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Origin of Ba-rich sanidine megacrysts in a porphyry from Papua New Guinea

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SUMMARY. A Miocene porphyry belonging to the shoshonite association contains 7 cm sanidine megacrysts in a groundmass of microphenocrysts of labradorite-bytownite, augite, sporadic hastingsite, magnetite, sphene, K feldspar, apatite, Ca zeolite and calcite. The megacrysts (Or_{78-94}) are enriched in BaO ($\simeq$ 2.0 wt%) and SrO relative to the groundmass. Although mineralogy and texture suggest that the megacrysts were *suspended* in a liquid, now represented by the groundmass, calculated liquid densities except for dry melts are less than those observed for the megacrysts and it is concluded that the original magma contained very little water. It possibly originated in a subduction zone with the main hydration taking place at shallow levels of intrusion during contact with groundwater. This produced zeolitization of the feldspars and may have played a part in the K enrichment at the margins of the sanidine megacrysts.

MEGACRYSTS of alkali feldspar, particularly anorthoclase, occur in a wide variety of alkali basalts and their differentiates. Their frequent euhedral form suggests that crystallization may have occurred in suspension in a liquid of similar density to that of the megacrysts, which may not be of the same composition as the final host rock. Chapman and Powell (1976) have shown that in the Permo-Carboniferous volcanics of Fife, Scotland, anorthoclase megacrysts crystallizing in suspension in a high level magma pool, were picked up and carried to the surface by a later surge of denser and more basic liquid. The purpose of the present paper is to investigate a situation in which density calculations could indicate that alkali feldspar megacrysts have been erupted in a relatively less dense magma. The assessment of the variable physicochemical conditions which could have prevailed during magma generation and eruption are a complement to the crystal flotation experiments of Campbell *et al.* (1978).

A porphyry with large sanidine megacrysts up to 7 cm in size and exhibiting exceptionally high Ba contents (up to 2.1 wt%) has recently been discovered in the Miocene shoshonite province of eastern Papua. The occurrence was as an isolated loose block in the Wamira River close to Dogura Mission in eastern Papua (see map, fig. 2) and is thought to originate in the dense forest highlands of the region. The area lies close to the eastern limit of alkali dyke intrusions described by I. E. Smith and Davies (1973) and the sample is evidently a representative of these intrusions. The specimen belongs to the shoshonite association (Joplin, 1971) which is well developed in eastern Papua. *Shoshonites* contain labradorite and potassium feldspar and typically contain 7-8% total alkali oxides together with high lime and alumina. They characterize regions of the crust which are undergoing stabilization such as partly welded areas within mobile belts (Joplin, 1968). They are known in 'island arc' environments but compared with tholeiitic and andesitic volcanism in these areas, seismic activity is no longer a controlling factor, and the generation of shoshonites marks the latest stages of island arc development (Jakeš and White, 1970).

Jacques (1976) has suggested that the shoshonite and related volcanics from the New Guinea highlands (NW of the present area) have originated as a result of melting of mantle plus silicic slab which was subducting north-eastwards, i.e. towards the Pacific away from the Australian plate. The fairly high and wide range of Sr isotope ratios in these

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rocks suggest some degree of sialic crustal contamination (Page and Johnson, 1974).

Although Hatherton and Dickinson (1969) and Jakeš and White (1970) relate present-day shoshonitic volcanism to deep focus earthquakes in the Benioff zone, i.e. as partial melts of subducted crust, the model is rejected by Johnson *et al.* (1971) for Palaeocene and Miocene shoshonites of the New Guinea highlands and eastern Papua, on lack of seismic evidence for such a zone in the area. The same would certainly apply to the Quaternary shoshonites which also occur in these areas.

The sanidine porphyry under investigation belongs to the earlier (Miocene) period of emplacement which I. E. Smith (1972) has shown took place prior to a block-faulting period of tectonic activity but after stabilization of the arc-trench system induced by the northward moving Australian plate (Davies and Smith, 1971).

