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The Relationship between Geothermal Gradient and the Composition of Granitic Magmas in Orogenic Belts

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Abstract. A comparison has been made between the average compositions of the granites in the Variscan, Caledonian, and Alpine orogenic belts of western Europe. Their respective compositions lie near the isobaric minima in the system Q—Or—Ab—H_2O for successively higher water pressures, whereas metamorphic facies series indicate that the three orogenic belts developed under successively lower geothermal gradients. These relationships are consistent with an origin of the granitic magmas by partial melting in the crust.

Introduction

The study of facies series in regional metamorphism has shown that a different thermal regime has prevailed in different orogenic belts (Miyashiro, 1961; Winkler, 1967). In some areas high temperatures have been attained under low pressures, indicating a high geothermal gradient, whereas in other areas equally high temperatures have only been attained under much higher pressures, indicating a low geothermal gradient. It may therefore be predicted that the temperatures necessary to initiate melting would be reached at different crustal levels in different orogenic belts, and that melting would therefore take place under different total pressures. It is possible that the magmas produced by partial melting would reflect these differences in pressure in their composition, and in order to test this possibility the author has calculated the average composition of the granitic magmas in three contrasting orogenic regions. These are the Variscan orogenic belt of western Europe, the Caledonian orogenic belt of the British Isles, and the Alpine orogenic belt of the Alps.

Miyashiro (1961) distinguished between three principal series of facies in metamorphic belts: the low pressure andalusite-sillimanite type, the intermediate pressure kyanite-sillimanite type, and the high pressure jadeite-glaucophane type. From the stability relationships of their characteristic minerals it may be inferred that these facies series originated under high, intermediate, and low geothermal gradients respectively (Winkler, 1967; Richardson, 1970). The three orogenic belts studied have been chosen to represent, as far as possible, each of these types of metamorphism. In the Variscan orogenic belt, Zwart (1967) has shown that regional metamorphism is predominantly of low pressure type. The Caledonian orogenic belt is Miyashiro's type example of the intermediate pressure facies series, although lower pressure mineral assemblages (Buchan type) are found in a limited area. It is not so easy to find an example of the high pressure type, as it is one of the characteristics of such metamorphic belts that they rarely contain granitic intrusions. The Alpine orogenic belt of the Alps has been chosen as the nearest approach to a high pressure belt which actually contains some granites. The metamorphism in the Pennine Alps is considered by Miyashiro (1961) to be of intermediate-high pressure type, but according to Winkler (1967) the regional metamorphism in the Alps represents the highest-pressure facies series which can be formed by dynamo-thermal metamorphism. The metamorphic belts quoted by Miyashiro as examples of the high pressure type do not contain any granites.

Calculation of the Average Compositions of the Granites

The sampling principles underlying the calculation of the average compositions were as follows.

Definition of the Target Population

The target population consisted initially of all the granitic rocks present in the three orogenic belts. Actual sampling was necessarily limited to the available population (Griffiths, 1967), i.e. those individual granite samples for which published analytical data are available.

A first step in defining the target population was to confine the study to intrusive granites, i.e. those for which a magmatic origin could reasonably be assumed. No analyses of migmatitic granites or granitic gneisses were used. A second step was to limit the compositions of the granites studied to those whose CIPW norms showed $Q + Or + Ab \geqq 80\%$. Some such limitation was necessary to separate the granites from the intermediate and basic rocks with which they are often associated, and a chemical limitation was considered to be more satisfactory and easier to apply than a petrographic one. The permitted range of normative $Q + Or + Ab$ of 80–100% is sufficiently large to include the majority of rocks described in the literature as granites, while being sufficiently narrow to enable a realistic comparison to be made between their compositions and the compositions represented by the experimentally investigated system Q—Or—Ab—H_2O.

In order to interpret the compositions of the rocks in terms of the system Q—Or—Ab—H_2O, the analyses were recalculated to $Q + Or + Ab = 100\%$. In effect, since these three normative constituents approximately correspond to the lowest melting-temperature fraction of granitic rocks (Winkler, 1967; Piwinskii and Wyllie, 1970), the comparison of recalculated Q, Or and Ab represents a further limitation of the target population to the minimum melting-temperature constituents of the granites. Subsequent references to normative Q, Or and Ab will refer to the norms recalculated to $Q + Or + Ab = 100\%$.

The Available Population

As a basis for this comparison, a thorough search was made of the geological literature of all the relevant countries, several thousand chemical analyses were examined, and the CIPW norms of many of them were calculated.

