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The Production of Granitic Melts during Ultrametamorphism

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Abstract. Data concerning the occurrence and mineralogy of granitic rocks and migmatites indicate that granitic liquids are not generally water saturated and do not form on minimum melting curves. Experiments on the partial fusion of crustal materials containing water only in hydrated phases demonstrate that water undersaturated melts with compositional affinities to the granite family are produced at temperatures and pressures in accord with observations on the metamorphic state of migmatite terrains.

Introduction

One of the outstanding problems of petrology has been to describe the conditions involved in the formation of granitic rocks. These rocks, of rather constant chemical composition, occur on a vast scale and often form the main mass of mountain ranges. The volumes of granitic batholiths can be so large that proposals to derive them by some diffusional method from pre-existing crustal materials were seriously considered until quite recently. These proposals also neatly avoided the apparent problem of finding the space or room for the masses involved were they to be derived from intrusive melts.

Today we are increasingly aware of the scale on which liquids of granitic affinity are the products of volcanism and it can no longer be doubted that appropriate silicate melts exist on an appropriate scale. Following the work of Tuttle and Bowen (1958) many experimentalists have shown that liquids of the desired chemical composition could be produced as the first melting fraction of crustal materials at very modest temperatures (650° C) if the melts were water saturated. In fact, these fusion temperatures are even lower than those recorded in the minerals formed during high grade metamorphism of the crust (Epstein and Taylor, 1967; Carmichael, 1967).

It thus seems probable that during the progressive metamorphism of partly wet buried sediments and igneous rocks, temperatures appropriate to fusion will be attained and that the first liquids produced by fractional fusion will be granitic in composition. As normal crust contains a large fraction of acidic composition, this fusion process will provide the thermal buffer system for the crust and higher temperature fusion products such as basalts are not likely to be produced at high levels.

The present work involves a study of the regions of fusion of high grade metamorphic rocks with particular reference to the genesis of melts of the granite family.

Geological Observations on the Conditions of Melting

If crustal melting processes produce the volumes of liquids required, then clearly we must start from a crust of at least normal thickness. Some regions where rocks of the highest grades of crustal metamorphism are exposed show strong evidence for the former presence of dispersed granitic liquids. Such migmatite areas provide a direct glimpse into the melting region where the phases present normally include garnet, biotite, sillimanite, hornblende, magnetite, pyroxene and feldspar. Experimental studies of phase equilibria of metamorphic minerals in migmatite regions indicate that melting occurs at pressures near the kyanite-sillimanite and basalt-eclogite transitions (Bryhni *et al.*, 1970) and at temperatures of the order of 800° C (Epstein and Taylor, 1967). Mineral assemblages and reactions also indicate that in such regions melts are undersaturated with water and water pressures are less than load pressures — not the situation found during progressive metamorphism prior to melting where it is generally considered that water and load pressures are similar. If water is added to systems of the type indicated above, reaction relationships between hydrated and anhydrous phases can be written (Fyfe, 1970, p. 204—205) indicating that water is not present in excess and that solid phases are buffering the partial pressure of water. Physical conditions are thus fitting to the thermal gradients implied by rather normal heat flow with melt generation at about 30 km depth (with temperatures about 800° C and load pressures about 10 kb.). Extreme depth cannot be involved as albitic plagioclase appears to be stable with respect to jadeite in all migmatite regions (Boettcher and Wyllie, 1968).

Direct measurement of the temperature of eruption of granitic liquids has not been made but careful study of the phases present in glassy rocks (Carmichael, 1967) indicates that temperatures of the order of 900° C may be involved.

Many geological data suggest that the P - T regions of granitic melt formation are above the minimum conditions found by Tuttle and Bowen and that melts are not water saturated. Natural temperatures are several hundred degrees higher and the melts are drier as suggested by the absence of excessive hydrothermal activity around high level intrusions such as the Sierra Nevada batholith of California. There is also compelling evidence for the ability of rising granitic liquids to dissolve or melt included materials, a process which suggests formation on a positive melting curve (increasing T of melting with P) rather than the negative curve of water-saturated melting. Harris *et al.* (1970) have indicated the problems associated with the extrusion of water saturated liquids. The problem is thus to find the correct pattern and region of melting of high grade metamorphic rocks.

