The Wolf Cave Gabbro - alkaline olivine basaltic magmatism in Jersey, Channel Islands

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An 8m thick coarse-grained olivine dolerite dyke, with well-developed chilled margins, trending NNE-SSW and occupying a steep-sided cove on the north Jersey coast, may show evidence for some flow differentiation. Texturally, the dyke is remarkable for the pronounced poikilitic relationship between the constituent mafic minerals. The textural and chemical relationships between the mineral phases are discussed. Rock and mineral chemistry indicate that magmatism was of alkaline-olivine basaltic type, contrasting markedly with most other hypabyssal basic magmatism in the island. A link with the prominent swarm of N-S basic dykes found on the adjacent North Brittany coast is postulated.

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Introduction

The island of Jersey, Channel Islands, forms one of the highest level (in a structural sense) and temporally latest segments of the late Precambrian-early Phanerozoic Cadomian orogenic belt in the northern Armorican Massif (Brown *et al.* 1990; Lees 1986, 1990). It is composed mainly of a succession of distal turbiditic flysch-type sediments and acid/intermediate volcanic rocks (Jersey Shale Formation and Jersey Volcanic Formations) intruded by three predominantly granitic igneous complexes (NW, SW and SE). A post-orogenic clastic molasse deposit (Rozel Conglomerate Formation) occurs in the NE of the island. Minor intrusions, predominantly dyke-like sheets but with some sills, are common and mostly concentrated in the plutonic bodies.

Minor intrusions of Jersey

Lees (1990) has divided the minor intrusions in Jersey (mostly dykes) into at least four groups, using the criteria of directional trend, petrology and petrochemical affinity:

(a) The Jersey Main Dyke Swarm (JMDS) trending NE-SW to E-W, the largest group, is confined to the south of the island. It is a composite dyke swarm, comprising acid and intermediate components as well as the dominant basic dykes, with a mature calc-alkaline to high-K calc-alkaline geochemical signature, ascribed to the end-Cadomian, post-orogenic intrusive phase.

(b) A pre- or ?early-JMDS phase of dykes and sills with various trends and types, found in the Jersey Shale Formation and the SW igneous complex (Bishop and Bisson 1989).

(c) Post-JMDS basic dykes, including both alkaline and tholeiitic types.

(d) Mica-lamprophyre-minette dykes, found all over the island (Lees 1974).

The post-JMDS group of basic dykes include those of calc-alkaline, tholeiitic, and alkaline-olivine basalt affinity. They are nearly all of broadly N-S trend and include numerous dykes in the NW igneous complex with some in the SW igneous complex. Some of the N-S dykes in the NW igneous complex have a calc-alkaline affinity indistinguishable from the JMDS, and must be regarded as part of that group.

Wolf Cave Gabbro Dyke

This is a highly distinctive coarse-grained dolerite dyke occupying a small steep-sided cove [63505620] cut into high (90m) cliffs on the north coast of Jersey some 0.5km west of Fremont Point. It intrudes the rhyolites of the Jersey Volcanic Formations (Bonne Nuit Ignimbrite Member of the St John's Rhyolite Formation (I.G.S. 1982) but only some 300m E of the contact of the Jersey Volcanic Formations with the marginal aplogranite fades of the NW igneous complex (Fig. 1). The dyke has been described by Groves (1927), and Wells and Wooldridge (1931); it became well known through its use as the petrographic illustration of `Olivine Gabbro (bojitic)' in Hatch, Wells and Wells textbook `Petrology of the Igneous Rocks' (1972).

A continuation of the dyke in a quarry above Cotil Point [631 15600] (Mourant 1977) is either displaced by faulting or, more likely, by an en echelon offset to the west (Fig. 1). Here it intrudes the marginal aplogranite so must postdate at least the eastern marginal fades of the NW Granite complex.

The dyke on the coast is c.8m wide. It is fully exposed on its western margin from the contact to c.1m inside, but extensive weathering to sea level exposes only highly spheroidally weathered material at the back of the cove. However, a laminated structure, indistinct but definite, may be seen which appears to be parallel to the margins of the intrusion.

Numerous loose boulders of fresh central material may be obtained from the beach of the cove. From these, it is obvious that the dolerite is heterogenous, with both the apparent grain-size and the colour index varying. Occasionally, bands resembling cumulate mafic layers may be observed. Also one or two sharp-sided leucocratic sheets or veins are visible, some 50mm or more wide.

