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A NOTE ON THE NATURAL FUSION OF GRANITE

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ABSTRACT

A small plug of basaltic-andesite has fused the granite into which it is intruded in a zone adjacent to the contact. The glass progressively decreases in amount away from the contact, and the analyses of two samples of this glass represent two points on a disequilibrium fusion curve. There is no evidence of metasomatism up to the stage where over half the granite has been fused.

INTRODUCTION

Partial fusion of quartzo-feldspathic rocks as a result of high temperature thermal metamorphism is sometimes displayed at the contacts of basic intrusions; many of the accounts and results of this phenomenon have been summarized by Butler (1961) and Wyllie (1961) who also give an extensive bibliography on the subject. This data on natural fusion taken with the experimental results of Tuttle and Bowen (1958) and von Platen (1965) on synthetic granite systems, together with the implications of the results of the strontium isotope technique (Faure and Hurley 1963) provoke renewed interest in the interaction of crustal material with magma, particularly of basic composition.

An example of natural fusion and accompanying thermal metamorphism described here is caused by the intrusion of a small Tertiary basaltic-andesite plug (200 feet in diameter) into granite, and is located east of the Sierra Nevada, in California.[1] The flow of magma through the plug, perhaps acting as a feeder to the associated basaltic-andesite lavas, has generated an extensive amount of liquid (black glass) immediately at, and adjacent to, the contact. Beyond the zone of fusion, the effects of thermal metamorphism may be seen in the constituent minerals of the granite; this note considers the fusion paths of granitic rocks and the mineralogical response to the heat effect of the plug, the details of which are almost identical to those described by Butler (1961) for the thermal metamorphism of arkose.

PETROGRAPHY

The basaltic-andesite plug contains both phenocrysts and xenocrysts enclosed in a groundmass of labradorite-adesine crystals of variable size, interstitial pyroxene and iron-titanium oxides. The phenocrysts are augite, plagioclase, olivine altered to iddingsite, and almost completely

[1] This plug is located in the eastern part of Sec. 25, T3N, R25E, MDBM, in Bodie quadrangle, just north of Mono Lake, California.

resorbed hornblende; the xenocrysts are quartz with pyroxene coronae, spongy sodic plagioclase and alkali feldspar, both feldspars having a texture suggestive of incipient fusion. Typically the xenocrysts increase in number toward the contact with the granite, from which they were probably derived.

The unmetamorphosed granite is coarse grained and is predominantly made up of orthoclase microperthite, plagioclase (An_{28}) and quartz with biotite as the most abundant accessory mineral. The mode of the granite is given in Table 1; the granite also contains unevenly distributed subordinate accessory minerals which include hornblende, sphene, apatite, zircon and iron-ore. Each of the principal constituents of the granite shows a progressive response to the heat effect of the plug as the contact is approached.

TABLE 1. MODAL ANALYSES ALONG A COMPOSITE TRAVERSE AWAY FROM CONTACT

(Vol. %)

Glass:	60.0	57.3	57.0	51.6	53.6	55.1	30.1	22.9	18.4	21.6	27.4	10.8	—
Quartz:	8.7	12.4	14.2	13.6	12.1	11.8	17.5	18.1	15.5	17.2	18.4	19.2	24.9
Plagioclase:	9.4	9.6	7.5	10.1	11.7	10.6	16.7	21.2	27.6	26.2	21.8	26.5	27.9
K-Feldspar:	19.1	18.7	19.0	22.4	20.4	20.4	31.6	31.1	33.7	29.8	26.9	37.8	39.5
Biotite:	2.8	2.0	2.3	2.3	2.1	2.2	4.1	6.7	4.8	5.2	5.5	5.7	7.2
Accessories:	—	—	—	—	—	—	—	tr	0.2	0.1	—	tr	0.5
Distance from contact	0	2″	8.5″	12″ (Analyses Nos. 2 and 3)	13″	17″	4′	8′ (Analysis No. 4)	10′	11′	12′	25′	Fresh granite (Analysis No. 1)

