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MAJOR ELEMENT CHEMISTRY AND TECTONIC
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ABSTRACT

MAJOR ELEMENT CHEMISTRY AND TECTONIC SETTING OF PLUTONIC ROCK SUITES

By

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Plutonic rock suites from compressional and extensional plate margins differ in major element chemistry and igneous petrogenesis. Comparisons among type examples of plutonic suites generated at the two types of plate margins show that extensional suites are more alkali enriched with respect to calcium and iron enriched with respect to magnesium than are compressional suites. Extensional suites have bimodal distributions of differentiation index and composition of normative plagioclase, whereas compressional suites have unimodal distributions. These differences may be related to extensive crustal melting and/or magma mixing in the generation of compressional suites, and limited melting and mixing in extensional suites. Extensional suites may also undergo melting and fractionation at lower water pressures. Comparison of possible compressional and extensional plutonic suites with criteria developed from the

comparison of type examples suggests that these criteria may be useful in the determination of tectonic setting.

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CHAPTER I

INTRODUCTION

It has long been recognized that igneous rock suites can be divided into two tectonic types, orogenic and anorogenic (see Barth, 1962, for review). Orogenic suites are associated with compressional tectonics, and commonly occur in fold belts. Anorogenic suites occur in areas of extensional tectonics, such as rift zones, or in areas of little or no tectonic activity.

In plate tectonics models, orogenic suites are generated in subduction zones at two types of compressional plate boundaries (Dickinson, 1971): ocean-ocean plate boundaries where oceanic lithosphere is subducted beneath oceanic lithosphere; and ocean-continent plate boundaries where oceanic lithosphere is subducted beneath continental lithosphere. A third type of compressional plate boundary is a continent-continent plate boundary. Due to the low density of continental lithosphere, subduction is restricted. Magmatism associated with continental collision, though discussed in general (Naylor, 1971; Gilluly, 1971; Dewey and Burke, 1973), has not been adequately evaluated due to the lack of unequivocal or easily accessible examples of collision generated suites.

Extensional (spreading) plate boundaries generate anorogenic suites, which are therefore common at newly formed continental margins or rift zones. Mantle plume activity may also generate anorogenic suites.

The relationship between tectonic setting and chemistry of volcanic rock suites has been well established (Martin and Piwinskii, 1972; Christiansen and Lipman, 1972). Also, plutonic suites have been compared with volcanic suites of known tectonic setting, thus allowing inferences to be made about the tectonic setting of the plutonic suites (Strong and Minatidis, 1975). However, there is a need to establish the direct relationships between tectonic setting and plutonic rock chemistry. The purpose of this paper is to document the chemical differences between plutonic rock suites associated with compressional and extensional plate boundaries, and to attempt to explain the differences in terms of current petrogenetic theories.

This research is concerned only with the major elements for reasons of economy and availability of data. Pearce and Cann (1973), Miyashiro (1975), and Strong and Minatidis (1975) have shown that trace elements are potential indicators of tectonic setting.

Previous Work

Martin and Piwinskii (1972) first quantitatively evaluated the relationship between the tectonic setting and chemistry of igneous rock suites. They distinguished orogenic and anorogenic volcanic suites on the basis of the frequency distribution on the differentiation index, DI (DI = normative Q + Or + Ab + Ne + Lc + Kp; Thornton and Tuttle, 1960). They showed that the DI frequency distributions of orogenic suites are unimodal with an intermediate mode, whereas those of anorogenic suites are bimodal with acidic-basic modes. They used AFM diagrams to show that anorogenic suites have stronger iron enrichment trends than do orogenic suites. They also showed that anorogenic suites contain more compositional scatter in variation diagrams of weight percent oxides versus DI.

Christiansen and Lipman (1972) used the alkali-lime index (ALI) to distinguish the two tectonic types of volcanic suites in the western U.S.A. The ALI (after Peacock, 1931) is a single value that characterizes a suite based on the variation of $CaO/Na_2O + K_2O$ versus SiO_2. The ALI is the value of SiO_2 for which $CaO/Na_2O + K_2O$ is equal to 1.00. They noted that orogenic volcanic suites have higher ALI values than do anorogenic volcanic suites. They also noted that the volcanic suites changed from unimodal (intermediate) to bimodal (acidic-basic), and related this to the change in tectonic setting that occurred when compression changed to extension about 30 million years ago.

Strong and Minatidis (1975) used the ALI to compare a plutonic suite with the volcanic suites of Lipman and Christiansen (1972) to establish a tectonic setting for the plutonic suite. Their use of AFM diagrams was limited by the fact that they did not compare their data with plutonic suites from extension zones.

Johnston et al. (1976) have attempted to distinguish granitic rocks from two types of tectonic settings. They concluded that extensional suites have alumina undersaturation, high FeO, and low MgO and CaO, whereas compressional suites have alumina oversaturation, low FeO, and high MgO and CaO.

Characteristics of Compressional and Extensional Plutonic Suites

General structural and compositional differences between compressional and extensional plutonic suites can be determined by examining Mesozoic-Cenozoic occurrences of plutonic rock suites of known tectonic setting.

Mesozoic-Cenozoic compressional suites are long, linear belts parallel to plate margins. Regional metamorphism is often associated in space and time with the forceful emplacement of the plutons. The suites are predominately intermediate in composition (quartz diorite-tonalite-granodiorite-quartz monzonite) with relatively minor amounts of ultrabasic, basic, acidic, and alkalic rocks. However, the sequence in a suite associated with a subduction zone is generally basic rocks first, with the intermediate rocks becoming more significant with time, and acidic rocks late (Larsen, 1948; Jakes and White, 1971, 1972; Presnall and Bateman, 1973).

Mesozoic-Cenozoic extensional suites often occur as local, spot-like complexes. Block faulting, cauldron subsidence, ring dikes, and cone sheets in subvolcanic complexes are common. If regional metamorphism is present, the emplacement of the plutonic suites follows the metamorphic event. End-member compositions (basic, acidic, and alkalic) predominate in extensional suites. Ultrabasic rocks are more common than in compressional suites. In quartz oversaturated rocks, intermediate compositions are relatively minor, except locally. Intermediate silica compositions may be significant as quartz undersaturated rocks. Coexisting acidic-basic magmas are relatively common, often as net-veined complexes. Carbonatites may be locally prominent in some extensional environments (MacIntyre, 1977).

Complications in the distinction of tectonic settings arise in those areas where both compression and extension occur in close proximity (time and/or space). Bussell et al. (1976) have described ring complexes at high crustal levels in the Peruvian Coastal Batholith, which is a compressional suite associated with subduction (Hamilton, 1969a). The nature of ring complexes requires extension, suggesting that both compression and extension have occurred in the same environment. Back-arc spreading in island arc complexes (Oxburgh and Turcotte, 1971; Karig, 1971) may produce a similar type of problem.

CHAPTER II

CHEMICAL CHARACTERISTICS OF PLUTONIC SUITES

Approach and Methodology

Published analyses of plutonic rocks were selected to evaluate chemical criteria for the distinction of extensional and compressional suites. The major source of data is a computer based set of igneous rock analyses compiled by Eastern Washington State College (Mutschler, Rougon, and Lavin, 1976a,b).

