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Olivine nodules and related inclusions in trachyte from the Jos Plateau, Nigeria

J. B. WRIGHT

Department of Geology, Ahmadu Bello University, Zaria, Nigeria

SUMMARY. A trachyte plug near Jos contains a suite of inclusions, commonly rounded and of large size, including olivine nodules, pyroxenites, and a variety of basic to intermediate plutonic rocks, as well as albite megacrysts.

The olivine nodules are typical of those found elsewhere in alkaline basic lavas and widely interpreted as upper mantle fragments. Most of the other inclusions contain evidence of crystallization at high pressures, even the syenites, which are interpreted as plutonic equivalents of the trachyte; for the feldspar in them is sanidine-microperthite.

Discovery of this inclusion assemblage in a trachyte provides further support for the thesis that alkaline salic lavas can be generated at sub-crustal depths, by partial melting beneath domically uplifted continental shield areas (Bailey, 1964).

The Nigerian Cenozoic volcanic province lies in an area of regional uplift, and is characterized by scattered small volcanic centres rather than by major eruptive foci. High pressure inclusions are being found at an increasing proportion of these centres, suggesting that the magmas rose directly and rapidly to the surface from the upper mantle levels at which they were all (including the trachyte) generated.

CENOZOIC volcanism on the Jos Plateau is represented by scattered thin flows and small cones mainly of alkaline olivine basalt. The only salic representative so far recorded is the trachytic Bokkos plug (MacKay *et al.*, 1949), which forms a conspicuous feature rising some 200 ft above the basalt-covered plains, about 40 miles south of Jos along the Bokkos road.

The grey-green trachyte exhibits flow-banding in places, and small irregular veinlets of white zeolite are locally developed. Most striking, however, are the abundant lherzolite and pyroxenite nodules, accompanied by a variety of plutonic syenite and diorite fragments, and large albite megacrysts.

In view of the petrological importance of these assemblages, results of a preliminary examination are presented now, because it is likely to be some time before more comprehensive investigations become possible.

The trachyte. The flow-textured trachyte is composed mainly of anorthoclase laths (R.I. limits 1·526–1·534, $2V_\alpha \sim 60°$, $r > v$), rarely more than 2 mm long, with simple and patchy multiple twinning. Clinopyroxene ranges from pale lilac titanaugite in the cores of a few microphenocrysts, through pale green aegirine-augite or hedenbergite (cf. Aoki, 1964), to bright green aegirine in the groundmass. Granular oxide is a groundmass accessory and zeolite is patchily developed. Fibrous zeolite in the veinlets is tentatively identified as natrolite. Thin calcite veinlets were also observed in thin section.

The inclusion assemblages

Lherzolite. Varying in size from small angular fragments up to ovoids 15 cm long, olivine nodules are of the usual kind, consisting mainly of magnesian olivine (γ 1·681±0·002, optically neutral), with smaller amounts of enstatite (γ 1·676±0·002, high $2V_\gamma$), bright green chrome diopside (β 1·685±0·002), and red-brown chrome spinel (n 1·78±0·01). Borders round the larger nodules have been differentially weathered out, but smaller fragments have narrow black rims, which are opaque to deep brown in thin section and mostly of amorphous aspect, although small pleochroic granules (amphibole?) are sometimes discernible. Thin discontinuous overgrowths of pale green clinopyroxene have developed outside these black rims.

Pyroxenites. Somewhat elongate ovoids of both ortho- and clinopyroxenite do not much exceed 6 cm in length. Two varieties of orthopyroxenite have so far been found, both with reaction rims against trachyte similar to those round lherzolite nodules: Monomineralic enstatite (γ 1·685±0·002, optically neutral) is slightly pleochroic (γ very pale green, α pale pink) and rich in small regularly arranged pale brown ilmenite (?) plates and colourless rutile (?) needles (cf. Moore, 1968), along with fine-scale clinopyroxene exsolution.[1] Monomineralic hypersthene (γ 1·705±0·002, moderate $2V_\alpha$, $r < v$) is similarly but more strongly pleochroic and has fewer inclusions.

Clinopyroxenite consists of colourless diopside (β 1·704±0·002) containing platy ilmenite (?) inclusions, accompanied by green picotite (?) spinel and by turbid material, possibly devitrifying glass. Contact reactions against the trachyte involved some alteration of the diopside and development of an outer pale green clinopyroxene rim.

Diorite. Inclusions similar in size to the pyroxenites, but of more gabbroic aspect in hand specimen, are composed of plagioclase close to An_{40}, and somewhat altered pale green clinopyroxene (β 1·706±0·002, high $2V_\gamma$, $r > v$) containing exsolution lamellae. There are also irregular veins and patches, consisting of more calcic plagioclase laths (An_{50-60}), skeletal oxide, and turbid devitrifying glass (?), which seem to have developed preferentially at plagioclase/pyroxene grain boundaries.

