SYNOPSES

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A composite tholeiite dyke at Imachar, Isle of Arran: its petrogenesis and associated pyrometamorphism

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THIS NW.-SE. dyke comprises two texturally distinct tholeiitic members. The outer (earlier) bears porphyritic plagioclases with essential olivine, plagioclase, and augite in a chloritized mesostasis; the inner carries porphyritic plagioclases in an olivine-free matrix showing ophitic and intersertal

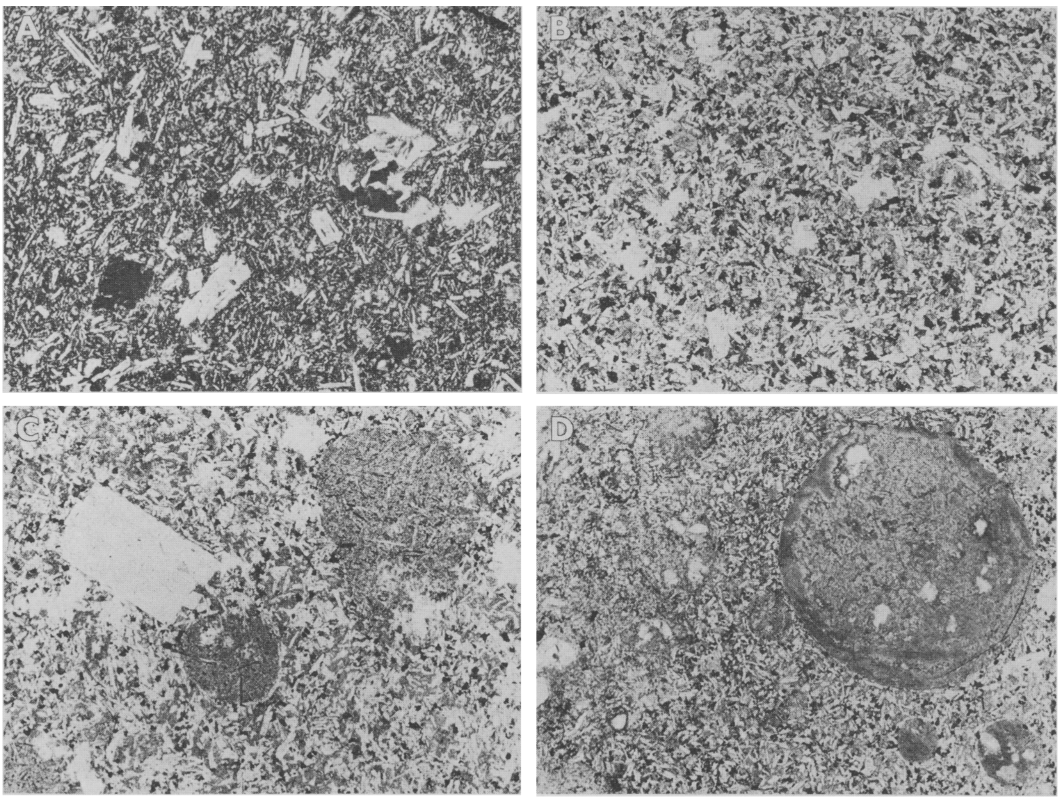

FIG. 1. Rocks of the Imachar composite dyke association (ordinary light, orange filter). A, olivine-tholeiite of outer dyke-component (analysed rock, R. 11269), × 14, to show seriate and intersertal texture of groundmass. B, variolitic tholeiite of inner dyke-component (analysed rock, R. 11272), × 7; matrix to show association of ophitic and intersertal textures. C, variolitic tholeiite of inner dyke-component (R. 11271) with plagioclase phenocryst and varioles, × 7. Note the textural relations of the central variole with its integument of plagioclase (labradorite) plates, and the partial disintegration of the variole-host margins in the other varioles shown. D, contact of variolitic tholeiite with buchite (in R. 11273), × 7. The 'intermediate zone' runs in a 'one o'clock' direction from the lower left-hand corner of the field, while the buchite occupies the upper left-hand area. The large variole, although it is abnormal in bearing recognizable quartz, in its marginal relations to the tholeiite matrix is typical of the many varioles disseminated within the inner dyke-component.

