GEOLOGICKÝ ZBORNÍK — GEOLOGICA CARPATHICA, 36, 2, BRATISLAVA, APRIL 1985,
Pp. 191—199

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SUITES WITHIN A GRANITOID BATHOLITH: A QUANTITATIVE JUSTIFICATION BASED ON THE LACHLAN FOLD BELT, S.E. AUSTRALIA**

(Fig. 1, Tab. 1)

Abstract: Numerous Suites within 102 plutons of I-type batholiths, Lachlan Fold Belt, S.E. Australia, were named by Chappell and co-workers. Objective cluster analyses, based on 32 chemical elements for 304 representative samples, appear to corroborate most, but not all, of these Suites. Because these analyses, based on chemical elements alone, identified most previously named Suites, the reality of these Suites is supported. Analogous, geographically discrete, suites probably occur in other batholiths throughout the world, and could indicate crustal heterogeneity and possible mineralized localities.

Резюме: Многочисленные серии в пределах 102 плутонов батолитов I-типа лахланской зоны складчатости, ЮВ Австралия были названы Чеппеллом и его сотрудниками. Объективные анализы скоплений основаны на 32 химических элементах для 304 избранных проб подтверждают большинство, но не все эти серии. Так как эти анализы основаны только на химических элементах определяют прежде всего тип серии, этим поддерживается существование этих свит. Аналогичные, географически отдельные свиты вероятно встречаются и в других батолитах по всему миру и они могут обозначать гетерогенность коры и возможные минерализованные месторождения.

Introduction

Characteristically, a batholith comprises a large number of discrete plutons, each of which has mappable boundaries and distinctive chemical and mineralogical composition. Mapped boundaries and radiometric studies commonly permit the temporal emplacement sequence to be identified. Geochemical differences in pluton composition through space and time are highly significant in unraveling the petrogenetic development of a batholith. This is particularly true if, as some have claimed, an individual igneous rock bears the distinctive geochemical signature of the parent material/s which melted (completely or partially) to yield it. Griffin et al. (1977) and Chappell (1978) claimed that chemical similarity permits individual groups of Paleozoic plutons within the Lachlan Fold Belt (S.E. Australia) to be grouped into suites, with the implication that each suite bears the geochemical signature of the distinctive parental crustal material from which it evolved.

Recently, Pitcher (1983, p. 5) concluded that "... geochemical data firmly establish the concept of evolutionary (granitoid sequences) and permit the realistic computer-aided modeling of the compositional variations ... The data also reveal that there are specific types of granite with unique geochemical

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** Paper presented by Whitten and Chappell (1984) in Section C.09.1.3 of International Geological Congress, Moscow.

signatures that not only provide the clue as to the nature of the source rocks but promise the possibility of genetic classification... Wholly predictable is... the close interrelationship between mineralization and granite type."

The term suite

About half a century ago, Alling used the terms Pacific, Atlantic, and Mediterranean Suites for sets of igneous rocks believed to have evolved under specific, dissimilar tectonic conditions. Although these particular terms rapidly gained disfavor, the use of the term suite in genetic classification has persisted, so that "...a suite is a group of rocks whose field relations and compositional characteristics make it appear that they have a common source" (Bayly, 1968). A group of hornblende-bearing granitoid rocks was called the Moonbi Suite by O'Neil et al. (1977) and was described in some detail by Chappell (1978); in these two papers, a granitoid suite was considered to be a set of cogenetic rock units. In subsequent work in S.E. Australia, Chappell and co-workers used chemical and mineralogical compositions to identify groups of granitoid plutons claimed to have been derived from the same source material (i. e., belonging to the same suite).