"Type" examples of plutonic rock suites were selected on the basis of published work on tectonic setting. The Sierra Nevada, Southern California, and Aleutian-Alaska Batholiths were selected to represent type examples of compressional suites (Hamilton, 1969a,b; Dickinson, 1970; Reed and Lanphere, 1973; Lanphere and Reed, 1973). Iceland, East Greenland (Tertiary), and the British Isles (Tertiary) were selected to represent type examples of extensional suites (Morgan, 1971, 1972; Brooks, 1973a,b; Einarsson, 1973).

Other suites were also investigated to evaluate the use of chemical criteria in determining the tectonic setting of plutonic suites. Possible compressional suites selected were the Boulder Batholith (Kistler, 1974), the Hercynian granites of the British Isles (Riding, 1974), and the South Mountain Batholith (McKenzie and Clarke, 1975). Possible extensional suites selected were the White Mt. Magma Series (Morgan, 1971), the Younger Granites of Nigeria (Bowden, 1970), and the Keweenawan plutonic rocks (Chase and Gilmer, 1973; Sims, 1976).

Table 1 lists the age, total number of samples, and abbreviation for each of the suites. Figure 1 shows the locations of the suites.

TABLE 1.--List of Suites.

Suite Code*	N#	Name	Age
ARA	138	Aleutian-Alaska Batholith	M-T
BIT	164	British Isles Tertiary	T
BLB	106	Boulder Batholith (Montana)	M
COR	058	Hercynian Granites (British Isles)	P
EGL	061	East Greenland Tertiary	T
ISL	104	Iceland	C
KEW	086	Keweenawan Plutonic Rocks	P€
NIG	089	Younger Granites of Nigeria	M
PSM	074	South Mt. Batholith (Nova Scotia)	P
SCB	087	Southern California Batholith	M
SRN	302	Sierra Nevada Batholith	M
WMT	094	White Mt. Magma Series	M

Ages: C = Cenozoic T = Tertiary M = Mesozoic
P = Paleozoic P€ = Precambrian

* Abbreviations from Mutschler et al. (1976b)

Number of plutonic rocks

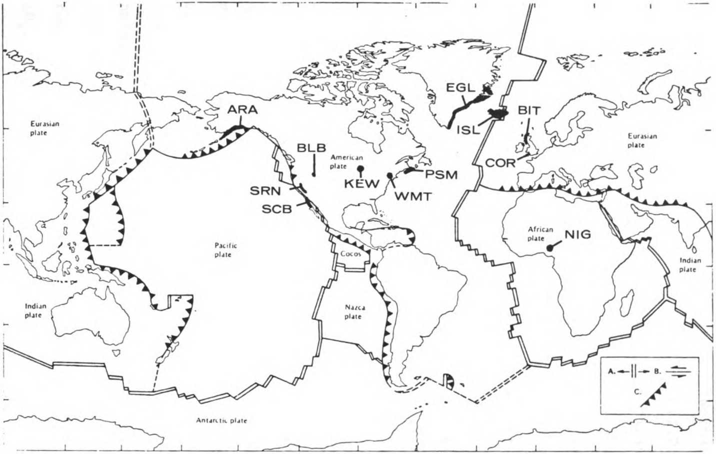


Figure 1.--Location map of suites (modified from Sawkins et al., 1974). Suite abbreviations are listed in Table 1.

Data

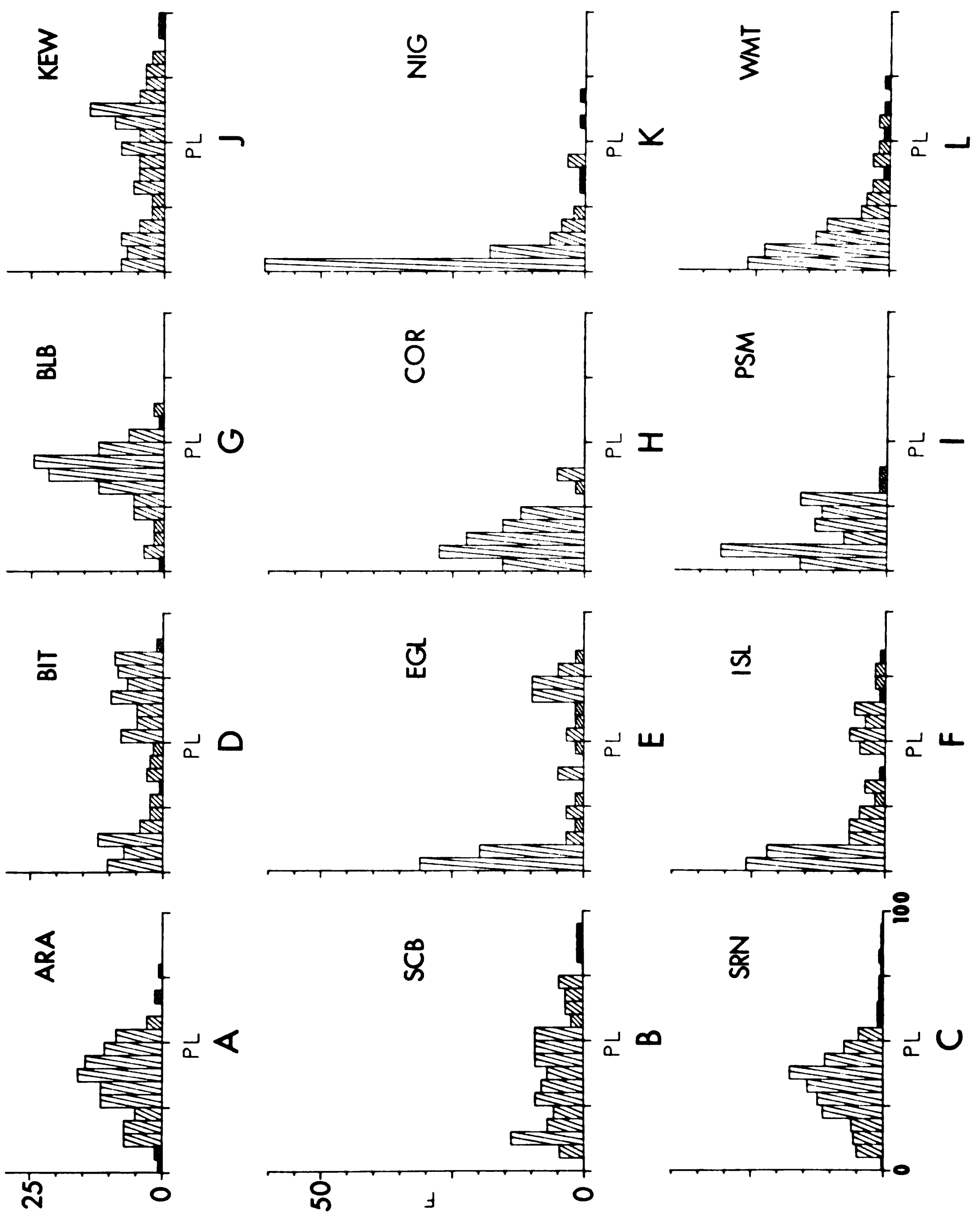
Data were taken as weight percent oxides and recalculated to 100 percent (anhydrous). Normative minerals were calculated using a modified C.I.P.W. norm computer program. Several petrochemical indicators were also calculated, including the differentiation index (DI), alkali-lime index (ALI), and types of alumina saturation.

