Tectonic discrimination of granitoids

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ABSTRACT

Granitoids as categorized by tectonic environment are (1) island arc granitoids (IAG), (2) continental arc granitoids (CAG), (3) continental collision granitoids (CCG), (4) post-orogenic granitoids (POG), (5) rift-related granitoids (RRG), (6) continental epeirogenic uplift granitoids (CEUG), and (7) oceanic plagiogranites (OP). Of these, the IAG, CAG, CCG, and POG are considered orogenic granitoids, and the RRG, CEUG, and OP are considered anorogenic granitoids.

The discrimination of granitoids is based on the major-element chemistry. Various discrimination plots are presented which sequentially discriminate the different tectonic environments. OP are separated from all other granitoids on the K_2O versus SiO_2 plot. Discrimination between group I (IAG + CAG + CCG), group II (RRG + CEUG), and group III (POG) granitoids can be achieved by using plots of Al_2O_3 versus SiO_2, FeO(T)/[FeO(T) + MgO] versus SiO_2, and AFM and ACF ternary diagrams. In the figures, group I and group II plot in individual fields. Identification of group III is different, in that group III does not have a unique field in which it plots. Group III is identified because it consistently displays characteristics of both group I and group II. Further discrimination within group I can be accomplished on the basis of Shand's index. Only CCG have A/CNK [AL_2O_3/(CaO + Na_2O + K_2O)] values greater than 1.15. It is not possible to discriminate between IAG and CAG. Further discrimination within group II is done using the TiO_2 versus SiO_2 plot.

The proposed discrimination scheme is applied to the Proterozoic granitoids of the midcontinent of the United States. It is shown that the Arbuckle granitoids are *not* anorogenic as previously thought.

INTRODUCTION

In this paper, we will attempt to show that the mineralogy and chemistry of granitoids can be successfully used to characterize the tectonic environment. The terminology used in this paper is described in Appendix 1. We have avoided using the I-, S-, A-, M-, or magnetite-, ilmenite-type classification of granitoid rocks because there exists considerable confusion in their definition and characteristics. Our classification of tectonic environments and the granitoid rocks selected to represent them is given in Appendix 2. The chemical and mineralogical data available on these suites of rocks form the data base for this paper.

METHOD OF STUDY

The existing literature was surveyed to identify suites of granitoid rocks with well-documented tectonic environments. Data for these granitoid rocks were collected and separated into three groups: (1) modal data, (2) major-element geochemical data, and (3) trace-element geochemical data. Because of our focus on granitoid rocks, mafic rocks were excluded from each of the above groups by using only modal data with greater than 2% modal quartz and major- and trace-element geochemical data for samples with greater than 60 wt. % SiO_2.

The data collected were adjusted in the following manner.

TABLE 1. GRANITOIDS AND TECTONIC ENVIRONMENT

Tectonic environment	Locality	References
1. Island arc	Papua New Guinea–Solomon Islands (21, 65)*	Griffin (1979), Johnson and Jaques (1980), Mason and Heaslip (1980), Mason and McDonald (1978), Whalen (1985)
2. Continental arc	Sierra Nevada batholith (101, 107)	Bateman (1983), Bateman and Chappell (1979), Bateman and Dodge (1970), Bateman and Lockwood (1970), Bateman and Wones (1972), Bateman and others, (1963), Hietanen (1973), Dodge and Moore, (1968), Miller (1977, 1978), Noyes and others (1983)
	Idaho batholith (54, 57)	Hyndman (1983, 1984), Shuster and Bickford (1985), Taubeneck (1971)
3. Continental collision	North and High Himalayas (59, 15)	Le Fort (1975a, 1975b, 1981), Cocherie (1976), Ghose and Singh (1977), Ferrara and others, (1983), Hamet and Allegre (1976), Vidal and others, (1982), Honegger and others (1982), Scharer and others (1986), Blattner and others (1983), DeBon and others (1986)
	South Brittany (24, 0)	Le Metour (1978), Strong and Hanmer (1981)
4. Post-orogenic	Egypt (66, 62)	Greenberg (1981a, 1981b, Hussein and others (1982), El-Gaby and others (1975), Rogers and others (1978), Rogers and Greenberg (1981a, 1981b)
5. Rift related	Oslo rift (61, 31)	Oftedahl (1978), Barth (1944), Neumann (1974, 1976, 1978), Neumann and others (1977), Petersen (1978), Schonwandt and Petersen (1983), Ramberg and Spjeldnaes (1978), Khalil and others (1978), Neff and Khalil (1978), Czamanske (1963), Czamanske and Wones (1973), Czamanske and Mihalik (1972), Jensen (1985), Bockelie (1978)
	Wichita Mountains (49, 34)	Gilbert and Donovan (1982), Johnson and Denison (1973), Hamilton (1956, 1959), Hanson and Al-Shaieb (1980), Merritt (1965), Powell and Phelps (1977), Huang (1958), Myers and others (1981), Gilbert (1983)
6. Aborted rift/hotspot related	Niger Nigeria (43, 60)	Black and Girod (1970), Cahen and others (1984), Bowden and Kinnaird (1984), Bowden and Whitley (1974), Bowden and Turner (1974), Lameyre and Bowden (1982), Bonin and Giret (1984), Imeokparia (1984), Aleksiyev (1970), Borley (1963), Greenwood (1951), Giret and others (1980), Clifford (1970), Harris (1970)
7. Plagiogranites	Karmoy Ophiolite	Pedersen and Malpas (1984)
	Canyon Mt., Oregon	Gerlach and others (1981)
	Indian Ocean	Engel and Fisher (1975)
	General (43, 15)†	Spulber and Rutherford (1982), Coleman and Peterman (1975), Coleman and Donato (1979)

*Numbers in brackets correspond to the number of analyses (major elements, modal) used in this study after the criterion described in the text has been applied.
†These numbers represent a total for all of the oceanic plagiogranites considered.

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TABLE 2. MINERALOGY OF GRANITOIDS BY TECTONIC ENVIRONMENT

	Orogenic				Anorogenic		
	IAG	CAG	CCG	POG	RRG	CEUG	OP
Type	2 feldspar; perth < plag	2 feldspar; perth < plag	2 feldspar; perth ~ plag	2 feldspar; perth ≥ plag	1 feldspar; perth ± Ab (primary?)	1 feldspar; perth ± Ab (primary?)	1 feldspar; plagioclase
Perthite composition (molecular)	>Or75	>Or75	>Or75	>Or75	~<Or50	~<Or50	. .
Plagioclase composition	Oligoclase-andesine	Oligoclase	Oligoclase	Oligoclase	Albite	Albite	Oligoclase-andesine
Type	Biotite ± hbld ± pyx	Biotite ± hbld ± epid	Biotite muscovite ± tour ± cord ± sill ± gt	Biotite ± hbld or biotite ± musc	Biotite ± hbld ± pyx or alkali amph ± biotite ± hbld ± pyx		Hbld ± pyx
H+/B+*	~<0.20–2.5	~<0.20–2.5	~<0.20–2.5	~<0.20–2.5	~>2.0–2.5	~>2.0–2.5	~>2.0–2.5
M+/B+†	. .	~<1.3	~>1.3	~<1.3	. .	. .	. .