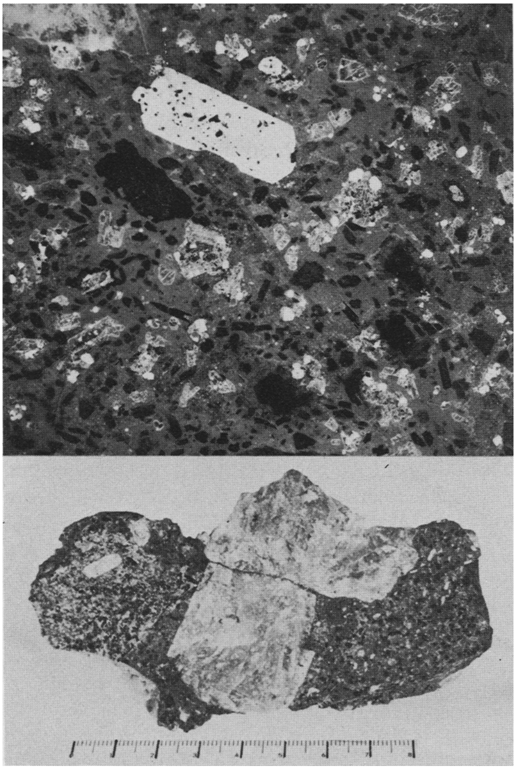

FIG. 1. Porphyry from eastern Papua New Guinea showing sanidine megacrysts. The groundmass, of 5 × the scale, shows microphenocrysts of labradorite-bytownite (pale grey) and clinopyroxene (black) in a fine matrix (grey).

Sanidine porphyry: petrography and chemical composition

The rock has a dull porcellanous medium green-grey (Munsell colour 1GY 5.1) groundmass flecked with very dark green 0.5–3 mm laths of augite. Pale pink (10 YR 7.5/1) euhedral megacrysts of sanidine up to 7 cm in size with bleached rims are a striking feature of the rock (fig. 1).

The chemical composition of the groundmass (Table I, nos. 1 and 2) falls within the shoshonite field of MacKenzie and Chappell (1972) which is limited by a range of 50–57% wt% SiO_2 and a lower limit of approximately 2 wt% K_2O. The alkali content is much higher than for most shoshonites from Papua New Guinea especially if an increment of sanidine megacrysts is added to the groundmass composition for whole rock comparison. The low TiO_2 content is typical of shoshonites as also are the high CaO and Al_2O_3 levels (Table I). Total iron is lower than most shoshonites which are in any case noted for a lack of iron enrichment (Jacques, 1976).

The yellow-green pleochroic pyroxene microphenocrysts are calcic, sodium-poor augites (see Table II) showing slight zoning towards more iron- and sodium-rich rims. They are associated with unzoned subhedral magnetite and minor amounts of apatite. Sporadic euhedral khaki-green amphibole phenocrysts of hastingsite composition (Table II) are homogeneous and contain inclusions of sphene. The latter also occur as phenocrysts. Labradorite (An_{68-77}) microphenocrysts are zoned towards more sodic rims (An_{55}, see Table II and fig. 2) and show varying degrees of alteration to zeolite, which is also common in the groundmass. The zeolites are highly calcic with Ca:Na:K ratios similar to those of co-existing feldspars. In addition, calcitic patches occur in the groundmass and very fine grained K-feldspar is common.

The sanidine *megacrysts* have 1 mm alteration margins which are turbid due to zeolitization. In polarized light they extinguish at different angles to the interior bulk of the crystals due to compositional variation, in particular an increase in K/Na (fig. 2 and Table II). *XRD* structure and composition measurements using 2θ (060) (after Wright, 1968) suggest a high-temperature structural state and confirm the very high $K_2O:Na_2O$ ratio. However, the optic plane is perpendicular to (010) (dispersion $r > v$) and is, thus, defined as 'low' sanidine (MacKenzie and Smith, 1956). A notable feature is the high BaO content which fluctuates, indicating zoning, but exceeds 2 wt% in parts of the core (Table II). It is greater than has previously been recorded for volcanic sanidines (J. V. Smith, 1974, vol. 2, p. 88). Although barium orthoclase

TABLE I. *Analyses of the groundmass of the east Papua porphyry used in density calculations*

PHN 3350	1	2
SiO_2	51.68	51.13
TiO_2	0.69	0.70
Al_2O_3	19.02	18.34
FeO*	6.46	6.55
MnO	0.22	0.22
MgO	2.30	2.29
CaO	7.71	7.83
Na_2O	3.78	3.53
K_2O	5.21	5.18
P_2O_5	0.40	0.45
H_2O	—	3.70
	97.47	99.92

Density of liquid (analysis no. 1)

(Oxidation ratio = $Fe_2O_3/(FeO+Fe_2O_3)$)

		°C	Oxidation ratio 0.1	Oxidation ratio 0.5
	Dry	1300	2.514	2.491
		1100	2.545	2.520
2 wt% H_2O	5 kb	1100	2.451	2.427
		1000	2.470	2.446
	1 kb	1100	2.423	2.400
		1000	2.442	2.418
	1 bar	1100	2.414	2.391
		1000	2.433	2.409

* Total Fe as FeO.