Several types of variation diagrams were used in an attempt to distinguish the two types of suites. Simple variation diagrams of weight percent oxides versus SiO_2, DI, or Larsen Index (Larsen Index = 1/3 SiO_2 + K_2O - CaO - FeO - MgO; Larsen, 1948) do not show clear differences between the two types of suites.

Histograms were used to illustrate the relative frequency distributions of the DI (Figures 2a-l) and the composition of the normative plagioclase, PL (Figures 3a-l). Comparison of the type compressional suites (Figures 2a-c, 3a-c) with the type extensional suites (Figures 2d-f, 3d-f) shows that the compressional suites have unimodal distributions with intermediate modes whereas the extensional suites have bimodal distributions with acidic-basic modes. Other types of relative frequency distributions were examined (for example, SiO_2, Larsen Index), but DI and PL are preferred because they indicate more clearly the differences between the two types of suites.

Figure 2.--Relative frequency distributions of DI: (a-c) type compressional suites, (d-f) type extensional suites, (g-i) possible compressional suites, (j-l) possible extensional suites. DI is the differentiation index (Thornton and Tuttle, 1960), and is given in class intervals of five. F is the relative frequency in percent. Suite abbreviations are listed in Table 1.

Figure 3.--Relative frequency distributions of PL: (a-c) type compressional suites, (d-f) type extensional suites, (g-i) possible compressional suites, (j-l) possible extensional suites. PL is the composition of the normative plagioclase in percent anorthite, and is given in class intervals of five. F is the relative frequency in percent. Suite abbreviations are listed in Table 1.


25
0
50
F
0
0
100
ARA
A
BIT
D
BLB
G
KEW
J
SCB
B
EGL
E
COR
H
NIG
K
SRN
C
ISL
F
PSM
I
WMT
L
PL

The alkali-lime index (ALI) is a useful classification of suites. The ALI values were determined in two ways. Smooth curves of $CaO/Na_2O + K_2O$ versus SiO_2 were hand-drawn, and a visual estimate of the value of SiO_2 for which the curve intercepts a ratio value of 1.00 was made. Also, third order "best fit" curves were calculated using SPSS subprogram Regression (Nie et al., 1975). Table 2 presents the ALI values for the suites. Third order equations were used to balance goodness of fit and simplicity. The data were edited for the use of samples with $CaO/Na_2O + K_2O$ less than 4.00, because the region of interest is for values near 1.00, and inclusion of higher values compresses the scale so that investigation of the desired area is difficult. Values for the Hercynian and South Mt. suites were not reported because of lack of appropriate compositional range that produces geologically unreasonable ALI values (less than 0 or greater than 100) or r^2 values that indicate poor fit (r^2 less than .5). Comparison of the type examples shows that compressional suites have ALI values that are high (60-64), whereas extensional suites have values that are low (50-56). This indicates that extensional suites are more alkali enriched with respect to calcium than are compressional suites.

AFM ternary diagrams also distinguish the two tectonic types of suites (Figures 4a-d). Comparison of

TABLE 2.--ALI Values for Plutonic Suites.

Suite Code	N*	Published Value #	Visual Estimate	Third Order Calculated	Mult. r^2 for calc.
ARA	135	-	61	61.6	.82
BIT	105	-	56	55.0	.91
BLB	105	58	58	59.1	.91
COR	$	-	-	-	-
EGL	043	-	50	50.9	.62
ISL	094	-	55	56.0	.97
KEW	076	-	52	50.8	.57
NIG	088	-	52	49.7	.85
PSM	$	-	-	-	-
SCB	078	64	64	63.5	.94
SRN	291	60,63@	62	61.4	.88
WMT	093	-	53	51.6	.71

* Data edited for use of $CaO/Na_2O + K_2O$ of less than 4.000 (see accompanying text)

\# From Kistler (1974)

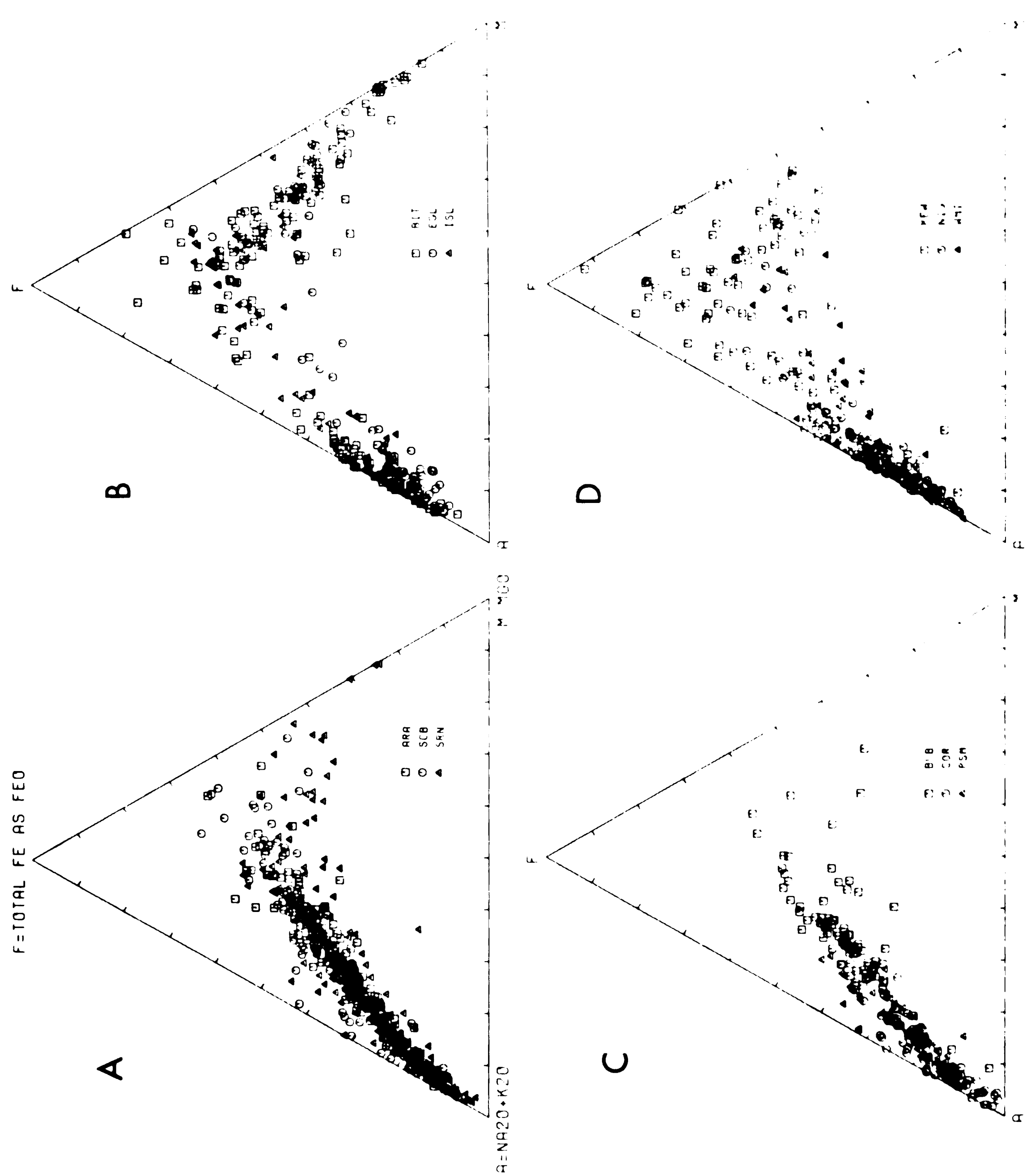
$ ALI not determined (see accompanying text)

@ 60 for the central SRN
63 for the western SRN

the type examples shows that extensional suites (Figure 4b) have stronger iron enrichment trends than do compressional suites (Figure 4a). The extensional trend tends to be closer to and more nearly parallel to the AF side at compositions approaching the A apex, whereas the compressional trend tends to be more nearly perpendicular to the FM side for the entire trend. Considerable overlap does occur.