Note: H+ = hbld + pyx + ol; B+ = biotite + epid; M+ = musc + cord + gt + tour + sill, as determined by modal analysis. For references, see Table 1. For classification of granitoids, see Appendix 2.

*When both amph and biotite present.

†When both musc and biotite present.

Modal data: (1) Any mineral reported as trace quantity was assigned a value of 0.01 vol. %, (2) modal values of perthite and myrmekite were included as alkali feldspar and plagioclase, respectively, and (3) reported free albite was assumed to be plagioclase.

Major-element data: (1) All iron was converted to total iron as FeO(T), (2) the analyses are used as reported and were not normalized to 100 wt. % or to a 100 wt. % anhydrous basis.

Trace-element data: (1) All analyses are in parts per million, (2) analyses reported as "trace" in the literature were assigned a value of 0.01 ppm in this study, and (3) analyses reported as less than a value "x" ppm were assigned a value x/2 ppm. The trace-element data are not presented in this paper.

LIMITATIONS OF THIS APPROACH

An outline of the approach utilized is to select well-documented suites of granitoid rocks and to characterize their tectonic environments from the available literature. The chemistry and mineralogy of the granitoid rocks are then presumed to be representative of granitoid rocks formed in that environment. Any differences identified between representative suites become the basis for discriminating the tectonic environment.

The limitations of this approach are (1) it is an empirical procedure, (2) a change in the definitions of the tectonic environment employed (see App. 2) or use of a different classification scheme can change the results, and (3) it is presumed that the suites of granitoid rocks chosen are representative of the tectonic environment and that the available analyses are representative of the suites. Further, all data are from Phanerozoic rocks.

Finally, the variables controlling magma generation are pressure, temperature, volatiles, and source rock. Magma generation is further complicated by magma dynamics and nature of surrounding crust. The obvious question is, does the kinematic plate-tectonic classification of geologic environments uniquely control the variables of magma generation and emplacement? General observation and common sense dictate that some of the variables may be controlled by plate dynamics and that others may not be. These variables and their relation to plate dynamics are not fully understood, suggesting that empirical discrimination schemes must be used with caution.

DISCUSSION

Table 1 summarizes the tectonic classification of the suites of granitoid rocks used in this study, including the references utilized in this paper to obtain information regarding tectonic environment, mineralogy, and chemistry of the granitoids. Detailed descriptions and definitions of the different tectonic environments are given in Appendix 2. Also included in Appendix 2 is the information regarding the specific suites of granitoid rocks chosen for this study.

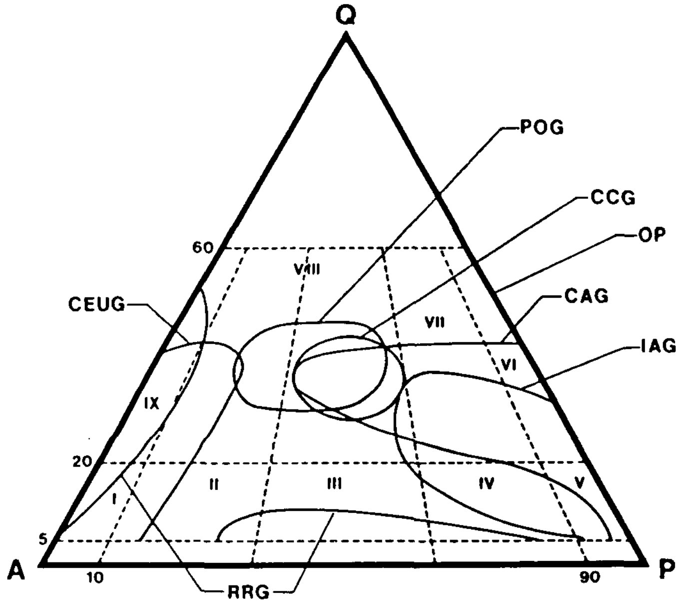

Figure 1. Modal quartz (Q)–alkali feldspar (A)–plagioclase (P) ternary plot. IAG = island arc granitoids, CAG = continental arc granitoids, CCG = continental collision granitoids, POG = post-orogenic granitoids, RRG = rift-related granitoids, CEUG = continental epeirogenic uplift granitoids, OP = oceanic plagiogranites. For references, see Table 1. I = quartz alkali syenite; II = quartz syenite; III = quartz monzonite; IV = quartz monzodiorite; V = quartz diorite; VI = tonalite, trondhjemite; VII = granodiorite; VIII = granite, IX = alkali granite.

Mineralogical Characteristics

In Figure 1, the modes of granitoid rocks from different tectonic environments are presented as fields (for clarity) on the QAP diagram (quartz–alkali feldspar–plagioclase normalized to 100%). Streckeisen (1976) nomenclature is strictly followed, and the information of Figure 1 can be summarized as follows. (1) IAG are quartz diorites, quartz monzodiorites, tonalites, and granodiorites; (2) CAG are tonalites, granodiorites, and granites (with A/P < 2.0); (3) CCG are granites (with A/P < 2.0); (4) POG are granites; (5) RRG show bimodal distribution and are alkali granites, quartz alkali syenites, and quartz monzonites; (6) CEUG are granites (with A/P > 2.0), alkali granites, quartz alkali syenites, and quartz syenites; and (7) OP are tonalites. Additional mineralogical characteristics as summarized in Table 2 are (1) in IAG, CAG, CCG, and POG, the alkali feldspars generally have compositions with Or greater than 75, whereas in RRG and CEUG, the alkali feldspars generally have compositions with Or less than 50; (2) the plagioclases in all granitoids range from albite to andesine; (3) of the mafic minerals, biotite is the most common. If calcic hornblende is present, it is reported to occur with biotite, except in OP and in some cases in IAG where calcic hornblende can occur without biotite. Alkali amphibole is reported only in RRG and CEUG and can occur with or without biotite. (4) Muscovite is reported in CCG, CAG, and POG. Other peraluminous minerals occur only in CCG.

