A Geochemical Classification for Granitic Rocks

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This geochemical classification of granitic rocks is based upon three variables. These are FeO/(FeO + MgO) = Fe-number [or $FeO^{tot}/(FeO^{tot} + MgO) = Fe^*$], the modified alkali–lime index (MALI) ($Na_2O + K_2O - CaO$) and the aluminum saturation index (ASI) [$Al/(Ca - 1·67P + Na + K)$]. The Fe-number (or Fe*) distinguishes ferroan granitoids, which manifest strong iron enrichment, from magnesian granitoids, which do not. The ferroan and magnesian granitoids can further be classified into alkalic, alkali–calcic, calc-alkalic, and calcic on the basis of the MALI and subdivided on the basis of the ASI into peraluminous, metaluminous or peralkaline. Because alkalic rocks are not likely to be peraluminous and calcic and calc-alkalic rocks are not likely to be peralkaline, this classification leads to 16 possible groups of granitic rocks. In this classification most Cordilleran granitoids are magnesian and calc-alkalic or calcic; both metaluminous and peraluminous types are present. A-type granitoids are ferroan alkali–calcic, although some are ferroan alkalic. Most are metaluminous although some are peraluminous. Caledonian post-orogenic granites are predominantly magnesian alkali–calcic. Those with <70 wt % SiO_2 are dominantly metaluminous, whereas more silica-rich varieties are commonly peraluminous. Peraluminous leucogranites may be either magnesian or ferroan and have a MALI that ranges from calcic to alkalic.

INTRODUCTION

Although granitoids are the most abundant rock types in the continental crust, no single classification scheme has achieved widespread use. Part of the problem in granite classification is that the same mineral assemblage, quartz and feldspars with a variety of ferromagnesian minerals, can be achieved by a number of processes. Granitoids can form from differentiation of any hypersthene-normative melt and from partial melting of many rock types. Furthermore, granitic melts may be derived solely from crustal components, may form from evolved mantle-derived melts, or may be a mixture of crustal and mantle-derived melts. Because of this complexity, petrologists have relied upon geochemical classifications to distinguish between various types of granitoids. Approximately 20 different schemes have evolved over the past 30 years [see Barbarin (1990, 1999) for a summary thereof]. Most of these schemes are either genetic or tectonic in nature. This paper is an attempt to present a non-genetic, non-tectonic geochemical classification scheme that incorporates the best qualities of the previous schemes, and to explain the petrologic processes that makes this scheme work.

IUGS CLASSIFICATION OF GRANITOIDS

The traditional IUGS petrographic classification of granitoids is based upon their modal abundances of quartz,

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plagioclase and alkali feldspar (Streckeisen, 1967). The IUGS classification focuses on differences in abundances and compositions of the feldspars and accounts for a wide variety of granitoids. The advantage of the IUGS classification is that, for most rocks, it can be readily applied in the field. Furthermore, it is inexpensive, simple to use, and truly non-genetic.

A major drawback of the IUGS classification scheme is that it ignores compositional variations apart from those that affect the feldspar abundances. Thus mafic and felsic granitoids may plot in the same field but have significantly different chemical compositions. Furthermore, the classification cannot address the presence or absence of minor phases, such as muscovite, which may carry significant petrologic implications. For this reason many petrologists have used additional schemes as a way to further classify granitoids.

PREVIOUS SCHEMES FOR THE CLASSIFICATION OF GRANITOIDS

Previous granitoid classification schemes have involved diverse criteria such as the presumed origin of the granitoid, mineralogy, geochemistry, and tectonic environment [see summary by Barbarin (1990, 1999)]. Of the 20 or so schemes proposed, the most commonly used ones are discussed below.

Alphabetic classification

The first of the modern geochemical schemes for classification of granitic rocks was introduced in an abstract by Chappell & White in 1974. They recognized two distinct granitoid types in the Lachlan Fold Belt of eastern Australia. The I-type is metaluminous to weakly peraluminous, relatively sodic, and has a wide range of silica content (56–77 wt % SiO_2). It was inferred to have formed from a mafic, metaigneous source. The other type is strongly peraluminous, relatively potassic and restricted to higher silica compositions (64–77 wt % SiO_2). Chappell & White called these S-type granitoids because these they are inferred to have formed from melting of metasedimentary rocks. This scheme received instant popularity and has been applied worldwide. It is based upon the assumption that one can easily distinguish the origin of the granitoid precursor. However, similar granitic compositions can be produced by partial melting of a variety of sources (Miller, 1985).

The alphabetic classification was augmented by another term, which was introduced by Loiselle & Wones (1979), also in an abstract. They recognized a distinctive type of granitoid that is relatively potassic, has high FeO/(FeO + MgO), and has high Zr and other high field strength elements. Because such granitoids were rarely deformed and were inferred to have intruded long after the youngest deformation event, they were called 'anorogenic'. Loiselle & Wones (1979) called these granitoids A-type because of their alkalinity, 'anhydrous' characteristics, and presumed anorogenic tectonic setting. Since then, numerous papers have been published on the definition, origin and evolution of A-type granitoids. In particular, there is considerable dispute as to the meaning of 'anorogenic', although most workers consider such granitoids to be related to some form of continental extension (Whalen et al., 1987; Eby, 1990; Frost & Frost, 1997).

Other alphabetic types of granitoid that have been proposed include M-type (White, 1979) and C-type (Kilpatrick & Ellis, 1992). M-type granitic rocks are thought to arise from the mantle, specifically in island arc settings (White & Chappell, 1983). The C-type was defined as charnockitic granitoids by Kilpatrick & Ellis (1992), who argued that a distinct charnockitic magma type is recognizable among both plutonic and volcanic rocks.

For all its popularity, the alphabetic classification has drawbacks. First, the two least commonly used classes (M-type and C-type) are imprecise. For example, granitic rocks with M-type characteristics can be of mantle origin or can arise by partial melting of juvenile crust (technically I-type). Furthermore, a mantle origin of a granitic magma may have little influence on the magma composition, for it has been argued that rocks as varied as tonalite (Tate et al., 1999), fayalite granite (Frost & Frost, 1997), and peralkaline granite (Barker et al., 1975) are of mantle derivation.

The presence of orthopyroxene, pigeonite or fayalite, which supposedly serve to characterize C-type granitic rocks, is a function of the fluid composition present at the time the magma crystallizes. Because biotite is likely to be stabilized relative to olivine or pyroxene in rocks that are relatively enriched in Mg, anhydrous assemblages are favored in rocks that are iron enriched (Frost et al., 2000). However, charnockites are not restricted to form from iron-rich bulk composition; they are found in magnesian granitoids as well (Frost et al., 2000).

A major problem with the alphabetical classification is that it carries the assumption that individual granitic rocks have a simple source, and that this source can be readily identified from the chemistry of the rocks. In actuality, granitoids rarely come from single sources, but instead are mixtures of mantle-derived mafic melts and melts of crustal rocks that may or may not contain metasedimentary components (John & Wooden, 1990; Miller et al., 1990). This has recently been demonstrated for the 'type' S- and I-type granitoids of the Lachlan Fold Belt (Collins, 1996). Furthermore, granitic rocks crystallize into a broad spectrum of compositions such that significant overlap exists between I-types and S-types

(Hyndman, 1984; Ague & Brimhall, 1988). Because of this, Ague & Brimhall (1988) and Barbarin (1990) introduced more detailed classifications, neither of which has achieved wide use.