The optical axial angles of both the orthoclase and plagioclase decrease, the former becoming almost uniaxial (sanidine) toward the contact. Biotite, which is the first mineral to respond to the onset of thermal metamorphism, changes color from greenish-brown to a reddish-brown and then becomes increasingly dusted with iron-ore grains eventually breaking down to a very fine-grained intergrowth of titaniferous iron oxides, orthopyroxene and sodic plagioclase which persists throughout the zone of melting. Sphene acquires a rim of opaque iron-oxides as the contact is approached, but the response of the other accessory minerals cannot be traced because of their uneven distribution; however hornblende is replaced in part by iron oxide dust, and thereafter its response of increasing grain size of the iron-ore as the contact is approached, cannot be distinguished from that of biotite, which behaves similarly.

The glass, which is dark brown or black, may form over sixty percent of the granite immediately at the contact (Table 1) so that the rock adjacent to the basaltic-andesite plug looks like a richly porphyritic pitchstone. There is a progressive decrease in the amount of glass away from the contact with the plug, which is illustrated by the modes of a composite traverse given in Table 1 and plotted in Figure 1. At a distance of approximately 35 feet glass is no longer found in the granite. The glass, often perlitic, commonly contains microlites; orthopyroxene forming small radiating clusters are most typical, but they are also found around the margins of residual quartz grains in a similar way to those

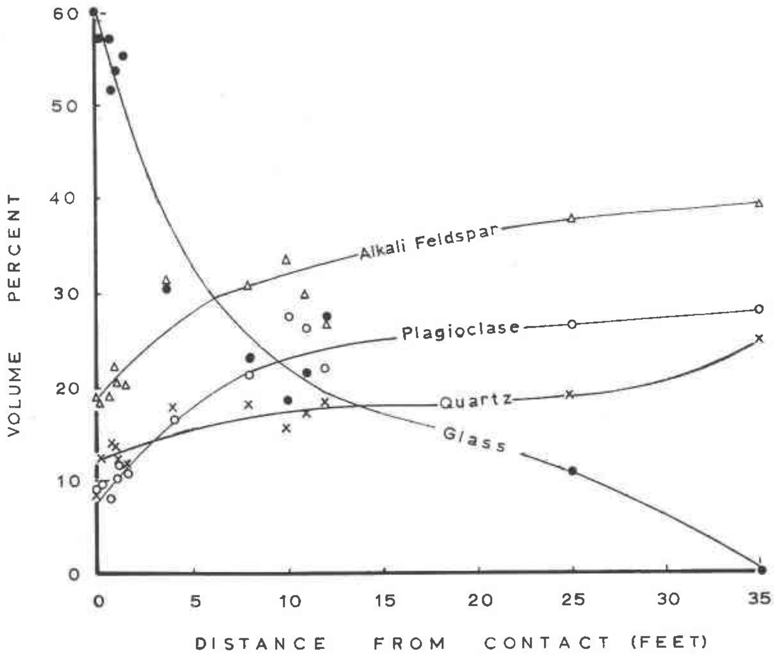

FIG. 1. Variation of volume percent of the major salic constituents and the glass in the partially fused granite with distance from the contact representing various stages of fusion. Data from Table 1. ● = glass, △ = alkali feldspar, ○ = plagioclase, × = quartz.

found around the quartz phenocrysts in the Arran pitchstones (Carmichael 1962). The glass also contains small microlites of quartz and feldspar identifiable only by X-rays; it usually tends to devitrify where it is present in small amounts; producing an extremely fine grained spherulitic intergrowth or quartz and feldspar.