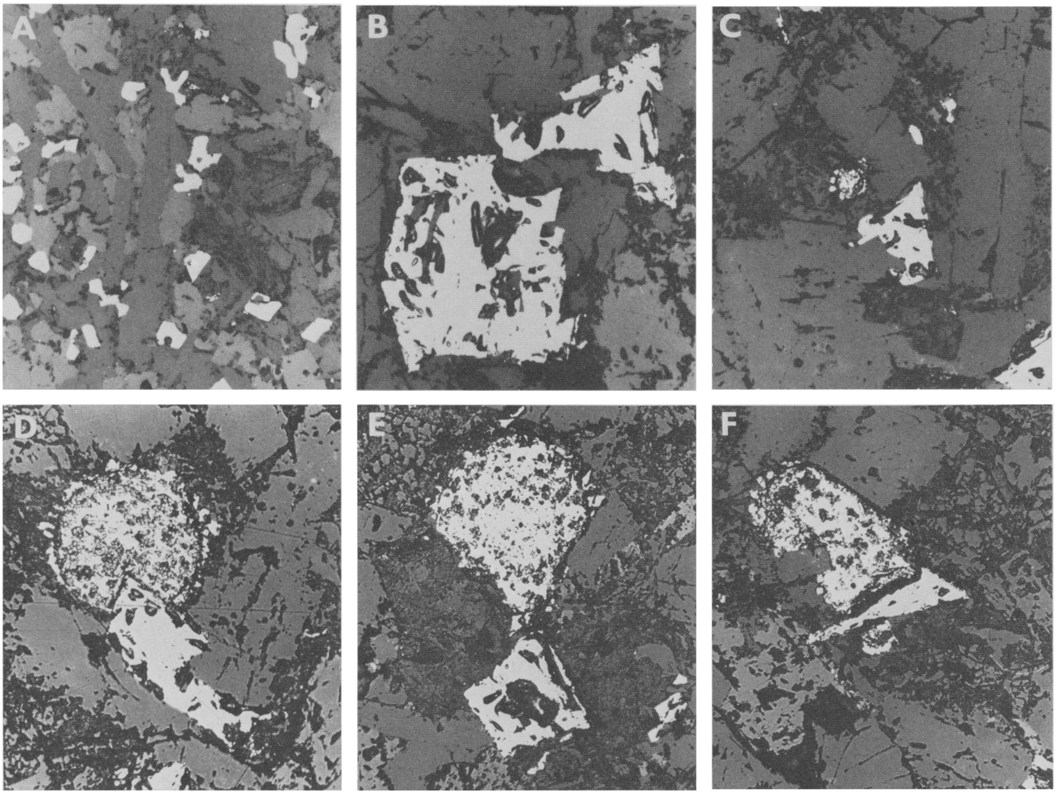

FIG. 2. Opaque constituents in polished sections of tholeiites from the Imachar composite dyke. Reflected light, × 125. Heavily pitted white areas represent pyrite; uniform pale grey, titanomagnetite; dark greys are silicates (plagioclase, augite, and mesostasis) of the host. The structures depicted in C to F are interpreted as indicating the former coexistence of immiscible sulphide and silicate melts. A, fine-grained titanomagnetite dispersed in mesostasis of outer tholeiite (R. 11269). B, coarser-grained titanomagnetite, associated equally with ophitic and intersertal fabrics, in inner tholeiite (R. 11272). C, typical spherical pyrite unit rimmed by microgranular titanomagnetite, in inner tholeiite (R. 11272). D, larger pyrite spherule in contact with titanomagnetite 'fish'; note otherwise undistorted circular outline of pyrite and its integument of microgranular titanomagnetite (R. 11272). E, 'pear-shaped' pyrite, which has maintained contact with nearby titanomagnetite crystal only by virtue of its own departure from spherical form (R. 11272). Apart from this pointed protrusion, the pyrite periphery remains circular. F, pyrite unit trapped between plagioclase tablets, with resultant distortion. Note that the 'free' margins of the pyrite retain circular outlines, with peripheral granules of titanomagnetite (R. 11272).

textures and disseminated varioles. The outer component had little metamorphic effect on its country-rock, but where the inner transgresses the outer to come into contact with the schistose-grits the latter are transformed to buchite. The outer component, after initial chilling, crystallized as a virtually closed system; the inner, on the contrary, shows no signs of chilling and bears evidence of crystallization as an open system. The variolitic structures in the inner component result from liquid immiscibility between droplets of acidic melt and basic host magma, the former originating as buchitic liquid caught up by the dyke magma at its contacts with mobilized country rock. Both components afford textural evidence of the immiscibility of a sulphide melt in the tholeiitic magma. The petrography and thermal behaviour of the inner dyke-member support its recognition as a probable former feeder to fissure eruption.

Full text in the Miniprint section, pp. M1-4.

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A COMPOSITE THOLEIITE DYKE AT IMACHAR, ISLE OF ARRAN: ITS PETROGENESIS AND ASSOCIATED PYROMETAMORPHISM

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THE Imachar composite dyke is exposed on the 8 m raised-beach platform of the W. coast of Arran, at a locality (NR/862412) some 750 m NNW of Imachar. Although it is indicated on the I.G.S. (Scotland) 1:50,000 Map, Special Sheet, Arran (solid edition, 1972) and earlier issues on the 1:63,360 scale, the dyke is not specifically referred to in either of the relevant Memoirs (Gunn 1903, Tyrrell 1928). The observations here recorded refer to that part of its outcrop fully exposed near to the seaward margin of the raised-beach platform; elsewhere the dyke is inaccessible to detailed examination.

The dyke strikes NW/SE and hades at about 10° to SW: it is intrusive into Dalradian country-rocks (Tyrrell 1928, pp.18-19) which strike N-S and in this vicinity are overturned seawards to show an easterly dip of about 45°. Occasional, always inverted, relict graded-bedding structures indicate that bedding and schistosity are closely concordant. The rocks are of chlorite grade and their origin from sediments of greywacke type remains evident.

The dyke comprises two distinct members, the width overall varying between 1.3 and 1.6 m. The outer member, which rarely exceeds 0.3 in total width, is rather irregular in its external contacts; the rock is grey, fine-grained and lacks conspicuous phenocrysts. It is distinctly chilled against mildly indurated country-rock but maintains its normal grainsize to its contacts with the inner component. The latter member averages 1.3 m wide, and is distinctly more uniform than the outer in width and trend. While its SW margin is almost continuously bounded by a screen (some 15 cm wide) of the outer component, the NE face of the inner abuts directly on modified schistose-grit country-rock over some two-thirds of the length of exposed contact. The rock of the inner component is brownish-grey and moderately fine-grained; it is not obviously porphyritic, but the presence of small rounded dark spots (the varioles) is characteristic. The marginal rock is quite unchilled at its contacts, whether with the outer dyke-member or with external country-rock, while the latter is profoundly modified. The normally light-grey schistose-grits are darkened by the development of blackish glass which is abundant at the contact and still detectable to a distance of at least 20 cm from the latter. The dyke as a whole shows rudely columnar cross-jointing as well as joints lying parallel to its strike. A strong jointing of the latter orientation also affects the adjacent vitrified and indurated schistose-grits.

Petrography of the dyke-rocks

(i) The outer member. This is an olivine-tholeiite bearing plagioclase as phenocrysts and glomeroporphyritic groups set in a matrix of augite, olivine, seriate plagioclase and intersertal mesostasis (see Fig. 1A). Individual plagioclase phenocrysts rarely exceed 1.3 mm long, and are generally of labradorite (an_{69})* with narrow rims graded outwards to an_{57}; although occasional phenocrysts of similar habit have large cores of bytownite (an_{82}): both appear to possess high-temperature structures.

*Plagioclase compositions are estimated from maximum symmetrical extinction angles α': (010) in zone normal to (010), using universal stage and Chudoba's curves, while structural state is identified on the basis of composition and optic axial angle, using J. R. Smith's curves (see Deer et al. 1963, figs. 55 and 51 respectively).

Table 1: Tholeiites from the Imachar composite dyke, Isle of Arran

Chemical Analyses	I	II
SiO_2	50.07	49.90
TiO_2	1.76	1.70
Al_2O_3	14.65	14.72
Fe_2O_3	5.13	4.63
FeO	7.93	8.08
MnO	0.26	0.21
MgO	5.46	5.55
CaO	8.90	8.98
Na_2O	3.57	3.03
K_2O	1.00	0.83
H_2O+	1.25	1.71
CO_2	0.27	0.27
P_2O_5	0.21	0.21
	100.46	99.82
S.G.	2.90	2.86
Titanomagnetite compositions		
Fe^o as FeO	82.1	80.0
TiO_2	13.5	16.2
Norms		
mt	62	55
usp	38	45

C.I.P.W. Norms		I	II
q		0.40	2.72
or		5.90	4.90
ab		30.21	25.65
an		21.01	24.12
di	wo	8.77	7.30
	en	4.95	4.28
	fs	2.88	2.67
hy	en	8.64	9.54
	fs	5.04	5.94
mt		7.43	6.71
il		3.34	3.23
ap		0.50	0.50
cc		0.61	0.61
Modes			
plagioclase		50.5	46.1
olivine		3.2[1]	nil
augite		29.8	25.8
titanomagnetite		9.5[2]	6.0
pyrite		0.2	0.2
mesostasis		6.8	21.3
varioles[3]		nil	0.6

Notes: [1] includes bowlingitic alteration products
[2] high estimate owing to small grainsize
[3] varioles include oligoclase 45%, dendritic magnetite 5% (high estimate as indicated in note 2) and chloritic base 50%.