Petrograpby

Four samples of the dyke, which have been used for petrographic, mineralogical and petrochemical analysis are: WC-1, from the western contact zone; WC-2, from the outer zone c.0.6m inside the W margin; WC-3, central coarse-grained fades; WC-4, central coarse-grained fades. The last sample contains a narrow (c.50mm) sharply
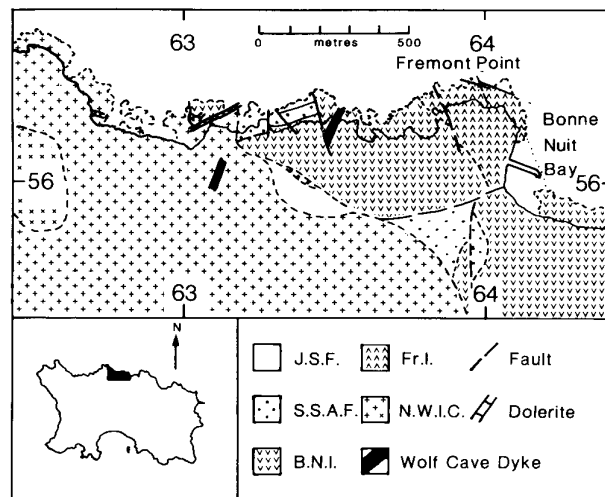

Figure 1. Simplified geological map of NE Jersey showing the location of the Wolf Cave Dyke (after the *1:25000* IGS Channel Islands Sheet No. 2). J.S.F. -Jersey Shale Formation; S.S.A.F. - St Saviour's Andesite Formation; B.N.I. - Bonne Nuit Ignimbrite; Fr.I. - Fremont Ignimbrite; N. W.I.C. - North West Igneous Complex (+ - Granite, x - Gabbro/Diorite).

Table 1. Representative mineral analyses (and calculated formulae) from the Wolf Cave dyke. Analyses express the range of variation within individual crystals. A blank field indicates that the concentration was below instrumental detection limit.