The first appearance of a liquid in the granite is found at the boundaries between quartz and plagioclase grains and between quartz and alkali feldspar grains. Butler (1961) described an identical onset of fusion between quartz and either of the two feldspars, and concluded that the composition of the liquid was homogeneous with respect to the alkali components of the feldspars. Whether or not the liquid is homogeneous (diffusion) cannot be checked in these samples with the electronprobe, as much of the glass has partially devitrified. As the liquid component increases, it pervades the whole rock as veins and pools of brown glass, and produces a rather characteristic anastomosing effect in the alkali feldspar, suggestive of preferential fusion along the cleavage and the interfaces of perthite lamellae and host. With more extensive generation of liquid, the spongy marginal "fingerprint" texture extends throughout the whole crystal. The plagioclase crystals do not show such an extensive reaction, maintaining their clean appearance longer than the alkali feldspar, although rarely, and immediately at the contact with the plug, they also become spongy in appearance. Quartz remains clean in all stages of the fusion, with sharp but irregular junctions with the liquid; frequently small veins of brown glass penetrate a quartz grain to give separate "islands" with a common optic orientation. Biotite, surrounded by a zone of glass, commonly indicates that its salic components have been preferentially extracted into the liquid.

Fusion Path of the Granite

The modal analyses of specimens along a composite traverse from the basaltic-andesite plug into the unmetamorphosed granite are given in Table 1 and are plotted in Figure 1. Although there is some variation in the modal composition of each specimen from one thin section to another, the smoothed curves (Fig. 1) show a clear trend. There is a progressive and parallel decrease of alkali feldspar and plagioclase toward the contact which indicates that both feldspars have been dissolved at the same rate. However, quartz has not been taken into solution at the same rate as the two feldspars, and relative to the feldspars, it is enriched in the residual crystalline assemblage immediately adjacent to the contact with the plug.

The analyses of the unmetamorphosed granite and a partially fused granite are given in Table 2 (Nos. 1 and 2) and their general similarity, apart from oxidation and the acquisition of water by the glass, indicates that there has been no significant gain or loss with the generation of 51.6 percent liquid. Two glasses from the fused granite have been analyzed, No. 3 which forms 51.6 percent of the rock (No. 2) and No. 4 which represents 22.9 percent of the fused granite.

The two glasses (Nos. 3 and 4, Table 2) represent two points on a fusion curve, which if continued to the stage of fusion of the granite would include the average bulk composition of the two rocks (Nos. 1 and 2) at its termination. Thus in the analyses of the sequence first liquid (No. 4), second liquid (No. 3) and potential ultimate liquid

(Nos. 1 and 2), it may be seen that the minor oxides TiO_2, CaO, MgO, P_2O_5 and total iron increase progressively. All the analyses show small amounts of normative corundum, which in the absence of muscovite, may be ascribed to the determined alkali deficiency in the analyzed granitic biotite (unpub. anal., A. L. Smith) and its extracted salic constituents.

The normative salic constituents (less anorthite) of the four analyzed rocks have been plotted in Figure 2; both glasses (Nos. 3 and 4) are enriched in normative orthoclase in relation to the rocks from which they

TABLE 2. ANALYSES, CIPW NORMS AND MODES

	1	2	3	4		1	2	3	4
							Norms		
SiO_2	71.41	69.67	69.83	72.72	qtz	29.0	28.9	26.0	34.3
TiO_2	0.31	0.32	0.26	0.17	or	27.8	26.2	37.8	34.0
Al_2O_3	14.43	14.48	13.36	12.34	ab	28.8	27.8	25.2	22.6
Fe_2O_3	0.97	1.23	0.88	0.85	an	7.8	8.9	2.8	1.7
FeO	1.01	0.82	0.70	0.24	cor	0.9	1.0	0.5	1.1
MnO	0.06	0.05	0.06	0.04	hy	2.1	1.4	1.4	0.3
MgO	0.55	0.55	0.43	0.12	mt	1.4	1.8	1.4	0.5
CaO	1.66	1.92	0.60	0.38	il	0.6	0.6	0.4	0.3
Na_2O	3.39	3.27	2.95	2.68	hm	—	—	—	0.5
K_2O	4.68	4.42	6.42	5.72	ap	0.2	0.2	0.1	0.1
P_2O_5	0.09	0.08	0.06	0.04			Modes		
H_2O^+	1.68	3.00	4.06	4.46	Quartz	24.9	13.6		
H_2O^-	0.12	0.16	0.07	0.12	Plagioclase	27.9	10.1	*n* 1.503	1.501
Total	100.36	99.97	99.68	99.88	K-feldspar	39.5	22.4		
					Biotite	7.2	2.3		
					Access.	0.5	51.6 (glass)		