Chemical Characteristics

The chemical characteristics of granitoid rocks from different tectonic environments are reported in Table 3 and can be summarized as (1) RRG and CEUG have a bimodal distribution of SiO_2, whereas the remaining granitoids have a unimodal distribution; (2) on the average based on alkali-lime index, IAG, CAG, CCG, POG, and OP are classified as calc-alkaline, whereas RRG and CEUG are classified as alkalic; (3) characteristics based on Shand's index are shown in Figure 2. Only the CCG are highly peraluminous (A/CNK > 1.15). Similarly, only the IAG, CAG, and OP are highly metaluminous (A/NK > 1.4), and only the RRG and CEUG are considerably peralkaline. (4) Additional characteristics are given as a range of values of various oxide ratios in Table 3.

TABLE 3. CHEMISTRY OF GRANITOIDS BY TECTONIC ENVIRONMENT

	Orogenic				Anorogenic		
	IAG	CAG	CCG	POG	RRG	CEUG	OP
Silica range (wt. %)	60-68 unimodal	62-76 unimodal	70-76 unimodal	70-78 unimodal	72-78 60-63 bimodal	71-77 60-62 bimodal	61-78 unimodal
Alkali-lime index	Calcic to calc-alkaline	Calc-alkaline	Calc-alkaline to alkali-calcic	Alkali-calcic	Alkalic	Alkalic	Calcic
Shand's index (Fig. 2)	Predominantly metaluminous	Metaluminous peraluminous	Peraluminous	Peraluminous metaluminous peralkaline (minor)	Peraluminous (minor) metaluminous peralkaline	Peraluminous (minor) metaluminous peralkaline	Peraluminous metaluminous
Na_2O/CaO (wt. %)	~1.0	~<4.0	~2.0-10.0	~2.0-18.0	~2.0-25.0	~1.0-12.0	~<4.0
Na_2O/K_2O (wt. %)	~0.4-3.0	~0.4-2.0	~0.4-1.5	~0.6-1.2	~0.7-1.0	~0.6-1.0	0.0-50.0
MgO/FeO(T) (wt. %)	0.3-0.85	0.10-0.50	0.05-0.6	0.02-0.30	0.0-0.20	0.0-0.12	0.0-0.70
MgO/MnO (wt. %)	12.0-28.0	2.0-38.0	2.0-45.0	2.0-18.0	0.0-7.5	0.0-7.5	0.0-50.0
$Al_2O_3/(Na_2O + K_2O)$ (molar)	>1.5	>1.1	>1.1	0.9-1.4	<1.15	<1.15	>1.0

Note: for references, see Table 1. For terminology, see Appendix 1.

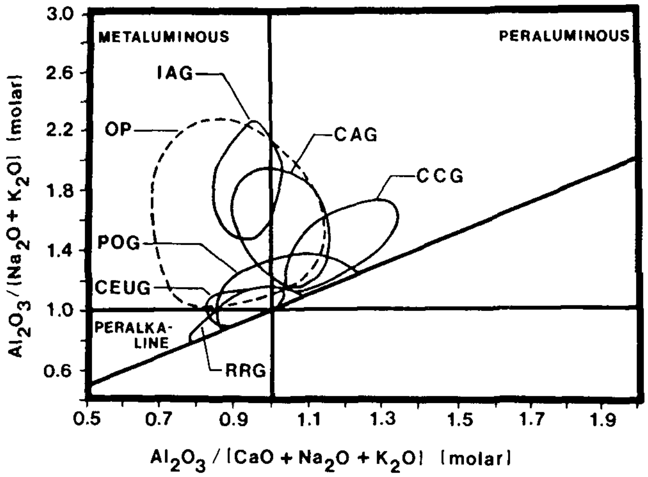

Figure 2. Shand's index. For references, see Table 1; for abbreviations, see Figure 1.

Major-Element Discrimination

Figure 3 is a flow sheet for the tectonic discrimination of granitoid rocks. The flow sheet shows the sequential steps one must follow to discriminate between tectonic environments. In utilizing the flow sheet, it is absolutely essential to discriminate between tectonic environments in the sequential order presented because once an environment is identified, its representative data are not longer plotted in the subsequent steps. The steps involved in discriminating between various tectonic environments on the basis of major-element chemistry of granitoids are as follows.

Step 1: Discriminating between OP and the rest of the granitoid rocks is achieved with a comparison of K_2O versus SiO_2 (Fig. 4). K_2O is a very mobile constituent, and it is possible for highly altered granitoids from any tectonic environment to have abnormally low K_2O values. This alteration can be easily identified petrographically, however. Furthermore, OP have distinctive mineralogy evidenced by the absence of alkali feldspar.

Step 2: Discrimination between group I (IAG, CAG, CCG), group II (RRG, CEUG), and group III (POG) granitoid rocks can be achieved by using Figures 5 through 8. Each of these figures consists of two plots, a and b, with plot a presenting group I and group II analyses and plot b data for group III. The discussion

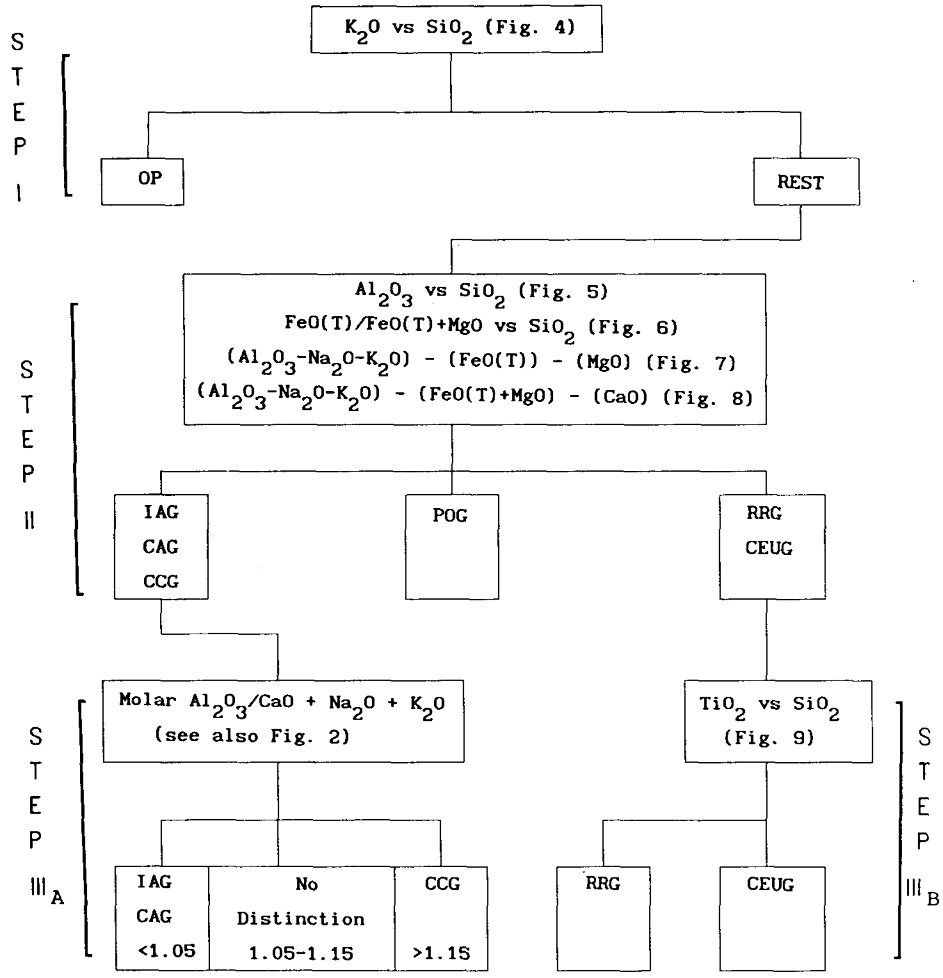

Figure 3. Discrimination scheme for granitoids.

