DISCUSSIONS

WATER PRESSURES DURING DIFFERENTIATION AND CRYSTALLIZATION OF SOME ASH-FLOW MAGMAS FROM SOUTHERN NEVADA

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I should like to make two observations which arise from the paper by Peter Lipman published in this Journal in December 1966. One concerns Lipman's comments regarding sodium leaching from the Taupo pumices; the second is to describe a third possible method of estimating water pressure in rhyolitic extrusive rocks.

1. *Sodium leaching in the Taupo (New Zealand) pumice glasses.—* Lipman (p. 812, 822) suggests that the Taupo pumices (Ewart, 1963) have undergone appreciable leaching of alkalis, in particular the selective loss of sodium, as a result of their high degree of hydration. To attempt to evaluate whether, in fact, selective alkali leaching has occurred, alkali determinations (by flame photometry) have been made on coexisting pumice and obsidian fragments from eight of the pumice horizons (referred to as members) within the Taupo pumice sequence. The results are presented in table 1. The samples were recollected from the original locality.

In the orignal work (Ewart, 1963), the obsidian fragments were regarded as being derived from the same magma as the coexisting pumices (in each horizon), mainly from the evidence of similarities of phenocryst mineralogy (see Ewart, 1963, table 3). In some of the obsidian fragments, there was evidence of partially assimilated xenolithic material (presumably wall rock). The percentage of recognizable xenoliths was, however, shown to be extremely small. It is therefore believed that the obsidians and coexisting pumices are chemically co-magmatic.

If preferential leaching of sodium had occurred due to the post-eruptive hydration of the pumice glasses, the Na_2O/K_2O ratios of the pumices should be consistently lower than the coexisting obsidians. From table 1, it is clear that this is not the case and that the Na_2O/K_2O ratios show reasonably close agreement for all eight pairs. The writer interprets this as indicating that preferential loss of Na_2O has not occurred from the Taupo pumice glasses. Some additional confirmation is obtained by the absence (with one exception) of normative corundum in the Taupo glasses (Ewart, 1963, table 7). Normative corundum should increase significantly as the result of alkali leaching of these rhyolitic glasses. A possible reason for the lack of sodium loss could be the very young age of the pumice deposits—all are younger than about 10,000 years.

2. *Additional method of estimating water pressures in acidic magmas.* —This method depends on combining both modal and chemical data in

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TABLE 1

Alkali analyses of coexisting obsidians and pumices from the Taupo Pumice sequence, New Zealand

Member number Material	5 O	5 P	7 O	7 P	10 O	10 P	12 O	12 P	14A O	14A P	14C O	14C P	16 (upper) O	16 (upper) P	19 O	19 P
Na_2O	4.74	4.55	4.69	4.49	4.68	4.48	4.60	4.52	4.76	4.66	4.52	4.32	4.79	4.54	4.56	4.28
K_2O	2.91	2.71	2.86	2.73	2.68	2.65	2.87	2.79	2.77	2.65	3.13	2.78	2.87	2.84	2.80	2.65
Na_2O/K_2O	1.63	1.68	1.64	1.64	1.75	1.69	1.60	1.62	1.72	1.76	1.44	1.55	1.67	1.60	1.63	1.62
Total ignition loss*	0.75	3.7	0.48	3.0	1.04	2.4	0.26	3.1	0.22	2.5	0.33	4.0	0.1	2.9	0.61	3.4

O = obsidian; P = pumice; all alkali analyses were done in duplicate.

* Includes $H_2O(-)$, $H_2O(+)$, and other volatiles.

relation to the experimental Q–Ab–Or–H$_2$O (Tuttle and Bowen, 1958) or preferably Q–Ab–Or–An (von Platen, 1965) systems. The method is best suited to 1-feldspar-quartz bearing acidic volcanic rock suites, which show only limited chemical variation. Such suites are found in the Taupo region, for example, as groups (or clusters) of co-magmatic rhyolite lavas and domes which are associated with various eruptive loci within the four main volcanic centers of the Taupo Volcanic Zone (Ewart, in press). The same technique can also be used for some of the ignimbrite units (ash-flow tuffs) which were also erupted from the volcanic centers. In these examples, the ignimbrite unit, or the groups of rhyolite lavas and domes, are each believed to have been erupted from a particular high level magma chamber, and in addition, different samples frequently exhibit a variation of phenocryst content, that is, they represent progressive stages of crystallization from the magma. In the ignimbrites, the variation in crystal content will be frequently evident as a systematic vertical variation. In the rhyolite lavas and domes, the variations of phenocryst content occur dominantly between different flows rather than within individual flows.