	WC-1	Olivine		Clinopyroxene		WC-3	Amphibole		Biotite	Plagioclase		Ore
		Core	Rim	Core	Rim		Core	Rim		Core	Rim	
SiO_2	38.80	38.20	36.31	50.39	48.52		41.06	43.80	34.86	50.82	63.08	0.28
TiO_2	0.09	0.23	0.13	1.40	1.55		3.89	0.88	5.76	0.00	0.00	51.37
Al_2O_3	0.14	0.13	0.03	3.29	4.58		9.56	9.65	12.94	30.90	22.73	0.08
FeO	19.94	24.94	31.98	7.63	7.68		21.06	19.37	24.63	0.64	0.44	44.43
MnO	0.34	0.42	0.60	0.22	0.00		0.22	0.21	0.12	0.00	0.00	2.03
MgO	41.15	36.57	29.43	14.69	13.81		7.33	9.77	7.98	0.00	0.00	0.78
NiO	0.83	0.91	0.19	0.00	0.00		0.00	0.00		0.00	0.00	0.16
CaO	0.30	0.24	0.29	21.59	21.96		10.97	11.08	0.08	14.67	4.31	0.06
Na_2O	0.15	0.23	0.15	0.34	0.31		2.91	2.58	1.16	3.21	9.14	0.26
K_2O	0.00	0.00	0.03	0.00	0.00		0.71	0.12	7.43	0.00	0.64	0.00
Cr_2O_3	0.04	0.00	0.00	0.21	0.35		0.00	0.00	0.05	0.00	0.00	0.09
Formulae												
Si^{4+}	0.985	0.993	1.004	1.880	1.835		6.356	6.656	5.516	2.315	2.794	0.007
Ti^{4+}	0.002	0.004	0.003	0.040	0.045		0.454	0.101	0.685	0.000	0.000	0.978
Al^{3+}	0.004	0.004	0.001	0.145	0.204		1.745	1.729	2.414	1.659	1.187	0.002
Fe^{2+}	0.424	0.542	0.740	0.239	0.243		2.727	2.462	3.127	0.025	0.017	0.940
Mn^{2+}	0.007	0.009	0.014	0.007	0.000		0.029	0.027	0.015	0.000	0.000	0.044
Mg^{2+}	1.558	1.416	1.213	0.817	0.778		1.685	2.215	1.883	0.000	0.000	0.030
Ni^{2+}	0.017	0.019	0.004	0.000	0.000		0.000	0.000	0.000	0.000	0.003	0.003
Ca^{2+}	0.008	0.007	0.009	0.863	0.890		1.821	1.000	0.013	0.717	0.205	0.002
Na^{1+}	0.007	0.011	0.008	0.025	0.023		0.879	0.761	0.356	0.284	0.785	0.013
K^{1+}	0.000	0.000	0.001	0.000	0.000		0.141	0.023	1.500	0.000	0.037	0.000
Cr^{3+}	0.001	0.000	0.000	0.006	0.011		0.000	0.000	0.007	0.000	0.000	0.002
[O]	4	4	4	6	6		23	23	22	8	8	3
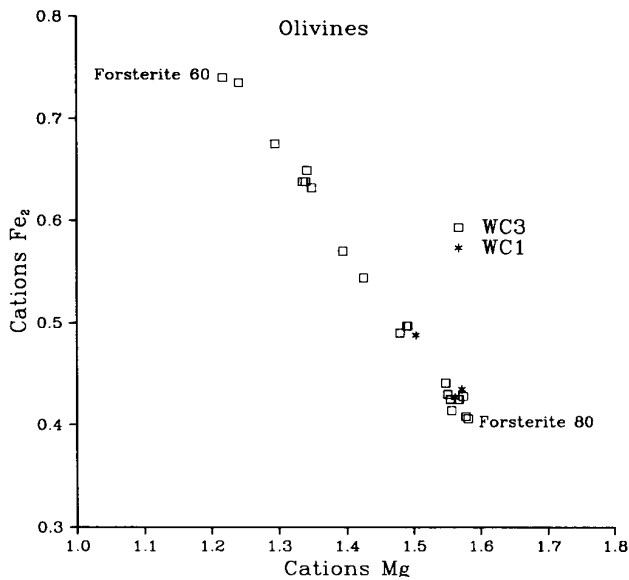
Figure 2. Compositional variation of olivines from Wolf Cave Dyke in terms of Fe^{2+} and Mg^{2+} cation contents.
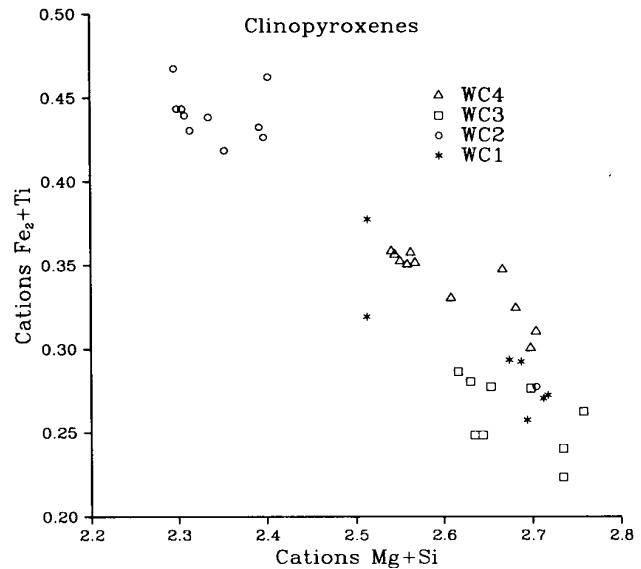
Figure 3. Compositional variation of clinopyroxenes from *Wolf* Cave Dyke. Binary plot *of* the coupled substitution $Fe^{2+} + Ti^{4+} = Mg^{2+} + Si^{4+}$ in the clinopyroxenes.

defined leucocratic vein which was analysed separately (ie. WC-4A, normal central facies; WC-4B, leucocratic vein facies).