Magnetite- and ilmenite-series granitic rocks

Granitic rocks were classified into magnetite-series and ilmenite-series by Ishihara (1977). Ishihara recognized that in Japan there is a distinct spatial distribution of granitic rocks that contain magnetite—coexisting with ilmenite—and those that contain ilmenite as the only Fe–Ti oxide. He recognized that the magnetite-series granitoids are relatively oxidized whereas the ilmenite-series granitoids are relatively reduced, and that both types are associated with distinctive ore deposits.

This classification scheme was well received because of its simplicity, its correlation with ore deposits associated with Cordilleran-type batholiths (Ishihara, 1981) and because of its ready application to large areas by use of aerial geophysical surveys (Gastil *et al.*, 1990). The system is not strictly geochemical, but is based upon reactions that remove magnetite (or inhibit its formation) during crystallization of granitic rocks. There are three processes that can control the stability of magnetite in granitic rocks: (1) reduction by combustion of carbon during melting of metasedimentary rocks (Ishihara, 1977); (2) in reduced rocks, consumption by reactions with the Fe–Mg silicates (Frost *et al.*, 1988; Fuhrman *et al.*, 1988; Frost & Lindsley, 1991); (3) in peralkaline rocks, consumption to make sodic pyroxenes and amphiboles. The Ishihara (1977) classification recognizes the first process but not the latter two. As a result, it is applicable to granitic rocks in magmatic arcs, but less so to more alkalic granites, where the latter two reactions may predominate. Thus although the distinction between ilmenite-series and magnetite-series granitic rocks is valid for Cordilleran granites, it is less applicable to granitoids from other tectonic environments.

Silicate mineralogy

Barbarin (1999) proposed a classification that is based upon the mineralogy of granitoids and its relationship to the aluminum saturation of the rock. The six granitoid types identified were then correlated with distinctive tectonic environments. This scheme has the advantage of directly relating composition to the mineralogy, but it has the disadvantage of compressing the wide range of bulk compositions of granitoids into six rock types.

R_1–R_2 discrimination diagrams

De la Roche *et al.* (1980) introduced a technique to characterize igneous rocks, which involved the variables called R_1 and R_2. This technique compresses the basalt tetrahedron of Yoder & Tilley (1962) into two dimensions that are defined by the cationic functions R_1 [4Si – 11(Na + K) – 2(Fe + Ti)] and R_2 (Al + 2Mg + 6Ca). This approach depicts the variation of silica saturation as well as the changes in Fe/(Fe + Mg) ratio and plagioclase composition that accompany differentiation. This makes it an ideal projection for mafic rocks; however, it is less suitable for granitic rocks because K-feldspar and albite plot at the same point. This means that the diagram cannot be used to distinguish between rocks with variable K/Na ratios and that most granitic rocks plot in a small area of the diagram (Bachelor & Bowden, 1985). This elegant approach is not widely used in North America, perhaps because the petrologic meaning for the R_1 and R_2 variables is not intuitively obvious.

Trace element discrimination diagrams

Pearce *et al.* (1984) introduced a geochemical method to characterize the tectonic environment of granitic rocks. More than 600 analyses were used to geochemically distinguish four major tectonic environments: ocean ridge granites; volcanic arc granites; within-plate granites; collisional granites. The best discriminators were plots of Nb vs Y, Ta vs Y, Rb vs (Y + Nb) and Rb vs (Y + Ta). This scheme is in wide use and is considered an important way to determine the tectonic environment of granitic rocks whose tectonic setting was not preserved.

Trace element compositions of granitoids are a function of the sources and crystallization history of the melt; the tectonic environment is secondary. For example, post-collisional granitoids can be derived from a number of different sources, depending on the composition of the crust thickened during orogenesis. These granitoids are also intimately associated with mafic magmas (e.g. Liégeois *et al.*, 1998), which may mix or mingle with the crustally derived melt component. Thus, the chemical composition of this tectonic group is influenced by a range of source components, which is why they plot over the range of fields defined by Pearce *et al.* (1984).

A NEW CLASSIFICATION SCHEME FOR GRANITIC ROCKS
Characteristics of geochemical classification scheme

We have developed a classification scheme based on the following criteria. First, the scheme must be chemical and not founded on judgments as to the origin or the

tectonic environment of any particular granitoid type. An *a priori* knowledge of the sources of the magma or tectonic environment for a suite should not be necessary for its application, nor should the application of the classification necessarily tell one much more than the broadest aspects of the tectonic environment. Second, it must be flexible enough to accommodate the wide range of compositions found in granitic rocks. Finally, the scheme should be based on major element compositions. Most trace elements in granitoids are *not* incompatible, and for this reason they provide a poor basis for any classification. Many trace elements in granitoids reside in minor mineral phases and thus the trace element concentration of a granitic rock may be more a function of the abundance of these phases than the composition of the original melt (Bea, 1996).

PROPOSED CLASSIFICATION SCHEME

We propose a three-tiered classification scheme that uses familiar chemical parameters, many of which appear in other geochemical classification schemes for granitoids (Petro *et al.*, 1979; Maniar & Piccoli, 1989; Barbarin, 1990, 1999). The first tier is determined by the $FeO/(FeO + MgO)$ ratio of the rock. This is a variable that conveys information about the differentiation history of the granitic magma. The second tier is the modified alkali–lime index of the rock ($Na_2O + K_2O - CaO$), which is expressed by compositions and abundances of the feldspars in the rock and which is related to the sources of the magma. The third tier is the aluminum saturation index, which is expressed in the micas and minor minerals in the rock. It is related to the magma sources and the conditions of melting.

In the following sections we use a number of distinctive granitoid suites to develop the classification scheme. This includes granitoids from the Cordilleran batholiths of western North America, the Caledonian granites, which typically are more alkaline than the Cordilleran granitoids, and the A-type granitoids, granitic rocks that are characteristically alkali rich with a high abundance of high field strength elements. Spreadsheets containing the data used to develop this classification scheme can be accessed at http://research.gg.uwyo.edu/granite/.

Fe-number or Fe*

It has been long recognized that there are fundamental differences between rock suites that undergo iron enrichment during differentiation while silica abundance remains low, and those that undergo silica enrichment with only minimal enrichment of FeO relative to MgO

(Nockolds & Allen, 1956). These two trends were originally referred to as the 'Skaergaard' and 'Cascade' trends, but are now usually referred to as 'tholeiitic' and 'calc-alkalic'. Miyashiro (1970) showed the rocks following these distinct trends could be distinguished on a plot of $FeO/(FeO + MgO)$ against silica (Fig. 1a). We refer to this variable as *Fe*-number. Numerous workers have used iron enrichment to distinguish between granitoids from different tectonic environments. In particular, suites with A-type characteristics are distinctly more iron enriched than the Cordilleran-type granitoids (Petro *et al.*, 1979; Anderson, 1983; Maniar & Piccoli, 1989; Frost & Frost, 1997).

In Fig. 1a we show that Miyashiro's boundary (modified at low silica so it is linear) does a good job in discriminating between the compositions of 175 A-type granitoids and 344 Cordilleran granitoids that have been analyzed for both ferric and ferrous iron. With our modification, 97% of the A-type granitoids lie above the boundary and 93% of the Cordilleran granitoids lie below it. Most of the deviation across this boundary occurs at high silica values.