Mineralogically, the Taupo rhyolitic eruptive rocks are characterized by phenocrystic plagioclase (usually andesine), normally quartz, plus small amounts of opaques, hypersthene ± hornblende ± biotite. The occurrence of plagioclase is in accord with the relatively high Na$_2$O/K$_2$O ratios (see Ewart, 1963, 1965, for more detailed discussions). In only rare cases has crystallization proceeded far enough for a second feldspar (potash-rich) to precipitate.

In the following discussion, the method in question will be applied to two ignimbrites, the Matahina Ignimbrite (Bailey, 1965) and the Whakamaru Ignimbrite (Ewart, 1965). The procedure is as follows:

(a) The "average" chemical composition of the rock suite in question is obtained (assuming only limited variation of chemistry), and the normative feldspar and quartz components calculated. The Q, Ab, and Or are recalculated to 100 percent and plotted on the ternary diagram (figs. 1B and 2B). The appropriate boundary curves are also plotted, both for the simple ternary system (Tuttle and Bowen, 1958) and the quaternary system (von Platen, 1965,[1] using the appropriate boundary curve for the normative Ab/An ratio of the analysis).

(b) The amount of Ab or Q (depending on the location of the plotted composition relative to the various boundary curves) that will crystallize until the residual liquid reaches each of boundary curves is calculated. It is then assumed that both Ab and Q crystallize together, and the residual liquid follows the respective boundary curve to the minimum. The amount of both Ab and Q that will simultaneously crystallize until the liquid reaches the respective minima are then calculated. The results are plotted for each water pressure (for example, fig. 1), and

[1] The diagrams published are for 2000 bars only.

the two points calculated for each boundary curve are joined. These lines effectively define the predicted amounts of Ab and Q that would progressively crystallize from a magma of given composition, under various
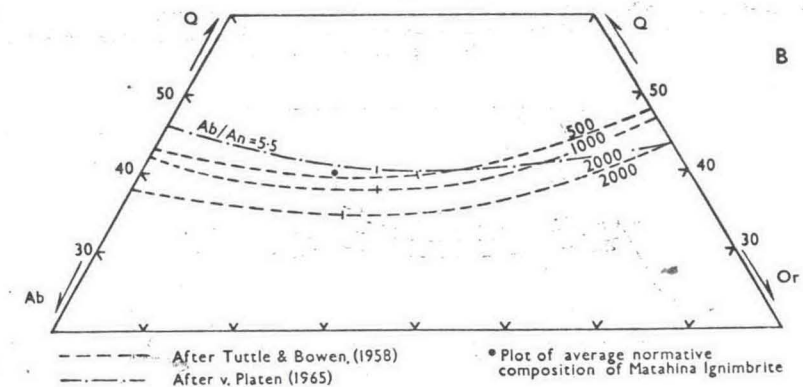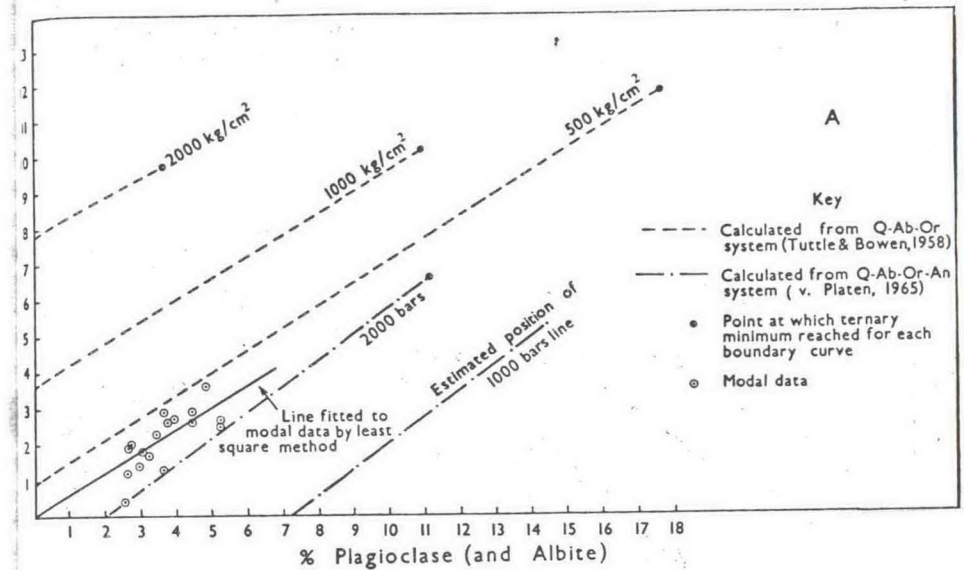