B. W. Chappell, W. Compston, and A. J. R. White (pers. commn, 1981) contended that "granitoid suite" should be used for a group of plutons (or a single pluton) produced from identical source material by the same, or by separate but indistinguishable, fusion events. They asserted that: "Granitoids within a suite will have many petrographic characteristics in common, but these lack the quantitative aspect necessary to infer derivation from identical sources. Characterization of a suite can be made using chemical and isotopic criteria and is achieved when all elements vary in concomitant fashion. Suites will normally encompass a range of chemical composition, but the specification of one element must define all others within the limits of sample variation of that suite. Specifically, no pluton should consistently give values for various elements that are biased away from the mean value of that element in the whole suite. If the density of sampling is sufficiently high and these requirements are met, then it can be confidently asserted that the granitoids were derived from identical source material." Although this particular suite concept does not seem to have been challenged in print, several petrologists have voiced scepticism about the reality and recognizability of such 'suites' within granitoid batholiths.

On the basis of newly assembled petrographic data for Lachlan Fold Belt, Chappell (pers. commn, 1981) recognized some 36 suites, while his co--workers (e. q., Beams, 1980) named many additional suites in this Belt. Numerous semiquantitative criteria were used to define these suites. For example, samples of Bega and Moruya Batholiths fall in diffuse areas on Harker diagrams for Sr v. SiO_2 and for Na_2O v. SiO_2, but, within these areas each suite is represented by distinctive linear sets. Beams (1980, Figs. 4 and 5) described 13 suites, the samples for each of which lie very close to a different line on each of the two Harker diagrams. A newly analyzed rock sample could apparently be assigned to a previously identified suite if its chemical analysis lay on that suite's linear trace on both Harker diagrams.

If such suites exist, and if they occupy discrete geographic areas, it is a matter of great importance in deciphering the petrogenetic history of these Paleozoic Australian batholiths. Their proven existence would suggest that unrecognized suites probably exist in batholiths of other parts of the world.

Chemical data available for Bega, Gabo and Moruya Batholiths

Due to intensive mapping and sample analysis by Chappell and co-workers, whole-rock chemical analyses for 32 elements (including FeO and Fe_2O_3) and complete modes are available for 304 representative granitoid samples of Bega, Gabo, and Moruya Batholiths, Lachlan Fold Belt, S.E. Australia. The chemical variables measured are SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, S, Ba, Rb, Sr, Pb, Th, U, Zr, Nb, Y, La, Ce, Nd, Sc, V, Cr, Co, Ni, Cu, Zn, and Ga; additionally, East and North Cartesian map coordinates are available. The 304 samples represent 102 individual named plutons which range in mapped surface area from 970 km^2 (Bemboka Pluton) to 0.1 km^2 (four different plutons). Full details are being published elsewhere by Chappell, although some of the relevant maps and petrographic and chemical analyses were recorded by Beams (1980). Chappel and co-workers assigned nearly 70 per cent of the analyzed samples to some 18 suites: in four cases, only two samples are assigned to a suite, whereas the Glenbog Suite comprises 43 analyzed samples from 14 plutons which range in surface area from 335.0 to 7.8 km^2. The status of the remaining 30 per cent of the samples was not explicitly defined but, in no case, are they from a pluton whose other samples were assigned to a Suite.

Numerical identification of suites

Althoug other variables were explicitly considered in identifying suites, Chappell and co-workers placed particular emphasis on the Sr v. SiO_2 and Na_2O v. SiO_2 Harker diagrams; the role of the other 29 analyzed elements was not evaluated in detail by them when identifying the suites. In this paper, numerical techniques using all of the analyzed chemical variables simultaneously have been used to test the reality of the recognized suites, that is to determine whether (a) discrete groups (e. g., suites) of samples exist or (b) the specimens reflect continuous variation within a single, essentially homogeneous, compositional domain (batholith).