Analyst: I. S. E. Carmichael; alkalis by R. N. Jack.
1. Granite, unmetamorphosed, 300 feet west of the plug (742-27).
2. Partially fused granite, 12 inches from contact with plug (742-46).
3. Glass from No. 2 above (742-46).
4. Glass from granite 8 feet from the contact (742-20).

have been derived. This potassic enrichment is in part due to the preferential extraction of the salic constituents of the biotite, but even if the glasses are recalculated to exclude the salic contribution of biotite, they remain relatively enriched in normative orthoclase (Fig. 2).

The composition of the granite falls, in terms of these three components, near the minima in the system represented in Figure 2, and if the results of Tuttle and Bowen (1958) are applicable to fusion, then it would be expected that the liquids so produced would also have a composition near the low-pressure minima. Winkler (1956) has discussed the generation of potassic liquids by partial fusion in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-$CaAl_2Si_2O_8$-SiO_2 using von Platen's data at 2000 bars water vapor pressure. He has shown that a series of planes, each representing a fixed An/Ab ratio of the plagioclase component in the system, contain "eutectics" where liquid, plagioclase, alkali feldspar, and quartz (plus gas) coexist (Winkler 1965, p. 186). These "eutectics," found in each plane of specified An/Ab ratio of the plagioclase, migrate toward the quartz-potassium feldspar join when projected into the system $NaAlSi_3O_8$-

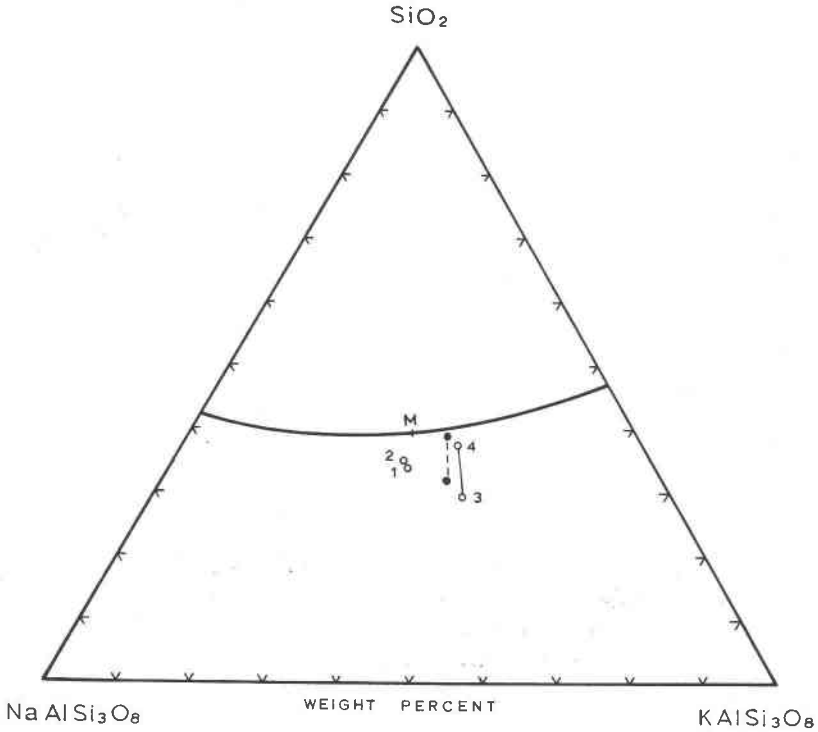

FIG. 2. Normative composition of the analyses of Table 2 plotted on the 500 kg/cm² isobaric phase diagram $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2 (after Tuttle and Bowen; 1958). 1 is unmetamorphosed granite, 2 is partially fused granite with 51.6% glass, 3 is the glass from 2, and 4 is glass forming 22.9% of partially fused granite. The solid circles represent the compositions of 3 and 4 after subtracting the salic contribution of the biotite to the glass.