Fig. 1

A. Graph showing the calculated amounts of quartz and albite crystallizing under various water pressures compared to the modal (phenocrystic) quartz and plagioclase for the Matahina Ignimbrite. The theoretical amounts of quartz and albite were calculated from the starting composition Q = 39.8, Or = 21.4, Ab = 38.8, using the boundary curves in the quartz-feldspar system after Tuttle and Bowen (1958) and von Platen (1965); the latter data incorporates the effect of An. The points where the calculated lines intersect the quartz or plagioclase axes indicate the amount of quartz or plagioclase crystallized when the liquid reached the respective boundary curve.

B. The average normative composition (in terms of Q, Or, and Ab) of the Matahina Ignimbrite plotted in the ternary system Q–Or–Ab. The positions of the boundary curves (for different water pressures), used in the construction of the data for A, are also shown. The minimum on each boundary curve is shown by a dash.

water pressures, as defined by the experimentally determined boundary curves.

(c) The modal quartz and plagioclase of the various samples are also plotted, and the line of best fit calculated. (It should be noted that the modes are in volume percent, and the calculated data in weight percent. However, in practice, the quartz and plagioclase occurring in the rocks
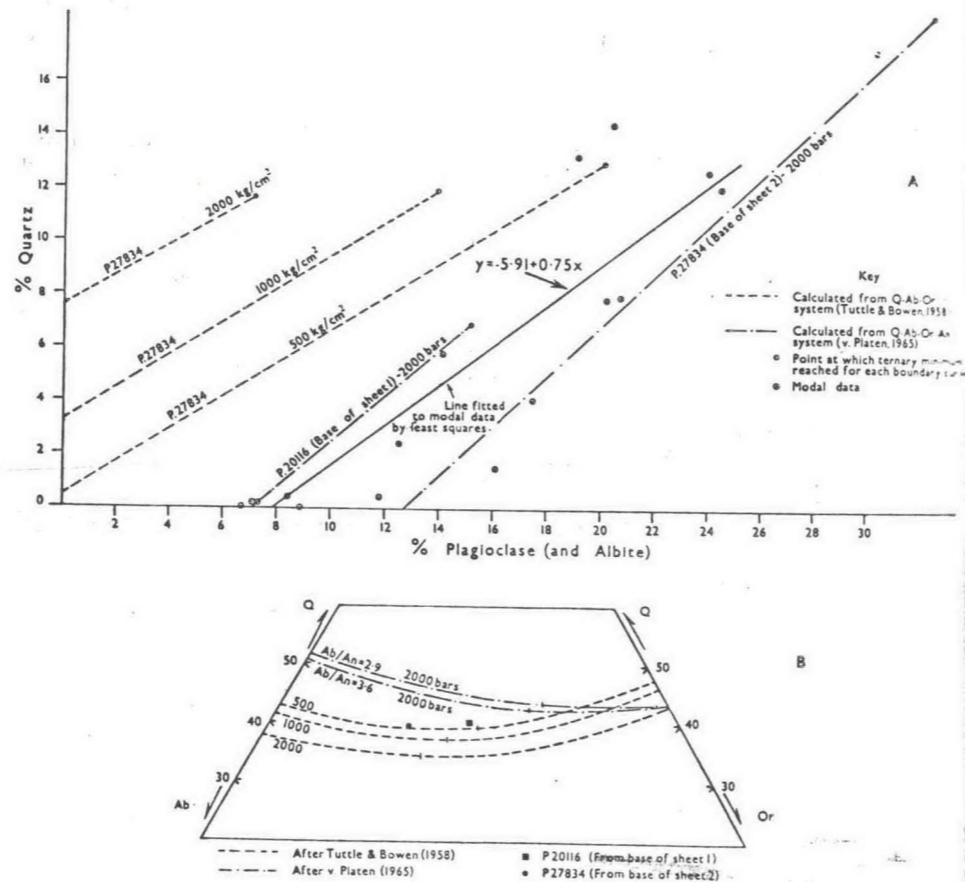