Because the *Fe*-number is unrelated to the alkalinity of a rock, we consider that the terms 'calc-alkalic' and 'tholeiitic' are misnomers and that more appropriate designations should apply. We propose the terms 'ferroan' and 'magnesian' to describe the two groups because these terms refer directly to the variables used in the diagram. For rocks with *Fe*-number <0·5, Mg is molecularly more abundant than Fe. There is a population of granitoids that are magnesian by our classification that actually have higher mole proportions of Fe than Mg. We consider these to be relatively Mg enriched compared with the whole population of granitoids.

Many modern chemical analyses do not distinguish between ferric and ferrous iron. For this reason we define another variable $Fe^* = [FeO^{tot}/(FeO^{tot} + MgO)]$ that can be used with analyses that do not distinguish ferrous from ferric iron. In Fig. 1b we show the distinction between 486 A-type granitoids and 538 samples of Cordilleran granitoids using a plot of $FeO^{tot}/(FeO^{tot} + MgO)$ against wt % SiO_2. In this diagram, the boundary is shifted slightly so that it distinguishes as much as possible between the populations of A-type and Cordilleran granitoids. The boundary between the two rock types is not as precise in the Fe* diagram as it is with *Fe*-number. About 96% of the A-type granitoids lie above the line whereas about 83% of the Cordilleran granitoids lie below it. Furthermore, excursions across the line are not restricted to rocks with >70 wt % SiO_2 but occur over the whole range of SiO_2 content.

As has been demonstrated above, *Fe*-number is preferable in almost all granitoids where analyses of ferrous and ferric iron are available. One exception is in the classification of suites that show widely variable Fe^{3+}/Fe^{2+} because of late, subsolidus oxidation. In such rocks
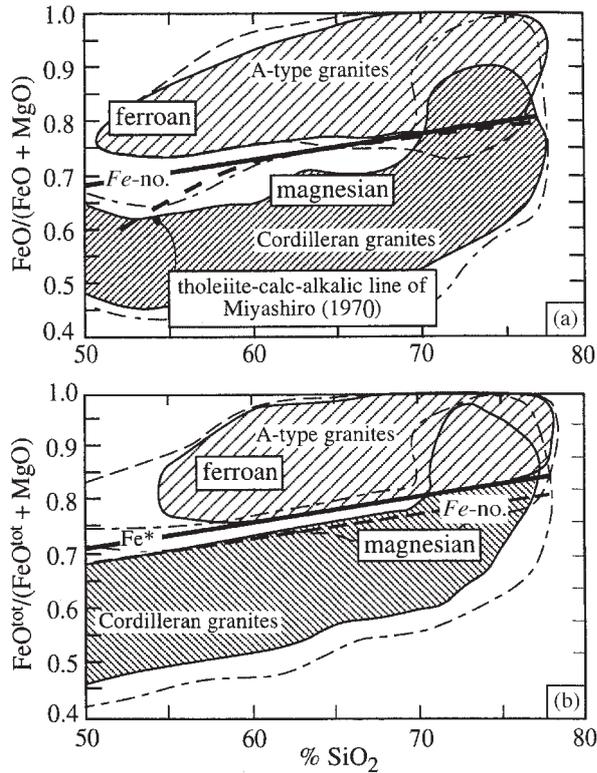
Fig. 1. (a) FeO/(FeO + MgO) vs weight per cent SiO$_2$ diagram showing the boundary between ferroan plutons and magnesian plutons. Boundary is based upon compositions of 175 A-type granitoids from western North America, Baltica, Africa and Australia, and 344 granitoids of the Mesozoic batholiths of North America. Patterned areas show where 95% of the analyses for each group lie; light dashed lines outline all the analyses of each group. Bold dashed line is the boundary between calc-alkalic and tholeiitic magmas defined by Miyashiro (1970). Equation of *Fe*-number line is: FeO/(FeO + MgO) = 0·446 + 0·0046 × wt % SiO$_2$. Sources of data, for A type: Eggler (1968), Barker *et al.* (1975), Collins *et al.* (1982), Salonsaari & Haapala (1994), Landenberger & Collins (1996), Duchesne & Wilmart (1997), King *et al.* (1997), Ferré *et al.* (1998), Smith *et al.* (1999); for Cordilleran granites: Larsen (1948), Bateman (1961), Hietanen (1963, 1976), Hotz (1971), Bateman & Chappell (1979), Hyndman (1984), Lewis *et al.* (1987), Liggett (1990), Sawaka *et al.* (1990), Tepper *et al.* (1993), Tate *et al.* (1999). (b) FeO^{tot}/(FeO^{tot} + MgO) vs weight per cent SiO$_2$ diagram showing the boundary between ferroan and magnesian plutons (continuous line). Boundary is based upon analyses of 486 A-type granites and of 538 Mesozoic batholiths from North America. Dashed line gives the boundary for iron and magnesian plutons based upon the FeO/(FeO + MgO) ratio. Fit to the Fe* line is FeO^{tot}/(FeO^{tot} + MgO) = 0·486 + 0·0046 × wt % SiO$_2$ Sources of data for A-type: same as in (a) and Anderson & Cullers (1978), Cullers *et al.* (1981, 1992), Anderson & Bender (1989), Kolker & Lindsley (1989) and Frost *et al.* (1999); for Cordilleran type: same as in (a) and Erikson (1969, 1977), Shuster & Bickford (1985), Ague & Brimhall (1988), Barth (1990) and Walawender *et al.* (1990).

the use of Fe* is preferable. In this paper we have used the Fe* diagram in our plots of leucogranites, A-type granitoids, and TTG (tonalitic, trondhjemitic, and granodioritic) gneisses because most available analyses do not distinguish between ferrous and ferric iron. In contrast, *Fe*-number is used our diagrams of Cordilleran and

Caledonian granitoids because a significant number of full analyses are available. Where we use the *Fe*-number diagrams we also show how the same analyses would plot on an Fe* diagram.

Modified alkali–lime index (MALI)

The secondary level of our scheme is based upon the alkali–lime classification of Peacock (1931). Peacock separated volcanic suites into four classes according to the alkali–lime index, that is, the SiO$_2$ content at which Na$_2$O + K$_2$O in a suite of lavas equalled CaO. Those suites that have an alkali–lime index >61 are calcic, those where it is between 56 and 61 are calc-alkalic, those where it is between 51 and 56 are alkali–calcic and those where it is <51 are alkalic. Although this scheme is widely used, it is difficult to apply except at silica values near where the intersection takes place. We extend it to a wider range in silica contents and reduce the three variables necessary for the classification (SiO$_2$, CaO, and Na$_2$O + K$_2$O) to two by introducing the variable Na$_2$O + K$_2$O – CaO. We call this variable the modified alkali–lime index (MALI). For any given suite, modified alkali–lime index increases with increasing weight per cent SiO$_2$; where MALI equals 0·0 the silica content is equivalent to the alkali–lime index of Peacock (1931).

Many comagmatic igneous suites show similar trends in a Na$_2$O + K$_2$O – CaO vs SiO$_2$ diagram. We have fitted the curves that bound the calcic, calc-alkalic, alkali–calcic, and alkalic fields so that the boundaries are parallel to common plutonic compositional trends and so that for each boundary MALI = 0·0 at the alkali–lime index defined by Peacock (1931). In Fig. 2 we compare these curves with well-studied plutonic suites that exemplify each of the fields. For ease of application we have included mathematical fits to these lines in the caption of Fig. 2. The fits have no statistical significance.