I. Olivine-tholeiite (R.11269), outer member of composite dyke. Analyst: W. N. Neilson.
II. Sparsely variolitic olivine-free tholeiite (R.11272), inner member of composite dyke. Analyst: D. L. Skinner.

Plagioclases of glomeroporphyritic groups show labradorite cores (an_{65-68}) but unlike the isolated phenocrysts have an intermediate structural state. A pale buff augite (γ : [001] 43°, $2V_γ$ 52.5°) is rare as phenocrysts, but appears in ophitic relation to the glomeroporphyritic plagioclases; it is notable that ophitic intergrowth is not otherwise present in this rock. Abundant matrix plagioclase (labradorite an_{58} of intermediate structural state), grading from 0.6 x 0.1 mm to hollow crystallites, determines a seriate texture. Granular olivines within the same size range are largely replaced by strongly pleochroic bowlingite, while matrix augite is unaltered. The abundant mesostasis is represented by a greenish-brown, weakly birefringent chlorite with much finely-granular opaque ore and intersected by randomly-orientated plagioclase microlites showing oblique extinction. The dominant ore mineral is a homogeneous titanomagnetite ($mt_{62}usp_{38}$) (Fig. 2A); minor pyrite forms rounded spots associated with titanomagnetite grains, while rare shredlike pyrite nested in chlorite is regarded as secondary.

A chemical analysis, C.I.P.W. norm and mode of the analysed rock are quoted under I, Table 1. These represent the average rock; chilled marginal material shows mesostasis 70 percent. by volume, while porphyritic and glomeroporphyritic plagioclase at 2.1 percent. and olivine pseudomorphs at 3.3 percent. are virtually unchanged. Augite is, however, much reduced at 1.2 percent. of the chilled rock. The tholeiitic character of the rock is indicated by its intersertal habit and by the presence of quartz in the norm; its affiliations are considered below.

(ii) The inner member. This olivine-free tholeiite bears porphyritic plagioclases up to 4 mm long as well as frequent spherical varioles (average diameter 2 mm) and occasional gas vesicles. Conspicuous among the phenocrysts are some bearing large cores of bytownite (an_{82}); these appear to correspond to the "anorthites" reported by Tyrrell (1917, p.307), Holmes et al. (1929, p.9 ff.) from certain other British tholeiites. Smaller and more numerous individuals have cores of labradorite-bytownite (an_{70}). These phenocrysts agree in showing high-temperature optics, and bear narrow rims zoned to labradorite (an_{66}), occasionally with the intervention of a strongly poikilitic zone. In contrast, rare labradorite (an_{66}) phenocrysts, sometimes distinguished by pronounced bending of albite-twinned individuals, show intermediate optics.

The matrix plagioclase (to 0.7 mm long), a labradorite (an_{66}) with high-temperature optics, is in ophitic relation with subhedral units of pale brownish augite (γ : [001] 39°, $2V_γ$ 49°) up to 1 mm across. Augite individuals are separated by areas of intersertal texture in which plagioclase is enclosed in greenish chlorite probably replacing original glassy mesostasis. Coarsely granular subhedral titanomagnetite ($mt_{55}usp_{45}$) is associated with the ophitic fabric rather than with the ultimate mesostasis. Examination of polished sections by reflected light shows the titanomagnetite to be a homogeneous phase (Fig. 2B). Minor pyrite forms sparse rounded grains (usually 0.03 to 0.05 mm diam.), each partly or wholly rimmed by titanomagnetite granules (Fig. 2C). Larger pyrite units are rare, and circular in section except where obviously distorted by contact with other matrix constituents (Fig. 2D-F). Fig. 1B depicts typical matrix relations within this rock.

The varioles are typically spherical bodies marked-off from the host fabric by polysomatic investments of labradorite platelets and minor augite identical with those of the host matrix (Fig. 1C) in ocellar fashion, although occasional plagioclases lie edge-on to the variole margin at which they are normally terminated. The internal structure of each variole is essentially random, with about 45 percent. by volume oligoclase (an_{23}; α': (010) 5°, α' ≈ 1.540), 50 percent. greenish chlorite and 5 percent. dendritic magnetite; additional microspherulitic chlorite may be present, and rarely calcite. Exceptionally, but significantly, some radially-disposed labradorites of the plagioclase integument may be continued into the variole by oligoclase in structural continuity.

Not all of the varioles have survived undeformed; where deformation has led to the rupture of the labradorite integument, the chloritic mesostasis of the variole is seen to be confluent with the host mesostasis. Varioles may approach 5 percent. by volume of the rock, but in some material fall short of 1 percent.

Contacts between the inner tholeiite and the outer are marked by an abrupt change from the partly ophitic matrix texture of the former to the wholly seriate and intersertal of the latter, and are highly irregular. The contact of the inner tholeiite against ultimate country-rock is followed rather closely by a strong joint-fissure and only a limited sample of this contact (Fig. 1D) is available for detailed study. Between the normal tholeiite and the actual contact is a narrow zone in which the normal groundmass texture is progressively replaced by an intersertal texture and modified mineralogy, as described below.

The chemical analysis, norm and mode of a representative sample of the inner tholeiite (II, Table 1) clearly indicate its tholeiitic character. The proportion of varioles in the analysed rock is too low to be accountable for the degree of oversaturation suggested by the norm. Discussion of petrogenesis is deferred to a later section.

(iii) The inner tholeiite/buchite contact. A narrow zone, 5 to 10 mm wide, of modified texture and mineralogy intervenes between the normal tholeiite and the buchite. This intermediate zone is abundantly variolitic, and bears frequent quartz granules in a matrix dominated by platy labradorite (cores an_{66} with more sodic rims) up to 0.2 mm long. Prisms of a faintly pleochroic enstatite (δ 0.01, γ=[001], $2V_γ$ large) displace clinopyroxene. Cordierite euhedra appear, becoming numerous as the buchite contact is approached. The coarser quartz grains within this zone are fringed by fibrous feldspar and quartz associated with enstatite clusters and filaments of an opaque mineral as yet unidentified. The ultimate mesostasis comprises colourless glass, irregular feldspar-quartz spherulites, disseminated magnetite grains and sporadic platelets of light brown biotite. The enstatite and cordierite show partial alteration to greenish chlorite and pinitic pseudomorphs respectively.