Degrees of alumina saturation are determined by comparisons of the molecular proportions of Al_2O_3,

Figure 4.--AFM ternary diagrams: (a) type compressional suites, (b) type extensional suites, (c) possible compressional suites, (d) possible extensional suites.

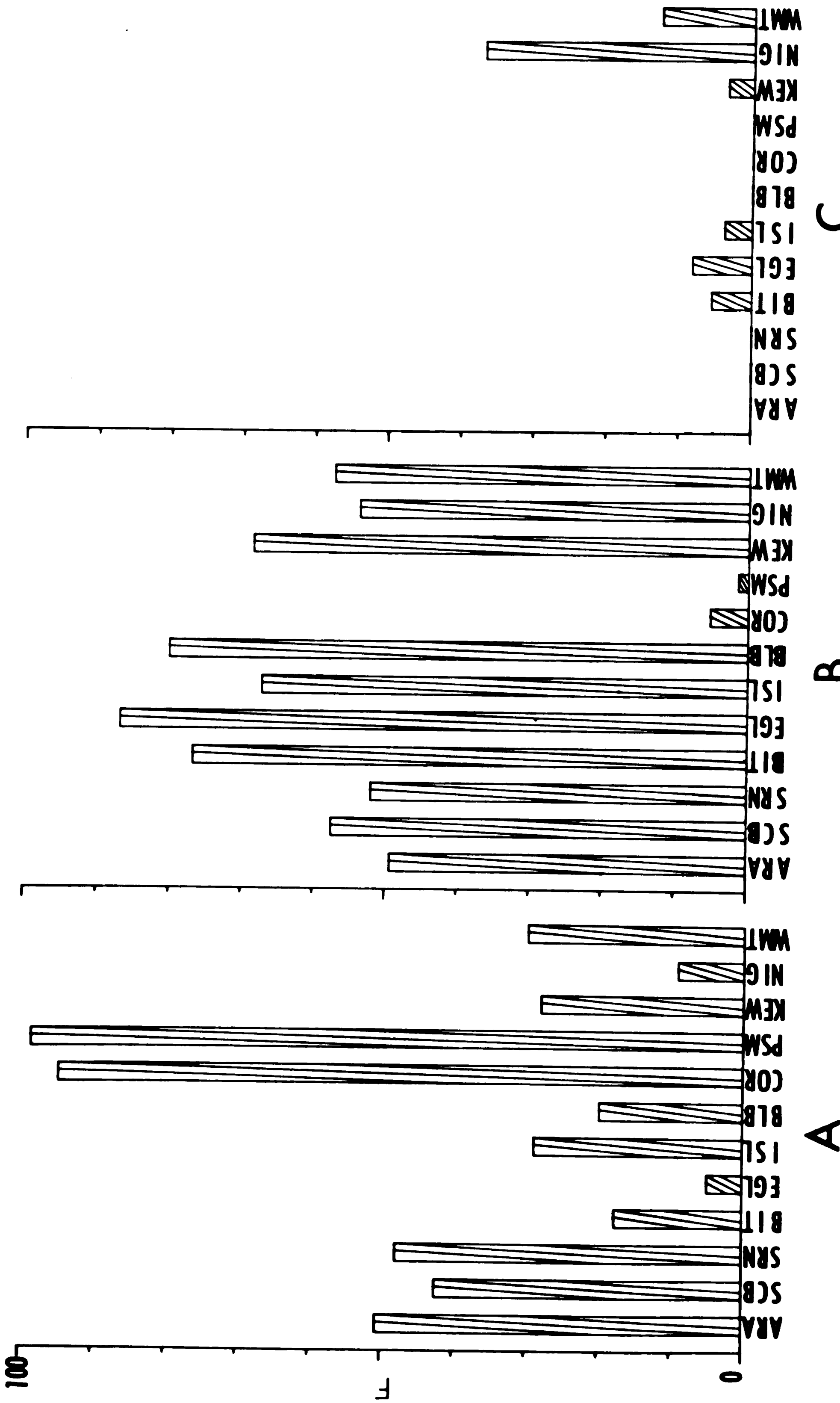


A
B
C
D
F=TOTAL FE AS FEO
A=NA2O+K2O
M=MGO
ARA
SCB
SAN
RIT
EGL
ISL
BIB
COR
PSM

$Na_2O + K_2O$, and $CaO + Na_2O + K_2O$ (Shand, 1927; Carmichael, Turner, and Verhoogen, 1974). Three main alumina saturation types may be considered. Peraluminous rocks have Al_2O_3 greater than $CaO + Na_2O + K_2O$ (molecular). Metaluminous rocks have Al_2O_3 greater than $Na_2O + K_2O$, but less than $CaO + Na_2O + K_2O$. Peralkaline rocks have Al_2O_3 less than $Na_2O + K_2O$. Peraluminous rocks are characterized by corundum in the norm, whereas metaluminous rocks are characterized by anorthite in the norm. Peralkaline rocks may have acmite, sodium silicate, or potassium silicate in the norm. Figure 5 presents the relative frequency distributions of the alumina saturation types of the suites. Comparison of type examples shows that only extensional suites have peralkaline rocks (Figure 5c). Compressional suites tend to have higher frequencies of peraluminous rocks (Figure 5a), whereas extensional suites tend to have slightly higher frequencies of metaluminous rocks (Fibure 5b). The variation in alumina saturation appears to be more due to variations in CaO and $Na_2O + K_2O$ than in Al_2O_3. Al_2O_3 versus DI or SiO_2 variation diagrams show that both types of suites have similar Al_2O_3 (also compare Table 3).

An attempt was made to evaluate the mean differences of variables for samples in a particular interval of SiO_2 (70.00-75.00 weight percent). This

Figure 5.--Relative frequency distributions of alumina saturation types: (a) peraluminous, (b) metaluminous, (c) peralkaline. F is the relative frequency in percent. Suite abbreviations are listed in Table 1.


A
B
C
ARA
SCB
SRN
BIT
EGL
ISL
BLB
COR
PSM
KEW
NIG
WMT
F
0
100

interval was selected because it is useful in the analysis of granites, and in some areas, granites are the predominant rock type. There is a need to distinguish granites from compressional and extensional environments. Tukey's test (Snedecor and Cochran, 1974) was used to test the equality of means for several variables for two type suites from each tectonic setting. Twenty samples were randomly selected from the appropriate interval for each of the four suites (exact results require equal sample sizes). Table 3 presents the results of the test. Compressional suites have higher CaO, and extensional suites have higher DI and total alkalies. Extensional suites are more alkali enriched with respect to calcium and iron enriched with respect to magnesium than are compressional suites, as shown by the differences in the two ratios in Table 3. Because the DI includes albite and orthoclase, but not anorthite, the difference in DI may also be related to the differences in CaO and $Na_2O + K_2O$. These results are consistent with those previously discussed (ALI, AFM) in showing alkali and iron enrichment in extensional suites.