Fig. 2

A. Graph showing the calculated amounts of quartz and albite crystallizing under various water pressures compared to the modal (phenocrystic) quartz and plagioclase for the Whakamaru Ignimbrite. The amounts of quartz and albite were calculated (using the data of von Platen for the Q–Or–Ab–An system) from the normative data of two samples of the ignimbrite, which represent the extremes of chemical variation found in this ignimbrite (Ewart, 1965). The theoretical quartz and albite crystallizing from one of the samples (P. 27834) under various water pressures are also calculated for the data of Tuttle and Bowen (1958). Further details are given in the text.

B. The normative compositions of the two samples of Whakamaru Ignimbrite (P. 27834 and P. 20116) plotted in the ternary system Q–Or–Ab. The positions of the boundary curves (for different water pressures) used in the construction of the data for A are also shown. The minimum on each boundary curve is shown by a dash.

in question have similar specific gravities, and thus no correction was considered as warranted.)

Theoretically (even if not in practice), it should now be possible to ascertain the water pressure during crystallization of the magmas by visual comparison of the calculated and modal data. This makes the usual assumptions, for example, that the magma is saturated with respect to water.

Application to the Matahina Ignimbrite.—In figure 1, the method has been applied to the Matahina Ignimbrite. Although only two complete recent analyses are available (Ewart, Taylor, and Capp, in preparation), additional partial alkali analyses indicate only small chemical variations within the ignimbrite. The average normative composition (Q = 39.8, Or = 21.4, Ab = 38.8, Ab/An = 5.5) from the two complete analyses has therefore been used. The modal data has been obtained on 17 samples (r = + 0.71 for the correlation between modal quartz and plagioclase). From figure 1, it is obvious that the consideration of An in the quartz-feldspar system makes a tremendous difference to the interpretation of "apparent" water pressures. From figure 1, it could be concluded (bearing in mind the assumptions made) that the Matahina Ignimbrite magma crystallized at a water pressure slightly in excess of 2000 bars (using von Platen's data). This is higher than the values deduced by Lipman for the Nevada ash-flow magmas.

Application to the Whakamaru Ignimbrite.—In figure 2, the more complex example of the Whakamaru Ignimbrite is considered. This is composed of three distinct flow units. The stratigraphically lowest unit (designated as sheet 1) shows a very strong upward increase in phenocryst abundance and upward decrease in K_2O (details are given by Ewart, 1965), which are interpreted to be the reverse of the original condition in the magma chamber. The chemical and mineralogical variations through the overlying sheets 2 and 3 appear to be much less important. In figure 2, the calculations have been based on a sample from the base of sheet 1 (sample number P. 20116: Q = 40.0, Or = 29.0, Ab = 31.0, Ab/An = 3.6) and a sample from the base of sheet 2 (sample number P. 27834: Q = 39.4, Or = 20.5, Ab = 40.1, Ab/An = 2.9). These two samples essentially represent the limits of chemical variation (see figure 2B). The calculations have not been made for P. 20116 for Tuttle and Bowen's (1958) boundary curves, owing to the proximity of the analysis of this sample to the minima according to the simple ternary system. The modal data is also plotted in figure 2 (r = + 0.88 for the correlation between modal quartz and plagioclase). From figure 2, it is evident that the modal data is bounded by the two 2000 bars lines, representing the boundary curves for the two extreme compositions. This can be illustrated further by examining the calculated position of the P. 20116 boundary curve line with the position of the fitted line (from modal data), at which both intersect the plagioclase axis. There is a near coincidence which is significant as the sample P. 20116 and the lowest phenocryst contents coincide near the base of sheet 1. The data imply that