which follows simply refers to Figures 5 through 8, implying discussion of both a and b plots. In these figures, groups I and II have their individual fields in which they plot; group III is different, in that it does not have a unique field. Group III can be identified because it consistently has characteristics of both group I and group II and, therefore, always plots in both fields in Figures 5 through 8. Figure 5, Al_2O_3 versus SiO_2, is discriminant for granitoid rocks with SiO_2 greater than 70.0 wt. %. Figure 6 is the FeO(T)/[FeO(T) + MgO] versus SiO_2 plot, which is an excellent discriminant at lower SiO_2 values for groups I and II with minor overlap at higher SiO_2. Figure 7 is the AFM, (Al_2O_3-Na_2O-K_2O)-[FeO(T)]-(MgO), ternary in weight percent and is an excellent discriminant between group I and group II. Figure 8 is the ACF, (Al_2O_3-Na_2O-K_2O)-[FeO(T) + MgO]-(CaO), ternary in weight percent, in which there is very little overlap between group I and group II.

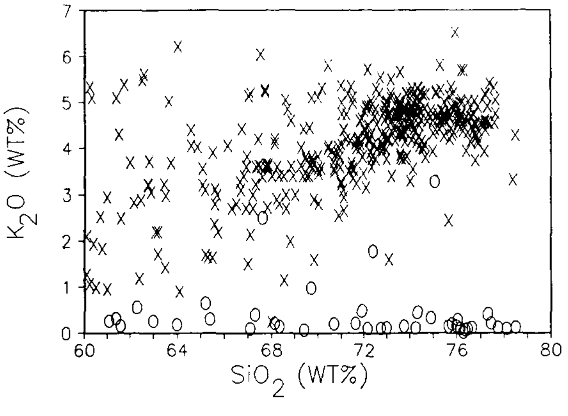

Figure 4. K_2O versus SiO_2. Distinction between oceanic plagiogranites (open circles) and granitoids from other environments (crosses).

Step 3A: Discrimination between CCG and IAG + CAG can be made on the basis of molar Al_2O_3/(CaO + K_2O + Na_2O) (A/CNK) ratio (Figs. 2 and 3). CCG do not have A/CNK values less than 1.05, whereas IAG + CAG do not have A/CNK values greater than 1.15. If the A/CNK ratio is between 1.05 and 1.15, it is not possible to discriminate between CCG and IAG + CAG. Furthermore, it is not possible to discriminate between IAG and CAG, using the data available from this study.

Step 3B: Discrimination between RRG and CEUG is possible using the TiO_2 versus SiO_2 plot (Fig. 9). RRG have a higher TiO_2 value than do the CEUG. There exists some overlap between the two fields.

APPLICATIONS TO THE PROTEROZOIC GRANITOIDS OF THE MIDCONTINENT OF THE UNITED STATES

Due to scarcity of Precambrian exposures in the central midcontinent of the United States, the study of the basement samples and the few key exposures forms the core of our knowledge regarding the geologic evolution of the region during the Precambrian. On the basis of the results of geochronological and petrographic studies of basement samples and the interpretation of geophysical maps, the Proterozoic tectonic history of the midcontinent of the United States between 1480 and 1340 Ma is interpreted as a period dominated by two short extensional events (Bickford and others, 1986). The two extensional events occurred between 1450–1500 and 1340–1400 Ma. These events are manifested by two widespread silicic granite-rhyolite terranes of the southern midcontinent which extend from Ohio to the Texas Panhandle (Bickford and others, 1986). These terranes are commonly referred to as the "anorogenic terranes" of the midcontinent. Only a few outcrops of these large terranes are exposed; most are buried in the subsurface along with the crucial field relations. In order to extract the maximum amount of information from these outcrops, the empirical discrimination schemes are needed to reconstruct the Precambrian evolution in the region.

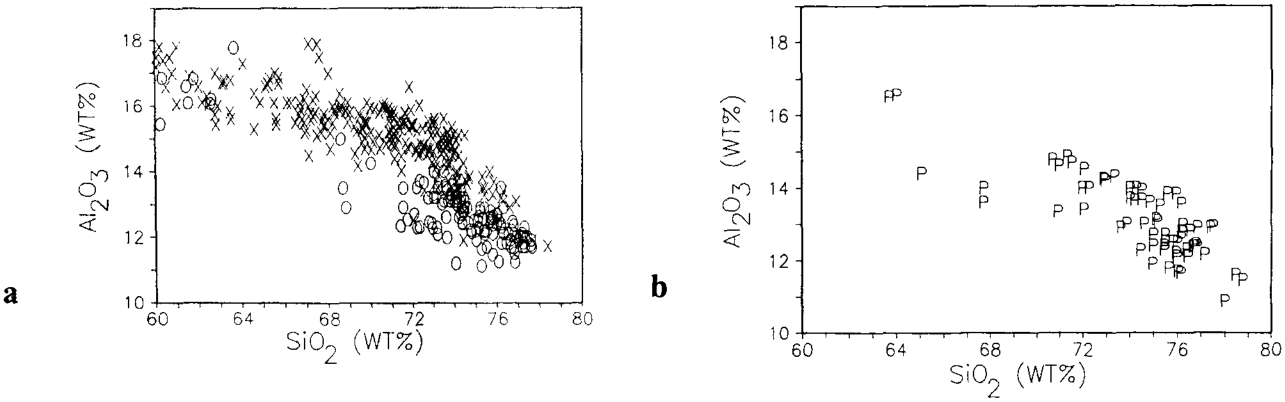

Figure 5. Al_2O_3 versus SiO_2. (a) Distinction between group I (IAG + CAG + CCG) (crosses) and group II (RRG + CEUG) (open circles). (b) Group III (POG) data.