The Variscan orogenic belt presents considerable sampling problems. The areas from which data have been drawn are south-west England, Brittany, the Massif Central of France, the Pyrenees, Alps, Vosges, Black Forest, Harz Mts., and the Bohemian massif. In some of these areas there are also granites of pre-Variscan age, and in the Alps there are also post-Variscan granites. The geological literature was carefully examined to ensure that as far as possible no granites formed other than during the Variscan orogeny were included in the compilation, and a few granites of dubious age were omitted. The Variscan data will be listed in detail elsewhere (Hall, 1971).

The Caledonian orogenic belt is relatively straightforward, and there is no problem of distinguishing Caledonian from non-Caledonian granites. The data on these granites has previously been summarised by the author (Hall, 1969) but some modifications have been made to bring the data into line with the sampling plan described here, and additional new analyses have been taken into account.

The Alpine orogenic belt of the Alps is the most difficult to sample on account of the small number of granitic intrusions which are present. An Alpine age has been assigned to a number of calc-alkaline intrusions along the length of the southern Alps from Traversella in the west to Pohorje in the east. However, recent isotopic age determinations have shown that several of these are actually much older than was previously thought, including the granites of Cima d'Asta (Ferrara *et al.*, 1962), Predazzo (Borsi and Ferrara, 1967) and Monte Sabion (Borsi *et al.*, 1966), all of which are of Permian (i.e. late Variscan) age. The results obtained by Borsi *et al.* (1966) also throw doubt on the age of all the granites lying immediately to the south and east of the Giudicarie (Judicaria) line, i.e. those of Val Meledrio, Bressanone, Ivigna and M. Croce. In most of the remaining intrusions, the dominant rock types are granodiorites, tonalites, and diorites, and rocks with $Q + Or + Ab \geqq 80\%$ usually occur only as minor dykes, pegmatites, aplites etc. The only substantial intrusions of true granitic rocks are those occurring in the Biella, Bergell and Adamello complexes, the Alpine age of each of which has been confirmed by isotopic age determinations. There are five intrusions which fulfil the sampling criteria listed below: (1) the granite of Valle de Cervo, Biella (Peyronel-Pagliani, 1961); (2) the S. Fedelino unit of the Bergell complex (Balconi, 1941); (3) the main intrusion of the Bergell complex (Weibel, 1960); (4) the Lago d'Avolo intrusion in the Adamello complex (Dieni and Viterbo, 1961); and (5) the granite of Malga Ervina in the Adamello complex (Dieni and Viterbo, 1961).

Sampling

There is no means of ensuring that the samples used to calculate each average are absolutely representative of the target population, but the following steps were taken to draw upon the available population in such a way as to obtain samples which are as representative as possible.

All analyses of minor intrusive phases or obviously unrepresentative material were excluded, for example microgranite or quartz-porphyry sheets, dykes or sills, pegmatites, aplites, and greisenized or other hydrothermally altered rocks. Spectrochemical analyses, those lacking determinations of important constituents, and all analyses published before 1920, were also excluded as being chemically unreliable. A few analyses published since 1920 were omitted in favour of later analyses of the same intrusions.

In order to reduce the weighting of intrusions represented by a large number of analyses, a single composition was chosen to represent each intrusion. For about half the intrusions there was only a single analysis available, and this was there-

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Table. *Average normative compositions of Variscan, Caledonian and Alpine granites*

	Mean	Standard deviation	Number of granites	Difference between means
Quartz				
Variscan	35.3	4.6	198	Significant at 99.5 % confidence level
Caledonian	31.8	4.7	41	Not significant at 95 % confidence level [a]
Alpine	25.1	11.2	5	
Orthoclase				
Variscan	32.0	3.9	198	Significant at 99.5 % confidence level
Caledonian	29.5	4.7	41	Not significant at 95 % confidence level
Alpine	29.1	11.0	5	
Albite				
Variscan	32.7	4.1	198	Significant at 99.5 % confidence level
Caledonian	38.7	6.8	41	Not significant at 95 % confidence level [a]
Alpine	45.9	10.3	5	

[a] The Mann-Whitney U-test indicates these differences to be significant at the 90 % confidence level.

fore used. Where an intrusion was represented by a number of analyses, the average was taken (after excluding analyses with $<80\%$ Q+Or+Ab). It is not supposed that such an average is necessarily representative of the intrusion as a whole, but it would probably be less unrepresentative than most single analyses.

After compiling the available data in accordance with the principles described above, compositions were available for 198 Variscan granites, 41 Caledonian granites, and 5 Alpine granites. The normative Q, Or and Ab contents (recalculated to Q+Or+Ab$=100\%$) were then averaged, and the results are given in the Table.

