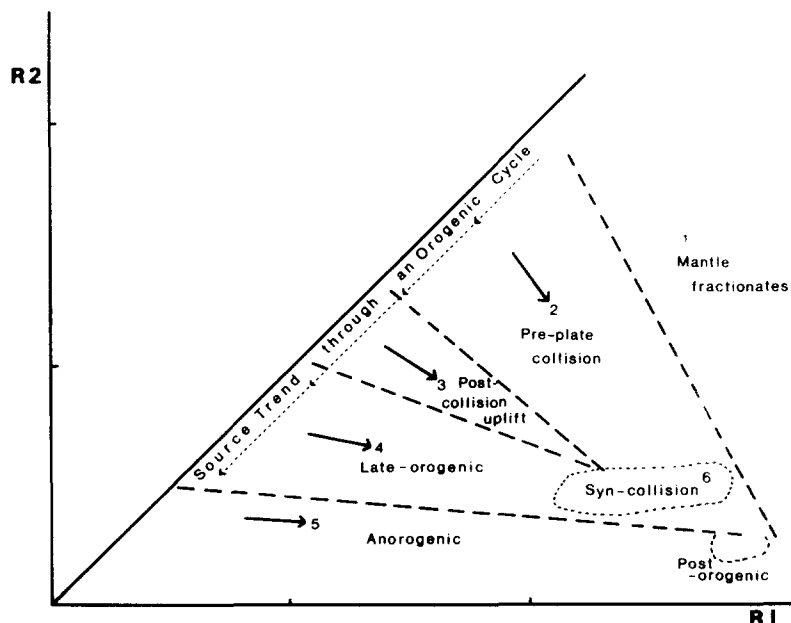


Fig. 10. Summary diagram of the major granitoid associations, based upon Pitcher (1979, 1982) and Harris et al. (1983). Petrological equivalents (after Lameyre and Bowden, 1982): group 1 — tholeiitic; group 2 — calc-alkaline and trondhjemitic; group 3 — high-potassic calc-alkaline; group 4 — sub-alkaline monzonitic; group 5 — alkaline and peralkaline; group 6 — anatectic 2-mica leucogranites.

$$R1 = 4Si - 11(Na + K) - 2(Fe + Ti)$$

$$R2 = 6Ca + 2Mg + Al$$

could explain the variability found in independent intrusions within a complex.

Chemical data from the Porphyritic Starav monzogranite, Etive complex, Argyll, when plotted on the R1—R2 diagram (Fig. 7) highlight three en echelon sub-trends (within time group B). These suggest that this intrusion was emplaced as a succession of at least three chemically distinct pulses, each of which underwent small but significant fractionation to more silicic compositions. Such fine discrimination is useful in the understanding of intrusive histories.

(2) An evolving source trend would terminate at group-4 compositions, since group 5 represents a different tectonic regime, viz. extensional as opposed to compressional regimes for groups 2—4. Thus the place of post-orogenic alkaline magmatism within the orogenic cycle cannot be considered as a continuation of the compressional cycle, but may be viewed as the result of a relaxation effect after plate collision which would generate tensional rifts and give rise to alkaline magmas. Such a complete cycle has been identified in Mali during the Pan-African orogeny (Black et al., 1979).

#### 4. Conclusion

Chemical data obtained from granitoids of known tectonic association, when plotted on the de la Roche R1—R2 multicationic diagram, generate definite zones which can be identified with known tectono-magmatic associations. By superimposing vectors which reflect changes in liquid compositions during fractional crystallisation or equilibrium partial melting on the diagram, constraints can be placed upon models which explain the generation of granitoid magmas. One model derived from the data presented here invokes fractional crystallisation of clinopyroxene + plagioclase + olivine from a melt of high-alumina basalt composition, which generates a source magma. At intervals through an orogenic cycle, this magma, at different stages of chemical evolution, mixes with felsic melts

generated by partial melting of felsic crustal material. The resultant intermediate compositions may then undergo limited in situ fractionation after intrusion into higher levels of the crust, to form granitoid series.

Thus the whole spectrum of magmatic activity during and after orogenic cycles may be represented on the de la Roche diagram using major-element oxide data in a clearer way than can be achieved on more traditional plots.

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