

# Anorthoclase megacrysts: physical conditions of formation

DOV BAHAT

Department of Geology and Mineralogy, Ben Gurion University of the Negev Beer Sheva, Israel

**SUMMARY.** Previous interpretations relating to precipitation of anorthoclase megacrysts from alkaline basaltic magmas under high-pressure conditions are contradicted. It is proposed that these feldspars were crystallized above the solvus from hydrous melts at shallow depths, under low-pressure equilibrium conditions. These melts had been considerably enriched with volatiles of sodium, strontium, and barium, and to some extent also of rubidium.

THE assemblage of large crystals (megacrysts up to about 12 cm in length) of anorthoclase (or sanidine), tschermakitic clinopyroxene, aluminous orthopyroxene, kaersutitic amphibole, titanomagnetite, apatite, and several other characteristic minerals form a recurring world-wide association (Irving, 1974). These megacrysts have been interpreted by a number of workers, including Kuno (1964), Green and Ringwood (1967), Binns (1969), Binns *et al.* (1970), Kutolin and Frolova (1970), Hoffer and Hoffer (1973), Bacon and Carmichael (1973), Laughlin *et al.* (1974), and Ellis (1976), as phases crystallized at high pressures from their host basic (basanite) or related magmas. This interpretation was based mostly on observations that these megacrysts were most commonly found in association with volcanic cones bearing xenoliths of olivine-rich, chrome-diopside-bearing lherzolite and other ultramafic rocks of presumed high-pressure origin (Irving, 1974). In some locations this assemblage contains plagioclase (mostly andesine) megacrysts rather than anorthoclase (Vitaliano and Harvey, 1965; Wright, 1968; Aoki, 1970; Bacon and Carmichael, 1973; Gutmann, 1974).

The above interpretation has not been satisfactorily supported by concrete evidence or theoretical considerations, and a number of the statements made were ambivalent. For instance, in a recent paper (Ellis, 1976), both (dry) anhydrous and hydrous pressures above 25 kbar were suggested to be the crystallization conditions of the Victoria (Australia) alkali feldspar megacrysts. A different interpretation of the physical conditions of anorthoclase megacryst formation is presented in

this study. This interpretation supports previous suggestions that the present host magma is not the parent magma (Irving, 1974; Chapman and Powell, 1976; Stuckless and Irving, 1976). A special reference is made to the Victoria anorthoclases.

## *Chemical composition*

Chemical analyses of anorthoclase phenocrysts from intermediate and acid lavas and anorthoclase megacrysts from volcanic cones are presented in Table I. The anorthoclase megacrysts from the volcanic cones are notably sodium-rich and potassium-poor compared with the phenocrysts of the lavas. Table I shows that anorthoclases 1-5, phenocrysts from intermediate and acid lavas, are poor in strontium and relatively poor in barium. Anorthoclase megacrysts 6-11, on the other hand, are associated with scoria ejected from volcanic cones. These feldspars are generally considerably richer in barium than the previous five specimens, and outstandingly richer in strontium. These new strontium analyses are as high as those given by Irving (1974), and higher than those reported by Carmichael and Mackenzie (1964). The anorthoclase megacrysts from the volcanic cones are relatively poor in rubidium (below 20 ppm), whereas the anorthoclase phenocrysts from the lavas are considerably richer in this element (54-120 ppm in trachyte and 282 ppm in solvsbergite).

Plagioclases from alkali basalts are normally considerably poorer in strontium and barium than anorthoclase megacrysts. For instance, results for a plagioclase from an alkali basalt from Japan, according to Griffin and Murthy (1969, Table 8) are 1150 ppm Sr, 248 ppm Ba, and 1.87 ppm Rb, and according to Philpotts and Schnetzler (1970, Table I) 1750 ppm Sr, 349 ppm Ba, and 6.12 ppm Rb. These results are close to Heier's data (1962, Table 5); Heier found that the arithmetic mean of 26 labradorites is 1129 ppm Sr, of 24 labradorites is 315 ppm Ba, and of 7 labradorites is 6 ppm Rb. For comparison, the megacryst from Mt. Franklin,

TABLE I. *Chemical analyses of anorthoclases with new data on strontium, barium, and rubidium*