The varioles within this zone may attain 5 mm diameter and project into, and be partly bounded by, normal tholeiite. Their relations to their host are identical with those of varioles already described. They are, however, distinctive in that they consist largely of close-set feldspar-quartz microspherulites nucleated by twinned oligoclase, along with quartz granules and irregular areas of quartz mosaic. These are intersected by linear sections of biotite (more or less chloritised) and enclose smaller platelets of fresh brown biotite and uniformly disseminated magnetite cubes averaging 0.002 mm across. These are occasionally supplemented by vermicular to spherulitic pale green chlorite which, along with a little calcite, may approach 10 percent. of the variole cross-section.

The intermediate zone passes abruptly outwards into the normal buchite, the contact being highly irregular owing to the presence of bulbous protrusions from the latter. The plagioclase and orthopyroxene of the intermediate zone disappear at this boundary; beyond it lies the buchite with its fresh glass groundmass and distinctive mineralogy.

Petrography and genesis of the buchite

At contacts with the inner tholeiite, the country-rock is conspicuously vitrified to at least 20 cm from the dyke margin; direct evidence of modification at greater distances is denied by deep erosion and widening along joints running parallel to the dyke contact. Where a screen of outer tholeiite intervenes, the country-rock shows some induration but only at the immediate contact with the outer tholeiite can incipient vitrification be recognised even in thin section. It is clear that the inner tholeiite dyke-member is solely responsible for the extreme metamorphic effects on the schistose-grit country-rock.

M2

Table 2: Buchites and schistose-grits from country-rock of the Imachar composite dyke, Isle of Arran

Chemical Analyses

	A	B	C	D	E	F	G
SiO_2	75.43	74.57	77.31	65.69	81.19	78.34	68.48
TiO_2	0.73	0.68	0.65	0.82	0.58	0.59	0.55
Al_2O_3	11.83	11.73	10.33	15.97	7.73	8.77	8.84
Fe_2O_3	0.35	0.84	0.82	1.25	0.61	0.72	1.03
FeO	3.36	3.06	2.86	4.96	2.40	2.55	2.36
MnO	0.04	0.04	0.03	0.06	0.03	0.05	0.17
MgO	1.13	1.22	1.03	1.82	0.90	0.90	1.22
CaO	0.15	0.35	0.15	0.15	0.35	1.23	6.24
Na_2O	2.11	2.23	2.16	1.40	1.75	1.88	2.93
K_2O	2.21	2.33	2.13	4.16	1.92	1.85	1.82
H_2O+	2.87	2.79	2.56	3.85	2.09	2.08	1.63
CO_2	0.09	0.14	0.12	0.20	0.33	0.99	4.14
P_2O_5	0.05	0.05	0.05	0.07	0.05	0.04	0.33
Total	100.35	100.03	100.20	100.40	99.93	99.99	99.74
S.G.	2.55	2.55	2.56	2.78	2.70	2.70	2.65
Modes							
Quartz	25.3	21.1	40.6	36.4	58.2	66.9	61.2
K-feldspars	-	-	-	0.7	5.9	2.5	1.6
Plagioclase	-	-	2.3	1.1	5.6	2.1	5.3
Muscovite	-	-	-	35.5	13.2	11.5	1.2
Penninite	-	-	-	25.0	14.7	14.4	-
Chlorite*	-	-	-	-	-	-	17.7
Zoisite	-	-	-	0.1	0.1	0.2	0.9
Opaque ores	0.5	1.1	0.6	1.2	0.4	0.1	0.9
Leucoxene	-	-	-	-	0.6	1.1	-
Calcite	-	-	-	-	1.3	1.2	12.1
Cordierite	18.8	14.9	3.4	-	-	-	-
Mullite	1.3	1.6	1.3	-	-	-	-
Hercynite	0.9	1.6	2.4	-	-	-	-
Glass	53.2	59.7	49.4	-	-	-	-

* Abnormal chlorite in zone of induration.

A. Cordierite-buchite at contact with inner tholeiite member of Imachar composite dyke. (R.11274).
B. Cordierite-buchite, 0-37 mm from contact. (R.11275-A).
C. Cordierite-buchite, 115-154 mm from contact. (R.11275-C).
D. Quartz-poor schistose-grit (chlorite-sericite-quartz schist), 2 m from contact. (R.11264).
E. Schistose-grit, 4.5 m from contact. (R.11261).
F. Schistose-grit, 2 m from contact. (R.11262).
G. Calcareous band in schistose-grit at 85 cm from contact. (R.11263).

The above localizations are given with respect to the NE contact of the Imachar composite dyke at NR/862412.

Analysis A by D. L. Skinner; analyses B to G by G. W. Robb.

The vitrified rocks are typical buchite (Harker 1932, p.70). Much of the rock has been transformed to a pale, locally streaky, biscuit-coloured glass (N_D 1.498 ± 0.002, density 2.36 $g.cm^{-3}$) in which patches and trains of corroded granular quartz represent original quartzose folia of the schistose-grit. Other relict minerals include granules of a homogeneous magnetite and occasional abraded zircons. The glass is mostly fresh and bears numerous small euhedra of cordierite, either clustered or as polysomatic lineages, in which (001) sections show the characteristic trillings. Granular hercynite is patchily developed and locally abundant, while slender colourless needles of mullite form loosely-felted patches. The identity of these crystal phases has been confirmed by X-ray diffractometer studies. In addition, some of the relict quartz grains are fringed by platy paramorphs after tridymite. The assemblage is in keeping with an origin by selective fusion of, and concurrent crystallization from, material of the schistose-grit. The localised streakiness of the glass suggests that even when generated as a liquid phase it was, and remained, highly viscous; this is confirmed by the formation and survival of the cordierite lineages.

Traced away from the contact with the inner member of the composite dyke, the proportion of glass and of new crystal phases decreases, although at 20 cm distance from the dyke margin the presence of glass within the modified country-rock is still obvious. Relict quartz is more prominent, while new cordierites are smaller. Hercynite is chiefly represented by dusty grey wisps apparently replacing chlorite of the antecedent schistose-grit.

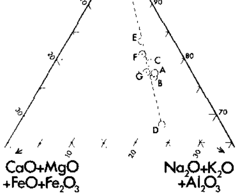

Fig. 3. Pseudoternary plot of analyses of schistose-grits and buchites associated with the Imachar composite dyke, in the triangle SiO_2 - $Na_2O+K_2O+Al_2O_3$ - $CaO+MgO+FeO+Fe_2O_3$.

