Sims, P. K. and P. B. Barton, Jr. (1961) Some aspects of the geochemistry of sphalerite, Central City District, Colorado. *Econ. Geol.*, **56,** 1211–1237.

White, A. J. R. (1962) Aegirine-riebeckite schists from South Westland, New Zealand. *J. Petrol.*, **3,** 38–48.

Williams, K. L. (1965) Determination of the iron content of sphalerite. *Econ. Geol.*, **60,** 1740–7.

——— (1967) Electron probe microanalysis of sphalerite. *Amer. Mineral.* **52,** 475–492.

Wright, J. B., (1967) Studies on the pyrrhotite and paragenesis of the Moke Creek Sulphide Lode, Wakatipu District. *New Zeal. J. Geol. Geophys.*, (in press).

THE AMERICAN MINERALOGIST, VOL. 52, MARCH–APRIL, 1967

THE EFFECT OF SYNNEUSIS ON PHENOCRYST DISTRIBUTION PATTERNS IN SOME PORPHYRITIC IGNEOUS ROCKS

Joseph A. Vance and John P. Gilreath, *Department of Geology, University of Washington, Seattle, Washington 98105.*

Introduction

Segregation of early crystals into clusters exhibiting glomero-porphyritic or synneusis structure characterizes many igneous rocks and is especially striking in porphyries. These widespread, but largely neglected, structures are of general petrologic interest for several reasons. First, their formation implies a drifting together and attachment of crystals freely suspended in a fluid medium (synneusis: Vogt, 1921). Such structures, accordingly, provide clear petrographic evidence of igneous origin. Moreover, this process of attachment controls several basic elements of the magmatic fabric, notably: (1) the mutual orientation of adjacent crystals in synneusis relation; (2) the nature of their common boundary; and, (3) the small-scale segregation of minerals within the fabric as a whole. A more general survey of the problem of synneusis will be given in a subsequent paper. The present note is concerned only with the last of these textural features.

It is a common observation that grouping of like crystals into glomeroporphyritic structures is more frequent than that of unlike minerals. If this relation is a general one, then synneusis is a selective process exerting a definite control on the distribution pattern of the minerals in the overall fabric. This study is an attempt to test this generalization and to quantitatively define the preferential character of synneusis for several common individual minerals and mineral pairs.

Procedure

Fourteen porphyritic rocks each containing two or three phyric minerals were chosen for study from the petrographic collection of the Geology Department of the University of Washington. The quantitative procedures followed here closely parallel those developed by Rogers and Bogy (1957) in a study of grain contact relations in granitic rocks. First the modal amount of the groundmass and of the phenocryst minerals was determined by point counting (1500 points, 300 from each of five thin sections) and the phenocryst percentages were recalculated to 100 percent. The length (hence area) of contact between each possibile phenocryst combination (*e.g.*, plagioclase-plagioclase, plagioclase-quartz, and quartz-quartz in a rock containing these two minerals as phenocrysts) was then determined by traversing the same thin sections at regular intervals and counting the number of times each type of contact was crossed (using a minimum of 500 points). In order to observe an adequate number of relations, five thin sections of each specimen were employed. These data were then used to calculate a ratio of that percentage of the total area of contact of mineral A occupied by mineral B/the recalculated modal percentage of mineral B (Table 1). In several specimens additional phenocryst minerals were present in small amount, but they were not included in the calculations. In most cases this nas not significantly affected the ratios determined for the other minerals.

Some inaccuracy is inherent in this procedure, especially in the identification of synneusis contacts. Recognition of contacts between crystals of unlike minerals is easy of course. Synneusis of like crystals is also easy to establish where textural evidence (*e.g.*, irregular external morphology characterized by blocky outlines and re-entrant angles incompatible with the growth of a single crystal; or the presence of multiple-zoned cores, as in plagioclase) demonstrates the participation of more than one crystal. Unavoidably, however, some synneusis contacts between like crystals must have been overlooked, for in some cases there is uncertainty as to whether one is dealing with a single crystal or with two individual crystals in parallel or twinned synneusis relation. In this study doubtful cases have been treated as single grains. As a consequence, the correct ratios for like minerals must be somewhat higher and those for unlike minerals somewhat lower than the ratios reported here. It will be seen, however, that the bias of this error is such as to reinforce the general conclusions reached.