Experimental Studies

The typical major minerals of diorites, granodiorites and granites (quartz and feldspars) were extracted from such rocks and mixed with either 10% or 50% of the major water-bearing phases of high grade metamorphic rocks (e.g. muscovite, biotite and hornblende). Chemical details relating to the materials considered in this paper (16 run compositions) are given in Table 1. A large number of experiments

Table 1. *Chemical analysis of raw materials*

Sample no.	102	105	D	G	H	B	M	P
SiO ₂	52.86	73.27	62.35	78.31	46.25	37.35	45.73	40.23
Al ₂ O ₃	18.23	13.24	19.45	12.48	8.52	16.81	32.85	16.65
Fe ₂ O ₃	2.12	0.23	0.14	Tr	2.30	2.48	0.55	0.29
FeO	5.54	1.89	0.38	0.08	12.08	20.49	3.02	2.06
MgO	3.20	0.68	0.28	0.03	11.71	6.40	0.19	20.82
CaO	7.85	1.64	5.75	1.27	12.69	0.17	0.04	0.14
Na ₂ O	3.34	3.13	5.98	3.20	0.83	0.41	0.59	0.38
K ₂ O	2.12	4.26	3.09	4.57	0.65	9.16	10.36	8.55
CO ₂	0.89	0.66	nd	nd	nd	nd	nd	nd
TiO ₂	1.32	0.27	0.88	0.09	3.04	3.44	1.51	7.66
P ₂ O ₅	0.86	0.25	0.76	0.12	nd	nd	nd	nd
MnO	0.05	0.01	Tr	Tr	0.27	0.77	0.16	0.05
H ₂ O	1.41	0.79	nd	nd	1.72	2.26	4.54	1.76
Total	99.79	100.32	99.06	100.15	100.06	99.74	99.54	98.59

102 = Ballachulish Quartz Diorite (mafic xenolith). 105 = Skiddaw Granite. D = Quartzofeldspathics: Ballachulish Quartz Diorite. G = Quartzofeldspathics: Skiddaw Granite. H = Hornblende: Ballachulish Quartz Diorite. B = Biotite: Skiddaw Granite. M = Muscovite: Cornish Granite. P = Phlogopite: Leucite Hills, Wyoming (volcanic association). Tr = Trace. nd = not determined.

These materials provided 16 types of run mixture containing 10% or 50% of the hydrate extracts within each quartzofeldspathic extract.

was conducted within the *P-T* region outlined above (Brown, 1970): for each composition the melting curve under water-saturated conditions was determined and also the conditions for the beginning of melting when water was present only in hydrated phases. Most experiments were of 14 days duration and it is not known if equilibrium was attained. In all cases oxygen pressure was buffered so that minimal changes in the oxidation state of iron occurred during the experiments.

Melting Curves

When the vapour pressure curve of a hydrated substance intersects the water-saturated melting curve of a mixture, the stable phase relations and melting region on *P-T* coordinates will be as shown schematically in Fig. 1. Here we consider a system of anhydrous solid phases (X) which reacts with water to produce an assemblage $Y \cdot nH_2O + Z$. The vapour pressure of mineral $Y \cdot nH_2O$ in the system lies along curve A-F-B; the water-saturated melting curve of system X lies along C-F-D. If the system $Y \cdot nH_2O + Z$ is studied without addition of excess water, the field of melting (partial or total) will be in the region enclosed by C-F-E. Melting relations of this type in the muscovite system have been described by Segnit and Kennedy (1961) and discussed in detail by Burnham (1967). Data found in this study are summarized in Fig. 2. Curves are shown for granitic and dioritic compositions only — granodioritic compositions fall in an intermediate position. It will be observed that the melting regions are of the

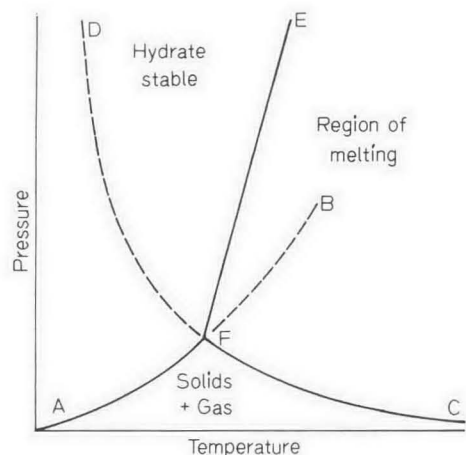


Fig. 1. Schematic diagram illustrating the decomposition of a hydrated mineral within a complex silicate system (see text)

form shown in Fig. 1. Lines representing initial melting within each mixture are approximately parallel, as might be expected, for the thermodynamic quantities involved must be similar.