The advantage of this method is that both mineralogy and chemistry are simultaneously considered. Furthermore, with refinements of the experimental data, it is conceivably possible that progressive changes of water pressure could be evaluated by this type of approach. Conversely, if an independent method of estimating water pressure were available, it should be possible to evaluate whether the magmas were saturated or not with respect to water. Data for the opaque minerals in many of the Taupo rhyolitic rocks (for example, Ewart, 1967) indicate that the magmas from which they were derived were almost certainly not saturated with respect to water. This uncertainty is probably the most important reason why the present experimental data cannot be used quantitatively. It is perhaps pertinent to note here that unpublished data of residual glasses from a number of rhyolitic samples from the Taupo Volcanic Zone seem to show better agreement with the data of Tuttle and Bowen (1958) than that of von Platen (1965). The explanation may lie in low water content of the original magmas.

One final comment is also appropriate on the use of von Platen's data in the above discussions. During the progressive crystallization of a magma, it was assumed that the Ab/An ratio remained unchanged, that is, a boundary curve of constant Ab/An ratio was assumed. This obviously will not be the case, although in the examples discussed, in which the crystal contents were relatively low, the effect is not too drastic. The net effect, however, would be for progressively higher Ab/An ratios in the residual liquid as crystallization proceeded, that is, the data of Tuttle and Bowen would become more applicable during the later stages of crystallization.

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REPLY TO EWART'S DISCUSSION

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I am grateful to Dr. Ewart for his interesting comments with which I am largely in agreement and would like to take this opportunity mainly to make a few additional observations.

Ewart's new chemical data on comparative alkali contents of the Taupo obsidians and pumices demonstrate convincingly that significant leaching of alkalis did not occur during hydration of the pumices; my suggestion to the contrary, based on apparent disequilibria between plagioclase phenocrysts and groundmass glasses (Lipman, 1966, p. 812, 822), is clearly untenable. This absence of alkali modifications in the young but strongly hydrated Taupo pumices is especially interesting as several previous studies have shown inverse correlations between Na_2O and H_2O^+ contents in glassy rocks (Lipman, 1965, fig. 8; Aramaki and Lipman, 1965, fig. 2; Truesdell, 1966, fig. 8), a relation suggesting that alkali leaching occurred concurrently with hydration. Since non-hydrated glasses, no matter how old, seem to show no alkali modification, Ewart's data suggest instead that hydration, by disrupting the glass structure, is a necessary precondition for movement of alkalis, but that the two processes can occur at different rates and are not necessarily concurrent.

With respect to Ewart's second observation, on an additional method for estimation of water pressures, the higher pressures determined by reference to the experimental data of von Platen (1965) for the system Q–Or–Ab–An are clearly more applicable to the relatively calcic New Zealand rocks (Ab/An = 5.5) than are the much lower pressures indicated by reference to the simple ternary system studied by Tuttle and Bowen (1958). As rhyolitic portions of the Nevada ash-flow tuffs are characteristically very low in calcium (Ab/An = 10-100), the effect of the An component on water-pressure estimates for these rocks should be much smaller. This effect of calcium content on estimates of water pressure was discussed qualitatively in my paper (Lipman, 1966, p. 811-812), written prior to publication of von Platen's data. It might also be noted that Ewart's additional method for estimating water pressures is only partly independent of two I discussed. In effect, his graphical method adds the phenocrysts to melt compositions of the experimentally determined system. The same result could be achieved by the more conventional calculation of groundmass composition of the rock, starting from a bulk-rock chemical analysis and a modal-phenocryst analysis.

Finally, Ewart mentions that study of opaque oxides from the Taupo rhyolites suggests their magmas were probably undersaturated with H_2O; this is very interesting. Similar conclusions have recently been drawn by Carmichael (1967) for a varied group of rhyolite fluidal-flow rocks. The relation between water pressure and total pressure is, of crystallization again occurred at a water pressure of the order of 2000 bars. The effect of considering An is also strongly apparent.