Aluminum saturation index (ASI)

The tertiary level of classification in our scheme is the aluminum saturation index (ASI) (Shand, 1943). This is defined as the molecular ratio Al/(Ca – 1·67P + Na + K). This expression of the ASI takes into account the presence of apatite, so that rocks that have ASI >1·0 are corundum-normative and are termed peraluminous (Zen, 1988). This means that they have more Al than can be accommodated in feldspars and that they must have another aluminous phase present. For weakly peraluminous rocks this phase may be aluminous biotite, but for more strongly peraluminous granites the phase can be muscovite, cordierite, garnet or an Al$_2$SiO$_5$ polymorph.
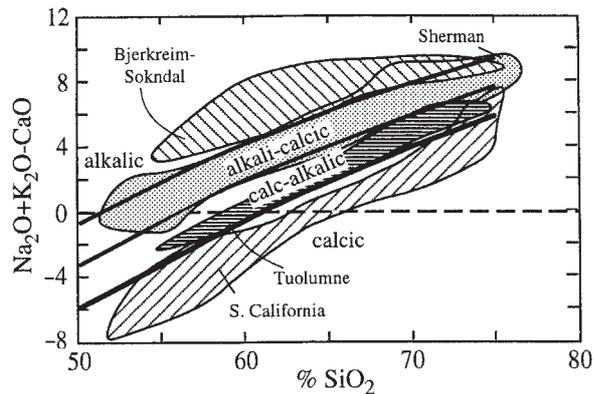
Fig. 2. Plot of $Na_2O + K_2O - CaO$ against SiO_2 showing the approximate ranges for the alkalic, alkali–calcic, calc-alkalic, and calcic rock series. Trends in the alkalic Bjerkreim–Sokndal intrusion (Duchesne & Wilmart, 1997), the alkali–calcic Sherman batholith (Frost *et al.*, 1999), the calc-alkalic Tuolumne series (Bateman & Chappell, 1979) and the calcic southern California batholith (Larsen, 1948) are shown for comparison. Fits to the boundaries are alkali to alkali–calcic: $Na_2O + K_2O - CaO = -41 \cdot 86 + 1 \cdot 112 \times$ wt % $SiO_2 - 0 \cdot 00572 \times$ wt % SiO_2^2, alkali–calcic to calc-alkalic: $Na_2O + K_2O - CaO = -44 \cdot 72 + 1 \cdot 094 \times$ wt % $SiO_2 - 0 \cdot 00527 \times$ wt % SiO_2^2, calc-alkalic to calcic: $Na_2O + K_2O - CaO = -45 \cdot 36 + 1 \cdot 0043 \times$ wt % $SiO_2 - 0 \cdot 00427 \times$ wt % SiO_2^2.

Although commonly taken to have formed from a sedimentary source (Chappell & White, 1974), strongly peraluminous melts may form by melting of biotite-bearing metaluminous felsic rocks (Miller, 1985) or even by water-excess melting of mafic rocks (Ellis & Thompson, 1986).

If ASI <1·0 but if molecular Na + K < molecular Al, then the rock is metaluminous. In such rocks there is likely to be excess Ca after aluminum has been accommodated in the feldspars. As a result, metaluminous rocks contain calcic phases such as hornblende and augite but lack either muscovite or sodic ferromagnesian phases. If ASI <1·0 and Na + K > Al, the rock is peralkaline. In these rocks there are more alkalis than are necessary to produce feldspar, which means that some alkali, particularly Na, must be accommodated in the ferromagnesian silicates. In weakly peralkaline rocks the alkali elements may go into hornblende, but the diagnostic minerals in strongly peralkaline rocks are the sodic amphiboles and pyroxenes.

Although we recognize three levels of the aluminum saturation index, these levels cannot apply equally to all the classes of the alkali–lime classification. For example, although calcic, calc-alkalic, and alkali–calcic rocks may be either metaluminous or peraluminous, they are not likely to be peralkaline. Likewise, alkalic rocks may be peralkaline or metaluminous, but they are not likely to have enough aluminum to be peraluminous.

The major granitoid groups

On the basis of the arguments given above, we divide the spectrum of granitoid compositions into 16 compositional groups. The ferroan and magnesian granitoids are each divided into four groups based upon the modified alkali lime index and each of these types is further divided into two groups based upon the aluminum saturation index (Table 1). Not all of these compositional types of granitoids are equally represented in nature. For instance, we have found very few examples of the ferroan calc-alkalic granitoids and no ferroan calcic granitoids.

The compositional ranges of the magnesian and ferroan granitoids are virtual mirror images of each other. The magnesian granitoids are most commonly calcic and calc-alkalic; there are fewer examples of magnesian alkali–calcic and alkalic granitoids. Indeed, the magnesian alkalic rocks listed on Table 1 are syenites, quartz syenites and nepheline syenites, and are not granites *senso stricto*. Conversely, with the ferroan granitoids calcic rocks are unknown, calc-alkalic rocks are rare, and alkali–calcic and alkalic rocks are abundant. In the magnesian granitoids, peraluminous compositions are most common among calc-alkalic rocks, though they are also represented in alkali–calcic granitoids and calcic granitoids, where they occur as cordierite-bearing tonalites and trondhjemites (Shimura *et al.*, 1992; Johnson *et al.*, 1997). Most of the ferroan series is metaluminous, but there are occurrences of peraluminous types that may be either alkali–calcic (Anderson & Thomas, 1985) or calc-alkalic (King *et al.*, 1997).

EXAMPLES OF GRANITOID TYPES
Peraluminous leucogranites

Most workers recognize that peraluminous leucogranites make up an important set of granitoid compositions. These granites have been called S-type (Chappell & White, 1974), syn-collisional granitoids (Pearce *et al.*, 1984), continental collision granitoids (Maniar & Piccoli, 1989), and muscovite–peraluminous granites (Barbarin, 1999). These rocks are muscovite-bearing, high-silica granites that occur as isolated plutons in the cores of overthickened metamorphic belts (see Le Fort, 1981). They are distinctive in that they typically are not associated with more mafic rocks. These leucogranites are thought to be generated by partial melting of metasedimentary rocks as a result of thermal relaxation and/or exhumation of the orogen (i.e. during the isothermal decompression part of clockwise pressure–temperature–time paths; England & Thompson, 1984).

As a group and as individual plutons, these granites span the whole range of granitoid compositions from magnesian to ferroan and from calcic to alkalic (Fig. 3).

Table 1: A geochemical classification scheme for granitoids

Fe-no. or Fe*: magnesian

MALI:	calcic		calc-alkalic		alkali–calcic		alkalic	
ASI:	metaluminous	peraluminous	metaluminous	peraluminous	metaluminous	peraluminous	metaluminous	peralkaline
Rock types	diorite, quartz diorite tonalite		diorite, monzodiorite, granodiorite		monzonite, syenite high K-granite		monzonite syenite granite	alkali fsp. syenite alkali fsp. granite
Occurrences	plutons on the outboard portions of Cordilleran batholiths plutons in island arcs plagiogranites		plutons in the main portion of Corderillan batholiths		plutons inboard from Cordilleran batholiths plutons associated with delamination of overthickened crust		plutons inboard from Cordilleran batholiths	
Examples	La Posta pluton (Walawender et al., 1990)	Cornucopia stock (Johnson et al., 1997)	Tuolumne suite (Bateman & Chappell, 1979)	N. Idaho batholith (Hyndman, 1984)	Ben Nevis (Haslam, 1968)	portions of the Vosges granites (Altherr et al., 2000)	Yamato Mtns (Zhao et al., 1995)	Shonkin Sag (Nash & Wilkinson, 1970)