1. Composition of groundmass (whole rock minus megacrysts).

2. Similar to 1; another portion of groundmass. In addition Sr, 945 ppm; Rb, 170 ppm; Ba, 1010 ppm. Analyses by XRF, A. Grey.

(hyalophane) is well established in the literature, barium sanidine is uncommon. An analysis of a whole megacryst showed that SrO also reached a significant level (0.43 wt%) which is higher than data given by J. V. Smith (1974, vol. 2, fig. 14-12).

The megacrysts are poikilitic with about 10% of inclusions of plagioclase (0.3 mm average size) ranging from bytownite to labradorite. Microphenocrysts of plagioclase in the groundmass have overlapping compositions and include a more sodic-rich composition (fig. 2, Table II) from a crystal rim.

Ba clearly substitutes overwhelmingly within the K-feldspar (sanidine) lattice compared with plagioclase and the groundmass (analyses in Table II and analysis no. 2 in Table I). The Ba fluctuations in the megacrysts do not permit a distribution relationship to be determined between evolving megacryst and coexisting silicate melt (groundmass). In any case, it has been shown that such distribution coefficients have limited usefulness, since they are critically dependent on not only temperature, but also the composition of solid, and especially liquid, phases (J. V. Smith, 1974, vol. 2, p. 26; Pierozynski and Henderson, 1978).

Density equilibrium

It is suggested that since the sanidine megacrysts are large and perfectly euhedral they were free floating at the time of their formation and, hence, in density equilibrium with their host liquid, assuming a static or non-convective system. Such proposals have been made for the formation of similar large euhedral feldspars (Bottinga and Weill, 1970; Chapman and Powell, 1976). Measured densities of the sanidine megacrysts, plus adjustments for *P* and *T*, can thus be combined with calculated model host liquid densities to allow estimations to be made of the host liquid properties at the time of crystallization, assuming density equilibration.

Density of sanidine megacrysts. Determinations on six fragments ranging from 5 to 22 g were carried out by weighing in air and toluene giving answers from 2.585 to 2.629 g/ml. The values are in the upper range of these given by Deer *et al.* (1966) due to the inclusions of labradorite (density 2.71 g/ml) and the high barium content. The

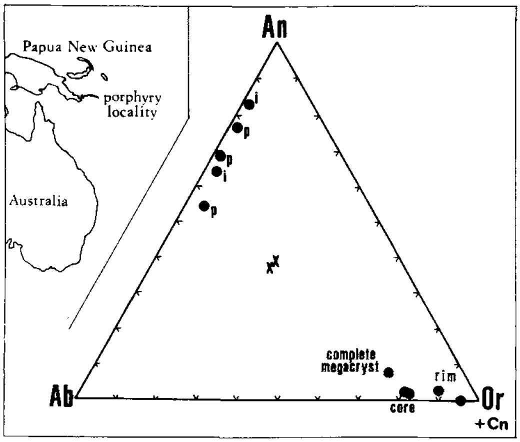

FIG. 2. Compositions, in terms of molecular feldspar end-members, of sanidine megacrysts (rim and core) plus labradorite-bytownite inclusions (i). The composition of a complete megacryst (with plagioclase inclusions) is shown. The groundmass ('liquid') compositions are indicated by crosses and microphenocrysts of labradorite-bytownite from the groundmass by '*p*'. Inset shows the location of the porphyry.

TABLE II. *Analyses of feldspars, clinopyroxene, and amphibole, from the east Papua porphyry*

	Sanidine megacrysts				Plagioclase						
	Rim		Core		Inclusions		Microphenocrysts			Cpx.	Amph.
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	64.0	61.3	62.5	62.9	51.8	47.4	51.2	49.4	54.4	45.2	37.2
Al_2O_3	19.4	17.8	20.2	19.8	31.0	34.1	31.7	32.7	29.1	7.2	14.4
FeO	nd	—	—	—	0.2	nd	nd	0.2	0.1	6.9	20.0
CaO	nd	0.6	0.45	0.53	13.0	16.7	13.7	15.3	11.3	22.9	11.7
BaO	0.7	1.6	2.1	1.4	nd	nd	nd	nd	nd	—	—
Na_2O	0.5	1.0	1.8	1.9	3.7	1.7	3.3	2.4	4.7	0.7	1.7
K_2O	16.0	15.0	13.1	13.3	0.5	0.3	0.3	0.3	0.8	nd	2.9
Sum	100.6	97.3	100.15	99.83	100.2	100.2	100.2	100.3	100.4	100.1*	(98.4)†
Mol %											
Ab	4.5	8.7	16.2	16.9	33.0	15.3	29.8	21.7	41.0		
An	—	2.9	2.2	2.6	64.1	82.9	68.4	76.5	54.4		
Cn	1.3	2.8	3.8	2.5	—	—	—	—	—		
Or	94.3	85.6	77.7	77.9	3.0	1.8	1.8	1.8	4.6		

* Includes Fe_2O_3, calculated, 7.3; TiO_2, 0.9; MnO, 0.5; MgO, 8.5.