Chemical analyses and modes of the buchite and of representative samples of adjacent schistose-grit are quoted in Table 2. From these it appears that the formation of buchite involves some increase in water content as compared with unmodified schistose-grit. Analysis D, which alone shows a higher water content than do the buchite analyses (A, B and C), represents a chlorite-sericite schist with less conspicuous quartz, and accordingly shows comparitively high contents of alumina, magnesia and potash. Fig. 3 shows points corresponding to Table 2 analyses, recalculated to a volatile-free basis, plotted on a SiO_2 - $Na_2O+K_2O+Al_2O_3$ - $CaO+MgO+FeO+Fe_2O_3$ triangle. Analysis G (Table 2), which shows excessive CO_2 and abnormally high CaO, has had the entry for the latter reduced by an amount equivalent to the reported CO_2 of the original analysis. The scatter of plotted points is considerable, but since all lie close to a straight line joining point D to the SiO_2 pole their dispersal is clearly caused by variation in the ratio of quartz to chlorite-sericite matrix in individual samples. Since points A, B and C show a slightly higher ratio of alkali oxides plus alumina to the cafemic oxides than is indicated by the line D - SiO_2 it appears that the buchite has received, in addition to H_2O, an accession of Na_2O+K_2O and/or Al_2O_3 such as normally occurs where basic magma is in reaction with siliceous rock material (Holgate 1954, p.445).

The temperature of flow of the buchite glass (separated from rock of analysis B, Table 2) has been investigated at atmospheric pressure, in a reducing environment, with the hot-stage microscope (Mercer and Miller 1963) and standard Pt-5% Rh/Pt-20%Rh thermocouple. Sintering (incipient fusion) of the powdered sample was noted at indicated temperature 1180°C, while the glass became confluent at 1250°C. Even at the latter temperature the viscosity remained high, as indicated by the irregular surface of the charge and the persistence of gas bubbles within it. The formation of the buchite was essentially a thermal effect of the rising tholeiitic magma of the inner dyke-member; these determinations confirm that the operative temperature approximated to that of the magma during its ascent of the dyke-fissure at the level examined.

Table 3: Thermal conductivities of dyke-rocks, buchites and country-rocks of the composite dyke at Imachar, Isle of Arran

Rock	No. of determinations (No. of specimens)	Thermal conductivity (c.g.s.u.)
Olivine-tholeiite (R.11269) (outer dyke-member)	3 (2)	4.22×10^{-3}
Variolitic tholeiite (R.11272) (inner dyke-member)	4 (2)	4.22×10^{-3}
Buchite (R.11274) close to contact with inner dyke-member: heterogeneous	2 (1) 2 (1)	5.70×10^{-3} 5.39×10^{-3}
Buchite (R.11275) approx. 10 cm from contact with dyke-member	2 (1)	6.03×10^{-3}
Schistose-grit (R.11265); country-rock at ca. 26.5 cm from contact with inner dyke-member	1 (1) 1 (1)	8.82×10^{-3} 9.33×10^{-3}
Schistose-grit (R.11261) approx. 4.5 m NE. of dyke contact	2 (2)	10.16×10^{-3}

Note: In the buchites and schistose-grits, the thermal conductivities determined are for heat-flow parallel to schistosity; this is in accordance with the field relations of the association.

Thermal conductivities have been determined for the rocks of the present association, using apparatus devised by Fraser (1968, p.112); the values found are quoted in Table 3. The thermal conductivities for the two tholeiites prove to be comparable with those determined for basalts by Poole and by Bridgman (quoted in Daly 1933, p.59) as 4.09×10^{-3} and 4.04×10^{-3} cgs units respectively. The slightly higher values found for the Imachar tholeiites are in keeping with their higher silica contents as compared with average basalt. The thermal conductivities of the schistose-grits and buchite are distinctly higher than those for the tholeiites, and range from maximum values in the unmodified grits to a minimum in buchite close to the dyke contact. Within the buchite a similar gradient of thermal conductivity exists. At the SW contact of the dyke, the outer tholeiite is approximately 15 cm wide; it follows from the respective thermal conductivities that this "screen" is equivalent, as thermal insulation to the inner tholeiite, to about 34 cm of schistose-grit of mean thermal conductivity 9.6×10^{-3} cgsu, or to a little more than 20 cm thickness of buchite of mean thermal conductivity 6.0×10^{-3} cgsu. Thus the absence of appreciable vitrification of country-rock external to the SW'ly outer tholeiite margin is not unexpected. It is only on the NE dyke margin, where the inner tholeiite is in direct contact with the schistose-grit country-rock, that buchite is developed in striking fashion.

Discussion

(i) Emplacement of the dyke-members: thermal conditions. The chemical differences between the outer and inner tholeiites of the Imachar composite dyke are, as will be shown, small by comparison with their obvious disparity as regards mineralogy and texture. Both of these points of difference are such as might have arisen from gross differences in cooling rates during emplacement and subsequent consolidation at the level now exposed.

The escape of heat from the outer tholeiite was rapid; the phenocrysts lie in an abundant mesostasis which increases in proportion as external contacts are approached. The sudden cooling of the mesostasis to a probably vitreous state may well have limited the normal peritectic reaction of silica-oversaturated fluid residuum with early-separated olivine, which thus survives in the mode. The frequent presence of a narrow spongy zone separating calcic cores from more sodic overgrowths in the larger plagioclases, and the seriate development of matrix plagioclase, must result from similar thermal conditions at an earlier stage.

The consolidation of the inner tholeiite was, by contrast, an unhurried process. This has resulted in the coarser crystallization of all but a minor proportion of mesostasis, reaction with which has eliminated early-separated olivine. The width of the buchite zone developed at the expense of contiguous schistose-grits bears witness to the attainment therein of high temperature, approximating to that of the tholeiitic magma, and the establishment of an unexpectedly low temperature-gradient within the immediate country-rock. This evidence indicates the availability of magmatic heat over a period of time which, although difficult to evaluate, must have been prolonged by comparison with the cooling interval for the outer tholeiite. The significance of this comparison is enhanced by the fact that the inner tholeiite is itself comparatively narrow. The contrast between the thermal behaviour of the inner tholeiite and that of the quartz-dolerite at Imachar Point (NR/863404) is also relevant, for although the latter is some 25 m wide at outcrop its metamorphic effect upon similar schistose-grit country-rocks is negligible. Yet as measured by their respective widths, the total heat available (assuming no superheat) per unit area of external contact for the Imachar Point dyke must have been of the order of twenty times that available from the inner tholeiite of the Imachar composite dyke. It is clear that the metamorphic effect of the latter cannot be ascribed uniquely to dissipation of heat from the limited volume of magma in the immediate vicinity of the level at present exposed, but must in part result from a continuous accession of heat from much larger volumes of magma rising, over a significant interval of time, to higher levels by way of the dyke-fissure.