Fe-no. or Fe*: ferroan

MALI:	calcic		calc-alkalic		alkali–calcic		alkalic	
ASI:	metaluminous	peraluminous	metaluminous	peraluminous	metaluminous	peraluminous	metaluminous	peralkaline
Rock types	none known	none known	granite	two-mica granite	ferrodiorite syenite, granite	two-mica granite	anorthosite ferrodiorite monzonite granite	alkali gabbro syenite alkali granite
Occurrences			some A-type plutons some granophyres in mafic plutons	some A-type plutons	A-type granites, granophyres associated with mafic dikes and plutons		within-plate plutons, plutons in cores of alkalic volcanoes	
Examples			Bunger Hills (Sheraton et al., 1992)	some Lachlan A-type granites (King et al., 1997)	Sherman batholith (Frost et al., 1999)	St. Vrain, Silver Plume (Anderson & Thomas, 1985)	Bjerkreim–Sokndal (Duchesne & Wilmart, 1997)	Na series of Pikes Peak (Smith et al., 1999)
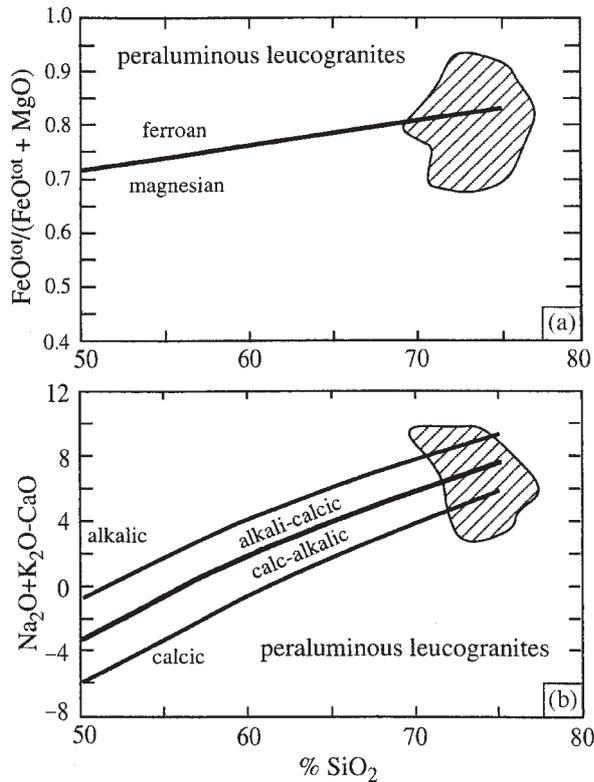
Fig. 3. $FeO^{tot}/(FeO^{tot} + MgO)$ vs wt % SiO_2 diagram (a) and $Na_2O + K_2O - CaO$ vs wt % SiO_2 diagram (b) showing the composition range of peraluminous leucogranites ($n = 90$). Data from: Le Fort (1981), Strong & Hamner (1981), Le Fort *et al.* (1987), Holtz & Barbey (1991), Nabelek *et al.* (1992), Inger & Harris (1993) and Searle *et al.* (1997).

Fig. 4. Composition range for 344 rocks from Cordilleran Mesozoic batholiths of North America. (a) $FeO/(FeO + MgO)$ vs wt % SiO_2 diagram. Dashed lines show where the same analyses would plot in terms of $FeO^{tot}/(FeO^{tot} + MgO)$. (b) $Na_2O + K_2O - CaO$ vs wt % SiO_2 diagram. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. Sources as in Fig. 1a.

The only consistent compositional features they share, as indicated by the name, are their high silica content and strongly peraluminous nature.

Cordilleran batholiths

Perhaps the most abundant granitoids on Earth are those that are the exposed plutonic parts of magmatic arcs. Most workers recognize these as a distinct geochemical type. This type is called volcanic arc granites (Pearce *et al.*, 1984), island arc and continental arc granitoids (Maniar & Piccoli, 1989), or amphibole-bearing calc-alkalic granites (Barbarin, 1999). Most of the rocks of this group are considered to be part of the I-type granitoids of Chappell & White (1974).

In our classification scheme, granitoids from the Cordilleran batholiths of western USA and northwestern Mexico are dominantly magnesian and are mostly calcic and calc-alkalic (Fig. 4). Rocks from individual plutons tend to plot in a relatively narrow range on a MALI diagram (Fig. 2). As a reflection of trends first observed by Moore (1959) and Bateman & Dodge (1970), calcic
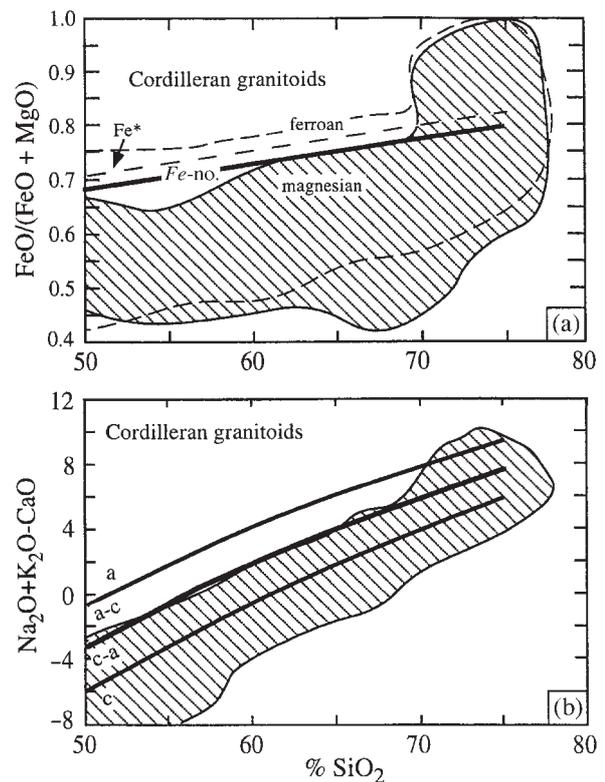
plutons tend to lie on the oceanward portion of batholithic belts, whereas calc-alkalic plutons lie inboard. Sparse alkali–calcic plutons lie even farther inboard (Anderson & Cullers, 1990; John & Wooden, 1990).

Most of the rocks that have <70 wt % SiO_2 are magnesian; many of them, such as the Tuolumne suite (Bateman & Chappell, 1979) have an *Fe*-number of <0·6. A small population of rocks with silica contents of >70 wt % are ferroan granitoids. In our database, there is a roughly equal proportion of metaluminous and peraluminous rocks. The metaluminous rocks tend to have a lower *Fe*-number, whereas the peraluminous rocks tend to have the higher *Fe*-number. In fact, all the ferroan granitoids from Cordilleran suites are peraluminous, as are all the rocks that are alkalic and alkali–calcic.

