Oligoclase–andesine phenocrysts and related inclusions in basalts from part of the Nigerian Cenozoic province

By J. B. Wright

Department of Geology, Ahmadu Bello University, Zaria, Nigeria

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Summary. The Benue trough is a graben structure containing folded Upper Cretaceous sediments. Mid-Tertiary to Recent rift-valley type vulcanicity in and near the trough was mainly basaltic (in the north at least), salic lavas being now represented mainly by a few eroded plugs. The Nigerian rocks are regarded as a practically extinct sub-province within a larger Gulf of Guinea alkaline province, dominated by the voluminous and still active vulcanicity of the Cameroun rift. The two structures have the same trend as other graben features further south along Africa's western margin.

Large sodic plagioclase crystals in a basalt plug within the Nigerian sub-province have rounded edges and more calcic overgrowths. They probably crystallized at deep crustal levels but are unaccompanied by any of the mafic phases that normally crystallize from basalts under high pressure. However, spinel crystals and olivine nodules found in a nearby plug indicate that the complementary mafic assemblage may be found not far away. Sparse published data on phenocrysts and inclusions in the Jos Plateau lavas offer some support for this suggestion.

Crystallization of sodic feldspars in basalt may have a bearing on the independent genesis of salic liquids, while apatite and magnetite inclusions in them suggest a possible link with carbonatites.

The principal features of Nigeria's Cenozoic alkaline province are summarized in fig. 1. The Benue trough is a graben structure (Cratchley and Jones, 1965), filled by up to 13 000 feet of Upper Cretaceous sediments, which were folded parallel to the trough axis and uplifted prior to onset of the Cenozoic vulcanicity (Carter *et al.*, 1963).

In the northern part of the province, on the Jos Plateau and the area near Gombe, basic lavas range from olivine basalt to basanite (Falconer, 1926; Carter *et al.*, 1963) and occur as plugs, lava plateaux, and thin flows emanating from small lava and cinder cones, some of which have a very youthful aspect. Trachyte and phonolite are represented only by a small concentration of plugs south of Gombe, and their advanced state of erosion suggests they belong to an early phase of the activity, which commenced about the mid Tertiary (Mackay *et al.*, 1949; Carter *et al.*, 1963). A few warm springs south of Bauchi may represent the final waning stages of activity in this region.

In the south, the Nigerian province passes into the larger, more varied and still active Cameroun volcanic belt, associated with a more conventional rift valley (Furon, 1963; but see Reyment, 1965), which extends seaward in a chain of volcanic islands. The Nigerian Cenozoic lavas should more properly be considered as a virtually extinct sub-province within a larger Gulf of Guinea alkaline province. Six hundred miles to the north-east, on a direct projection of the Benue trough beneath the Chad Depression, lie the Tertiary to Recent alkaline volcanics of Tibesti (cf. Furon, 1963). In fig. 2, Bailey's (1964) maps have been expanded to include these structures.

The phenocrysts and inclusions. Fig. 1 also shows the location of a basaltic plug exposed on the Gombe–Biu highway, which contains numerous fragments and crystals of sodic plagioclase up to 3 cm long, many with sub-rectangular shape and rounded edges. A summary description and discussion of this singular occurrence has already been communicated (Wright, 1968), and further details are presented below, together with some additional observations.

Other phenocrysts visible in hand specimens of the basalt include black pitchy-lustred titanaugite, dark-green olivine, and titaniferous magnetite, rarely exceeding 5 mm in diameter. Microphenocrysts are up to 1 mm long and comprise subhedral titanaugite, slightly serpentinized olivine, lathy labradorite, and rounded titanomagnetite, while red-brown biotite flakes, blue-green chlorite, and zeolites are additional minerals in the groundmass.

Both large and small titanaugite crystals have β 1·708±0·002, and could not be distinguished optically. The same is true for olivines, whose β refractive index (1·698±0·002) suggests compositions around Fa_{20-25}, consistent with values quoted for other basaltic olivines in the region (Carter *et al.*, 1963; Mackay *et al.*, 1949). Some of the titanaugite crystals have been extensively replaced by very fine-grained skeletal red-brown to pinkish-green amphibole (kaersutite?) with low extinction angles and refractive indices in the range 1·705–1·715.