† Includes TiO_2, 2.5; MnO, 0.5; MgO, 7.5; H_2O not determined.

1, Sanidine megacryst, 0.7 mm from margin. 2, Altered (zeolitized) margin of sanidine megacryst. 3, 4, Portions of zoned interior of megacryst. 5, 6, Plagioclase inclusions in megacryst, most sodic and calcic spots; mean value of data is close to average of these two analyses. 7, 8, Plagioclase micro-phenocryst: most sodic and calcic spots of interior. 9, Plagioclase micro-phenocryst: sodic rim. 10, Clinopyroxene. 11, Amphibole, impossible to calculate Fe^{2+}/Fe^{3+} but black colour suggests substantial Fe^{3+}. Analyses by electron microprobe by R. L. Hervig using the following standards: K, Al, Si asbestos microcline; Ca, Na, An_{60} synthetic glass; and Ba, Corning W glass.

volume change with increasing temperature is expected to be similar to that of adularia for which J. V. Smith (1974, vol. 1, p. 291) quotes an increase of 2.2 % for Or_{90} Ab_{10}, and 3.4 % for Or_{76} Ab_{24} at 1000 °C. Thus, for the Papua sanidines (Or_{94-78}) the volume increase (density decrease) is *c.*3 %. The counter-effects of increasing pressure (J. V. Smith, vol. 1, p. 509) are given by: $1.78P\text{-}4.2P^2 = (V_0\text{-}V)/V$ where P is in megabars. Thus for sanidines in a magma at 5 kb the density increase due to pressure alone is *c.*1 %. The net decrease in density ranges is shown in fig. 3 for temperatures of 800 and 1000 °C.

Density of silicate liquid. The density of a silicate liquid can be calculated using the method of Bottinga and Weill (1970), which involves the expression:

$$\text{Density} = \frac{\Sigma x_i\ M_i}{\Sigma x_i\ V_i}$$

where x_i is the mole fraction of oxide i in the liquid, M_i is the molecular weight of i, and V_i is the partial molar volume of i. Pressure is suggested to have little effect on V_i at least for crustal pressures, other than V_{H_2O} which varies according to:

$$V_{H_2O} = 24.7 \times 10^3\ (T\text{-}900) - 1.5 + 8.4 \times 10^{-2}\ P^2 - 1.4\ 10^{-3}\ P^3$$

where P is in kb and T is in °C. The variation of V with temperature is approximately linear, allowing the calculations of liquid densities at lower temperatures from extrapolation of the tables in Bottinga and Weill (op. cit.). For the purposes of this model, liquid composition was taken as that of the porphyry groundmass separated from the megacrysts. The magma density calculations were performed for a variety of possible conditions of P, T, water content, and oxidation state which may have pertained at the time of feldspar crystallization. Some constraints could be placed on these variables as a first approximation. For example, it is likely that a water pressure of several kb existed at the time of initial sanidine precipitation in order to suppress the formation of leucite, of which there is no vestige. Calculations were thus made for pressures up to 5 kb for both a dry magma and a wet magma, the latter being implied by the occur-