Interpretation of the Data

The data summarized in Table 1 indicate a general tendency for preferential synneusis of the like minerals investigated, and a compensating

TABLE 1. RATIOS OF THE PERCENTAGE OF THE TOTAL CONTACT AREA OF PHENOCRYST MINERAL A OCCUPIED BY PHENOCRYST MINERAL B DIVIDED BY THE RECALCULATED MODAL PERCENTAGE OF MINERAL B

Specimen	Mineral A (modal % of phenocrysts not recalculated)	Mineral B		
#1		Plagioclase	Hypersthene	
ROSS PASS	Plagioclase (15.3)	1.60	0.25	
Andesitic Vitrophyre	Hypersthene (2.5)	0.30	5.17	
#2		Augite	Olivine	
TILLAMOOK BURN	Augite (17.3)	1.67	0.40	
Mafic Diabase	Olivine (20.8)	0.75	1.17	
#3		Leucite	Augite	Plagioclase
VESUVIUS	Leucite (17.6)	1.12	0.68	1.80
Leucitite	Augite (14.7)	0.69	1.32	1.21
	Plagioclase (2.8)	0.83	0.54	4.44
#4		Plagioclase	Olivine	
EP8c	Plagioclase (23.4)	0.94	1.56	
Basalt	Olivine (2.1)	0.75	3.82	
#5		Plagioclase	Augite	
PREDAZZO	Plagioclase (18.2)	1.73	0.14	
Basalt	Augite (15.5)	0.14	1.86	
#6		Plagioclase	Quartz	
Suiattle-1	Plagioclase (25.4)	1.48	0.12	
Dacite	Quartz (14.0)	0.24	2.39	
#7		Plagioclase	Quartz	
SUIATTLE-2	Plagioclase (29.1)	1.42	0.06	
Dacite	Quartz (13.1)	0.06	3.10	
#8		Plagioclase	Sanidine	Quartz
TREPCA	Plagioclase (24.3)	1.49	0.65	0.00
Rhyodacite	Sanidine (16.5)	1.69	0.35	0.01
Porphyry	Quartz (6.7)	0.00	0.09	6.16
#9		Plagioclase	Sanidine	Quartz
JAKE'S VALLEY	Plagioclase (12.9)	1.63	0.93	0.13
Rhyodacite	Sanidine (13.1)	1.83	0.98	0.09
Porphyry	Quartz (10.6)	0.26	0.11	3.01
#10		Plagioclase	Orthoclase	Biotite
KRANZ-97	Plagioclase (31.5)	1.05	1.12	0.46
Rhyodacite	Orthoclase (8.6)	1.03	0.91	0.92
Porphyry	Biotite (4.6)	0.91	1.50	2.07
#11		Orthoclase	Plagioclase	Quartz
LOON LAKE	Orthoclase (21.8)	0.86	1.84	0.38
Quartz	Plagioclase (14.3)	1.03	1.60	0.15
Monzonite	Quartz (11.2)	0.24	0.41	3.24
Porphyry				

TABLE 1—(*continued*)

Specimen	Mineral A (modal % of phenocrysts not recalculated)	Mineral B		
#12		Plagioclase	Sanidine	
88	Plagioclase (30.4)	1.14	2.35	
Latite	Sanidine (12.2)	1.21	0.48	
Porphyry				
#13		Plagioclase	Hornblende	
80	Plagioclase (9.7)	1.85	0.33	
Hornblende	Hornblende (11.7)	0.54	1.39	
Andesite				
#14		Plagioclase	Hypersthene	Augite
KRANZ-207	Plagioclase (19.3)	1.19	0.23	0.32
Pyroxene	Hypersthene (3.5)	0.29	4.03	2.84
Andesite	Augite (1.7)	0.35	2.31	5.58