The inner tholeiite member thus probably served as a feeder for a considerable igneous body, since removed by erosion, at a higher level; this may have been of sill form, or alternatively a body of lava fed by fissure-eruption. In the latter event especially the rising magma may well have acquired significant superheat resulting from the release of gravitational energy (Harris 1962, pp.783-786). Some such superheat of the inner tholeiite magma accords well with the formation of buchite at contacts with schistose-grits; the absence of significant vitrification at contacts with the outer tholeiite indicate that its magma did not possess superheat at the time of emplacement. Against the citation of superheat of gravitational origin for the inner tholeiite magma it may be argued that the small width of the member would offer resistance sufficient to inhibit this effect: it is, however, likely that the present outcrop of the inner tholeiite is appreciably narrower than was the active fissure during the upward passage of magma. Cessation of flow must have followed on decrease of magmatic pressure at depth, permitting the constriction of the dyke-fissure prior to the consolidation of magma remaining within it.

(ii) Tholeiite petrogenesis. Although the tholeiites of the Imachar composite dyke are petrographically distinct, their chemical analyses (I and II, Table 1) show only minor differences. As compared with the outer tholeiite, the inner (II) shows a marginally lower total Fe oxides content and slightly decreased oxidation thereof, but neither is competent to account for the salient differences of mineralogy between these rocks. The lower alkali content reported in analysis II, while reflecting the more conspicuous presence of phenocryst bytownite cores in the inner tholeiite, must also arise from some loss of alkalis to the buchite. That this loss, which must have been initiated early in the crystallization of the tholeiite, caused the early separation of bytownite is possible since there is no positive evidence for the intratelluric origin of these phenocrysts. The occasional distortion of albite twin-lamellae appears to be confined to less calcic plagioclase insets with optics indicative of an intermediate structural state; these were probably incorporated at depth, from a basic intrusive the fabric of which had already suffered deformation.

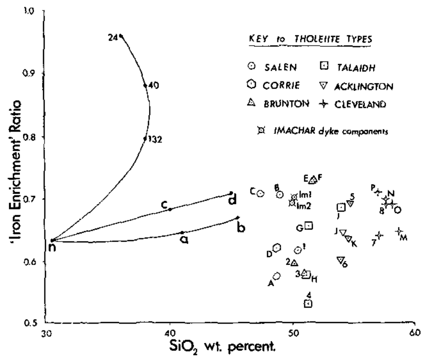

Fig. 4. Plot of Iron Enrichment Ratio ($FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$) against SiO_2 content for analysed tholeiites. Analyses represented by points 1-8 and A-P are those quoted by Holmes (Holmes et al. 1929, pp.16,23,28,33 and 40). Points Im 1 and Im 2 represent the analyses I and II of Table 1 herewith. The curves divergent from point "n" on the left of the diagram are redrawn from Osborn (1959, fig. 9a). Their absolute positions with respect to the scatter of the plotted tholeiites are not significant to this discussion.

Fig. 4 shows the relationship between "iron enrichment", represented by the ratio ($FeO+Fe_2O_3$)/($FeO+Fe_2O_3+MgO$), and silica percentage for a series of named tholeiites from Tertiary dykes in Scotland and northern England, quoted by Holmes et al. (1929). Points corresponding to the components of the Imachar composite dyke are also plotted. It will be noticed that any given tholeiite type shows considerable scatter in respect of the iron enrichment ratio, whereas for silica content the spread is relatively small. The fields occupied by individual named tholeiites show considerable overlap, the Salen, Corrie and Brunton types especially being imperfectly separated. The same figure incorporates curves, after Osborn (1959), p.629, fig. 9a), representing composition trends shown by successive liquids derived by fractional crystallization from a common initial melt in the system $MgO-FeO-Fe_2O_3-SiO_2$ under controlled conditions of oxygen partial pressure (p_{O_2}). The curve 'n-132-40-24', relating to conditions of constant composition (i.e. constant ratio FeO/Fe_2O_3), implies a rapid iron enrichment in successive liquids. With p_{O_2} constant (curve 'n-c-d') the rate of iron enrichment in the liquid phase is much reduced, while with p_{O_2} progressively rising (curve 'n-a-b') there is at first no significant iron enrichment; only in the later residua does a gradual increase in this ratio appear. By analogy with these trends, the scatter of tholeiite compositions shown in Fig. 4 may be interpreted as indicating that a major factor in the diversification of these rocks is the pre-emplacement fractional crystallization of parent magma under a rather wide range of p_{O_2} conditions. Since the Imachar tholeiites are among those which show the highest values of iron enrichment ratio, they would appear to represent liquids derived under a close approximation to "closed system" conditions, notwithstanding that their divergent mineralogy and textures reflect the widely dissimilar conditions which obtained during subsequent crystallization.

The outer tholeiite shows near-contemporaneous crystallization of olivine, and later augite, with plagioclase; the titanomagnetite present is finely granular and virtually confined to the mesostasis. Early crystallization must therefore have taken place with increasing iron enrichment of the liquid phase, thus indicating the continuance of closed-system conditions to final consolidation. The inner tholeiite, by contrast, shows early separation of plagioclase, only later to be joined by augite which is always in ophitic relation with groundmass plagioclase. The bulk of the titanomagnetite of the rock builds coarse crystal-grains, associated as much with the ophitic areas as with intervening areas of intersertal texture. Thus the greater part of the iron ore of the rock separated from the earlier magmatic liquids, and in particular prior to the development of the ultimate mesostasis since this last bears only a little skeletal ore; the crystallization must therefore have taken place under conditions analogous to those which determined Osborn's curve 'n-a-b' (Fig. 4). Such conditions, with p_{O_2} increasing with advancing crystallization, are those of an open system and are in keeping with the evidence of reaction between the dyke magma and its walls.

The constitution of the homogeneous titanomagnetites of the Imachar tholeiites provides further evidence of their differing cooling histories. The magnetic ore separated from the outer tholeiite has TiO_2 13.5 percent. ($mt_{62}usp_{38}$) while that from the inner tholeiite has TiO_2 16.2 percent. ($mt_{55}usp_{45}$). Comparison with a schematic diagram due to Buddington et al. (1955, p.514, fig. 2) showing temperature-composition relationships for magnetite-ilmenite intergrowths in the presence of discrete ilmenite grains, is probably valid insofar as the magnetite-ilmenite intergrowths represent the final product of exsolution and oxidation of magnetite-ulvöspinel solid solutions (Buddington et al. 1964, pp.352-354). Since ilmenite is completely absent from the present associations, the minimum temperatures of crystallization of the titanomagnetites, respectively 960°C and 980°C according to Buddington's diagram, are probably significantly lower than the actual temperatures of separation of these ores. The respective temperature levels are of course fully in keeping with textural and other evidence already referred to.