Results and Discussion

The differences between the average compositions of Variscan, Caledonian and Alpine granites are small, and statistical tests have been applied to evaluate the significance of these differences. The significance of the differences between the mean compositions of Variscan and Caledonian granites have been estimated by a normal-distribution test and by Student's t-test. Both tests show the differences to be significant at the 99.5% confidence level for each normative constituent. The differences between Caledonian and Alpine granites have been examined by a modified t-test for samples of unequal size and variance, and by the non-parametric Mann-Whitney U-test. Both tests show that the differences between the means are not significant at the 95% confidence level. This result does not mean that the Alpine and Caledonian granites are not different in composition, only that there is too little data and too large a scatter of compositions to establish that the differences between the means are significant. The Caledonian granites *can be confidently stated* to be poorer in normative Q and Or and richer in Ab than the Variscan granites, while the Alpine granites *appear on the existing evidence* to be even poorer in Q and Or and even richer in Ab.

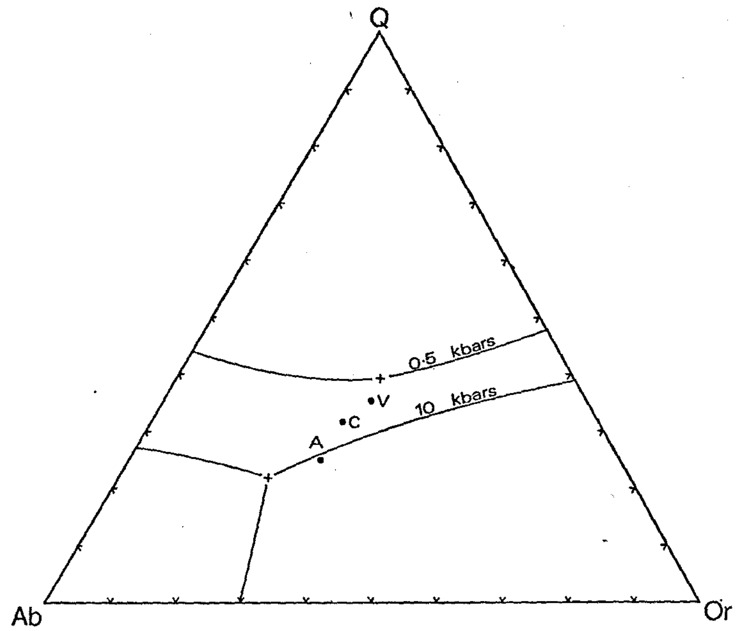
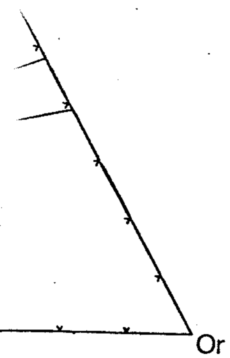


Fig. 1. The compositions of the average Variscan (*V*), Caledonian (*C*), and Alpine (*A*) granite in relation to the system Q—Or—Ab—H_2O. Crosses indicate the isobaric minima at water pressures of 0.5 and 10 kilobars (after Tuttle and Bowen, 1958; Luth, Jahns and Tuttle, 1964)

Fig. 1 shows the mean compositions of the granites in the three orogenic belts in relation to the isobaric minima in the system Q—Or—Ab—H_2O. Minimum melting-temperature compositions in this system, and in rocks containing an appreciable proportion of these normative constituents, are governed principally by the pressure of water. Luth (1969) indicated that they would also be affected slightly by total pressure, but the results of the melting experiments of Brown and Fyfe (1970) suggest that differences between total pressure and water presure have a relatively minor effect on melt compositions. Assuming that total pressure is roughly equal to lithostatic pressure, Fig. 2 shows some of the relevant melting relationships. Under a geothermal gradient of 20°/km, rocks containing the constituents of granite start to melt at a depth of the order of 30 km and at a temperature of about 600° C, assuming that a small amount of water is present (Tuttle and Bowen, 1958; Wyllie and Tuttle, 1960). Melting at this temperature only proceeds to the extent that there is enough water available to saturate the melt, over 10% H_2O being required at this pressure. If the water is not available, a considerable rise in temperature is needed to bring about complete melting. Whereas the temperature at a depth of 30 km would only just be enough for melting to start under a geothermal gradient of 20°/km, it would be sufficient for melting of the granitic constituents to be virtually complete under a geothermal gradient of 40°/km, even in the absence of a large amount of water. It is unlikely that the rocks undergoing melting would contain sufficient water to saturate the magma if melting was complete, and consequently if melting proceeds far beyond