antipathy toward synneusis for most of the unlike mineral pairs.[1] If contact and attachment of a given phenocryst pair have occurred randomly, then that percentage of contact area of a mineral A which is in contact with mineral B should be proportional to the recalculated modal percentage of mineral B in the rock. Thus, ratios close to 1.0 would indicate that the proportion of contacts between those particular phenocysts corresponds broadly to statistical probability and that synneusis was not selective. Ratios significantly greater than 1.0 would indicate preferential synneusis, while values significantly less than 1.0 would reflect antipathy.

The tendency for preferential synneusis of like crystals in the porphyritic rocks studied is clear from the data summarized in Table 1 and Figure 1. With the single exception of potassium feldspar in two specimens, all the like minerals show ratios near or greater than one. The order of increasing tendency for preferential synneusis is fairly consistent for the feldspars and quartz in the rocks studied, being potassium feldspar, plagioclase, and quartz in that order.

The variations observed for a given mineral in different rocks arise in part from the limitations of the ratio itself. Where synneusis has taken place selectively only those ratios obtained from rocks in which the phenocryst minerals are present in subequal amounts have precise quantitative significance allowing direct comparison with ratios from other rocks.

[1] Implicit in this discussion is the conviction that almost all the contacts between phenocrysts in the specimens studied are directly or indirectly the result of synneusis. It is true that in most specimens a part, and commonly a large part, of the contact area between grains developed by crystal growth after synneusis. The fact that these crystals are in contact at all, however, reflects their initial attachment by synneusis. Morphological evidence rules out epitaxis as a factor in formation of the glomero-porphyritic aggregates studied.

The influence of this factor is evident from Figure 1, in which, significantly, the six highest ratios shown were all obtained on minerals present in modal amounts only a small fraction of that of the associated phenocryst minerals. Similarly, the rather low ratios of certain other phases (*e.g.*, the plagioclase/plagioclase ratios) in part reflect the occurrence of these phases in modal amounts considerably greater than that of the associated phenocryst minerals. A large part of the variation of ratios for the same mineral in different rocks appears to be the result of other factors, however. The history of turbulence would appear to be the most important of these. Because synneusis implies differential movement of crystals within the melt, turbulence is normally a necessary condition of the process. Thus, the number and vigor of episodes of turbulence, and their timing with respect to the crystallization sequence, must profoundly influence the ultimate synneusis patterns. Grain size is a further important factor. Since surface area varies inversely with grain size, phenocrysts of a fine grained mineral will have a larger area potentially available for synneusis than phenocrysts of a coarse grained mineral in the same melt. Smaller crystals also have a shorter distance to travel into contact with one another than larger widely-spaced ones. It appears significant that potassium feldspar, the only mineral which consistently shows ratios less than one, occurs as large phenocrysts in all the rocks studied.

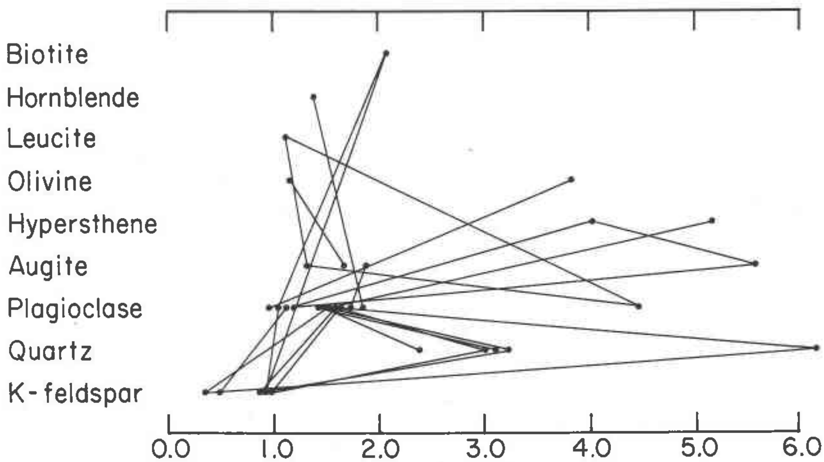

FIG. 1. Ratios of the total contact area of a given phenocryst mineral occupied by other crystals of the same mineral/the recalculated modal percentage of the mineral. The tie lines connect the ratios determined for different phenocryst minerals associated in the same rock.