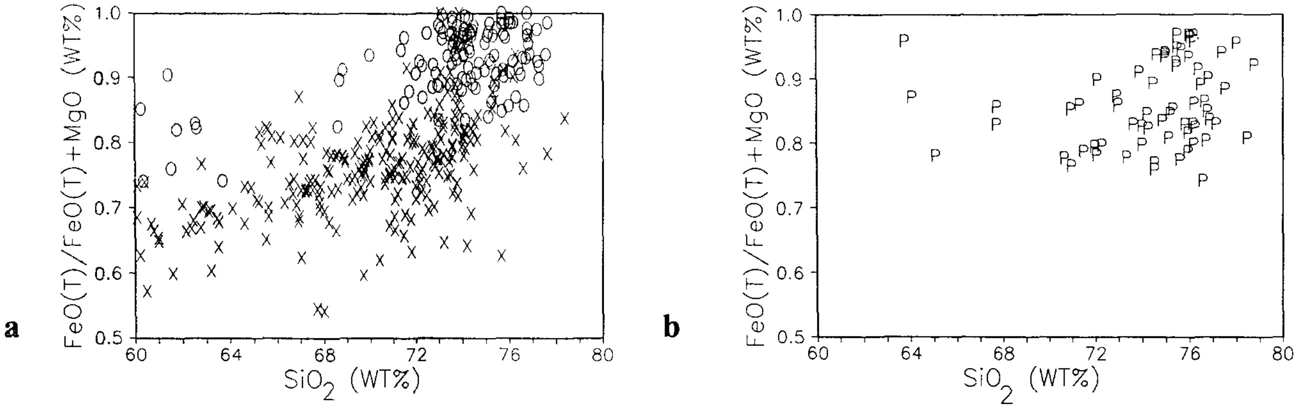

Figure 6. FeO(T)/[FeO(T) + MgO] versus SiO_2. (a) Distinction between group I (IAG + CAG + CCG) (crosses) and group II (RRG + CEUG) (open circles). (b) Group III (POG) data.

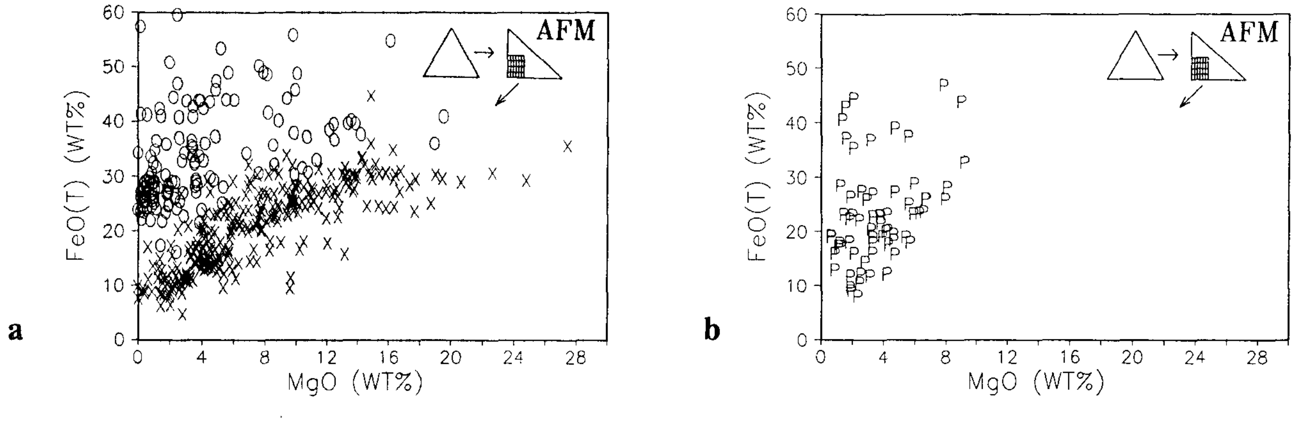

Figure 7. $(Al_2O_3\text{-}Na_2O\text{-}K_2O)$-[FeO(T)]-(MgO) ternary. (a) Distinction between group I (IAG + CAG + CCG) (crosses) and group II (RRG + CEUG) (open circles). (b) Group III (POG) data.

Exposures in the St. Francois Mountains, southeastern Missouri, are considered a part of the older 1450–1500 Ma anorogenic terrane (Bickford and others, 1980). Farther north, another key exposure of the older terrane is the Wolf River batholith of central Wisconsin (Van Schmus and Bickford, 1981; Anderson and Cullers, 1978). Spavinaw granite of northeastern Oklahoma and the Arbuckle granitoids of southern Oklahoma are considered exposures of the younger 1340–1400 Ma anorogenic terrane, although comprehensive studies of these have

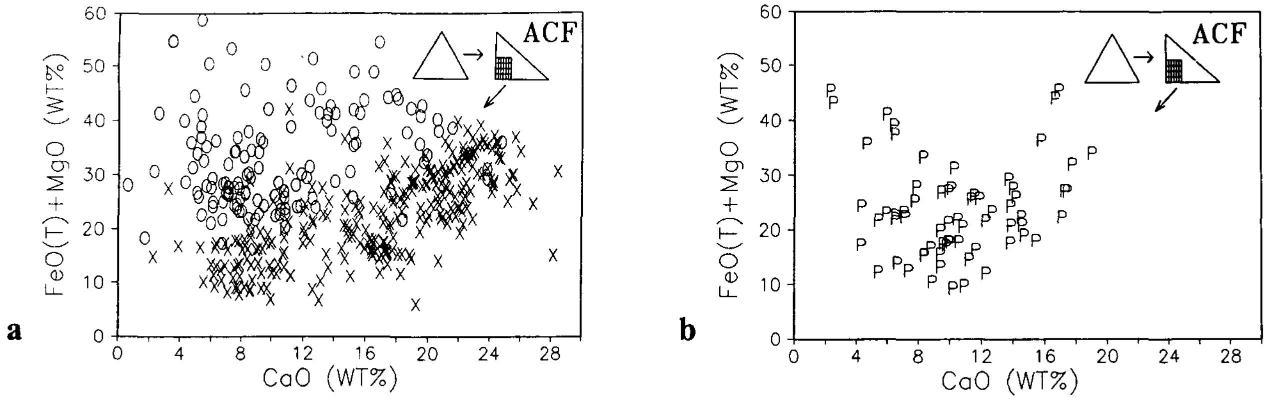

Figure 8. (Al_2O_3-Na_2O-K_2O)-[FeO(T) + MgO]-(CaO) ternary: (a) Distinction between group I (IAG + CAG + CCG) (crosses) and group II (RRG + CEUG) (open circles). (b) Group III (POG) data.