For discrete-group identification, numerous techniques could be used. The BMDP Cluster Analysis computer program P2M (Dixon, 1981) is convenient. This program forms clusters of samples based on the Euclidean distance (i. e., the square root of the sum of squares of the differences between the values of the variables for two cases) separating the samples in n-space, when n variables are simultaneously considered. Because the variables are of very dissimilar magnitude, each is normalized initially so as to have equal 'weight' (importance or influence) in the analysis. The clusters are formed according to a linkage rule that determines the distance between any two clusters or samples. Initially, each cluster contains only one sample. By a stepwise process, the two most similar (closed in n-space) clusters are joined to form a new cluster until all samples are in one cluster. The BMDP program generates a tree diagram on the line printer, and, as implemented on a UNIVAC 1100/80 Computer, 32 variables for 304 samples are readily considered simultaneously. However, the size of the resulting tree diagram is so great (2 × 1 metres) that, for convenience, most analyses in this study were made for subsets of the data set.

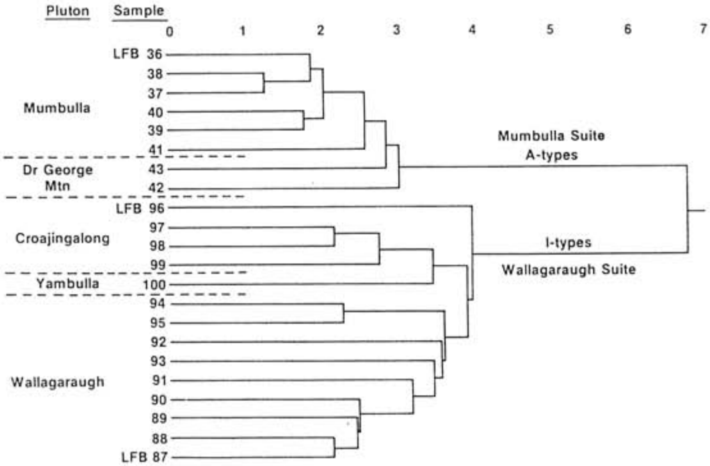

Fig. 1. Cluster analysis (based on 28 normalized chemical components and two geographic coordinates) for 22 samples from Mumbulla and Wallagaraugh Suites; horizontal scale is Euclidean distance between linked samples (or sample groups) in 30 space.

To illustrate the technique, cluster analysis based on 30 variables for 8 samples from the A-type Mumbulla Suite and 14 samples from the I-type Wallagaraugh Suite is illustrated in Figure 1. These are two of the Suites recognized by Chappell. (I- and A-type granites are two of three dissimilar major granitoid groups; the terms are used according to the definition of Chappell—White (1974) for I-and S-type granites and of Loiselle—Wones (1979) for A-type granites). All analyzed variables were included except P_2O_5, S, and MnO, and total iron was used rather than FeO and Fe_2O_3; East and North were included as variables. The two Suites are discretely identified in Figure 1; the cluster of A-type rocks is (6.777—3.942) distance units from the cluster of I-type granitoids. The Mumbulla Suite rocks come from two mapped plutons; the six rocks of Mumbulla Pluton comprise a cohesive set, and the two Dr George Mtn Pluton rocks are distanced from the Mumbulla Pluton specimens (Fig. 1). Specimen LFB41 is somewhat anomalous as a member of Mumbulla Pluton (Fig. 1) because, in 30-dimensional space, it is (2.576—2.041) distance units from the other samples. For all Mumbulla Pluton samples except LFB41 the standard deviations of the normalized analytical data are less than 1.5, except for five standard deviations of 1.50 to 1.61 scattered between four samples. By contrast, sample LFB41 has some significantly larger standard deviations, namely:

Pb = 2.224 Cu = 2.328 Zn = 1.840;

these seem to account for the distancing of LFB41 from the other samples in the cluster analysis.

For Wallagaraugh Suite, samples from Croajingalong, Yambulla, and Wallagaraugh Plutons are neatly separated (Fig. 1), with the exception of sample LFB96, which is distanced from all other members of the Suite. This sample is unique in this Suite in having many large standard deviations, namely:

SiO_2 = —2.446	MgO = 2.176	Sr = 2.303
TiO_2 = 2.634	CaO = 2.122	V = 2.505
Al_2O_3 = 2.062	Total Fe = 2.349	Cr = 2.693.