	1	2	3	4	5	6	7	8	9	10	11
SiO <sub>2</sub>	—	63.04	64.64	—	66.85	—	63.76	—	—	64.90	65.23
Al <sub>2</sub> O <sub>3</sub>	—	21.26	20.00	—	18.70	—	22.07	—	—	20.61	20.68
Fe <sub>2</sub> O <sub>3</sub> †	—	0.76	0.62	—	0.78	—	0.14	—	0.18	0.29	0.20
MgO	—	nil	0.13	—	—	—	—	—	—	0.02	—
CaO	0.24	2.18	2.20	1.56	0.04	—	1.78	—	0.31	0.74	0.87
Na <sub>2</sub> O	7.78	6.80	6.69	6.73	7.91	—	8.34	—	8.74	8.52	8.45
K <sub>2</sub> O	5.37	5.29	5.36	5.76	5.59	—	3.14	—	3.94	3.52	3.78
BaO	*0.013	*0.104	*0.180	*0.106	(*)	*0.21	0.18	*0.31	0.22	0.49	0.18
SrO	*0.006	*0.035	*0.055	*0.039	(*)	*0.77	0.25	*0.85	0.27	0.80	0.22
Rb <sub>2</sub> O	*0.062	*0.022	*0.012	*0.026	—	(*)*	—	(*)*	—	—	—
H <sub>2</sub> O <sup>+</sup>	—	—	—	—	—	—	0.20	—	—	—	0.26
H <sub>2</sub> O <sup>-</sup>	—	—	—	—	—	—	nil	—	—	—	0.06
Total	—	99.48	99.88	—	99.87	—	99.86	—	—	99.79	99.93
Feldspar components (wt %)											
An	1.9	10.74	10.84	7.74	0.2	—	8.8	—	1.5	3.67	4.30
Ab	65.83	57.54	56.61	56.95	66.9	—	70.6	—	73.9	72.09	70.70
Or	31.74	31.26	31.67	34.04	33.0	—	18.6	—	23.2	20.80	22.30
Cn	0.03	0.25	0.44	0.26	(*)	0.51	0.4	0.76	0.5	1.20	0.40
Sf	0.02	0.11	0.17	0.12	(*)	2.42	0.8	2.67	0.8	2.51	0.70

1. Anorthoclase in solvsbergite, Hanging Rock, Victoria. 2. Anorthoclase in trachyte, Turritable Falls, Victoria. 3. Anorthoclase in trachyte, Turritable Falls, Victoria. 4. Anorthoclase in trachyte, near Camel's Hump, Victoria. 5. Anorthoclase in obsidian, Pantelleria. 6. Anorthoclase in scoria, Mt. Anakie, Victoria. 7. Anorthoclase in scoria, Mt. Anakie, Victoria. 8. Anorthoclase in scoria, Mt. Franklin, Victoria. 9. Anorthoclase in scoria, Mt. Franklin, Victoria. 10. Anorthoclase in scoria, Mt. Noorat, Victoria. 11. Anorthoclase in scoria, Mt. Erebus, Antarctica. Nos. 5, 7, 9, and 11 are from Carmichael and Mackenzie (1964) and no. 10 from Irving (1974).

\* New analyses of strontium, barium, and rubidium carried out by D. Virgo using the X-ray fluorescence method; other analyses by the writer using wet chemical methods (Bahat, 1970).

(\*) Undetected, when limit of detection is 20 ppm.

† Total iron as Fe<sub>2</sub>O<sub>3</sub>.

Victoria, contains 7227 ppm Sr, 2665 ppm Ba, and less than 20 ppm Rb (13.7 ppm according to Stuckless and Irving, 1976).

Hence, there is a factor of (as much as) 5–9 difference in Sr and Ba coupled with a factor of (only) 2 difference in Rb in favour of anorthoclase megacrysts compared with plagioclases from alkali basalts. There is an enrichment in sodium, strontium, and barium, and depletion in rubidium in the anorthoclase megacrysts compared with anorthoclase phenocrysts. Apparently, feldspars derived from their alkali basalt magma in a normal process of fractionation do not have a similar distribution of trace elements to that in anorthoclase megacrysts.

#### *Crystallization under low water pressure*

Anorthoclase megacrysts are characteristically structurally homogeneous, clear, transparent, and show sharp interference figures (Mackenzie and

Smith, 1956; Smith and Mackenzie, 1958; Wilkinson, 1962; Bahat, 1968, 1970; Irving, 1974). This implies that following crystallization they were quenched from above the solvus without exsolution.

Feldspar megacrysts have been interpreted as near-liquidus phases of basaltic magmas at moderate pressures. Irving (1974), on the other hand, suggested that, by analogy with crystallization processes in granite pegmatites, the precipitation of these crystals from hydrous basaltic magma may be enhanced nearer to the solidus, where water pressures are higher. Hence, Irving considers near solidus megacryst precipitation from both acid and basic hydrous magmas. Possible precipitations of anorthoclase megacrysts from intermediate and acid hydrous magmas are considered below.