Moderately zoned microphenocryst plagioclase laths have refractive indices and extinction angles appropriate to the compositional range An_{54-62}, while similar measurements on a number of the large crystals, which are quite fresh, unzoned, and sparsely twinned, gave compositions between An_{18} and An_{42}. Reaction rims round the large crystals (fig. 3)

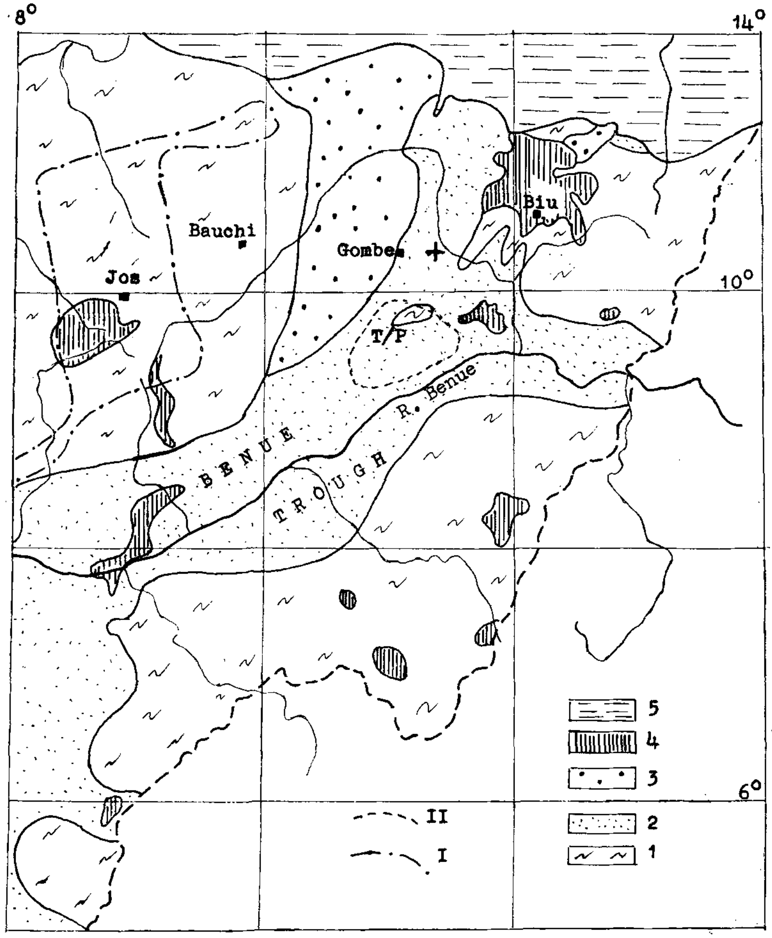

FIG. 1. Summary map, simplified from Geological Map of Nigeria, 1964, showing principal features of the Nigerian Cenozoic alkaline province. 1. Metamorphic basement. 2. Upper Cretaceous fluviatile and marine sediments. 3. Lower Tertiary fluviatile sediments. 4. Main areas of Cenozoic lava, exclusively basic in north, predominantly basic in south. 5. Pleistocene lacustrine sediments (Chad basin). I. Approximate limit of Younger Granite occurrence. II. Approximate limit of maximum volcanic plug concentration south of Gombe. T/P. Maximum concentration of trachyte and phonolite plugs. + Location of basaltic plugs east of Gombe, described in this account.

are discontinuous but otherwise have uniform thicknesses of between 0·2 and 1 mm on different crystals. Most rims consist of two layers about equally thick: the inner ones have sharp contacts against unaltered feldspar and consist of plentiful minute clino-pyroxene prisms and oxide granules, with some red-brown biotite flakes, in slightly turbid plagioclase. The outer layers are of clear plagioclase, still structurally continuous with the rest of the crystal, but having extinction angles at least 10° *higher* and perceptibly greater relief. Outer