a) Dyke margin

The margins of the dyke have been chilled against the country rock. Prominent in this facies are pseudomorphs of original microphenocrysts of olivine which now consist of a chlorite-type mineral. These microphenocrysts, up to 0.5mm in their longest dimension, retain their original orthorhombic symmetry and contain small granules of secondary titanite (sphene). There is also a smaller proportion of microphenocrysts of clinopyroxene present (c.0.3mm long) which

often show an 'hour-glass' structure and occasionally form glomerocrysts. Plagioclase feldspars, which are scattered throughout the rock, may reach 0.55mm in length. Clinopyroxene, the usual mafic groundmass phase in basic igneous rocks, is replaced by a fresh brown amphibole. Some amphibole rims have a deep green colour. Plagioclase feldspar also forms a high proportion of the groundmass.

b) Inner facies (fine-grained)

Away from the immediate margin, the grain-size increases and the proportions of the primary minerals change markedly. The overall texture displayed in this zone is subophitic to ophitic with no obvious

'phenocryst' phase. No fresh olivine is present in this facies. Clino-pyroxene has a delicate lilac-brown pleochroism with rims of brown amphibole in crystallographic continuity. Few grains of brown amphibole exist as discrete crystals and, as in the marginal facies of the dyke, are often optically zoned from deep green to paler green rims. The main difference between this facies and the chilled margin is the severe reduction in the proportion of olivine present.

Superimposed upon the primary igneous fabric are vesicle-like patches up to 2mm in diameter. Their infill consists of radiating growths of prehnite, chlorite with included granules of titanite, euhedral grains of green amphibole, and the occasional rhomb of calcite. If these patches are indeed vesicles then the process of vesiculation must have followed shortly after the inception of amphibole crystallization, as some bladed crystals of amphibole pass from the main fabric of the rock into them. This facies, of all those present in the Wolf Cave Dyke, shows the best development of a secondary mineralogy.

c) Central facies (coarse-grained)

The textures in the central portion of the dyke are quite unlike those of the marginal rocks and all the major phases are usually very fresh. With the exception of some leucocratic patches, olivines are much more abundant in this rock type; their crystal size is larger (maximum dimension >2mm) and they are often optically zoned. The few grains which are altered have developed iddingsite along the fractures. The olivines are sub-rounded and are almost invariably partially or completely surrounded by a brown variety of amphibole or more rarely brown biotite.

Clinopyroxene has the same dimensions as the olivine and it, too, has epitaxial overgrowths of brown hornblende. These clinopyroxenes often display good 'hour-glass' structure, together with oscillatory zoning, indicating an early stage of disequilibrium. The primary brown amphibole always seems to be in reaction relationship with either olivine or clinopyroxene and does not form separate crystals.

Plagioclase feldspars are usually fresh; alteration (white-mica) is confined to cleavage traces and grain boundaries. Most are continuously zoned from core to rim and exhibit normal zoning. Ore minerals and apatite are present as accessory phases. There is a discontinuous reaction relationship between the mafic silicates, which seem to have crystallized in the order: olivine - clinopyroxene - ore mineral - amphibole - biotite.

In contradistinction to the simple alteration mineralogy in the plagioclase feldspars, there is a much more complex pattern developed around olivine crystals and within interstitial sites. Within this complex array of secondary minerals there appears to be a continuum of crystallization from a magmatic through a post- magmatic/deuteric stage to a lower temperature alteration. The sequence in the secondary mineral growth is: prismatic deep-green amphibole - palegreen acicular amphibole/green biotite - chlorite - prehnite and occasionally pumpellyite.

Mineral chemistry

Olivine

Olivine is present only at the extreme chilled margin and in the central zone. At the margin the olivines are largely pseudomorphed by chlorite but remnants do remain. The compositions of these olivines vary between Fo_{79} and Fo_{75}, values similar to those obtained by Drever and Johnston (1967) from a whole series of picrite minor intrusions. Olivines from the interior of the dyke are much more variable and are zoned with respect to Mg^{2+} and Fe^{2+}. Core compositions are similar from crystal to crystal (ie. Fo_{77}-Fo_{80}) but they zone outwards to a minimum of Fo_{60} (Fig. 2). The contents of minor components in these olivines is low but variable: CaO (0.18-0.35%); MnO (0.19-0.60%); and NiO (0.0-0.90%). The increase in MnO closely follows the increasing fayalite composition of the olivine, while the NiO value is closely coupled with that of increased forsterite.
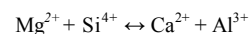
Pyroxene

Almost all the clinopyroxenes in the Wolf Cave Dyke are diopside in composition (Morimoto 1988) and plot in a small area of the Ca-Mg-Fe^{2+} compositional space. The analyses include both phenocryst and groundmass clinopyroxenes from the marginal and interior facies of the dyke. There are only slight differences in chemical composition of clinopyroxenes, whether olivine is. present or absent. These analyses are typical of those developed in alkali basalt sills and dykes (Wilkinson 1956; Henderson and Gibb 1988) and similar to those of the albite dolerites of Guernsey (Lees et al. 1989).