A-type granitoids

The distinctive potassic granites termed A-type by Loiselle & Wones (1979) differ from the granitoids of the Cordilleran batholiths (Fig. 5). The 'A-type' rocks are much more iron enriched and plot in the ferroan alkali–calcic
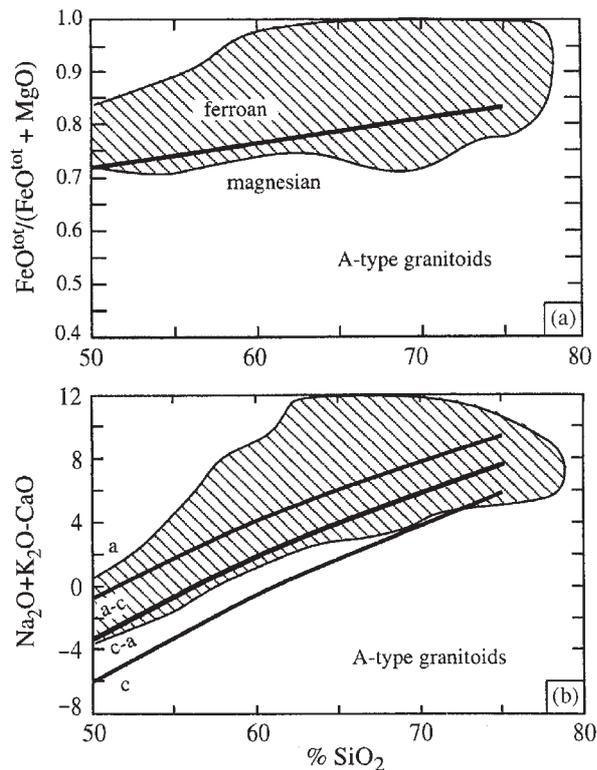
Fig. 5. The composition range for 486 samples from A-type batholiths. (a) $FeO^{tot}/(FeO^{tot} + MgO)$ vs wt % SiO_2 and (b) $Na_2O + K_2O - CaO$ vs wt % SiO_2. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. References as in Fig. 1b.

Fig. 6. The composition range for 135 Caledonian post-collisional plutons from Britain and Ireland. (a) $FeO/(FeO + MgO)$ vs wt % SiO_2. Dashed line shows where the analyses would plot in terms of $FeO^{tot}/(FeO^{tot} + MgO)$. (b) $Na_2O + K_2O - CaO$ vs wt % SiO_2. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. Sources: Gardiner & Reynolds (1931, 1937), Anderson (1937), Nicholls (1951), Hall (1966, 1972), Haslam (1968), Leake (1974), Sweetman (1987) and Weiss & Troll (1989).

and ferroan alkalic fields. A few suites, such as the charnockites of the Bunger Hills (Sheraton *et al.*, 1992) and the granophyres of Red Hill (McDougall, 1962) are ferroan calc-alkalic. The ferroan alkalic rocks also include monzonitic and syenitic rocks associated with anorthosites and layered mafic intrusions (Kolker & Lindsley, 1989; Scoates *et al.*, 1996; Duchesne & Wilmart, 1997). The late-stage portion of alkalic complexes such as Coldwell complex (Mitchell & Platt, 1978), the Gardar province (Ferguson, 1970), and the Monteregian province (Valiquette & Archambault, 1970) also plot into the ferroan–alkalic field.

Most of the A-type granitoids are metaluminous, although some, such as the sodic granites of the Nigerian province (Bowden & Turner, 1974), and portions of Pikes Peak (Smith *et al.*, 1999) and the Sherman batholiths (Frost *et al.*, 1999), are peralkaline. There are A-type granitoids that are peraluminous (Anderson & Thomas, 1985).

Caledonian granitoids

A fourth major type of granitic rocks consists of high-K alkali–calcic granitoids typified by the post-tectonic Caledonian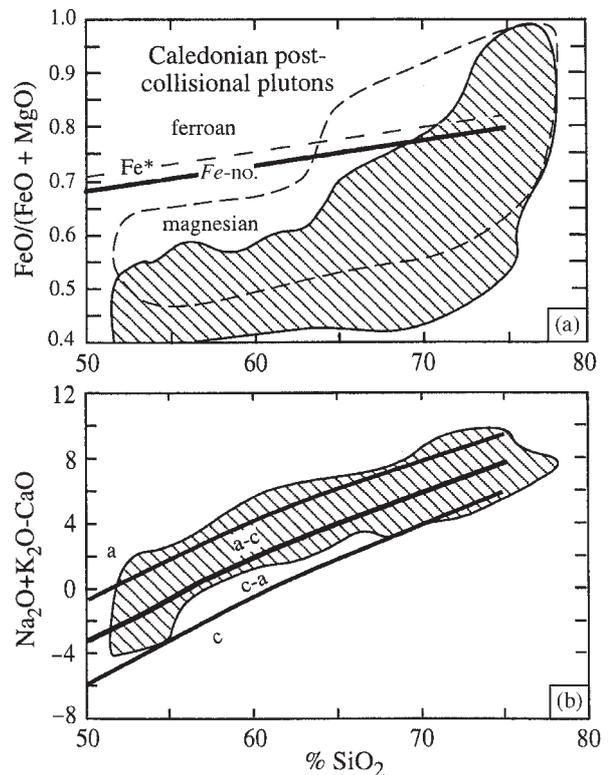 granitoids of Ireland and Britain. These plutons are commonly referred to as post-orogenic granitoids (Maniar & Piccoli, 1989), shoshonitic granitoids (Duchesne *et al.*, 1998; Liégeois *et al.*, 1998) and K-rich calc-alkaline granitoids (Barbarin, 1999). These rocks are predominantly alkali–calcic and magnesian, although at silica abundances >70% some of these granitoids are calc-alkalic. They are distinctive in their high potassium content and their lack of iron enrichment (Fig. 6). Most are metaluminous, although many of the most siliceous varieties are peraluminous.

Lachlan Fold Belt granitoids

Because of the many papers that have been written on the granitoids of the Lachlan Fold Belt (e.g. Chappell & White, 1974; Collins *et al.*, 1982; White & Chappell, 1983; King *et al.*, 1997), it is important to see how they fit into our classification (Fig. 7). In our classification, the S-type granitoids of the Lachlan Fold Belt are compositionally similar to the I-type. I-type granitoids are
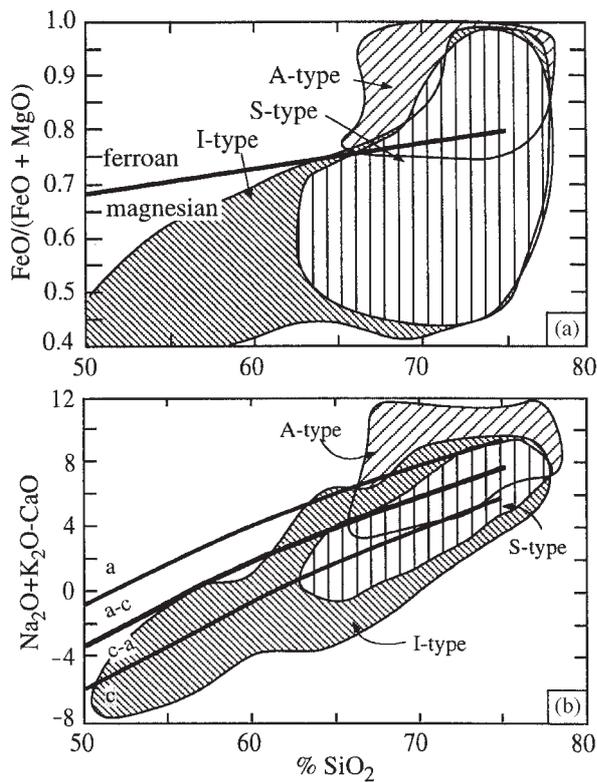
Fig. 7. (a) FeO/(FeO + MgO) vs wt % SiO$_2$ and (b) Na$_2$O + K$_2$O – CaO vs wt % SiO$_2$ plots showing the composition range for rocks from Lachlan Fold Belt. A-type $n = 67$; I-type $n = 1155$; S-type $n = 720$. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. Data from Landenberger & Collins (1996) and AGSO (Australian Geological Survey Organization) database (http://www.agso.gov.au/geo-chemistry/rockchem/).