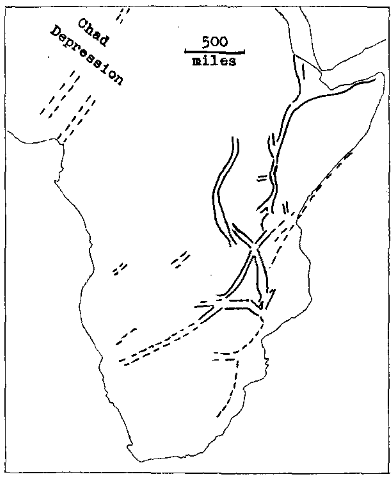

FIG. 2. Mesozoic and younger rifts and related structures associated with predominantly alkaline igneous activity, in central and southern part of Africa. Modified from Bailey (1964) with the help of Furon (1963).

margins of the more calcic overgrowths are almost always rudely crenellate where they approximate to {001} and {100} planes, which make high angles with the albite twin lamellae (fig. 3), whereas margins subparallel to {010} are smooth. Irregular patchy and vein calcite, which ramifies through and around some crystals, is probably a post-eruptive alteration product—it is the only recognizable mineral in some rims.

Stumpy subhedral 1 mm apatite prisms occur in the outer portions of a few feldspar crystals and have also been found in the basalt. They are grey and faintly pleochroic, slightly zoned, and crowded with subparallel linear inclusions. Microphenocrysts of similar aspect have been observed in Dunedin mugearites (cf. Benson, 1940), and are described from carbonatites (Girault, 1966). Almost perfect 1 mm magnetic octahedra, presumably titaniferous magnetite, can also be found in the outer parts of larger feldspar crystals.

Origin of the sodic feldspar. If the large crystals were xenocrysts, they would have been derived from anorthositic intrusions into the

FIG. 3. Part of reaction rim round sodic plagioclase crystal in basalt near Gombe. Crystals of calcic plagioclase, serpentinised olivine, titanaugite, and titanomagnetite in a basaltic groundmass (fine stipple). Inner part of reaction rim (coarse stipple) consists of clinopyroxene, magnetite, and biotite in turbid plagioclase. Outer rim is of clear, more calcic plagioclase, with rudely crenellate margin. Diameter of field 1·5 mm.

metamorphic basement beneath the surrounding sediments. Carter *et al.* (1963) mapped a number of small basic and intermediate masses, including some very plagioclase-rich dioritic varieties. Plagioclase in these rocks is variably zoned and does not exceed 5 mm in length, however, while apatite is the colourless and inclusion-free variety typical of diorites. The hypidiomorphic granular and poikilitic textures also make it difficult to see how plagioclase could be selectively removed from such rocks by the passage of basaltic magma, and an accidental inclusion origin must accordingly be rejected.

Composition and appearance of the oligoclase–andesine crystals have already been cited as evidence favouring a deep crustal origin (Wright, 1968). The problem this presents is briefly this: From experimental data, Green and Ringwood (1967) predict that at high pressures sodic plagioclase should separate from basalt melts in amounts greatly subordinate to a mafic assemblage including aluminous pyroxenes, magnesian olivine, and spinel, as in a Japanese suite described by Kuno (1964)—instead of which, not only is the feldspar abundant here, but so far *no* mafic phases of convincingly high-pressure origin have been found with it.

The geotectonic environment of the Nigerian sub-province could hardly influence deep-level crystallization processes so as to prevent the separation of mafic phases. A more satisfactory explanation is that a suite similar to the one described by Kuno did crystallize at depth, but became physically separated so that the lighter feldspars were concentrated and carried up in one conduit, while the heavier mafic minerals emerged elsewhere and may yet be found in other plugs or flows not far away. Some additional evidence supports this second alternative.