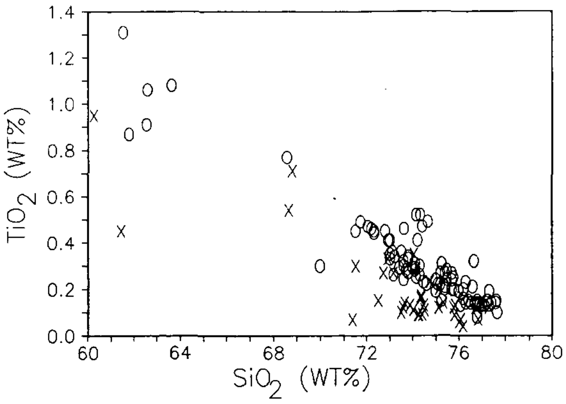

Figure 9. TiO_2 versus SiO_2. *Distinction between RRG (open circles) and CEUG (crosses).*

not been completed (see Bickford and others, 1986; Bickford and Lewis, 1979; Thomas and others, 1984; Denison and others, 1984; Denison, 1973).

Recently, the petrology of the Arbuckle granitoids was studied in detail (Maniar, 1987; P. D. Maniar and E. G. Lidiak, unpub. data), and in this paper, the chemical characteristics of the Arbuckle granitoids will be compared to those of both the St. Francois Mountain granitoids and the Wolf River batholith. We shall attempt to establish the tectonic environment of the Arbuckle granitoids and the older anorogenic terrane, utilizing the proposed tectonic discrimination scheme. We shall show that the Arbuckle granitoids display orogenic characteristics and

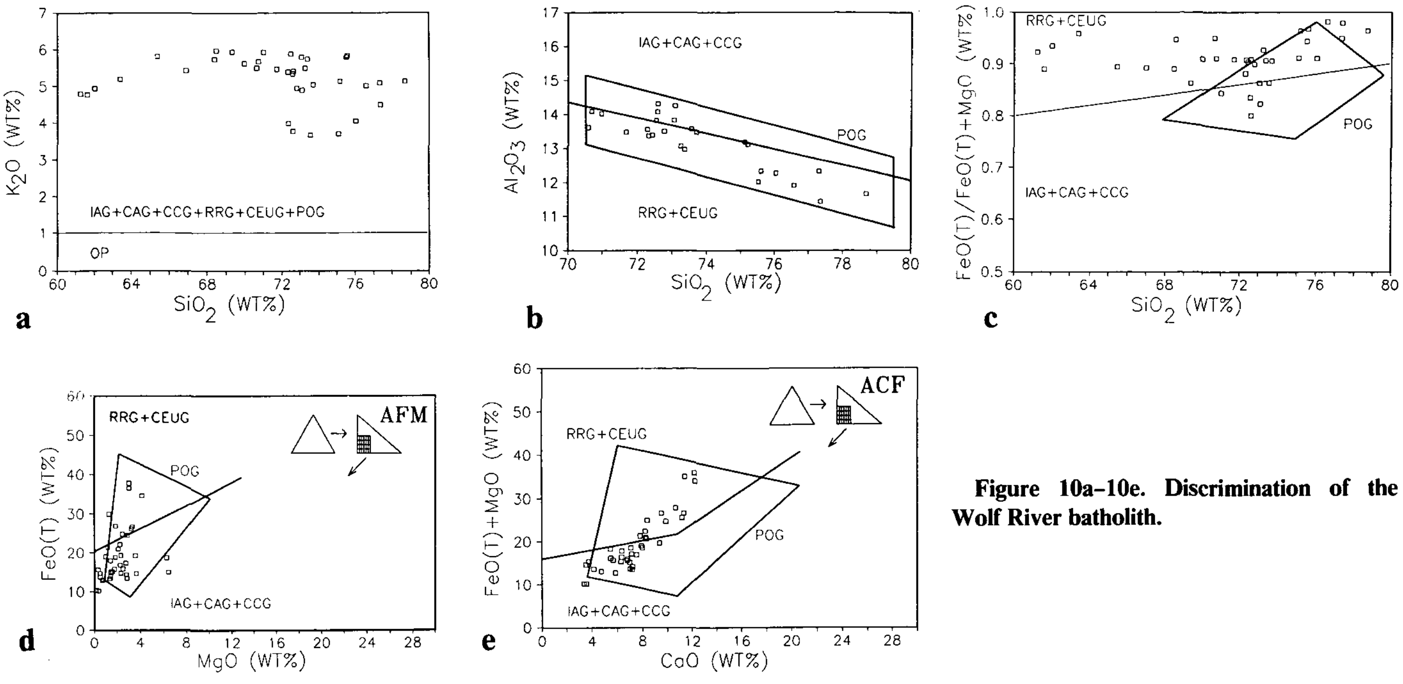

Figure 10a-10e. Discrimination of the Wolf River batholith.

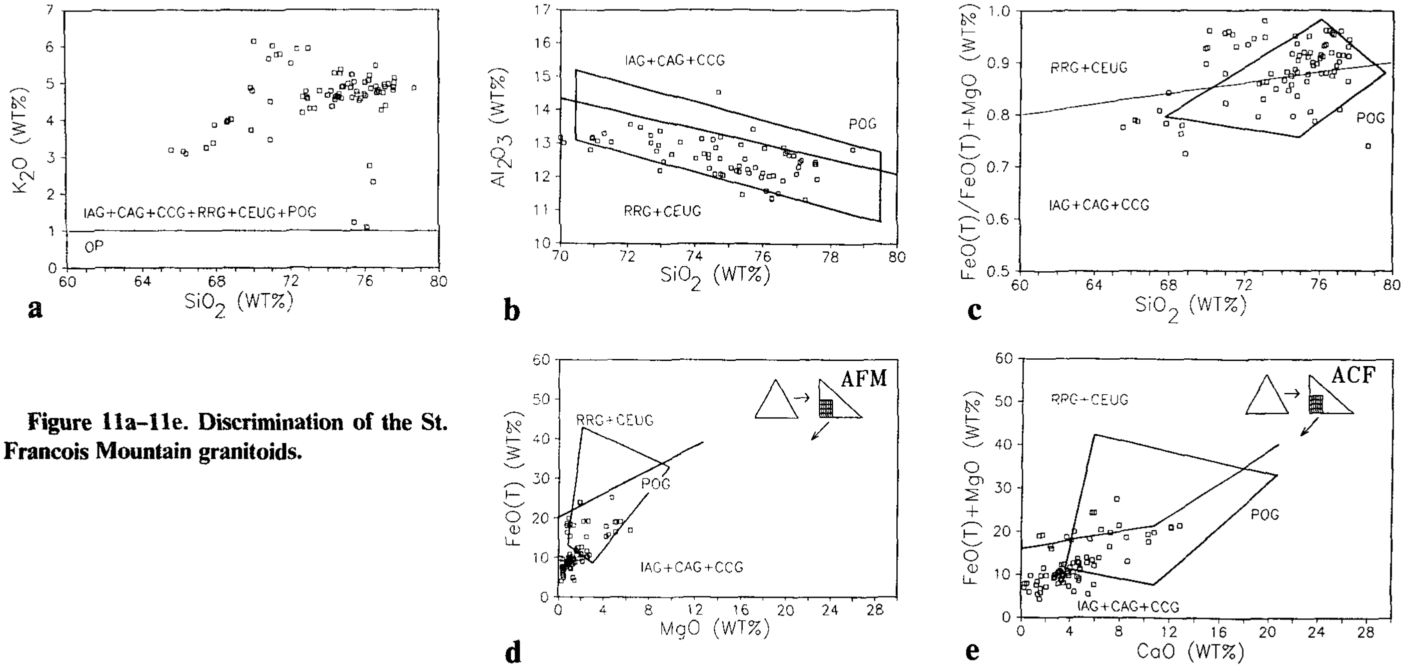

Figure 11a–11e. Discrimination of the St. Francois Mountain granitoids.