Fig. 8. (a) FeO^{tot}/(FeO^{tot} + MgO) vs wt % SiO$_2$ and (b) Na$_2$O + K$_2$O – CaO vs wt % SiO$_2$ plots showing the composition range for rocks for Archean tonalitic gneisses. $n = 55$. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. Sources of data: Viljoen & Viljoen (1969), Barton (1975), Hurst *et al.* (1975) and Barker *et al.* (1979a, 1979b).

dominantly calc-alkalic and calcic; <1% are alkali–calcic. Both S- and I-type are dominantly magnesian, but, like the Mesozoic batholiths of western North America (Fig. 4), a considerable population of the silica-rich granitoids are ferroan. The major difference lies in the fact that the S-types are invariably peraluminous (by definition), whereas the I-types are mostly metaluminous. The A-type granitoids of the Lachlan Fold Belt are similar to A-type granitoids from other areas (Fig. 5), but they tend to be less iron enriched.

Archean TTG gneisses

Tonalitic, trondhjemitic, and granodioritic (TTG) gneisses are characteristic of the Archean eon and are typified by high Na$_2$O and low K$_2$O. In our classification, they are magnesian calcic and calc-alkalic granitoids, though a small number are alkali–calcic (Fig. 8). In this regard, they are different from tonalitic rocks of the
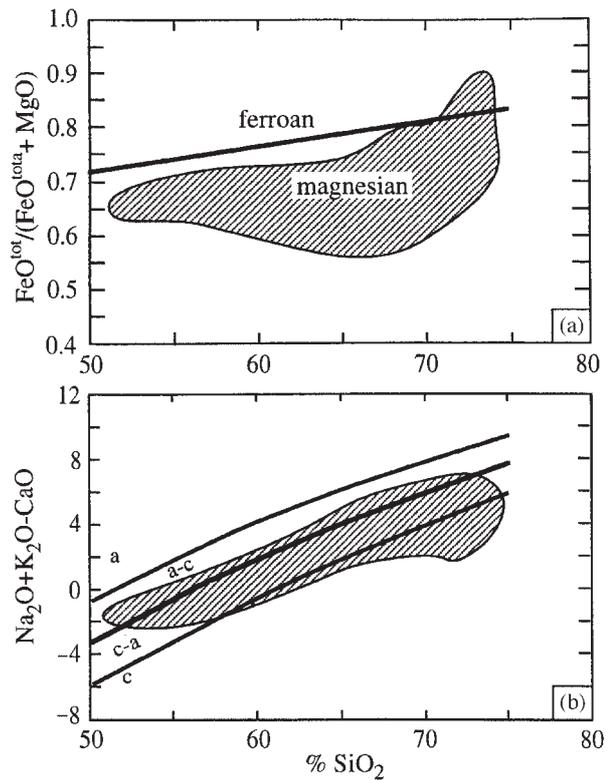
Mesozoic Cordilleran batholiths, which tend to plot entirely in the calcic field. Archean tonalites and trondhjemites have low K$_2$O (<3%) and high Na$_2$O (>4%), similar to tonalites in the Cordilleran batholiths (Fig. 9a), but their CaO is lower than Cordilleran TTG (Fig. 9b). This causes the MALI of Archean TTGs to be higher than in similar rocks from the Cordilleran batholiths.

DISCUSSION

The chemical discriminators used here are sensitive indicators of both the source regions of granitic magmas and the differentiation paths followed by these magmas. For example, the *Fe*-number is most strongly affected by the differentiation paths followed by the magmas. It has long been postulated that crystallization of anhydrous silicates drives a melt to higher Fe/(Fe + Mg) ratios, whereas the early crystallization of magnetite inhibits iron enrichment during differentiation (Osborn, 1959). This is well recorded in volcanic rocks where reduced basaltic rocks, such as tholeiites and alkali basalts, undergo reduction (i.e. iron enrichment in the silicates) during
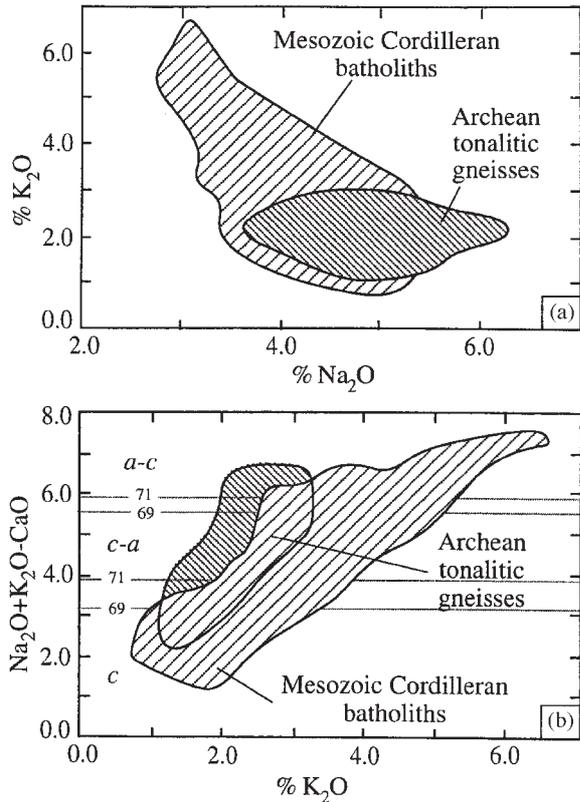
Fig. 9. (a) K_2O vs Na_2O and (b) $Na_2O + K_2O - CaO$ vs K_2O diagrams comparing the compositional trends of Archean tonalitic gneisses and Mesozoic granites of the Cordilleran batholiths for rocks with 69–71 wt % SiO_2. a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. The numbers refer to the position of the respective boundaries at that percentage of SiO_2. $n = 83$ for the Cordilleran batholiths; $n = 17$ for the Archean gneisses. Sources of data are the same as for Figs 1b and 8.

Fig. 10. $Na_2O + K_2O - CaO$ vs H_2O diagram showing the effect of pressure and the abundance of water on the composition of melt produced during experimental melting of a biotite gneiss and pelitic biotite–muscovite schist. Data from Holtz & Johannes (1991) (3 and 5 kbar) and Patiño Douce & Harris (1998) (6 and 10 kbar).

differentiation whereas the relatively oxidized basaltic rocks from arcs do not (Frost & Lindsley, 1991). This suggests that iron-enriched melts derived from reduced basaltic sources (either tholeiitic or mildly alkalic) make important contributions to ferroan granitoids (Frost & Frost, 1997). Magnesian granitoids in contrast are probably related to island arc magmas, which follow relatively oxidizing differentiation trends.