As average crustal rocks in their high grade metamorphic state contain most of their water in biotite and hornblende, the shaded area of Fig. 2 might be the major area of production of large masses of granitic liquids. This region, found in these studies, is in striking accord with the information from migmatite regions and the temperature of extrusion of acid rocks.

From Fig. 2 we would expect that as metamorphic rocks become progressively buried and heated an initial liquid fraction would be produced, dependent on the amount of muscovite present, followed by a biotite fraction and finally a hornblende fraction. Each liquid, if formed on a large enough scale, could move upwards invading the crust. Alternatively, if formed in small volumes, it might remain and mix with a later fraction to achieve the mass necessary to overcome the forces resisting upward motion (Fyfe, 1970). (It should be noted that biotite and hornblende have very wide intervals of breakdown which can overlap. Fig. 2 focusses attention only on the beginning of melting for these minerals.)

As hydrated phases react to provide water for melting, refractory residues remain. Significant phases observed included pyroxenes, aluminium silicates (dominated by sillimanite) and magnetite. Pyroxene and magnetite resulted mainly from experiments with biotite, phlogopite and hornblende. These residues would lead to rocks of the granulite facies of metamorphism.

The extent of melting at any given temperature depends on the width of the reaction zone of the hydrate concerned (narrow for muscovite if excess quartz is present, broad for biotite and hornblende) and the quantity of the hydrate in the mixture. The varying quartzofeldspathic mineralogy of granites, diorites etc. also produces temperature differences reflecting directly their different water-saturated melting curves (see Fig. 2).

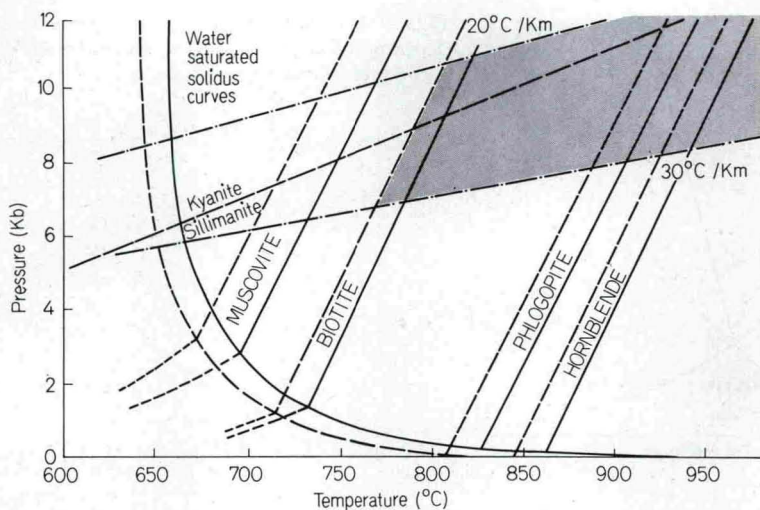


Fig. 2. The beginning of melting recognised within dry granitic (dashed lines) and dioritic (solid lines) mixtures resulting from the decomposition of the various indicated hydrated phases. Also indicated are the water saturated solidus curves determined for the two quartzofeldspathic mineral types together with possible geothermal gradients and the kyanite/sillimanite equilibrium boundary curve. Major production of natural granitic liquids is most likely in the shaded area

Chemical Composition of Melts

A selection of microprobe analyses of early melt fractions is given in Table 2. These represent melts formed within 20°C of first melting. Probe analysis showed the liquids to be quite homogeneous and if allowances were made for water content, oxide totals lay in the range $100 \pm 3\%$. The data in Table 2 are calculated on a dry basis and redistributed to total 100%. This should allow the most useful comparison with natural rocks.

Examination of the chemical data indicates that primary melt compositions are all remarkably similar. They also fall near to the granite system ternary minimum of Tuttle and Bowen. In general, there is a gradual progression from liquids of granodioritic to granitic affinity across Table 2 from left to right; a response to decreasing pressure and temperature. These melt compositions are compared with the compositions of the granite ternary minimum (Tuttle and Bowen, 1958; Luth *et al.*, 1964) for the appropriate pressures in Fig. 3 where normative ternary components are plotted.

Certain variations of genetic significance appear from the data:

1. *Ab/Or* ratios increase with increasing pressure. Corresponding increases in total alkalis and decreases in normative quartz values indicate that the liquids have greater dioritic affinity at higher pressures. These trends reflect those of earlier workers (Tuttle and Bowen, 1958; Luth *et al.*, 1964) who found that the composition of the granite ternary minimum became enriched in the albite component as pressure was increased.