Little systematic variation in clinopyroxene substitution can be gleaned from quadrilateral components; more appears to be revealed by consideration of the minor components, Ti^{4+} and Al^{3+}. Tracy and Robinson (1977) first suggested that there was a relationship between the entry of Ti^{4+} into the pyroxene lattice and substitutions in both the octahedral and tetrahedral sites of the type:

$$Fe^{2+} + Ti^{4+} + 2Al^{3+} \leftrightarrow 2Mg^{2+} + 2Si^{4+}$$
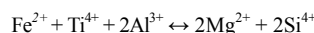
This complex substitution was supported by the experiments of Sack and Carmichael (1984) and by observations of the variations in clinopyroxene chemistry from alkali basalt dykes (Henderson and Gibb 1988). This relationship was also noted by Lees et al. (1989) in the clinopyroxenes from the albite dolerites of Guernsey. There is a strong negative correlation (r = 0.93) between $Fe^{2+}+Ti^4$ and $Mg^{2+}+Si^{4+}$ in the clinopyroxenes from the Wolf Cave dyke, which provides support for such a coupled substitution outlined above (Fig. 3).

This substitution, however, cannot be the only one involving the entry of Al^{3+} into the pyroxene structure as there is excess Al^{3+} over that required for the above substitution (i.e. $Ti4:Al^3+=1:2$). This phenomenon was also noted in the albite dolerites of Guernsey (Lees et al. 1989). The $Ti^{4+}:Al^{3+}$ ratio varies from 1:5 to 1:4 in the Wolf Cave clinopyroxenes (Fig. 4), similar to both the Guernsey and Lugar Sill (Henderson and Gibb 1988) clinopyroxenes, indicating that a second coupled substitution is involved:

$$Mg^{2+} + Si^{4+} \leftrightarrow Ca^{2+} + Al^{3+}$$

As with the quadrilateral components, Ti^{4+} and Al^{3+} concentrations are higher in the clinopyroxenes from the olivine-free marginal facies.
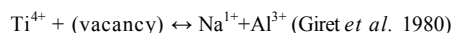
Amphiboles

The analysed amphiboles are both brown and green varieties. The brown amphiboles are almost always from crystals which poikilitically enclose previously crystallized olivines and diopsides. There is no chemical difference between the amphiboles which develop on olivine or pyroxene.

The brown amphiboles are calcic and are rich in Ti^{4+}. As they contain below 0.5 atoms Ti^{4+}, they are titanian ferroan pargasite (maximum value 0.46 atoms Ti^{4+}) (Leake 1978). The main chemical variation in the amphiboles is the $Mg^{2+}:Fe^{2+}$ ratio, where the maximum Mg^{2+} content is 3.6 atoms, and Fe^{2+} 3.8 atoms. The brown amphiboles from the marginal facies of the dyke are groundmass phases only (WC-1 and WC-2) and they appear to be more Fe^{2+} rich than the poikilitic amphiboles from the interior of the dyke (WC-3 and WC-4).

The late magmatic/deuteric amphiboles can easily be discriminated from magmatic ones using the Ti^{4+} content (Fig. 5, upper part). There is a continuum of compositions from the magmatic titanian pagasites through magnesian hastingsites to actinolites which are on the base of the Mg^{2+}-$Ti^{4+}*3$-Fe^{2+} triangle (Fig. 5, upper part).

A number of coupled substitutions have been suggested for the incorporation of Ti^{4+} into the amphibole lattice (Robert 1976; Giret et al. 1980). One of these substitutions involves vacancies in the lattice:

$$Ti^{4+} + (vacancy) \leftrightarrow Na^{1+}+Al^{3+} \text{ (Giret et al. 1980)}$$

As there are few vacancies in the titanian ferroan pargasites and the $Ti^{4+}:Al^{3+}$ ratio is constant at 1:4, the favoured coupled substitution for inclusion of Ti^{4+} into the amphibole lattice is:

Table 2. Petrochemical analyses of the zones of the Wolf Cave dyke. The mean of analyses of the albite-dolerite dykes of Guernsey (Lees *et al.* 1989) is included for comparison.