Comparisons of the possible compressional and extensional suites may be useful in determining how well the suites fit their postulated settings, and how useful the chemical criteria (established by comparison

TABLE 3.--Comparison of Means of Variables for SiO_2 Interval 70.00-75.00%.

	BIT		ISL		ARA		SCB		
DI	88.87	a	91.97	a	83.10	b	83.34	b	**
Al_2O_3	13.34	a	13.23	a	14.90	b	13.95	a	
Fe_2O_3	1.23	b	1.90	a	0.73	b	1.14	b	
FeO	1.97	a,c	0.79	d	1.13	c	1.56	a,d	
MgO	0.31	a,b	0.22	a	0.52	b	0.54	b	
CaO	1.24	a	0.86	a	2.40	b	2.22	b	**
Na_2O	3.79	a,b	4.35	a	4.09	a,b	3.53	b	
K_2O	4.78	a	4.08	a,b	2.62	c	3.41	b	
TiO_2	0.29	a	0.26	a	0.25	a	0.26	a	
$Na_2O + K_2O$	8.57	a	8.40	a	6.68	b	6.91	b	**
$CaO/Na_2O + K_2O$	0.152	a	0.104	a	0.382	b	0.342	b	**
FeO*/FeO* + MgO	0.907	a	0.928	a	0.791	b	0.829	b	**

Suites with the same letter show no significant difference for that variable at $\alpha = .05$ with Tukey's test.

* FeO = total iron as FeO

** variable suitable for distinction of compressional and extensional suites

of type suites) are in unambiguously determining the tectonic setting of plutonic rock suites.

A comparison of the relative frequency distributions of DI and PL of the possible compressional suites shows that the Boulder Batholith (Figures 2g, 3g) resembles the type examples with an intermediate, unimodal distribution, whereas the Hercynian suite (Figures 2h, 3h) and the South Mt. Batholith (Figures 2i, 3i) have unimodal distributions that are skewed toward the acidic end-members. Comparison of the possible extensional suites shows that the Keweenawan suite (Figures 2j, 3j) is similar to the type examples in having a bimodal distribution, whereas the Nigerian suite (Figures 2k, 3k) and the White Mt. Magma Series (Figures 2l, 3l) have acidic modes that predominate over the basic "modes" of the suites such that the distributions appear unimodal with acidic distributions. The White Mt. and Nigerian suites differ from the Hercynian and South Mt. suites in that the latter suites lack basic rocks.

Comparison of ALI values for "possible" suites (Table 2) shows that the Keweenawan, White Mt., and Nigerian suites are consistent with extension in having ALI in the 50-56 range. The Boulder Batholith has an ALI (58) that is intermediate between type examples of compressional and extensional suites. ALI values were not reported for the Hercynian or South Mt. Batholith suites because these suites lack the appropriate compositional range.

Comparison of AFM ternary diagrams for the possible compressional and extensional suites (Figures 4c and 4d, respectively) shows that the suites are consistent with their postulated tectonic setting. Although the Keweenawan trend does not fall as close to the AF side as the type extensional suites, it does define a strong iron enrichment trend.

Comparison of alumina saturation frequency distributions for the possible compressional and extensional suites with those of the type examples (Figures 5a-c) shows that the Keweenawan, Nigerian, and White Mt. suites are consistent with extension in having peralkaline rocks, and relatively low frequencies of peraluminous rocks. The Hercynian and South Mt. suites are consistent with compression in lacking peralkaline rocks, and having high frequencies of peraluminous rocks for the Hercynian and South Mt. suites are higher than for type suites. The Boulder Batholith is anomalous in resembling extensional suites in having low frequencies of peraluminous rocks, but resembling compressional suites in lacking peralkaline rocks. Metaluminous frequencies do not appear to be useful in that considerable overlap of the possible suites suggests that both types of environments have about the same distributions of metaluminous rocks.

Considering the data as a whole, the type examples show clear differences between compressional and extensional suites. Application of the criteria to the other suites produces many exceptions. However, the Keweenawan suite is consistent with extension. The Younger Granites of Nigeria and the White Mt. Magma Series are consistent with extension, except for the relative lack of basic rocks. The Boulder Batholith is consistent with compression, except for enrichment in alkalies that causes it to fall in anomalous positions for ALI and alumina saturation. The Hercynian granites of the British Isles and the South Mountain Batholith are consistent with compression except for the skewness of the frequency distributions of DI and PL to the acidic end-members, and higher frequencies of peraluminous rocks.

CHAPTER III

DISCUSSION OF PETROGENESIS OF PLUTONIC SUITES

Compressional Suites

Three regions of melting are present in subduction zones: the subducted oceanic lithosphere, the overlying mantle wedge, and the overlying crustal complex (oceanic or continental).

Melting of the upper portion of the subducted oceanic lithosphere has been proposed by many workers (for example, Fitton, 1971; Boettcher, 1973; Marsh and Carmichael, 1974; Younker and Vogel, 1976), but melting may be limited by the heat sink effect of endothermic dehydration reactions (Anderson et al., 1976). Frictional heating (Turcotte and Schubert, 1973) appears to be the most significant source of heat for dehydration or melting. Wyllie et al. (1976) have reviewed experimental evidence on the compositions of magmas derived by melting of the downgoing slab, and have concluded that the magmas are of intermediate composition, but are not primary andesite or tonalite. Subducted sediments, if present, may also melt to produce granitic magmas (Huang and Wyllie, 1973).

The mantle wedge overlying the downgoing slab may melt in response to two main processes: (1) water derived from the dehydration of the downgoing slab lowers the solidus temperatures of the mantle material (Wyllie, 1971), and (2) water and/or magma derived from the slab reduces the density of the mantle material which produces diapiric uprise and melting in the rising diapirs by adiabatic decompression (Ringwood, 1975). The composition of the liquids produced depends, in part, upon the water content. Higher water contents drive the composition of the liquids toward more intermediate compositions (Ringwood, 1975; Yoder, 1976: Wyllie et al., 1976).

The overlying crustal complex may be melted by the heat transported by the rising mantle derived magmas (Younker and Vogel, 1976). Melting of most crustal rocks produces magmas that are generally granitic in composition. Granites represent the minimum melting composition, whereas melting at temperatures higher than the minimum produces more intermediate compositions (Tuttle and Bowen, 1958; Winkler, 1976; Brown, 1970, 1973; Fyfe, 1973; Presnall and Bateman, 1973).

Alternative heat sources for melting are decay of radiogenic heat elements and conduction from the hotter underlying mantle, but Younker (1974) has shown that only large amounts of mantle derived magmas can supply the heat necessary for significant amounts of crustal melting. Other factors to be considered are the lowering of solidus temperatures by non-hydrostatic stress or introduction of volatiles from below. The former has yet to be quantitatively evaluated (Yoder, 1976). The latter is a possibility in light of the dehydration of the downgoing slab in subduction zones, and needs further evaluation.

Two alternatives that account for the predominately intermediate composition and unimodal distribution of plutonic suites generated at compressional plate margins are:

1) Crustal derived magmas mix in varying proportions with mantle derived magmas to produce magmas of intermediate composition (Younker and Vogel, 1976). Magma mixing has been demonstrated to be a viable petrogenetic process by Eichelberger (1975) and Anderson (1976). Mixing may be promoted by deformation.