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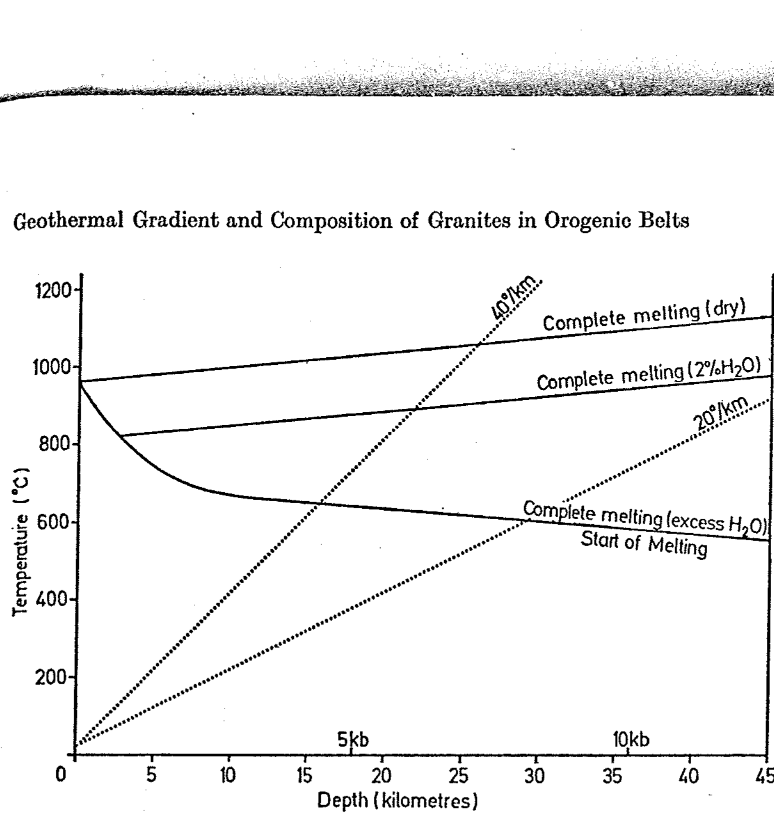

Fig. 2. The variation in melting temperatures of the minimum-melting constituents of granite with pressure and depth (after Tuttle and Bowen, 1958, p. 122). Two possible geothermal gradients are indicated

its commencement the water pressure is likely to fall well below the total pressure (Luth, 1969; Piwinskii and Wyllie, 1970). Magmas formed under a high geothermal gradient will therefore either have formed at a low P_{total} by very incomplete melting, with P_{H_2O} approaching P_{total}, or under a higher P_{total} but with P_{H_2O} much less than P_{total}. In contrast, under a low geothermal gradient melting is less likely to proceed beyond a partial stage in which P_{H_2O} is not much less than P_{total}, while P_{total} is high. Either way, the lower the geothermal gradient, the higher is the water pressure under which melting would occur.

The positions of the mean Variscan, Caledonian and Alpine granites fall near the isobaric minima in the system Q—Or—Ab—H_2O for successively higher pressures of water. In view of the successively lower geothermal gradients inferred for the respective orogenic belts from metamorphic facies series, the relationship between the compositions of the granites is exactly what would be expected if the magmas were produced by melting at a depth determined by the geothermal gradient. This result supports the widely held view that most granites in orogenic belts originate by partial melting in the crust.

It has already been pointed out by Zwart (1967) that granites are most abundant in orogenic belts that show the low pressure type of metamorphism (e.g. the Variscan), less abundant in those that show the intermediate pressure type of metamorphism (e.g. the Caledonian), and rare in those that show the high pressure type of metamorphism (e.g. the Alpine). Obviously, if the geothermal gradient is high, a larger vertical range of crust reaches melting temperatures, and the minimum melting temperature is more likely to be exceeded, than if the geothermal gradient is low. Because of the abundance of granites in low-pressure metamorphic belts, compilations of analyses, such as Washington's tables, will contain a high proportion of this type of granite. Thus the composition of the average Variscan granite lies near the frequency maximum of granitic compositions calculated by Tuttle and Bowen (1958, p. 79). The author's earlier observation (Hall, 1967, p. 169) that the Caledonian granites appear to be anomalously rich in normative albite reflects the relatively smaller abundance of granites in intermediate- and high-pressure metamorphic regions. The average composition of Alpine granites is even more untypical of granitic rocks as a whole.

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