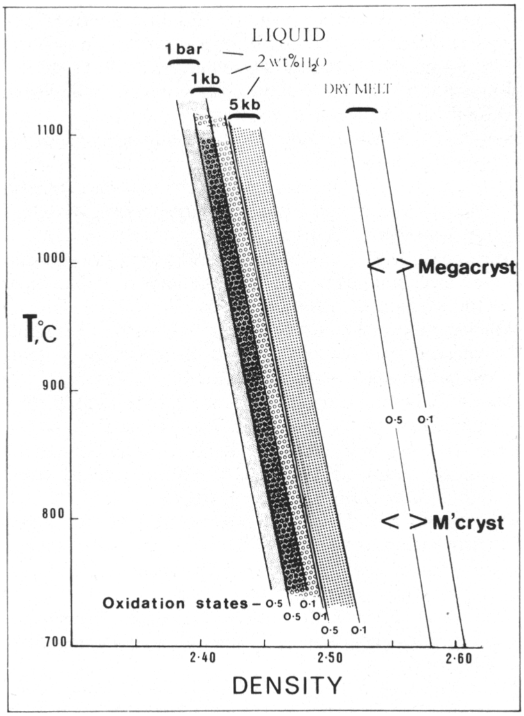

FIG. 3. Liquid densities calculated from the porphyry groundmass at varying pressures, oxidation states, and water contents, at possible temperatures at which the megacrysts formed. The figures for the oxidation state relate to the ratio $Fe_2O_3/(Fe_2O_3+FeO)$. The density ranges for megacrysts at 800 and 1000 °C are based on measured values with adjustments for increased temperature under a pressure of 5 kb (see text).

rence of amphibole in the shoshonites. A spread of oxidation ratios $Fe_2O_3/(Fe_2O_3+FeO)$ of 0.1 to 0.5 is thought to encompass the field of likely oxygen activities in the magma. The results of the calculations are shown in fig. 3, with liquid density plotted against a range of temperatures from 750 to 1100 °C.

Discussion

The density of the megacrysts is seen to be comparable with that calculated for an anhydrous melt (fig. 3). For liquids with 2 wt % H_2O, of varying oxidation ratios and under pressures ranging from 1 bar to 5 kb the densities are less than those which would permit sanidine megacryst flotation under static conditions. The possibility must, therefore, be considered that the initial melt had a lower water content. This is supported by the fact that there is only a sporadic distribution of one *primary* hydrous mineral (amphibole).

Feldspar inclusion relationships indicate that plagioclase crystallized before sanidine. This would be at fairly high liquidus temperatures ($>$ 900 °C) in spite of being depressed under high P_{H_2O} (Schairer and Bowen, 1948; Yoder *et al.*, 1957). With continuing crystallization, the liquid composition approached the plagioclase/K-feldspar cotectic (at $T < c.850$ °C for $P_{H_2O} = 5$ kb) and sanidine started to crystallize. Plagioclase and sanidine continued to co-precipitate on cooling with the plagioclase becoming increasingly sodic (from An_{64} as the most sodic trapped-inclusion to An_{55} as the most sodic rim on a microphenocryst free to continue to equilibrate with the liquid). The potassium-rich nature of the liquid is reflected in the relative notional proportions of plagioclase and orthoclase in the rock groundmass including the microphenocrysts (fig. 2). Upward intrusion of the magma with sanidine megacrysts in density equilibrium eventually encountered groundwater in open fissures at shallow depths. The resultant lowering of the liquid density (fig. 3) would enhance any diapiric motion which the stock-shaped bodies (I. E. Smith, 1972) may have possessed. This increased flow-rate may have been sufficient to overcome the gravitational effects on the megacrysts in a less dense liquid. Viscosity may have decreased initially due to the higher water + alkali content (cf. Kushiro, 1976) but it would increase rapidly as a result of subsequent out-gassing and depressurizing. It is probable that this was the major factor, rather than convection, in maintaining megacrysts in suspension during the final stage of emplacement. Hydration reactions, particularly of plagioclase to form zeolites, probably took place at this level.

The tectonic setting of the porphyry has a bearing on its origin. It lies close to the outcrop of the eastern Papua mafic-ultramafic oceanic slab which was underthrust by the NE-moving (subducting) edge of the Australian plate in Eocene-Oligocene times (Davies and Smith, 1971). Considering the post-Miocene (shoshonite intrusion) uplift ('thousands of metres' even in Recent times—I. E. Smith, 1972) it seems that the shoshonite magmas originated at depth in a subduction situation involving some crustal melting as in the case of the New Guinea highlands (Jacques, 1976). If this is the case then some of the observations concerning subduction models apply. Marsh and Carmichael (1974) have calculated that in the subduction and melting of oceanic crust the high pressure assemblage includes sanidine which buffers the concentration of K_2O in the melt (K_2O increases with depth; cf. Hatherton and Dickinson, 1969). The amount of water in the magma at source is only about 0.5 wt %. This agrees with our deductions, although our calculations are based on much lower temperatures and pressures.

A notable late stage chemical effect is the K-enrichment of the megacryst margins (fig. 3). This cannot be explained in terms of magmatic crystallization trends with falling temperatures. It is suggested that it may be connected with the late hydration event possibly resulting in metasomatic introduction of K from the wall rock.

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