2) Compositionally intermediate magmas are derived by the melting of crustal rocks at temperatures higher than the minimum melting temperatures. Equilibrium fusion events of this type followed by fractional crystallization of the magmas have been

proposed by Presnall and Bateman (1973) to account for the spectrum of rock types observed in the Sierra Nevada Batholith.

Both of these processes may operate, but both are dependent upon large amounts of heat for crustal melting, which according to Younker (1974) can only be supplied by the flux of mantle derived magmas.

Extensional Suite

Gravitational instabilities in the mantle result in the diapiric uprise of hot mantle material. When rising mantle diapirs impinge upon the lower crust, rifting may begin (Morgan, 1971, 1972; Burke and Wilson, 1976). Melting in the rising mantle material produces predominately basaltic liquids (Ringwood, 1975).

The composition of basaltic liquids produced by melting is controlled by pressure, volatiles, and the degree of melting. Alkalic liquids are produced at greater depths (higher pressures) than are tholeiitic liquids (Ringwood, 1975; Yoder, 1976). Melting in the presence of high water pressures drives the composition toward more intermediate compositions (Ringwood, 1975; Yoder, 1976; Wyllie et al., 1976), whereas melting in the presence of high CO_2 pressures drives the composition of the liquids toward more alkalic, quartz undersaturated compositions (Yoder, 1976; Wyllie and Huang, 1976). Small degrees of melting produce alkalic liquids, whereas moderate degrees of melting tend to produce tholeiitic liquids (Ringwood, 1975; Yoder, 1976).

Compressional suites have tholeiitic to andesitic basalts, whereas extensional suites have alkalic to tholeiitic basalts, suggesting that the extensional suites have mantle derived liquids produced by smaller degrees of melting at higher total and CO_2 pressures than those associated with compressional suites.

Fractional crystallization of basaltic magmas may also be important, and some of the alkalic basaltic rocks in extensional zones may represent liquids modified by the high pressure fractionation of orthopyroxenes, which produces alkalic, quartz undersaturated basaltic liquids (Ringwood, 1975; Yoder, 1976). These alkalic basalts may be fractionated at crustal levels to produce syenitic rocks.

If a sufficient flux of magma intrudes the overlying crust, melting of the crustal rocks will produce granitic liquids (Younker, 1974). The differences of rock type distributions between compressional and extensional suites may be due to either greater degrees of magma mixing or greater degrees of crustal melting at temperatures higher than the minimum melting temperature in compressional areas. Coexisting acidic and basic magmas appear to have been common in extensional areas, whereas evidence for mixing of the magmas in minor. The lack of mixing may be related to the tectonics of the areas, because in extensional areas, the magmas are passively emplaced. However, in compressional areas, deformation may tend to mix the magmas.

A consequence of the quiet tectonic environment is that in some of the extensional zones, fractionation of basic liquids may occur, producing layered gabbroic complexes. Wager and Brown (1967) have reviewed the nature of layered gabbroic complexes. Strong iron enrichment trends in these complexes is evidence for fractionation at low water pressures. Only minor amounts of granitic liquids are produced by the fractionation of these magmas. In extensional areas where granitic rocks are abundant, they are most likely produced by the melting of crustal rocks, and not by the fractionation of basic magmas (for example, Dunham and Thompson, 1967).

The production of syenitic rocks by the fractionation of basaltic magmas, combined with the generation of granitic rocks by melting of crustal rocks, accounts for the coexistence of quartz oversaturated and undersaturated rocks in some complexes (Chapman, 1976). Chapman (1976) also suggested that minor mixing of the syenitic and granitic magmas could produce small amounts of alkali granites and quartz syenites in the same complexes.

The granitic rocks in extensional zones are iron and alkali enriched when compared with granitic rocks in compressional zones. Smaller degrees of melting at lower water pressures in extensional zones may account for these differences. Brown and Fyfe (1970) have shown that the initial granitic magmas formed by fusion of crustal rocks associated with muscovite breakdown at relatively low temperatures are low in MgO. Bowden (1970) suggests that the alkali enriched rocks in Nigeria are the initial crustal melting products, whereas less alkali enriched rocks are products of more extensive melting.

If extensional granitic rocks represent more limited crustal melting than do compressional granitic rocks, there may be a major thermal difference between the two types of plate margins. The analysis of Younker (1974) shows that higher heat flux is required for more extensive melting, and that the heat flux may be related to the flux of mantle derived magmas through the crust. Compressional suites may therefore represent suites generated in areas of higher heat flux of mantle derived magmas, or flux over more extended periods of time. Extensional suites may have a shorter time of residence over the region of high heat flux, and after the crust moves off the area of rifting (and high heat flow), magma generation is greatly reduced.

Suites That Depart From Type Examples

The comparison of the possible compressional and extensional suites with the type examples has shown that certain inconsistencies exist for the possible suites. These inconsistencies suggest that the petrogenesis of these suites departs from the petrogenesis of the type examples.

The Boulder Batholith is consistent with type compressional suites except that is slightly more alkalic. This may be due to the variation in the source rock that was melted to produce the suite (Kistler, 1974). Alternatively, the difference may be related to the depth of the subduction zone, in a manner analogous to that suggested by Dickinson and Hatherton (1967) for the variation in K_2O. The Boulder Batholith is further to the east ("inland") of the postulated plate margin than the other western U.S.A. batholiths.

The Hercynian granites and the South Mt. Batholith are consistent with type compressional suites except for the predominance of silica rich and alumina oversaturated rocks. Two alternatives may be considered to account for these differences. First, Paleozoic subduction may have been fundamentally different from Mesozoic-Cenozoic subduction. Second, the nature of the differences suggests a larger crustal component in their petrogenesis.

McKenzie and Clarke (1975) describe the South Mt. Batholith as post-tectonic, but generated in response to the Acadian orogeny. This batholith may have formed by predominately crustal fusion caused by crustal thickening and heating due to continental collision. Both of these hypotheses remain to be tested.

The White Mt. Magma Series and the Younger Granites of Nigeria are consistent with type extensional suites except that the acidic modes predominate over the basic modes in the relative frequency distributions of DI and PL. In the case of the White Mt. Magma Series, the basic rocks may lie concealed at depth (Chapman, 1976). The Nigerian suite has no appreciable amount of basic rocks associated with it (Wright, 1970). The lack of basic rocks in these suites suggests that mantle derived magmas may have solidified at the mantle-crust interface where the granitic magmas were generated. The rise of these granitic magmas produced predominately acidic suites. An alternative is that the granitic magmas were generated by heat flow from the mantle without the emplacement of mantle derived magmas. Younker (1974) concluded that heat flow by conduction without penetration by mantle derived magmas is not a likely source of crustal melting.

CHAPTER IV

CONCLUSIONS

The major element chemistry of plutonic suites indicates some trends that may be used to distinguish compressional and extensional plutonic suites. The chemical criteria that most clearly show the differences between the two tectonic types of suites are:

1) Frequency distributions of DI and PL show that unimodal (intermediate) distributions are characteristic of compressional suites, whereas bimodal (acidic-basic) distributions are characteristic of extensional suites. Unimodal acidic distributions may be ambiguous.
2) Alkali-lime index (ALI) values for extensional suites are in the range 50-56, whereas ALI values for compressional suites are in the range 60-64. The intermediate range (56-60) may be ambiguous.
3) AFM ternary diagrams show that extensional suites have stronger iron enrichment trends than do compressional suites.