$KALSi_3O_8$-SiO_2 (Fig. 2) (*op. cit.* Fig. 34). His conclusion is that the more anorthite there is in the plagioclase of the rock, then the more potassic is the liquid produced in the early stages of fusion of this rock. Neither von Platen (1965) nor Winkler (1965) produce the evidence necessary to support this conclusion, namely that throughout the fusion or crystallization interval, the compositions of the liquid *and* the feldspars remain in the plane in which the bulk composition of the initial mixture lies. Indeed, this would be in direct conflict with the evidence of natural acid liquids, whose plagioclase pehnocrysts are enriched in the anorthite component in relation to the liquid (Carmichael 1963); furthermore, the data given in Table 2 and also by Butler (1961) show that the composition of liquids generated by fusion of salic material is also impoverished in the anorthite component. Thus Winkler's "eutectics," which are only eutectics if the liquid and solid are confined to the composition plane of the initial mixture, are piercing points and represent the intersection of the four-phase curve liquid, plagioclase, potassic feldspar and quartz with whatever plane of An/Ab ratio of the plagioclase component is specified. Winkler's (*op. cit.* p. 187–189) concept of the fusion paths of acid gneisses being controlled by "eutectics" therefore may be quite fallacious; there is also no necessity for the liquid produced by fusion to move up the four-phase curve. Whether it does so or not will be entirely controlled by the bulk composition of the material being fused, in particular the Na/K ratio (Carmichael 1963), and the approach to equilibrium.

As both glasses occur with residual quartz, plagioclase and potassic feldspar, they would, if a quenched equilibrium exists, represent two points on the four-phase curve. Thus in projection in Figure 2, this four-phase curve would join both glasses and would represent the projected position of the curve (corrected or uncorrected for the salic contribution of biotite) for liquids with 1.7 and 2.8 percent normative anorthite respectively (Table 2). This projected trend is in conflict with the evidence of the paths of crystallization of natural acid liquids, for which the four-phase curve shows no such alarming contortions (Carmichael 1963).

It may be doubted if equilibrium did exist during fusion between the liquid (glass) and the solid phases, a conclusion substantiated by the way in which fusion progresses in relation to the minerals. For a rock equivalent in composition to the salic constituents (less anorthite) of this granite (Fig. 2), an approach to the equilibrium fusion path would be indicated if quartz was consumed throughout at generally the same rate as either of the feldspars (Fig. 1). The attainment of the equilibrium fusion path may also require the feldspars to be in the appropriate high-temperature modifications, the absence of which has been suggested by Tuttle and Bowen (1958) to account for the discrepancy between their results for the dry melting of granite (960°C) and the "metastable" melting of Greig, Shepherd and Merwin (1931) (800°C).

The trend of the fusion curve represented in Figure 2 must reverse its trend of silica depletion if complete fusion of the granite were achieved; this reversal is quite unlike any corresponding curve of crystallization found in the simple granite system (Tuttle and Bowen 1958). It would appear then that disequilibrium fusion could produce three general liquid trends each dependent on the relative rate of fusion of the principal salic minerals. If quartz and plagioclase were fused preferentially, then the disequilibrium fusion path would trend initially toward sodic enrichment; if quartz and potassic feldspar, then an early potassic trend would be taken by the liquid (Ackermann and Walker 1960; in this example the widespread soda metasomatism may have modified the composition of the liquid (Butler 1961)), and finally if the two feldspars were fused preferentially, then the fusion curve would show depletion in the silica component initially (Fig. 2). Disequilibrium fusion will be encouraged by a rapid rate of heating, great variation in the grain size and surface area of the constituent minerals, a factor known to affect the experimental attainment of equilibrium (*e.g.*, Hamilton *et al.*, 1964), and an inhomogeneous liquid phase preserved by slow diffusion rates. It is obviously impossible to predict the disequilibrium fusion path; the evidence of rocks indicates that the first liquid is generated at quartz-feldspar boundaries, so that its composition will be somewhere on the boundary curve of Figure 2, and of course it must end at the composition of the rock being fused if the metasomatism which often accompanies fusion is neglected (Butler 1961).