The equilibrium diagram of the system Ab–Or–H<sub>2</sub>O at 5 kbar H<sub>2</sub>O pressure (Yoder *et al.*, 1957) and Morse (1970) shows that since the solidus and the solvus approach each other and form a trun-

cated contact, most anorthoclase megacrysts must have been crystallized at water pressures below 5 kbar in which an intersection of the solidus and the solvus did not occur. The height and configuration of the feldspar solvus change drastically with addition of anorthite (Morse, 1968). Stewart and Roseboom (1962) reported that with increasing vapour pressure of volatiles and addition of other components (note below) to the ternary solid solution (Ab-Or-An) the temperature of intersection of the solidus and solvus would be lowered. The intimate association of vesicles commonly observed with the anorthoclase megacrysts suggests the association of the feldspar megacrysts with sources rich in volatiles (Frisch and Wright, 1971; Gutmann, 1974).

Thus, considering the fact that calcium and probably strontium and barium promote the intersection of the solidus and solvus in alkali feldspar, the effect of unmixing by water pressure must have been minimized during crystallization of homogeneous anorthoclase megacrysts. Therefore, conditions are expected to have been low water pressure, possibly below about 3.6 or 2.3 kbar H<sub>2</sub>O pressure (Stewart and Roseboom, 1962).

The determination of the density of euhedral anorthoclase megacrysts from Fife, Scotland, led Chapman and Powell (1976, fig. 1) to the conclusion that these crystals had been formed whilst suspended in a liquid differentiate no more basic than trachyandesite. On the basis of experimental study of anorthoclase-basanite stability, Chapman (1976) suggested a pressure limit of 8–9 kbar (dry) at 1150–200 °C, and this limit is depressed in a residual liquid (with the presence of water) to 5 kbar. Note also a study by Irving (1977). Gutmann (1977) considered that the maximum pressure of formation of labradorite megacrysts from Sonora, Mexico, was 3.8 kbar, or possibly even 1 kbar or less (Gutmann, 1974).

#### *Equilibrium crystallization from an acid liquid at shallow depth*

The feldspar megacrysts are commonly chemically homogeneous and unzoned (Wright, 1968; Bahat, 1968; Binns, 1969; Binns *et al.*, 1970; Aoki, 1970; Bahat, 1970; Laughlin *et al.*, 1974). Zoning of feldspars is one of the most common manifestations of disequilibrium (Stewart and Roseboom, 1962). One may therefore expect that the homogeneous feldspar megacrysts crystallized under equilibrium conditions (Albarede and Bottinga, 1972).

However, crystallization of these feldspars under equilibrium conditions from the *host* melt (Binns, 1969; Bacon and Carmichael, 1973; Laughlin *et al.*,

1974) is questioned. Feldspar phenocrysts that crystallize from an acid magma (pantellerite) and that are in equilibrium with the plagioclase components of their respective residual glasses, are extremely fresh, i.e. unresorbed (Carmichael, 1960). Alkali feldspar phenocrysts that crystallize from an intermediate (trachyte) magma and are in disequilibrium with the matrix (Bahat, 1971a) show some resorption. Resorption is higher in those trachytes that are more basic and occurs also in plagioclase phenocrysts that crystallize from two-feldspar intermediate (trachyte) magmas (Carmichael, 1965; Rahman and Mackenzie, 1969). A long crystallization of anorthoclase megacrysts from a basic magma, early (Laughlin *et al.*, 1974) or late (Irving, 1974) in the process, would have resulted in considerable resorption and heterogeneity in the feldspar composition. Also, crystallization at great depths (a pressure of 25–30 kbar corresponds to a depth of about 80–100 km) would have caused a considerable resorption of the feldspar during its ascent to the surface. However, the anorthoclase megacrysts are mostly unresorbed or only slightly resorbed (Bahat, 1970; Laughlin *et al.*, 1974). These megacrysts most commonly are found coated with vesicular basic lavas, and a lack of resorption of the feldspars is a consequence of only a short contact between the latter and the melt.

Irving (1974) has pointed out on the basis of regular variation in chemical compositions of clinopyroxene megacrysts that this mineral precipitated from a differentiating magma. Neither experimental nor field evidence for co-precipitation of anorthoclase and pyroxene has yet been recorded. This suggests that whereas pyroxene could have crystallized under deep-seated conditions (Irving, 1974), a further differentiated magma at shallow depths could have produced the anorthoclase megacrysts. Various authors have described shallow (several km deep) magmatic chambers vertically connected to the main magmatic source and to the surface (Eaton and Murata, 1960; Branch, 1966; Rhodes, 1976). It is suggested that the feldspar megacrysts crystallized under hydrous conditions in such magmatic chambers, and were brought to the surface by later (Chapman and Powell, 1976; Stuckless and Irving, 1976) ascending basic (basanitic or alkali-basaltic) magmas that frequently also carried mafic megacrysts from deep-seated origins.