4) Peralkaline rocks are characteristic of extensional suites, whereas compressional suites tend to have higher frequencies of peraluminous rocks. Metaluminous rocks are common in both suites. Differences in alumina saturation appear to be more controlled by CaO and $Na_2O + K_2O$ than by Al_2O_3.

The use of single criteria to determine tectonic setting may give ambiguous results. Several criteria should be used, as consistent results from several indicators assure the best estimate of the tectonic setting of a plutonic rock suite. Conflicting results from different criteria suggest that the petrogenesis of the suite is different from those suites selected as type examples. Thus, these criteria may also be valuable in determining areas of unique petrogenesis.

Ambiguous results may also occur because of the lack of proper sampling. Frequency diagrams can only work when the total areal distribution is evaluated. Variation diagrams are successful only if the complete compositional spectrum is sampled.

There are several petrogenetic differences between extensional and compressional suites. Compressional suites have more intermediate rock types due to more extensive melting of the continental crust (or arc complex in island arcs). Extensional suites have acidic-basic associations due to limited melting and mixing. Insome areas, extensional plutonic suites appear unimodal due to the lack of rise of mantle derived magmas from the mantle-crust boundary, where granitic magmas are generated to eventually form predominately acid complexes.

Extensional suites are more alkalic than compressional suites due to the depth of origin of the basic magmas and the small degrees of melting of the crust to form acidic magmas. Syenitic rocks are most likely formed by fractionation of the basic magmas, whereas granitic rocks are most likely formed by melting of crustal rocks. Iron differences are probably due to the higher water pressures and degrees of melting in compressional areas, which produce less iron enrichment than in extensional areas, where water pressures and degrees of melting are lower.

REFERENCES

REFERENCES

Anderson, A.T. "Magma mixing: Petrological Process and Volcanological Tool," J. Volc. Geotherm. Res., 1, 3-33, 1976.

Anderson, R.N., Uyeda, S., and Miyashiro, A. "Geophysical and Geochemical Constraints at Converging Plate Boundaries - Part I: Dehydration in the Downgoing Slab," Geophys. J. Roy. Astron. Soc., 44, 333-357, 1976.

Barth, T.F.W. Theoretical Petrology, Second Edition, 416 pp., John Wiley & Sons, New York, 1962.

Boettcher, A.L. "Volcanism and Orogenic Belts - The Origin of Andesites," Tectonophysics, 17, 223-240, 1973.

Bowden, P. "Origin of the Younger Granites of Northern Nigeria," Contrib. Mineral. Petrol., 25, 153-162, 1970.

Brooks, C.K. "Tertiary of Greenland - A Volcanic and Plutonic Record of Continental Break-up," in Arctic Geology, edited by M.G. Pitcher, Amer. Assoc. Petrol. Geol. Mem., 19, 150-160, 1973a.

Brooks, C.K. "Rifting and Doming in Southern East Greenland," Nature Phys. Sci., 244, 23-25, 1973b.

Brown, G.C. "A Comment on the Role of Water in the Partial Fusion of Crustal Rock," Earth Planet. Sci. Lett., 9, 355-358, 1970.

Brown, G.C. "Evolution of Granite Magmas at Destructive Plate Margins," Nature Phys. Sci., 241, 26-28, 1973.

Brown, G.C., and Fyfe, W.S. "The Production of Granitic Melts During Ultrametamorphism," Contrib. Mineral. Petrol., 28, 310-318, 1970.

Burke, K.C., and Wilson, J.T. "Hot Spots on the Earth's Surface," Sci. Amer., 235, 46-57, 1976.

Bussell, M.A., Pitcher, W.S., and Wilson, P.A. "Ring Complexes of the Peruvian Coastal Batholith: A Long-standing Subvolcanic Regime," Can. J. Earth Sci., 13, 1020-1030, 1976.

Carmichael, I.S.E., Turner, F.J., and Verhoogen, J. Igneous Petrology, 739 pp., McGraw-Hill, New York, 1974.

Chapman, C.A. "Structural Evolution of the White Mountain Magma Series," Geol. Soc. Amer. Mem., 146, 281-300, 1976.

Chase, C.G., and Gilmer, T.H. "Precambrian Plate Tectonics: The Midcontinent Gravity High," Earth Planet. Sci. Lett., 21, 70-78, 1973.

Christiansen, R.L., and Lipman, P.W. "Cenozoic Volcanism and Plate-tectonic Evolution of the Western United States. II. Late Cenozoic," Phil. Trans. Roy. Soc. London, Ser. A, 271, 249-284, 1972.

Dewey, J.F., and Burke, K.A. "Tibetan, Variscan, and Precambrian Basement Reactivation: Products of Continental Collision," J. Geol., 81, 683-692, 1973.

Dickinson, W.R. "Relations of Andesites, Granites, and Derivative Sandstones to Arc-trench Tectonics," Rev. Geophys. Space Phys., 8, 813-860, 1970.

Dickinson, W.R. "Plate Tectonic Models for Orogeny at Continental Margins," Nature, 232, 41-42, 1971.

Dickinson, W.R., and Hatherton, T. "Andesitic Volcanism and Seismicity Around the Pacific," Science, 157, 801-803, 1967.

Dunham, A.C., and Thompson, R.N. "The Origin of Granitic Magmas - Skye and Rhum," Geol. Soc. Australia J., 14, 339-343, 1967.

Eichelberger, J.C. "Origin of Andesite and Dacite: Evidence of Mixing at Glass Mountain in California and at Other Circum-Pacific Volcanoes," Geol. Soc. Amer. Bull., 86, 1381-1391, 1975.

Einarsson, T. "Geology of Iceland," in Arctic Geology, edited by M.G. Pitcher," Amer. Assoc. Petrol. Geol. Mem., 19, 171-175, 1973.

Fitton, J.G. "The Generation of Magmas in Island Arcs," Earth. Planet. Sci. Lett., 11, 63-67, 1971.

Fyfe, W.S. "The Generation of Batholiths," Tectonophysics, 17, 273-283, 1973.

Gilluly, J. "Plate Tectonics and Magmatic Evolution," Geol. Soc. Amer. Bull., 82, 2383-2396, 1971.

Hamilton, W. "The Volcanic Central Andes - A Modern Model for the Cretaceous Batholiths and Tectonics of Western North America," in Proceedings of the Andesite Conference, edited by A.R. McBirney, Oregon Dept. Geology and Mineral. Bull., 65, 175-184, 1969a.

Hamilton, W. "Mesozoic California and the Underflow of the Pacific Mantle," Geol. Soc. Amer. Bull., 80, 2409-2430, 1969b.

Huang, W.L., and Wyllie, P.J. "Melting Relations of Muscovite-Granite to 35 kbar as a Model for Fusion of Metamorphosed Subducted Oceanic Sediments," Contrib. Mineral. Petrol., 42, 1-14, 1973.

Jakes, P., and White, A.J. "Composition of Island Arcs and Continental Growth," Earth Planet. Sci. Lett., 12, 224-230, 1971.