With nine large standard-deviation values, it is not surprising that this sample is not closely clustered with other samples from Croajingalong Pluton. The reason for these large standard deviations for sample LFB96 bears study, but, for present purposes, it is assumed that all of the chemical analyses are equally accurate.

This example indicates that, for these clearly dissimilar groups of granitoids (i. e., Suites of A- and I-type rocks), the BMDP Cluster Analysis computer program is successful in separating Suites and in identifying samples drawn from individual plutons. Although 30 variables were used simultaneously, the method seems to be very sensitive to individual analytical values with large standard deviations.

For the 304 analyzed samples from Bega, Gabo, and Moruya Batholiths, the cluster diagram is 14 times the width of Figure 1. Also, additional different cluster analyses could be made for an almost limitless number of different combinations of variables (e. g., each element singly, every possible pair of elements, every triplet, every 4, every possible 5, ... every possible 31, all 32 elements). The ratios (e. g., FeO/Fe_2O_3) of all elements taken 1, 2, 3, 4, ... at a time could also be used. Complex ratios could be justified; for example, mol. Al/(Ca + Na + K) was advocated as an important variable by Chappell—White (1974). Naturally, the plethora of all reasonable possibilities has *not* been examined. Because equal weight is given to all variables, and it is not known *apriori* (a) whether some variables are more significant than others for suite identification, and (b) whether some element/s are 'wild' (in the sense of not varying within the batholith sympathetically and compatibly with the other variables), use of all variables together probably provides the severest test of cluster analysis for identifying suites. (Although, as quoted above, Chappell, Compston, and White opined that "...specification of one element must define all others ... of that suite ...", this assertion has not be rigorously proved).

Initially, in analyzing all 304 samples, all chemical variables (but no spatial variables) were included; striking clusters emerged with broad similarities to the Suites identified by Chappell and co-workers. Sporadic samples were 'misclassified' in the sense of being separated from their alleged Suite (cluster);

Table 1

Synopsis of cluster analysis of Bega, Gabo and Moruya Batholith granitoid samples, Lachlan Fold Belt, Australia

Good Suites			Composite suites			Not suites		
Suite Number	Suite Name	No. of Samples	Suite Number	Suite Name	No. of Samples	Suite Number	Suite Name	No. of Samples
2	Xmas	2	5	Cobargo	13	1	Moruya	17
3	Gabo Island	9	8	Candelo	12	7	Warri	2
4	Mumbulla	8	10	Bemboka	39	11	Drummer	2
A	Brogo	7	13	Glenbog	43	12	Coolan-gubra	6
B	Wangera-bell	3				14	Kybean?	2
C	Kameruka	10				15	Tonghi	15
6	Wallaga-raugh	14				17	Rock Flat	3 2
D	Braidwood	12						
9	Why Worry	13				18	Rossi	
16	Bukalong	3						

miscellaneous other specimens were insinuated within putative Suites.

Because (by normalizing) equal weight was given to each variable, a few variables giving obvious problems were omitted from some analyses. For example, S content is so low by comparison with its detection limit that analyses effectively give 0 or 1 only. Although very fresh rock had always been analyzed, localized oxidation makes it prudent to use total Fe, rather than FeO and Fe_2O_3 separately. Concerns about analytical reliability for the very small P_2O_5 and MnO contents led to their omission. Chappell (pers. commn, 1981) suggested that U might be subject to leaching loss and that Cu could vary as a result of local minor whole-rock alteration; however, both U and Cu were retained in the cluster analyses. Omission of P_2O_5, MnO, and S, and use of total Fe (instead of FeO and Fe_2O_3) caused two significant changes in the clusters:

a) A few samples previously separated from their pluton by the cluster analyses, became clustered into homogeneous groups.

b) Samples alleged to belong to the same Suite became more closely clustered into homogeneous groups.

Credence is lent to these cluster-analyses results by

a) most of the clusters corresponding closely, or identically, to the Suites independently identified by earlier workers using other variables, and

b) almost identical results coming from cluster analyses of trace elements only (i. e., omitting all major elements).