Syenites. Ovoids of syenite are the commonest, as well as the largest inclusions, reaching 20 cm in length. Two kinds have so far been distinguished: Mafic syenite consists mainly of finely microperthitic *sanidine* ($2V_\alpha \sim$ 20–30°, $r > v$), commonly with narrow clear rims, especially against both the host trachyte and pale green clinopyroxene, which resembles that in the diorite (β 1·704±0·002), but is more altered. Vermicular reaction products have developed between pyroxene and feldspar crystals in the vicinity of opaque oxide grains. Subhedral inclusion-filled apatite crystals strongly resemble inclusions within oligoclase crystals from Gombe basalt, about 200 miles to the east (Wright, 1968), but have slightly higher refractive indices (ω 1·638 as against 1·632). Leucosyenite contains no apatite and much less oxide and pyroxene, which is also greener and has β 1·708±0·002. Sanidine (R.I. limits 1·520–1·528, $2V_\alpha \sim$ 20–30°, $r > v$) forms over three-quarters of the rock, and differs from that in the mafic variant only in being more coarsely microperthitic.

Albite megacrysts. White feldspar crystals with rounded outlines up to 10 cm across

[1] Magnesian olivine and colourless clinopyroxene have now been found along with enstatite in such inclusions.

are a conspicuous feature of the inclusion assemblage. Thin sections of {001} cleavage pieces are unzoned and have symmetrical extinction angles around 5° on albite twins, which are developed on two scales (relatively broad regular bands and very fine discontinuous lamellae), and which are length fast and give a nearly centred flash figure. Wide diffuse bands sub-perpendicular to albite twins are probably pericline lamellae making a small angle with {001}. Cleavage fragments have refractive index ranges from 1·536–1·541 and from 1·529–1·533, and give moderate optic angles ($2V_\alpha \sim 40–60°$, $r > v$). The data suggest a high-temperature plagioclase close to albite in composition.

Inclusions in surrounidng lavas

Smaller but otherwise identical lherzolite nodules and albite crystals, as well as fragments of gabbro and microperthite syenite, occur in the olivine basalt lavas, some of which have trachyandesitic tendencies (cf. MacKay *et al.*, 1949). Gabbro inclusions have been previously recorded (MacKay *et al.*, 1949), along with 'anorthosite and lumps of ilmenite', which were not found during the present study.

At least some of the lavas must pre-date the trachyte, which contains fragments of them, complete with their inclusion assemblages.

Discussion

There can be little doubt that the majority of the Bokkos inclusions are derived from great depth. Lherzolite nodules in alkaline lavas are now almost universally considered to be upper mantle fragments (Harris *et al.*, 1967), while orthopyroxene is incompatible with alkaline magmas except at pressures appropriate to upper mantle levels (Green and Ringwood, 1967). Rutile in orthopyroxene appears also to indicate high crystallization pressures (Moore, 1968). Diopside in the clinopyroxenite resembles abundant megacrysts associated with olivine nodules (cf. Falconer, 1926) and other high-pressure phases such as magnesian ilmenite and garnet at basaltic cones elsewhere on the Plateau. Although the inclusions of basic to intermediate composition can be regarded as plutonic (intra-crustal) equivalents of the basaltic and trachytic lavas, the syenites carry evidence of deep-level crystallization, for sanidine-microperthite appears to be a contradiction in terms except at very high pressures (Dickey, 1968). The large size of albite megacrysts and the rounded outlines of all larger inclusions are certainly consistent with derivation from considerable depths.

Lherzolite inclusions by themselves are rare in phonolite (de Roever, 1961; Wright, 1966), and rarer still in trachyte. An assemblage such as this one in the Bokkos plug must be almost unique, and has important implications for alkaline petrogenesis. Bailey (1964) suggested that gentle doming of a continental shield could lead to subcrustal pressure relief, partial melting and concentration of low-temperature fractions and fluxes, yielding large volumes of alkaline salic lavas. The mechanism was proposed to account for the volume predominance of phonolite and trachyte over basic associates in the East African Rift Valley volcanic province (cf. Wright, 1965). The occurrence of high-pressure phases, in particular upper mantle fragments, in trachyte as well as in phonolite, can hardly fail to provide strong support for Bailey's hypothesis.