Gutmann (1974, 1977) reached similar conclusions in regard to the origin of labradorite megacrysts in alkali basalts, through a different line of reasoning. He proposed that the presence of fluid inclusions in these crystals had been a consequence of a simultaneous crystal-inclusion growth at very shallow depths under low pressures.

*Hydrothermal conditions and gaseous transfer*

Bowen and Tuttle (1950) and Orville (1963) showed that homogeneous alkali feldspars can be readily crystallized from glass powders of appropriate compositions under hydrous conditions at various *P-T* conditions above the solvus. Smith and Parsons (1974) and others have synthesized homogeneous alkali-feldspars (from gels) by hydrothermal methods.

Feldspar megacrysts commonly appear with rounded or partially rounded shapes that show no recognizable crystal forms (Vitaliano and Harvey, 1965; Wright, 1968; Binns, 1969; Dasch, 1969; Laughlin *et al.*, 1974; Chapman and Powell, 1976). Subhedral feldspar megacrysts with a prismatic habit and well developed crystal faces have also been found (Bahat, 1970; Irving, 1974; Chapman and Powell, 1976; Gutmann, 1977). Euhedral feldspar megacrysts, however, are rarer (Irving, 1974), and have been described by Chapman and Powell (1976) and Gutmann (1977). On the other hand, feldspars that crystallize from host melts in plutonic pegmatites under equilibrium conditions, or terminate the magmatic differentiation in solvsbergites under shallow conditions (Bahat, 1971b), are often euhedral (Bahat, 1970). This supports the suggestion that feldspar megacrysts crystallize under unusual equilibrium conditions probably not in their host magma (Chapman and Powell, 1976).

Two possible interpretations of the rounded morphology are that either the relative growth rates of the planes involved did not remain constant (Peterson and Francis, 1977), or these crystals suffered from chemical solution or mechanical attrition prior to eruption (Mitchell and Giardini, 1977). The solubility of alkali feldspars in fluids and vapours of alkali chloride solutions and water in hydrothermal systems has been discussed by Orville (1963), and is suggested as the possible cause of rounding of anorthoclase megacrysts. Rounding is expected to develop at shallow depths where fluids exsolve from the magma (Gutmann, 1974) and a rapid expansion of water vapour occurs (Dawson, 1971). These promote mechanical attrition and chemical solution of the feldspar megacrysts.

Bowen and Tuttle (1950) located the alkali feldspar binary minimum under 1000 and 2000 bars pressure of H<sub>2</sub>O at Ab<sub>70</sub>Or<sub>30</sub> wt% (Ab<sub>71.2</sub>Or<sub>28.8</sub> mol%). Irving (1974) has observed that chemically analysed anorthoclase megacrysts from various localities fall around Ab<sub>76</sub>An<sub>5</sub>Or<sub>19</sub> (mol%). Assuming equilibrium crystallization, this distribution suggests crystallization from liquids more sodic than the binary minimum. The liquid

would be richer in sodium than the highly sodium-rich solvsbergites with normative feldspar components Ab<sub>66.4</sub>An<sub>1.9</sub>Or<sub>31.7</sub>, recalculated to 100 wt% (Bahat, 1971a). Therefore some alkali transfer mechanism is necessary to derive this unusual sodium-rich liquid.

A mechanism of a segregated vertical volatile transfer through the conduit can explain the extreme sodium enrichment. Smyth (1927), Edwards (1935), Hamilton (1965), and others have suggested that release of gases from the magma and volatile streaming permitted the transfer of alkalis in general and soda in particular to upper parts of magmatic chambers. It may also explain the low concentration of Rb in the anorthoclases from the New England district of New South Wales (Wilkinson, 1962) and, in fact, in all other anorthoclase megacrysts (Table I), although alkali olivine basalt series are enriched in Rb (Stuckless and Irving, 1967; Kay and Gast, 1973).

In a study on the geochemistry of alkaline rocks (nepheline syenites from Stjerneroy, North Norway), Heier and Taylor (1964) observed a strong concentration in barium and strontium and some concentration in rubidium and cesium (but relative depletion of Rb and Cs compared to K and Na). They contemplated the possibility of a selective concentration of these elements in a gaseous phase. The relative concentrations of Na, Sr, Ba, and Rb in the nepheline syenites parallel the relative concentrations of these elements in the anorthoclase megacrysts compared with plagioclases from alkali basalts.

Hence, it is suggested that the alkali and alkaline-earth composition of anorthoclase megacrysts was essentially determined by the concentrations of these elements by hydrous residual magmas in shallow magmatic reservoirs. These elements were introduced at least partly by a mechanism of selective gas transfer.

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