should not be considered anorogenic. The tectonic discrimination diagrams have been created utilizing a data base for Phanerozoic granitoids, and it is assumed to be applicable to the Proterozoic granitoids. As discussed, the Wolf River batholith and the St. Francois Mountain and the Arbuckle Mountain granitoids are isolated Proterozoic outcrops with no data from the unexposed areas. This incomplete nature of the data must be taken into account in interpreting the diagrams.

In Figure 10, the chemical data for the Wolf River batholith taken from Anderson and Cullers (1978) are plotted on the discrimination diagrams proposed. It is observed that the rocks classify as POG on the Al_2O_3 versus SiO_2 plot and the AFM and ACF ternaries but as RRG or CEUG on the FeO(T)/[FeO(T) + MgO] versus SiO_2 plot. Therefore, we consider the Wolf River batholith to have formed during the crust-stabilizing post-orogenic environment.

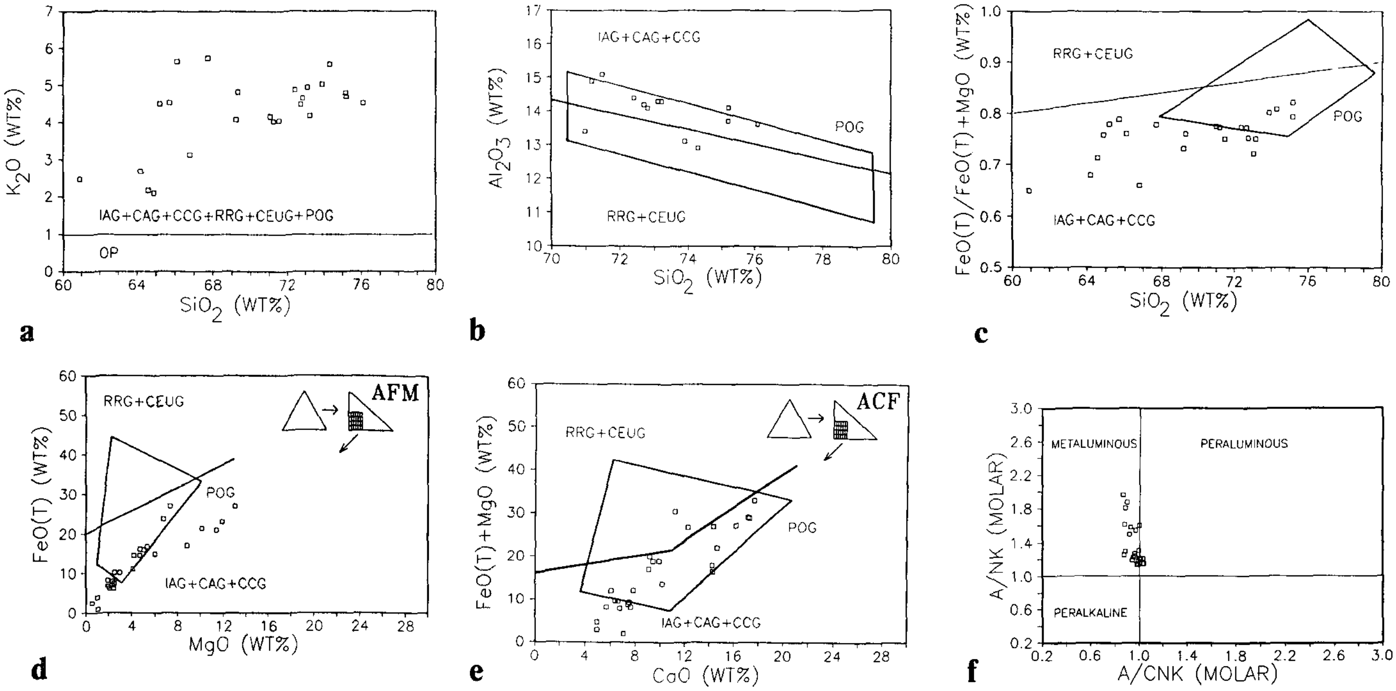

Figure 12a–12f. Discrimination of the Arbuckle Mountain granitoids.

In Figure 11, the chemical data for the St. Francois Mountain granitoids taken from Bickford and others (1980) are plotted on the discrimination diagrams. The St. Francois Mountain granitoids classify as RRG or CEUG on the Al_2O_3 versus SiO_2 plot but as POG on the FeO(T)/[FeO(T) + MgO] versus SiO_2 plot and the AFM and ACF ternaries. Therefore, we consider the St. Francois Mountain granitoids to have formed in an environment similar to that of the Wolf River batholith. The older anorogenic terrane may represent a major crust-stabilizing tectonic episode following an orogeny. Because post-orogenic plutons are high-level plutons emplaced at very shallow depths, much of the evidence for the orogeny may lie buried under the post-orogenic plutonism and its associated volcanism.

In Figure 12, the chemical data for the Arbuckle Mountain granitoids are presented on the discrimination diagrams. The Arbuckle granitoids are distinctly different from both the Wolf River batholith and the St. Francois Mountain granitoids in that the Arbuckles classify as orogenic granitoids. On the plots of Al_2O_3 versus SiO_2 and FeO(T)/[FeO(T) + MgO] versus SiO_2 and on the AFM and ACF ternaries, the Arbuckle granitoids classify as IAG or CAG or CCG. Further, on the Shand's index plot, they are metaluminous and therefore not collision related. The Arbuckle granitoids are IAG or CAG orogenic granitoids. This is further substantiated by the mineralogy of the Arbuckle granitoids (Maniar, 1987; P. D. Maniar and E. G. Lidiak, unpub. data). We propose that the Arbuckles no longer be considered a part of the younger anorogenic terrane; rather, the Arbuckles present evidence of an orogenic event during the Middle Proterozoic in the southern midcontinent of the United States.