Bailey's proposed mechanism is readily applicable to the Nigerian Cenozoic volcanic province, which has been undergoing broad regional uplift since at least Cretaceous times (MacKay *et al.*, 1949), and probably much earlier (cf. Wright, at the press). Furthermore, the scattered small centres typifying volcanic activity over the province as a whole preclude development of differentiating intra-crustal magma chambers of any size. Much more significant, however, are the high-pressure phases being found in a growing proportion of cones and plugs, which provide strong evidence for movement of magma direct to the surface from upper mantle levels, without passing through an intermediate-level magma chamber on the way. Ascent to the surface might well have been quite rapid, for inclusion-bearing lavas tend to be rich in volatiles (Harris *et al.*, 1967), which presumably also flux the growth of large megacrysts and plutonic crystal aggregates at depth. The presence of large albite megacrysts and syenite fragments accompanying olivine nodules in the Bokkos trachyte leads to the preliminary conclusion that the trachyte was not only generated at upper mantle levels, but had already commenced to crystallize there prior to eruption. Trachytes and phonolites elsewhere in the province (e.g. Carter *et al.*, 1963) could have originated in a similar manner.

The increasingly widespread discovery of sodic plagioclase megacrysts among high-pressure inclusion assemblages in these lavas (two others are now known in addition to the Gombe and Bokkos occurrences) may not be unrelated to the fact that large parts of the volcanic field are underlain by Middle Jurassic Younger Granites (Jacobson *et al.*, 1958), with strongly sodic peralkaline affinities.

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A further visit to the Bokkos plug has provided additional data, summarized below:

The sketch-map (fig. 1), compiled from enlarged aerial photographs, shows the main trachyte exposure, which forms the steep-sided Umat Hill, to be roughly crescentic in plan. An isolated mound of the trachyte, complete with inclusions, rises a few feet above the level ground underlain by basalts south-west of the summit. The surrounding topography is subdued, low hills of lateritized basalt rising between cultivated alluvial areas. The region covered by the map is shown as laterite and Older Basalt overlying metamorphic Basement on the Geological Survey of Nigeria 1 : 100,000 Series, Sheet 189 (Kurra), 1962.

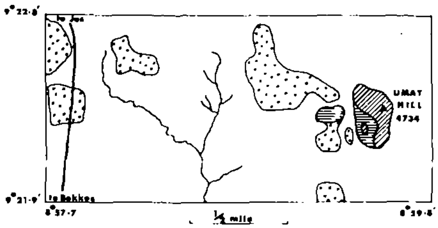

FIG. 1. Sketch-map of Bokkos plug region. Diagonal ruling: trachyte. Horizontal ruling: inclusion-bearing basalts. Open circles; laterised basalt. Blank: alluviated areas. Grid coordinates are approximate.

Large (up to 10 cm) coarse-grained (*c.* 1 cm) pyroxenite inclusions have been found, differing slightly from the smaller and finer-grained varieties already described. They consist chiefly of clinopyroxene, β 1·698±0·002, moderate to high $2V_\gamma$, $r > v$, pale grey in thin flakes, distinctly pleochroic in thicker fragments, γ' pale grey, α' pink; and hypersthene, markedly pleochroic, γ green, α pink, γ 1·715±0·002, moderate $2V_\alpha$. At least some of the inclusions also contain inclusion-filled apatite crystals (ω 1·636±0·002) and opaque oxides.

The anorthosite fragments and lumps of ilmenite reported by Mackay *et al.* (1949), have now been found. Coarse grained anorthosite inclusions, up to 15 cm across, consist of plagioclase in the An_{50} range, with subordinate hypersthene and opaque oxides. Plagioclase crystals of similar composition also occur in the single ilmenite lump recovered, and are bordered by 1-mm rims of prismatic hypersthene.

A single 2 cm inclusion of either titaniferous (?) magnetite or highly magnetic ilmenite contains also a 2 mm red garnet with well-developed dodecahedral and icositetrahedral faces, and a grey 2 mm apatite (?) prism. Further examination of this unique fragment is deferred until access to better laboratory facilities is possible.

The assemblages containing hypersthene and calcicpla gioclase probably represent crystal accumulates separated from the basalt during its ascent. Albite megacrysts and syenite inclusions in the basalt indicate that trachyte magma was already crystallizing at depth, prior to eruption of the basalt, which was therefore able to incorporate these salic inclusions. The trachyte eruption following soon afterwards along the same conduit, swept up pieces of the basalt and its plutonic segregates, in addition to carrying its own plutonic phases. The very intimate association of basalt and trachyte readily explains the occasional trachyandesitic varieties among the lavas. It is worth recording that if the basalts are surface flows, then the trachyte must be an extrusive plug, implying high viscosity at the time of eruption.

Concluding note. MacKay *et al.* (1949) provided a quite accurate summary of the inclusion assemblages described here, but because those assemblages were recorded as occurring in the *basalt*, not in the trachyte, their petrogenetic significance remained undetected for another twenty years.

This is the fifth contribution from Ahmadu Bello University Geology Dept. to the Nigerian Upper Mantle Project.