A secondary effect on *Fe*-number, which is seen particularly at high silica contents, is the composition of crustal melts. Peraluminous leucogranites show a wide range in *Fe*-number (Fig. 3), which is probably related to differences in source rock composition (Nabelek *et al.*, 1992), as well as the degree of melting (Holtz & Johannes, 1991; Patiño Douce & Beard, 1996; Patiño Douce & Harris, 1998). The incorporation of crustal melts with this wide range of *Fe*-number may be an explanation for the small population of ferroan Cordilleran granitoids and magnesian A-type granitoids that are found at high silica contents.
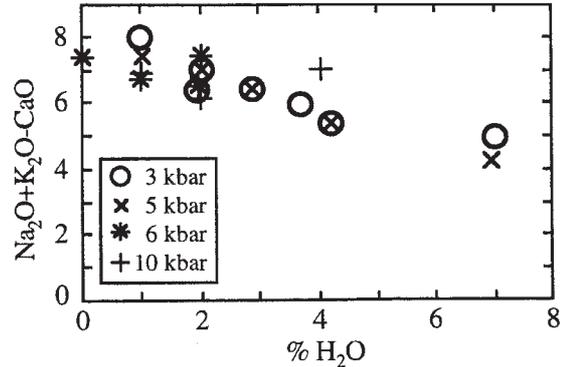
Variations in the modified alkali–lime index can be caused by either the sources or differentiation history of a magma. As noted above, the MALI for Cordilleran batholiths seems to be related to the source region for the parent melts, with the plutons becoming progressively more potassic (and alkalic) as one moves away from the subduction zone. At least a portion of this variation is likely to be contributed by a mantle-derived component, because this increase in K_2O away from a subduction zone is also seen in island arc lavas, where a continental contribution is lacking (Dickenson, 1975). The high MALI of Caledonian granites may also have a mantle contribution, because modern analogues of post-tectonic granites, the high-K lavas of the Tibetan plateau, are largely mantle derived (Arnaud *et al.*, 1992; Turner *et al.*, 1996).

The wide range in modified alkali–lime index from peraluminous leucogranites (Fig. 3) indicates that MALI can also be affected by the composition of crustally derived melt. The variation in MALI for peraluminous leucogranites seems to reflect differences in water pressure at the time of melting. Experimental melts produced from biotite gneiss (Holtz & Johannes, 1991) and pelitic biotite–muscovite schist (Patiño Douce & Harris, 1998) show a decreasing MALI with increasing water content (Fig. 10). This trend results because increasing water pressure produces increased melting of plagioclase at the expense of micas (Patiño Douce & Harris, 1998).

We have defined the trends on the MALI diagrams using a large number of granitic batholiths, which suggests that most granitoid plutons follow sub-parallel alkali–lime trends during differentiation. Thus one explanation for a suite of rocks that cross the trend lines shown in Fig. 2 would be that it involves mixing of more than one magma. It is also possible, however, that differentiation can cause a suite of rocks to become more alkalic.
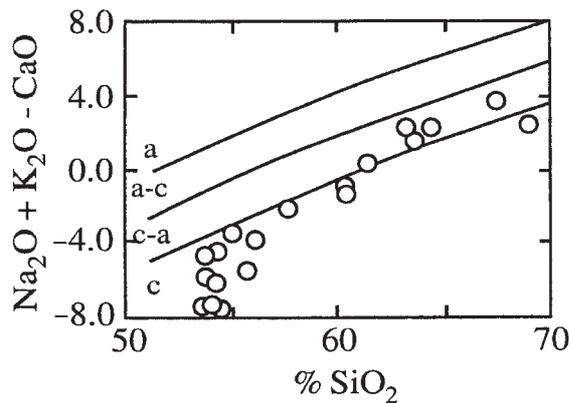
Fig. 11. $Na_2O + K_2O - CaO$ vs wt % SiO_2 diagram showing the change in MALI during differentiation of the Red Hill dolerites. a, alkalic; a-c, alkali–calcic; c-a, calc-alkalic; c, calcic. Data from McDougall (1962).

For example, extreme differentiation of calcic tholeiitic magmas usually results in calc-alkalic or alkali–calcic granites. This is particularly well shown by differentiation of the Red Hill dolerites (McDougall, 1962) (Fig. 11).

The aluminum saturation index is predominantly determined by the composition of the source region and the nature of the melting process. Although crystallization of olivine, pyroxenes, and hornblende clearly increases ASI of a magma and it is possible for small volumes of peraluminous magma to be produced in this way, the process is highly inefficient (Zen, 1986). This means that the ASI of a granitic rock is mostly a function of the sources of a magma, with peraluminous magmas formed from hydrous melting of mafic rocks (Ellis & Thompson, 1986) or by melting of pelitic or semi-pelitic rocks (Holtz & Johannes, 1991).

In our classification scheme, we use the term calc-alkalic in the manner that it was originally defined—to describe suites of rocks that show moderate enrichment in calcium over the alkalis (Peacock, 1931). Because there is a wide range of granites that may have this chemical property (see Table 1), we contend that the use of 'calc-alkalic' as a term to describe Cordilleran batholiths should be dropped. If one wishes to use a chemical (as opposed to a geographic) term to describe these rocks, it would be better to use 'calc-magnesian'. This term adequately indicates that the granitoids in the Cordilleran batholiths are calcic or calc-alkalic and that they lack marked iron enrichment.

Although the classification scheme presented here is entirely chemical, it can be construed to have tectonic implications. For example, ferroan granitoids reflect a close affinity to relatively anhydrous, reduced magmas and source regions. Such conditions are common in extensional environments. Because these magmas are also generally hotter, they are likely to undergo extensive fractionation toward iron-rich, alkalic compositions (Frost & Frost, 1997). In contrast, the magnesian series reflects a close affinity to relatively hydrous, oxidizing magmas and source regions (Frost & Lindsley, 1991), which is consistent with origins that are broadly subduction related. The leucogranites tend to be associated with over-thickened orogens; they are usually produced by small degrees of melting that is typically ascribed to a stage of crustal rebound, without any direct mantle contribution. However, it is possible, perhaps likely, that leucogranitic crustal melts make major contributions to the silica-rich magmas in other settings (Figs 4–6), leading to a significant mixing component in the trends used to define our compositional groupings.

It is important to note that there is no *a priori* reason that would restrict any particular granitoid type to any particular tectonic environment. This arises from the fact that the geochemical compositions of granitic magmas reflect the compositions of their source rocks rather than their tectonic setting (e.g. Pearce *et al.*, 1984). For example, the geochemical classification is not able to distinguish a granitoid formed in a subduction setting and one formed from source rocks that had been formed in an earlier subduction-related setting. Furthermore, many granitic systems are demonstrably open to a variety of chemical inputs. Thus, their geochemical features must reflect this variety of inputs, each of which may or may not be related to tectonic setting.

CONCLUSIONS

By using three straightforward chemical parameters we can distinguish among the commonly recognized granitoid types, without having to rely on presumed modes of formation or tectonic setting. In addition to serving as a means of classification, the scheme presented here also provides a means for using major element analyses of granite suites to better understand their origin and evolution. For example, the high *Fe*-number of ferroan granites probably reflects derivation from reduced basaltic rocks, by either fractional crystallization or partial melting (Frost & Frost, 1997). Similarly, the variation in MALI shown by peraluminous leucogranites probably reflects variations in water pressure in the source regions (Holtz & Johannes, 1991; Patiño Douce & Harris, 1998). We suggest that further study may explain what controls some of the other major element chemical trends we have identified. For example, why do plutonic suites with so many different chemical characteristics follow similar trends on a MALI–SiO_2 diagram (Fig. 2), whereas others, such as differentiated layered mafic intrusions (Fig. 11), do not? More detailed investigations into the causes of these various trends may provide petrologists with

important insights into the mineralogic controls of granitoid chemistry.

The proposed classification frees granite petrologists to discuss the compositional features of granitic rocks without recourse to either genetic or tectonic preconceptions. Such freedom will permit a more comprehensive view of granite petrogenesis and the remarkable range of processes and environments in which granitic rocks form.

ACKNOWLEDGEMENTS

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