The tholeiitic magma of the outer member of the Imachar composite dyke, in that its crystallization shows late separation of titanomagnetite, behaved as a virtually closed system. This condition would maintain the partial pressure of water vapour in the crystallizing magma at a maximal level, and by analogy with the experimental system diopside-anorthite-water (Yoder 1954, p.107) would cause the primary phase (plagioclase) to be joined by olivine, and subsequently augite, at an early stage of crystallization; the rock texture indicates that this was indeed the case. The textural relations in the inner dyke-member, on the contrary, confirm its behaviour as an open system, as witness the early separation of titanomagnetite. Under the reduced partial pressure of water vapour thus implied, the separation of the greater part of the stoichiometric plagioclase before the appearance of augite is precisely as would be expected by analogy with the system diopside-anorthite-water (Yoder 1954, p.107).

Reference to Fig. 4 shows that the points corresponding to the components of the Imachar composite dyke are only slightly offset, towards lower iron enrichment, from positions lying between the most iron-enriched examples of the Salen and Brunton type tholeiites. In keeping with this relationship, the inner component at Imachar shows the association of ophitic and intersertal textures characteristic (Bailey et al. 1924, pp.371-372) of these types. In the absence of olivine and the presence of bytownite-cored phenocrysts, the Imachar rock resembles the "anorthite-bearing Brunton type" tholeiite of the Tynemouth dyke (Holmes et al. 1929, pp.20-21) but differs in possessing a higher degree of iron enrichment. The outer component of the Imachar dyke is, by contrast, texturally unlike both Salen and Brunton types; yet it is difficult to find grounds for an alternative affiliation.

(iii) The variolitic structure and its origin. The origin of varioles has been accounted for in terms of the immiscibility of igneous melts of contrasted (i.e. acidic as against basic) compositions. Levinson-Lessing (1935) postulated their origin by a spontaneous splitting of a previously homogeneous magma into immiscible liquid fractions under the influence of falling temperature alone. The present writer, on the other hand, has concluded (Holgate 1954) that igneous immiscibility phenomena in general, and the formation of varioles in particular, normally follow from the accidental introduction of portions of more or less highly siliceous material, usually but not necessarily solid initially, into contact with basic magma.

Yoder (1971) reports on an experiment purporting to test the validity of the proposed liquid immiscibility in igneous melts. He used a basalt (SiO_2 48.25 percent.) and an acid craignurite (SiO_2 71.80 percent.) from a composite intrusion at Craignure, Isle of Mull.[2] The powdered samples, packed end-to-end with excess water in a closed capsule, were heated to 1200°C for one hour. After quenching, the product was sectioned across the interface between the contrasted glasses. The surface of contact, represented in his fig. 1 (Yoder 1971, p.106) appears as a sharply-defined and evenly curved shallow meniscus. Referring to a "schematic presentation" of the compositional variation across the interface, Yoder (1971, pp.107-108 and fig. 2) considers that compositional gradients across the basalt-rhyolite junction "are most likely the result of diffusion in the melts" and that liquid immiscibility "is not involved". He overlooks the more objective significance of the well-defined meniscus, the presence of which must indicate surface-tension at the interface between the contrasted melts, a condition unlikely to hold if there were complete miscibility between them. More recent studies by McBirney (1975), McBirney and Nakamura (1974), De (1974), Gélinas et al. (1976) and others have each yielded evidence of the liquid immiscibility relation which Yoder has until very recently (Yoder 1976, pp.495, 496) sought to discredit. The validity of liquid immiscibility as a mechanism essential to the genesis of the variolitic inner tholeiite member of the Imachar composite dyke is therefore best assessed on the basis of the internal evidence discussed in the present contribution.

The variolitic tholeiite at Imachar is especially important in that the occurrence affords direct evidence as to the source of the varioles. Those situated within or near to the "intermediate zone" contain highly acidic material (with relict quartz) which has clearly been derived as droplets, ingested by the tholeiite at an external contact, of buchitic liquid. Although the contents of varioles lying within the body of the inner tholeiite show a different mineralogy, they too are significantly more acidic than their host, and furthermore show textural relations to the host matrix identical with those shown by varioles from the vicinity of the dyke/buchite contacts. The conclusion that all of the varioles in this dyke-member are of similar origin therefore appears unavoidable. Initiated as droplets of buchite melt, the variole contents were progressively made over, chiefly by loss of SiO_2 and gain of alkalis and Al_2O_3 (Holgate 1954, pp.450-452), to constitutions approaching equilibrium with the host magma. Progressive crystallization of the latter generated residua of compositions convergent upon, and finally confluent with, the variole contents (Holgate 1954, p.455).

The development and persistence of a polycrystalline integument about each variole, formed of plagioclase plates matching in composition those of the host matrix, is understandable only if the variole contents were, over the earlier part of the crystallization interval of the host magma, nonconsolute with the latter. The mantling plagioclases, initially wetted by chance contact with the fluid contents of the variole, were thereafter retained by surface tension which, to judge from textural evidence, remained effective until a late stage of the consolidation of the host. Only in the final stages were there developed textures indicating the failure of the immiscibility relation. The available composite tholeiite-buchite thin sections described of necessity represent this latest stage of the variolite genesis.

(iv) Magma/sulphide-melt immiscibility. The immiscibility of sulphide melts in natural silicate magmas has long been accepted by ore mineralogists on the strength of analogy with observed relations in sulphide-ore smelting technology. Recent work by Skinner et al. (1969), Haughton et al. (1974) and others has given support based on field observations and experimental investigation of sulphides in recent basaltic lavas, but no textural evidence of such a relation in crystalline igneous rocks has hitherto been reported. The occurrence in the Imachar tholeiites of textures suggestive of sulphide immiscibility are therefore of particular interest. Pyrite, a minor constituent of both dyke members, is present as circular spots (Fig. 2, A and B) which in the inner member average 0.02 to 0.03 mm diameter. The majority of these can be seen to be at least partly rimmed by numerous tiny granules of titanomagnetite (Fig. 2C). Their forms as seen in polished section strongly suggest that the pyrite units represent drops of sulphide melt constrained to spherical forms by surface-tension forces. The peripheral granules of titanomagnetite, precipitated from the host magma and subsequently wetted by fortuitous contact with the molten sulphide globule, were thereafter retained to contribute to an integument which has often survived the crystallization of the host. In this there is a clear analogy with the larger-scale varioles and their polysomatic plagioclase investments.