CONCLUSIONS

The mineralogy and chemistry of granitoid rocks can be successfully used to discriminate between various tectonic environments. Even though the data for these discrimination diagrams are from well-characterized Phanerozoic granitoids, it seems applicable to the Proterozoic. Applications to granitoids from the midcontinent provide valuable information regarding the possible tectonic environment of these rocks.

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APPENDIX 1. TERMINOLOGY

1. Streckeisen (1976) classification is strictly followed.

2. The term "granitoid rocks" is used to encompass any or all of the following: alkali granite, granite, granodiorite, tonalite, trondhjemite, quartz diorite, quartz syenite, quartz monzonite, quartz alkali syenite.

3. Granitoid rocks are described using Shand's index as

$$\text{peraluminous: } A/CNK > 1.0,$$
$$\text{metaluminous: } A/NK > 1.0 \text{ and } A/CNK < 1.0,$$
$$\text{peralkaline: } A/NK < 1.0,$$

with all ratios being molar ratios and A = Al_2O_3, C = CaO, N = Na_2O, and K = K_2O.

4. Granitoid rocks are also characterized according to the alkali-lime index (Peacock's index) as the SiO_2 value (in weight percent) where (Na_2O + K_2O)/CaO ratio (in weight percent) equals 1.0.

SiO_2 (wt. %)	Alkali-lime index
<51.0	Alkalic
51.0–56.0	Alkali-calcic
56.0–61.0	Calc-alkalic
>61.0	Calcic

APPENDIX 2. GRANITES AND TECTONIC ENVIRONMENT

Granitoid rocks can be broadly classified on the basis of their tectonic environment into orogenic and anorogenic classes. Orogenic granitoid rocks can be subdivided into island arc granitoids (IAG), continental arc granitoids (CAG), continental collision granitoids (CCG), and post-orogenic granitoids (POG). The anorogenic granitoid rocks can be subdivided into rift-related granitoids (RRG), continental epeirogenic uplift granitoids (CEUG), and oceanic plagiogranites (OP). We shall briefly define the various tectonic environments of granitoid rocks and give a short summary of the suites of rocks chosen to represent these environments.

Orogenic Granitoid Rocks

Orogeny is characterized by deformation, plutonism, and metamorphism. It may end in collision between an island arc and continental masses, or it may end when plate motions change.

Island Arc Granitoids (IAG). The island arc granitoids are rocks of magmatic arcs formed by subduction of one oceanic plate beneath another oceanic plate. The Papua New Guinea–Solomon Islands region of southeast Asia is an example where IAG are exposed (Griffin, 1979; Mason and McDonald, 1978). Oligocene or younger (30–4 Ma) granitoid rocks from the region are used to represent this environment.

Continental Arc Granitoids (CAG). The continental arc granitoids are rocks of magmatic arcs formed on the continent owing to the subduction of an oceanic plate beneath the continent. The Sierra Nevada and Idaho batholiths of the western United States are examples where CAG are exposed (Bateman, 1983; Hyndman, 1983; Noyes and others, 1983; Bateman and Chappell, 1979). Data from Cretaceous plutons of the Sierra Nevada and Idaho batholiths are used in this study.

Continental Collision Granitoids (CCG). The continental collision granitoids are rocks intruded during the continent-continent collision phase of an orogeny. The North and High Himalayan region of Asia and the Armorican massif of southern Brittany are examples where CCG are exposed (DeBon and others, 1986; Strong and Hanmer, 1981; LeFort, 1975a, 1975b, 1981; Le Metour, 1978). For the Himalayan region, all data are from the Cenozoic granitoid rocks, whereas for southern Brittany, all data are from Carboniferous granitoid rocks.

Post-orogenic Granitoids (POG). The post-orogenic granitoids are rocks intruded during the last phase of an orogeny, generally after the deformation in the region has ceased. These granitoid rocks are associated with the orogeny in both space and time. It has been suggested (Rogers and Greenberg, 1981a, 1981b) that they represent the transitional phase of the continental crust undergoing stabilization following the orogeny. The Younger Granites of Egypt are an example where POG are exposed (Cahen and others, 1984; Rogers and others, 1978), and data for this study were specifically taken from these 560–600 Ma granitoid rocks.

Anorogenic Granitoid Rocks

The word "anorogenic" is traditionally defined as that which is not associated with an orogeny; specifically, it is the absence of any evidence (such as deformation or metamorphism) of an orogeny (of the appropriate age). For purposes of this paper, we restrict anorogenic granitoids to those found in (1) rift-related areas, (2) continental areas of epeirogenic uplift, and (3) oceanic environments.

Rift-Related Granitoids (RRG). The rift-related granitoids are rocks associated with the rifting of the continental crust. The process of rifting involves several stages of development, which on a structural basis, consist of crustal uplift → formation of a rift graben → formation of an ocean basin. The early phase of crustal uplift is not unique to rifting, and similarly, once an ocean basin is formed, evidence relating granitoid rocks to rifting may be obscured by later processes. Therefore, in this paper, RRG are defined on a more restrictive basis as granitoid rocks associated with formation of a rift graben. The Oslo region of Norway and the Wichita Mountains of southern Oklahoma are examples where RRG are exposed (Bockelie, 1978; Gilbert, 1983; Gilbert and Donovan, 1982; Oftedahl, 1978; Petersen, 1978; Schonwandt and Petersen, 1983). For the Oslo region, all data are from the Permian intrusives exposed in the Oslo graben, whereas for the Wichita Mountains, the data are from the Middle Cambrian Wichita Granite Group of the Southern Oklahoma aulacogen.

Continental Epeirogenic Uplift Granitoids (CEUG). There are granitoid rocks associated with continental areas which have experienced epeirogenic crustal uplift with no subsequent development into a rift. This uplift is possibly due to hot-spot activity or an aborted rifting event. The Younger Granites of Niger-Nigeria are examples where CEUG are documented (Cahen and others, 1984; Lameyre and Bowden, 1982; Black and Girod, 1970). Data for this paper are taken from (1) Air Highlands granitoids (500–440 Ma), (2) Northern Nigerian granitoids (350–250 Ma), and (3) Central Nigerian granitoids (200–150 Ma). No associated orogeny is recognized during this time period, and the only tectonic disturbance is the epeirogenic uplift of the crust.

Oceanic Plagiogranites (OP). There are granitoid rocks found in minor proportions in association with abundant mafic rocks. Oceanic plagiogranites are commonly observed on oceanic islands and mid-ocean ridges. There are occurrences of plagiogranites associated with layered intrusions on continents, but these are not included in this study. All data used in this paper are from oceanic plagiogranites (Coleman and Donato, 1979; Coleman and Peterman, 1975).

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