Jakes, P., and White, A.J.R. "Major and Trace Element Abundances in Volcanic Rocks of Orogenic Areas," Geol. Soc. Amer. Bull., 83, 29-39, 1972.

Johnston, J.S., Mutschler, F.E., and Barr, D. "Granites and Granites - A Statistical Investigation of Paleo Stress Gauges," Geol. Soc. Amer. Abstr. Programs, 8, 943, 1976.

Karig, D.E. "Origin and Development of Marginal Basins in the Western Pacific," J. Geophys. Res., 76, 2542-2561, 1971.

Kistler, R.W. "Phanerozoic Batholiths in Western North America: A Summary of Some Recent Work on Variations in Time, Space, Chemistry, and Isotopic Compositions," Ann. Rev. Earth Planet. Sci., 2, 403-418, 1974.

Lanphere, M.A., and Reed, B.L. "Timing of Mesozoic and Cenozoic Plutonic Events in Circum-Pacific North America," Geol. Soc. Amer. Bull., 84, 3773-3782, 1973.

Larsen, E.S., Jr. "Batholith and Associated Rocks of Corona, Elsinore, and San Luis Rey Quadrangles, Southern California," Geol. Soc. Amer. Mem., 29, 182 pp., 1948.

MacIntyre, R.M. "Anorogenic Magmatism, Plate Motion, and Atlantic Evolution," J. Geol. Soc. London, 133, 375-384, 1977.

Marsh, B.D., and Carmichael, I.S.E. "Benioff Zone Magmatism," J. Geophys. Res., 79, 1196-1206, 1974.

Martin, R.F., and Piwinskii, A.J. "Magmatism and Tectonic Settings," J. Geophys. Res., 77, 4966-4975, 1972.

McKenzie, C.B., and Clarke, D.B. "Petrology of the South Mountain Batholith, Nova Scotia," Can. J. Earth Sci., 12, 1209-1218, 1975.

Miyashiro, A. "Volcanic Rock Series and Tectonic Setting," Ann. Rev. Earth Planet. Sci., 3, 251-269, 1975.

Morgan, W.J. "Convection Plumes in the Lower Mantle," Nature, 230, 42-43, 1971.

Morgan, W.J. "Deep Mantle Convection Plumes and Plate Motions," Amer. Assoc. Petrol. Geol. Bull., 56, 203-213, 1972.

Mutschler, F.E., Rougon, D.J., and Lavin, O.P. "Petros--A Data Bank of Major-Element Chemical Analyses of Igneous Rocks for Research and Teaching," Computers and Geosciences, 2, 51-57, 1976a.

Mutschler, F.E., Rougon, D.J., and Lavin, O.P. "Petros: A Data Bank of Major-Element Chemical Analyses of Igneous Rocks for Research and Teaching (version 2.1)," Dept. Geol., Eastern Washington State College, Cheney, Washington, 1976b.

Naylor, R.S. "Acadian Orogeny: An Abrupt and Brief Event," Science, 172, 558-560, 1971.

Nie, N.H., Hull, C.H., Jenkins, J.G., Steinbrenner, K., and Bent, D.H. SPSS: Statistical Package for the Social Sciences, Second Edition, 675 pp., McGraw-Hill, New York, 1975.

Oxburgh, E.R., and Turcotte, D.L. "Origin of Paired Metamorphic Belts and Crustal Dilation in Island Arc Regions," J. Geophys. Res., 76, 1315-1327, 1971.

Peacock, M.A. "Classification of Igneous Rock Series," J. Geol., 39, 54-67, 1931.

Pearce, J.A., and Cann, J.R. "Tectonic Setting of Basic Volcanic Rocks Determined Using Trace Element Analyses," Earth Planet. Sci. Lett., 19, 290-300, 1973.

Presnall, D.C., and Bateman, P.C. "Fusion Relations in the System $NaAlSi_3O_8$-$CaAl_2Si_2O_8$-$KAlSi_3O_8$-SiO_2-H_2O and Generation of Granitic Magmas in the Sierra Nevada Batholith," Geol. Soc. Amer. Bull., 84, 3181-3203, 1973.

Reed, B.L., and Lanphere, M.A. "Alaska-Aleutian Range Batholith: Geochronology, Chemistry, and Relation to Circum-Pacific Plutonism," Geol. Soc. Amer. Bull., 84, 2583-2610, 1973.

Riding, R. "Models of the Hercynian Foldbelt," Earth Planet. Sci. Lett., 24, 125-135, 1974.

Ringwood, A.E. Composition and Petrology of the Earth's Mantle, 617 pp., McGraw-Hill, New York, 1975.

Sawkins, F.J., Chase, C.G., Darby, D.G., and Rapp, G., Jr. The Evolving Earth: A Text in Physical Geology, 477 pp., MacMillan, New York, 1974.

Shand, S.J. The Eruptive Rocks, 488 pp., Wiley, New York, 1927.

Sims, P.K. "Precambrian Tectonics and Mineral Deposits, Lake Superior Region," Econ. Geol., 71, 1092-1127, 1976.

Snedecor, G.W., and Cochran, W.G. Statistical Methods, Sixth Edition, 593 pp., Iowa State Univ. Press, Ames, 1974.

Strong, D.F., and Minatidis, D.G. "Geochemistry and Tectonic Setting of the Late Precambrian Holyrood Plutonic Series of Eastern Newfoundland," Lithos, 8, 283-295, 1975.

Thornton, C.P., and Tuttle, O.F. "Chemistry of Igneous Rocks: I. Differentiation Index," Amer. J. Sci., 258, 664-684, 1960.

Turcotte, D.L., and Schubert, G. "Frictional Heating of the Descending Lithosphere," J. Geophys. Res., 78, 5876-5886, 1973.

Tuttle, O.F., and Bowen, N.L. "Origin of Granite in Light of Experimental Studies in the System $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O," Geol. Soc. Amer. Mem., 74, 153 pp., 1958.

Wager, L.R., and Brown, G.M. Layered Igneous Rocks, 588 pp., Freeman, San Francisco, 1967.

Winkler, H.G.F. Petrogenesis of Metamorphic Rocks, Fourth Edition, 334 pp., Springer-Verlag, New York, 1976.

Wright, J.B. On: "Origin of the Younger Granites of Northern Nigeria," by P. Bowden, Contrib. Mineral. Petrol., 29, 89-90, 1970.

Wyllie, P.J. "Role of Water in Magma Generation and Initiation of Diapiric Uprise in the Mantle," J. Geophys. Res., 76, 1328-1338, 1971.

Wyllie, P.J., and Huang, W.L. "High CO_2 Solubilities in Mantle Magmas," Geology, 4, 21-24, 1976.

Wyllie, P.J., Huang, W.L., Stern, C.R., and Maaløe, S. "Grantic Magmas: Possible and Impossible Sources, Water Contents, and Crystallization Sequences," Can. J. Earth Sci., 13, 1007-1019, 1976.

Yoder, H.S., Jr. Generation of Basaltic Magma, 265 pp., National Academy of Sciences, Washington, D.C., 1976.

Younker, L.W. "Role of Mantle Derived Magmas in the Production of Crustal Melts," Ph.D. thesis, 72 pp., Michigan State Univ., E. Lansing, MI, 1974.

Younker, L.W., and Vogel, T.A. "Plutonism and Plate Dynamics: The Origin of Circum-Pacific Batholiths," Can. Mineral., 14, 238-244, 1976.