Other inclusions. Just over a mile west of the feldspar-rich plug is a small hill formed of picritic olivine basalt rich in phenocryst and microphenocryst olivine ($\frac{1}{2}$ to 5 cm; β again $1{\cdot}698 \pm 0{\cdot}002$). Titanaugite ($\beta$ $1{\cdot}705 \pm 0{\cdot}002$) forms scattered phenocrysts up to 1 cm long, and is the main constituent of the groundmass, where subordinate plagioclase is represented by small laths and very rare microphenocrysts. Phyric titanomagnetite is also found.

Of particular interest are sub-rounded crystals up to 1 cm across, of greyish *spinel* with refractive index close to 1·80, accompanied by 1 to 3 cm *olivine nodules* of the usual kind, comprising: magnesian olivine, β $1{\cdot}666 \pm 0{\cdot}002$; orthopyroxene, γ $1{\cdot}675 \pm 0{\cdot}002$; bright green chrome diopside, β $1{\cdot}692 \pm 0{\cdot}002$; and red-brown spinel, n $1{\cdot}77 \pm 0{\cdot}02$.

A single small (1 mm) *orthopyroxene* fragment was seen in one thin section, surrounded by a clinopyroxene reaction rim, the outer layer of which is titanaugite. It may be from a disintegrated nodule.

Signs of layering in a 2 cm *gabbro* inclusion suggest it may be part of an alternating sequence of hypidiomorphic granular (almost granoblastic) plagioclase- and pyroxene-rich aggregates, in which most crystals are between ½ and 2 cm across. Unzoned plagioclase is sparsely twinned and close to An_{60}, according to refractive index measurements, and exhibits marked strain extinction. The aggregates of titanaugite (β 1·705±0·002, optically indistinguishable from phenocrysts in the basalt) are enveloped and veined by irregular reaction zones: brown turbid glass contains clusters of small clinopyroxene prisms and titaniferous (?) magnetite subhedra, with skeletal ilmenite (?) and brown amphibole (?). This inclusion is most reasonably explained as a fragment of the basaltic magma itself, crystallized under plutonic conditions but at comparatively shallow depth. The larger titanaugite, olivine, and titanomagnetite phenocrysts in both these plugs could have formed at about the same level.

There are also several *quartz–sanidine–clinopyroxene–glass* and *clinopyroxene–glass* assemblages, formed by reaction and recrystallization of xenoliths from the surrounding Bima Sandstone, a thick sequence of fluviatile arkosic grits and sands (Carter *et al.*, 1963). Such xenoliths are well documented from a number of localities in other countries (e.g. Searle, 1962) and these are not significantly different.

Concluding remarks. The spinel crystals and olivine nodules offer some hope that a mafic suite complementary to the oligoclase–andesine crystals can be found in the vicinity. Further encouragement comes from published descriptions of basalts on the Jos Plateau, in which (magnesian) olivine, enstatite, and ilmenite crystals, as well as olivine nodules, have been recorded (Falconer, 1926; Mackay *et al.*, 1949). A basalt with andesine and amphibole phenocrysts and a small oligoclase–sodic-pyroxene trachyte are also mentioned.

Harris *et al.* (1968) correlated the incidence of crystals and inclusions from deep crustal and upper mantle levels with pyroclastic tendencies in the host basalts and related rocks, due to a higher content of volatiles, especially water and CO_2. Occurrence of P_2O_5 in the volatile phase is indicated by the apatite inclusions found here and recorded also from anorthoclase crystals among the diverse ultrabasic assemblages of the Deborah Volcanic Formation, New Zealand (Dickey, 1965). Anorthoclase phenocrysts have also been reported in basaltic rocks whose mineralogy seems otherwise quite ordinary (Benson, 1941; Vlodavetz and Shavrova, 1957). The deep-level crystallization of anorthoclase and sodic plagioclase might be viewed as a single problem related to the independent generation of alkaline salic magmas, already mooted elsewhere (Bailey, 1964; Wright, 1966). The presence of magnetic spinel inclusions along with apatite in the sodic plagioclase crystals may also be relevant to evidence of immiscibility between silicate-rich and apatite–magnetite-rich melts (Philpotts, 1967), not only in calc-alkaline anorthositic provinces, but also in alkaline carbonatitic ones.

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