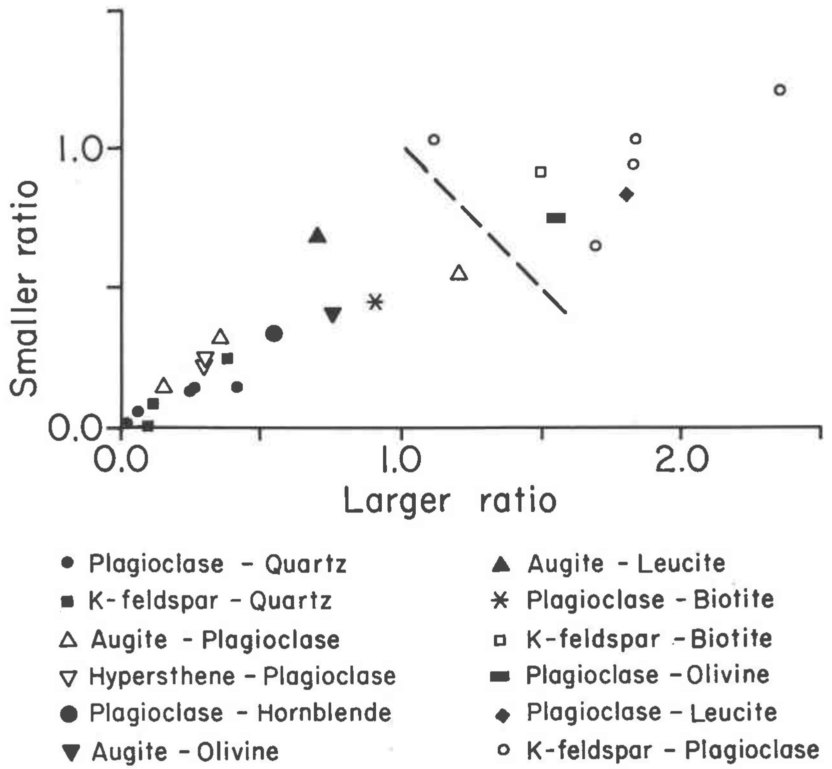

FIG. 2. Plots of the larger ratios of Table 1 against the smaller ratios for each of the phenocryst pairs investigated. Pairs showing preferential synneusis plot to the right of the dashed line, antipathetic pairs plot to the left.

The data also indicate common antipathy of unlike minerals for synneusis, although there are several conspicuous exceptions to this generalization. It will be noted that for each synneusis pair involving two different minerals two unequal ratios are obtained. To facilitate visualization of these relations, the larger ratio has been plotted as a function of the smaller ratio for each synneusis pair (Fig. 2). Of twenty-six relationships established between unlike mineral pairs, in only four do both ratios exceed 1.0 and only that involving hypersthene and augite (2.31/2.84, not plotted) is notably high. In most plots both ratios are substantially less than one. Five of the plots in which one or more ratios exceed one involve potassium-feldspar and plagioclase; in each case small plagioclase laths have become attached to crystal faces of large potassium-feldspars and incorporated within them during further growth (see Frasl, 1954; Hibbard, 1965). The preferential synneusis of these two minerals contrasts with the antipathy shown by most of the other mineral pairs studied. It should be pointed out that the high ratios of the two feldspars in part reflect the large mutual contact area arising from complete enclosure of the plagioclase within the potassium-feldspar host. These ratios are not strictly comparable with the ratios of the other mineral pairs, since the latter mostly involve crystals which are not complexly intergrown or extensively included within one another. One of the most conspicuous patterns observed between unlike minerals is the consistent and strong aversion to synneusis of the pairs quartz-plagioclase and quartz-potassium feldspar (the highest quartz/feldspar ratio determined was only 0.41). Preliminary study of other porphyritic rocks and of granitic igneous rocks indicates that this particular antipathetic relation is characteristic of many silicic igneous rocks. The data of Figure 2, while fragmentary, show that plots for a given pair of unlike minerals from different rocks tend to fall together within a relatively restricted area and suggest that consistent synneusis patterns are characteristic of unlike mineral pairs just as they are of individual minerals.