Results

Detailed description of the complete cluster-analysis results for the Lachlan Fold Belt granitoids would require familiarity with the regional geology; this will be published elsewhere. For present purposes, only summary results for 23 previously named Suites are presented. Table 1 is a synopsis of cluster-analysis results based on 30 variables (28 chemical components and 2 geographic coordinates as for Figure 1) for 304 granitoid samples. Eighteen Suites originally recognized by Chappell are numbered in Table 1; also included are four of the largest additional Suites (A through D) named by Beams (1980). In this Table, "Good Suites" means that cluster analyses suggest these pre-identified Suites are real, in the sense that they are clearly identified by this objective technique; all, or almost all, samples are assigned correctly. "Composite Suites" also comprise discrete sets, but cluster analyses suggest that each should be divided into two or more suites. By contrast, current cluster analyses do not substantiate the previously named Suites listed as "Not Suites" in Table 1; in a diagram similar to Figure 1, individual specimens of these supposed Suites are separated across the diagram so that, on this basis, the samples do not seem to derive from cohesive sets (suites).

All plutons represented in Table 1 are I-type granitoids, except Suites numbered 1, 2, 3, and 4 (from Gabo and Moruya Batholiths) which are A-type granitoids that outcrop east of the large Bega Batholith; the latter comprises a generally north-south belt east and southeast of Canberra. A comparable area and number of analyzed granitoid samples are available from the western flank of Lachlan Fold Belt; the majority of these are S-type granitoids, but with sporadic I-type plutons. Cluster analyses of these S-type rocks yield distinctive groups, broadly corresponding to the Suites previously named by Chappell and co-workers; that is, the results are analogous to those summarized in Table 1.

Significance of results

This preliminary account draws attention to the important fact that the reality of Suites (distinctive, discrete, chemical entities) within the Paleozoic Lachlan Fold Belt of Australia, appear to be corroborated by the cluster-analysis results. On this basis, it is difficult to avoid the conclusion that (a) these Suites represent plutons, or sets of plutons, which are genetically discrete and (b) the distinctive geochemistry of each Suite bears the geochemical signature of the particular different crustal material from which it was evolved at depth by partial melting (mobilization). This raises the possibility of

a) mapping the chemical composition and variability of the crustal rocks occurring below the fold belt which the granitoids were derived, and

b) developing a genetic classification of granitoids.

It is unlikely that these Paleozoic batholiths are unique in possessing suites. Batholiths of other ages and other parts of the world will almost certainly be found to comprise comparable discrete sets of suites. For economic geologists, it will be important to determine with which suites mineralization is associated and to review, on a global basis, what characteristics are shared by mineralized suites. This can be expected to provide important bases for

a) further petrogenetic understanding of mineralization associated with granitoids, and

b) predicting more accurately areas favorable for mineral prospecting.

Because chemical analyses are percentage data of constant sum for each sample, particular hazards arise in many types of multivariate analyses (cf., Chayes, 1971; Aitchison, 1981; 1984). Although trace elements are not so directly constrained by constant-sum considerations as are major elements, analogous mathematical problems may be inherent because, in granites, many trace elements are strongly correlated with certain major elements. Also, because of some inherent problems and properties of cluster analysis, it is prudent to treat results based on 30 + variables for 304 samples with caution and circumspection. While the results in Figure 1 are very reassuring, those in Table 1 are worrying; what is the real reason for the three groups in Table 1? Because of the importance of being able to identify suites objectively and correctly, and the potential global petrogenetic importance of the suite concept, these and related issues are subjects of longing research. Since completion of the work reported in this paper, a wholly different statistical study has been initiated and is yielding rewarding results (Whitten et al., 1984).

Acknowledgement: A grant from the American Philosophical Society (Penrose 8868) and computing facilities at Australian National University and at Michigan Technological University are gratefully acknowledged.

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Manuscript received November 9, 1984

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