Occasional larger pyrite individuals in the inner tholeiite show these relationships still more clearly. In Fig. 2D the large titanomagnetite grain is partly enclosed by the pyrite which, while still molten, adhered to it. It is unlikely that the titanomagnetite was actually pressed into contact since the remainder of the pyrite periphery retains its spheroidal form and granular integument. Adhesion of the sulphide melt to a titanomagnetite grain is even more convincingly shown in Fig. 2E where the grain only maintains contact with a pear-shaped pyrite by virtue of the latter's departure from a spherical form. Its present shape no doubt results from a recessive movement of the titanomagnetite relative to the sulphide globule while the host mesostasis was still fluid. Fig. 2F, on the other hand, appears to represent a sulphide globule confined and distorted, while still fluid, by adjacent plagioclases displaced by movement in the host mesostasis.

Summary and conclusions

The Imachar composite dyke is important as affording evidence of the emplacement and crystallization of two tholeiite members which, despite their chemical similarity, show petrographic individuality which can only be a consequence of differing circumstances of emplacement and the divergence of their subsequent cooling histories.

The outer and earlier member shows textural evidence of rapid intrusion followed by the immediate onset of crystallization, the latter being initiated under temporary conditions of undercooling which, in addition to marginal chilling, resulted in the development of poikilitic overgrowths on earlier-formed, probably intratelluric, plagioclase phenocrysts and glomeroporphyritic xenocrystal groups. Continued crystallization produced further, entire, mantling overgrowths of less calcic composition on the plagioclase phenocrysts, while new individuals of a seriate succession of smaller plagioclases were developed in the matrix. The ferromagnesian silicates joined plagioclase rather early in the crystallization sequence, while iron ores (titanomagnetite) are virtually confined to the ultimate mesostasis. These characters indicate crystallization under essentially closed-system conditions, and are compatible with the failure of this member to reach the contemporary earth-surface. Its thermal effects on its country-rocks are small, as is appropriate to a minor intrusive which served as a conduit to a limited volume of magma.

The inner tholeiite shows, in contrast, no evidence of chilling against its country-rocks which, where initially schistose-grits, have suffered transformation to cordierite-buchite over a distance in excess of 20 cm from contact. This implies a major accession of heat, supplied over a comparatively protracted period. Petrographically the rock offers evidence of rather slow cooling from an unusually high initial temperature, since its not infrequent bytownite, and the majority of its labradorite-cored phenocrysts lack poikilitic overgrowths such as are characteristic of the outer member. It is likely that the few plagioclase phenocrysts present in the inner tholeiite which do show poikilitic mantles have been derived from mobilized outer tholeiite, while the occasional plagioclases showing mechanical distortion are labradorites of intermediate structure acquired by the rising magma from a crystalline basic mass at greater depths. The early separation of titanomagnetite and delayed appearance of augite indicate crystallization under virtually open-system conditions, all being in keeping with the view that the inner tholeiite reached the contemporary earth-surface and there served as feeder to fissure-eruption of lava. Since under such conditions the rapidly rising magma is likely to have acquired significant superheat of gravitational origin, the conversion of immediately contiguous schistose-grits to buchite is readily understood.

The original connotations of the terms "variole" and "variolite" have been lost sight of by a majority of petrologists active during the past century. The term variolite and the adjectival "variolitic" have been widely used in connection with rocks which have little or no textural or structural similarity to the true variolites. Rocks having the characters implicit in the early usage do indeed exist, and for this reason a return to this usage is long overdue. In the inner, variolitic, tholeiite at Imachar varioles have resulted when droplets of buchitic melt became dispersed in the tholeiitic magma, and it is concluded that it is only in this manner that they have been developed in the present association. The survival of the structure until the consolidation of the host is a consequence of the immiscibility of acidic in basic melts at liquidus temperatures, a relation which fails only when advancing crystallization of the host yields a mesostasis convergent on the composition of the intra-variolitic liquid.

Reflected-light examination shows that the titanomagnetites of both dyke-members have homogeneous structure despite their quite high content of ulvöspinel molecule as revealed by chemical analysis. Their individual compositions and deduced temperatures of crystallization accord well with their textural relations to the respective host rocks. The textural evidence of sulphide immiscibility in both tholeiites is of general interest, while in the present context the relations of the pyrite bodies to their host rocks is strikingly analogous to those of the varioles in the inner tholeiite.

The recognition of the inner tholeiite as a former feeder for lava extrusion is important in that it suggests the directly volcanic function of one more of the many dykes of the Hebridean Tertiary swarms (Holgate 1969, pp.133-134).

For figs.1&2 see the synopsis (this vol.)

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Specimens referred to in the present paper are identified by their accession numbers in the Geological Collections of the Hunterian Museum, The University of Glasgow.

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Ahmad & Morris: Noble metals in laterites

GEOCHEMISTRY OF SOME LATERITIC NICKEL-ORES WITH PARTICULAR REFERENCE TO THE DISTRIBUTION OF NOBLE METALS

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The definition of the term "laterite" and its origin is discussed in detail by Maignien (1966). Ferruginous deposits of this type occur in India, Malaysia, Indonesia, Australia, Cuba, the Hawaiian Islands, and the tropical regions of Africa and Central and South America. For laterization the following conditions appear to be pretty essential:

(1) a warm humid tropical or subtropical climate conducive to extensive chemical weathering;

(2) a flat, or nearly level topography (peneplain) where water has relatively little power to wash away products of chemical weathering;

(3) sufficient time of exposure to the weathering process.

Nickel is enriched in various profiles which have originated from such weathering of ultrabasic rocks and, whilst sulphide minerals, particularly pentlandite, currently provide the major source of the element, lateritic ores are worked on a large scale (Boldt and Queneau, 1967; Skinner, 1976) and are considered to contain about 75 per cent of the known reserves of nickel (Canterford, 1975). Platinum and palladium may exhibit similar apparent radii in crystals of analogous type [single-bond metallic r: Pt, 1.295 Å; Pd, 1.283 : octahedral covalent r; Pt(IV), 1.31; Pd(IV) 1.31 : ionic r; Pt^{2+}, 0.80; Pd^{2+} 0.86; Pauling, 1960; Ahrens, 1952] and these magnitudes correspond quite closely to those for nickel [single-bond metallic r; Ni, 1.154 Å : octahedral covalent r: Ni(II) 1.39 : ionic r: Ni^{2+}, 0.72]. Moreover, the second ionization potentials of platinum (18.56eV), palladium (19.42), and nickel (18.15) are of like order. Such similitude in properties led one of us to suggest that there might be a notable concentration of platinum and palladium in lateritic nickel-ores.