Conclusions

The contact relations between the phenocryst minerals studied reveal a moderate to strong general tendency for preferential synneusis of crystals of like minerals which is balanced by an antipathetic relation between unlike minerals in the same rocks. These tendencies are expressed in a small-scale, but marked segregation of the early crystals within the fabric. Although further study will be needed to define the full range of behavior of the common individual minerals and mineral pairs with respect to synneusis, the available data indicate that specific minerals tend to exhibit consistent patterns. Petrographic reconnaissance of many other igneous rocks, including plutonic rocks, suggests that both the broader synneusis trends recognized in this preliminary study and the selective synneusis patterns recognized here have wide general validity.

Acknowledgments

This study would not have been possible without the paper by Rogers and Bogy (1958) on grain contact relations in granitic igneous rocks. The ratio which they devised for quite a different purpose is the only workable approach we have been able to find which permits quantitative treatment of the synneusis relations of phenocrysts. We wish to thank the following graduate students—Boyce Meinhardt, Perry Klein, and K.

Peccato—for independent determinations of modes and phenocryst ratios for several specimens as a check on our own determinations.

References

Frasl, G. (1954) Anzeichen schmelzflüssigen und hochtemperierten Wachstums an den grossen Kalifeldspaten einiger Porphyrgranite, Porphyrgranitgneise und Augengneise Oesterreichs. *Geol. Bundesanstalt, Jahrb.* **97**, 71–132.

Hibbard, M. J. (1965) Origin of some alkali feldspar phenocysts and their bearing on petrogenesis. *Amer. J. Sci.*, **263**, 245–261.

Rogers, J. J. W., and Bogy, D. B. (1958) A study of grain contacts in igneous rocks. *Science*, **127**, no. 3296, 470–471.

Vogt, J. H. L. (1921) The physical chemistry of the crystallization and magmatic differentiation of the igneous rocks. *J. Geol.* **29**, 318–350.

THE AMERICAN MINERALOGIST, VOL. 52, MARCH–APRIL, 1967

NEW DATA ON TRIDYMITE

Raymond W. Grant, *Department of Geology, University of Vermont, Burlington, Vermont.*

The chemical composition of natural tridymite is poorly known. Of the ten tridymite analyses cited by Frondel (1962), eight were made before 1878 and the other two are spectrographic analyses in which the percent of SiO_2 was not determined. The only recent complete analysis of tridymite is given by Sato (1962).

Chemical, x-ray, and optical data on tridymite from two localities are given in this paper. One specimen is of the meteorite from Steinbach, Germany[1] (Harvard University Meteorite Collection, spec. no. 3). The other is from a "lithophysae in rhyolite, Mule Springs, 100 M. N. E. of Lakeview, Oregon" (Harvard No. 11285).

The chemical analyses of these two tridymites together with the recent analysis by Sato (1962), are given in Table 1. The samples were prepared by heavy liquid separation and hand picking.

Table 2 lists the optical properties and densities of all three tridymites. The indices of refraction increase as the amount of solid solution of Na, K, Ca, and Al increases, as was noted by Frondel (1962). The exact relationship between the composition and the indices of refraction is still not

[1] The Steinbach meteorite is a stony-iron (siderophyre) and has several synonyms (Prior, G. T., 1953). The tridymite from this meteorite was originally described as asmanite (Story-Maskelyn, 1871).