Table 2. *Melt compositions—analyses redistributed to 100% neglecting water contents*

Run no.	2	13	122	216	222	24	35	43	55	115	116	201	236	164	171
Run composition	DH 50	GH 10	DH 50	GH 10	GH 10	DB 50	GB 10	DB 10	GB 10	GB 10	GB 50	GM 10	GM 50	DM 50	GM 10
Pressure Kb.	4	4	2	2	1	10.5	10.5	4	4	2	2	4	4	2.5	2.5
Temperature °C	900	900	885	872	870	820	820	760	760	730	730	700	690	705	705
SiO ₂	73.34	74.41	73.65	74.49	74.34	68.86	73.08	72.61	72.92	74.02	71.85	74.26	72.97	72.98	74.62
Al ₂ O ₃	13.25	14.50	13.08	14.30	15.43	15.08	15.53	15.30	16.12	15.76	15.12	15.84	16.42	16.66	15.53
Fe ₂ O ₃	0.33	0.16	0.31	0.18	0.09	0.46	0.16	0.24	0.15	0.15	0.40	0.09	0.16	0.19	0.10
FeO	1.74	0.87	1.53	1.02	0.49	3.81	1.27	2.00	1.25	1.27	3.27	0.35	0.70	0.77	0.39
MgO	1.22	0.73	1.50	1.02	0.60	0.98	0.30	0.51	0.51	0.32	0.73	0.09	0.15	0.18	0.13
CaO	1.43	0.42	1.77	0.89	0.76	0.74	0.36	0.59	0.74	0.23	0.39	0.27	0.34	0.44	0.34
Na ₂ O	5.13	4.83	4.51	4.38	4.43	5.31	5.30	4.89	4.51	4.21	4.20	4.44	4.40	3.86	3.98
K ₂ O	3.10	3.18	3.16	3.35	3.43	3.53	3.76	3.66	3.47	3.80	3.57	4.29	4.48	4.49	4.35
TiO ₂	0.37	0.87	0.35	0.35	0.40	1.12	0.19	0.16	0.29	0.21	0.37	0.31	0.33	0.41	0.50
MnO	0.09	0.03	0.14	0.02	0.03	0.11	0.05	0.04	0.04	0.03	0.10	0.06	0.05	0.02	0.06
Normative ternary components															
Quartz	30	34	34	36	37	23	27	30	34	36	34	33	31	35	36
Albite	49	45	44	42	41	53	49	46	43	39	41	40	40	36	36
Orthoclase	21	21	22	22	22	24	24	24	23	25	25	27	29	29	28

Quartzofeldspathic Extracts = G, Granite; D, Diorite (see Table 1). Hydrated Minerals = H, Hornblende; B, Biotite; M, Muscovite (see Table 1). 10, 50 = Percentage of hydrated mineral in each mixture (by weight). Ferric/Ferrous iron ratios are adjusted to reflect those of the parent hydrate.

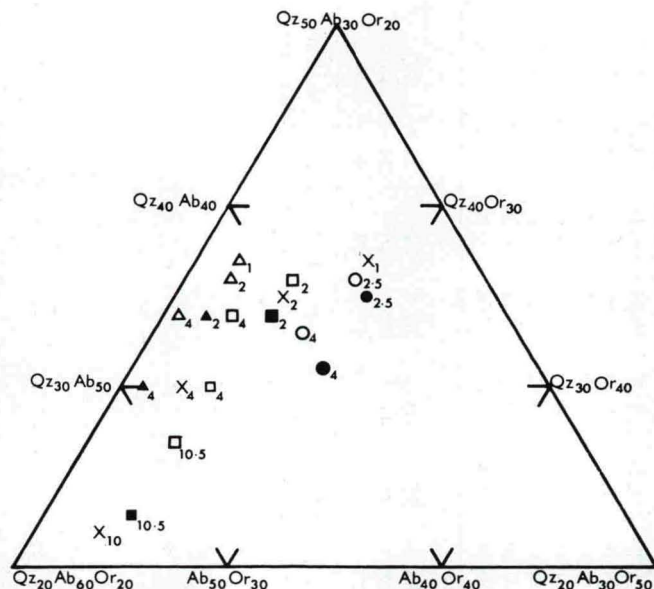


Fig. 3. Normative ternary components of early liquid compositions resulting from hydrate induced melting within dioritic (small symbols) and granitic (large symbols) quartzofeldspathic mineral mixtures. Open symbols — mixtures with 10% hydrated minerals. Closed symbols — mixtures with 50% hydrated minerals. Mixtures: Δ Hornblende, \square Biotitic, \circ Muscovitic, \times Plots of the ternary minimum and eutectic compositions in the granite system (after Tuttle and Bowen, 1958; Luth *et al.*, 1964). Small figures indicate pressures in kilobars. Qz Quartz, Ab Albite, Or Orthoclase

2. The bulk composition of the quartzofeldspathic host has little influence over early melt compositions but progressive melting must move the liquids towards the bulk composition. Since average crust contains a large fraction similar in composition to the ternary minimum, it is likely that the effects of progressive melting will be relatively minor.