Fractional fusion is a term sometimes found in the literature (*e.g.*, Brown 1963; Butler 1961), but it is not clear what is meant, or what process is being described, by its use. To the writers fractional fusion could mean a disequilibrium fusion path, or a fusion path which is the reverse in sense of a fractional crystallization liquid path appropriate to a specified bulk composition, or it could mean partial fusion with or without the physical separation of liquid from the crystal residue. Where fusion occurs, there are only two possible conditions, equilibrium or disequilibrium; if the fusion path is a disequilibrium path then it cannot be predicted by any reference to crystallization paths; the possible connotation of the equivalence of fractional fusion paths with fractional crystallization paths in reverse should be eliminated by either dropping the term fractional fusion, or specifying in more detail what is being postulated by its use.

It has been noted above that biotite, the principal repository of Rb (and hence Sr^{87}) in granitic rocks has its salic constituents extracted preferentially into the liquid. If liquids derived by partial fusion of granitic or sialic material are available for subsequent intrusion or eruption (perhaps after accumulation by a migration allied to that of oil?), then these liquids (or rocks) may have higher values of the ratio Sr^{87}/Sr^{86} than those derived by total fusion. Moreover if biotite is stable under the conditions of fusion, a not impossible condition from the data of Wones and Eugster (1965) then the liquids produced by partial fusion may have very different Sr^{87}/Sr^{86} ratios. Such a varied role of biotite in a process of complete or partial fusion may be one of the contributing factors to the observed variation of the Sr^{87}/Sr^{86} ratios of granitic rocks (Hamilton 1965, p. 102–120).

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REFERENCES

ACKERMANN, P. A. AND F. WALKER (1960) Vitrification of arkose by Karroo dolerite near Heilbron, Orange Free State. *Quart. J. Geol. Soc. Lond.* **116,** 239–254.

BROWN, G. M. (1963) Melting relations of Tertiary granitic rocks in Skye and Rhum. *Mineral. Mag.* **33,** 533–562.

BUTLER, B. C. M. (1961) Metamorphism and metasomatism of rocks of the Moine Series by a dolerite plug in Glenmore, Ardnamurchan. *Mineral. Mag.* **32,** 866–897.

CARMICHAEL, I. S. E. (1962) A note on the composition of some natural acid glasses. *Geol. Mag.* **99,** 253–264.

——— (1963) The crystallisation of feldspar in volcanic acid liquids. *Quart. J. Geol. Soc. Lond.* **119,** 95–131.

FAURE, G. AND P. M. HURLEY (1963) The isotopic composition of strontium in oceanic and continental basalts: application to the origin of igneous rocks. *J. Petrology,* **4,** 31–50.

GREIG, J. W., E. S. SHEPHERD AND H. E. MERWIN (1931) Melting temperatures of granite and basalt. *Carnegie Inst. Wash. Yearb.* **30,** 75–78.

HAMILTON, D. L., C. W. BURNHAM, AND E. F. OSBORN (1964) The solubility of water and effects of oxygen fugacity and water content on crystallisation of mafic magmas. *J. Petrology,* **5,** 21–39.

HAMILTON, E. I. (1965) *Applied Geochronology.* Academic Press, London.

PLATEN, H. VON (1965) Kristallisation granitischer Schmelzen. *Beitr. Mineral. Petrolog.* **II,** 334–381.

TUTTLE, O. F. AND N. L. BOWEN (1958) Origin of granite in light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O. *Geol. Soc. Amer. Mem.* **74,** 1–153.

WINKLER, H. G. F. (1965) *Petrogenesis of Metamorphic Rocks.* Springer-Verlag, New York.

WONES, P. R. AND H. F. EUGSTER (1965) Stability of biotite: experiment, theory and application. *Amer. Mineral.* **50,** 1228–1272.

WYLLIE, P. J. (1961) Fusion of Torridonian sandstone by a picrite sill in Soay (Hebrides). *J. Petrology,* **2,** 1–37.