3. Normative orthoclase contents are dependent on the hydrated mineral associated with fusion. High temperature melts from hornblende are granodioritic and plot towards the *Ab-Qz* side of the ternary minimum. Low temperature muscovite melts are granitic and plot towards the *Or-Qz* side.

4. Increase in the amount of a hydrate tends to reduce normative quartz as these are low silica phases.

5. The mafic content of the liquids is very sensitive to temperature; for example, low magnesium contents are associated with muscovite melting.

Geological Implications

The experimental data presented above indicate that the melting of metamorphic rocks in the amphibolite facies can produce a series of silicate liquids with compositions appropriate to the granite family. The bulk of melt production in nature is probably coupled with the destruction of biotite and hornblende.

Temperatures of melt formation lie 100–300° C above water-saturated minimum melting temperatures.

Using the simplest possible model: if homogeneous crustal material (resting on a basic or ultrabasic basement) is progressively buried and heated, a series of liquids would be produced starting from granitic fractions and moving towards more basic types with increasing pressure and temperature. These liquids could collect and invade the crust by a mechanism similar to that envisaged by Elsassner (1963) for the process of core formation. On this model, only large volumes of liquid would be capable of rising fast enough through solid high viscosity crust to avoid cooling to the point of crystallization. Once the mass is largely crystalline the density contrast necessary for upward motion is removed. Thus, small fractions of liquid might not rise but remain to mix with later increments of melt — this would apply to the trivial amounts of minimum melt that might be present in a rock.

Harris *et al.* (1970) have suggested, very plausibly, that liquids cannot move far once they enter the solid phase region of Fig. 2. If this is true and crystallization rates are fast relative to the rate of ascent, then granitic liquids (the coolest and most aqueous) would form only relatively deep intrusives while more basic types would be capable of high level intrusion. Along the same line of argument, acid extrusives would represent the driest and hottest melts of the granite family.

As the viscosity of the crust in a zone of partial melting must be low, (Fyfe, 1970) separation of liquid and refractory solid residue is likely to be rapid in terms of the times involved in a fusion cycle. The magma chamber formed by such separation would be floored by a residue rich in hornblende and pyroxene — a rock with affinities to the pyroxene granulite facies. Such high grade metamorphic rocks are thus likely to reflect the presence of a melt and conditions where water vapour pressure is lowered by the presence of melt.

The above model is certainly too simple to account for all observations regarding the order of intrusion of granitic rock types. In general, most of the base of the crust is solid and melting must be considered a thermal accident (Elder, 1968) perhaps induced by mechanisms related to plate tectonics. Large areas of continental basements are formed of granite gneisses and rocks with affinities to the granulite facies. If new meta-sedimentary and meta-igneous rocks are deposited on these and then depressed, heating from the base will first affect already highly desiccated rocks from a previous cycle. In this case the first liquids produced from such a basement could well be granodioritic and, as the isotherms rise in the crust, granitic liquids could follow. As the first major melt fraction from the basement rises, materials from above richer in hydrates will descend into the melting zone. There is also no reason why melting at more than one level should not be virtually synchronous. The apparent situation within many continental margin batholiths where younger granites intrude older granodiorite masses lends considerable support to this latter model.

The rate of ascent of a plutonic mass of granite may be quite slow. The only constraint is that the mass must not crystallize during an ascent perhaps of the order of 10–20 km. Rates as low as a few cm per year are not impossible if cooling is dominantly by conduction. If the time of ascent is of the order of

thousands of years, even allowing for the high viscosity of acidic melts, some degree of settling of the first phases to crystallize, particularly biotite and hornblende, is possible. This could lead to the impoverishment of mafic constituents in high level granites and in particular extrusives.

It appears that careful experimental study of the types of granitic melt formed from differing crustal materials and by differing hydrate breakdown reactions may allow a reasonable analysis of the sequence of intrusive and extrusive events. For a specific region, given age relations and chemical data it should be possible to set limits on the type of crust producing a granitic sequence, and to analyze the thermal history of a crustal segment as a function of depth and time.

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