	WC-1	WC-2	WC-3	WC-4A	WC-4B	average ab-dol.
SiO2	45.6	44.45	45.98	45.85	47.76	46.54
TiO2	1.99	1.87	1.73	2.05	2.25	1.54
Al2O3	14.64	14.04	12.81	14.41	18.23	16.01
Fe2O3	2.19	2.78	2.09	2.74	1.5	2.97
FeO	11	10.9	10.49	9.17	7.73	7.03
MnO	0.22	0.21	0.19	0.16	0.13	0.21
MgO	8.11	9.03	11.62	9.45	4.21	6.39
CaO	8.5	8.16	8.8	9.32	9.6	8.56
Na2O	2.91	2.29	2.33	2.94	4.52	3.15
K2O	0.73	0.96	0.73	0.86	1.03	1.7
P.05	0.3	0.27	0.25	0.28	0.33	0.55
TOTAL	99.48	98.19	99.33	99.69	100.23	
Totalk	3.64	3.25	3.06	3.8	5.55	4.72
TotFe3	14.41	14.89	13.77	12.93	10.09	10.28
Rb	21	42	19	26	31	332
Sr	386	381	326	418	490	332
Y	25	20	22	21	26	34
Zr	126	122	106	110	141	206
Nb	24	22	20	20	22	18
Ni	204	240	329	232	69	37
Cr	210	198	91	231	5	63
V	281	271	251	293	314	218
Zn	131	116	105	98	90	163
Na/K	3.55	2.13	2.85	3.05	3.91	1.59
K/Rb	288.5	189.7	318.9	274.5	275.8	244.1
Zr/Y	5.04	6.1	4.82	5.5	5.42	6.78
Y/Nb	1.04	0.91	1.1	1.05	1.18	2.03
Zr/Nb	5.25	5.55	5.3	5.24	6.41	11.86
Nepheline				1.34	6.33	
Feldspar	53.66	50.25	46.37	51.07	59.07	
CPX	12.7	11.04	15.95	16.85	15.72	
OPX	2.26	7.54	5.55			
Olivine	19.92	17.92	22.26	19.46	8.97	
Fe-ore	7.96	7.58	6.32	7.86	6.44	

$$Fe^2 + Ti^{4+} \leftrightarrow Mg^{2+} + Si^{4+}$$
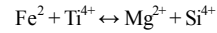
with compensating Al^{3+} substitution in both octahedral and tetrahedral sites. That this substitution is valid for these amphiboles can be demonstrated in Fig. 6 where the correlation coefficient, r, is -0.82 for all amphiboles, but when Ti-free amphiboles are removed from the equation it becomes -0.93, which is very similar to the value calculated for the clinopyroxenes.

Biotite

Biotite is only present as a minor hydrous phase in the central zone of the dyke (WC-3, WC-4). With the exception of two analyses (with 0.20 atoms of Ti per formula unit) (Fig. 5, lower part), they are titaniferous (up to 0.69 atoms of Ti per formula unit) and are closely related to the titanian ferroan pargasite in their relationship with the earlier formed olivine and clinopyroxene. These highly titaniferous biotites are members of the phlogopite-annite series. There are deficiencies in both the octahedral and `potassium' sites in the biotites, a phenomenon which was also noted in biotites from similar dykes in Cornwall (Floyd and Rowbotham 1982).

Robert (1976) proposed a substitution for the entry of Ti^{4+} into the biotite structure whereby as Fe^{2+} increased in the octahedral sites it facilitated the entry of Ti^{4+}. This relationship can be seen in Fig. 7.

Feldspars

The core compositions of plagioclase feldspars are close to $An_{70}Ab_{30-29}Or_{0-1}$. The amount of zoning is limited within the centres of individual grains to 10-15% An content but they often have rims which are much more albitic i.e. there is a compositional jump in many crystals. The most albitic rims in WC-3 are $An_8Or_8Ab_{84}$ and in WC-4 $An_9Or_1Ab_{90}$. The zoning is always from calcic cores to sodic rims. No alkali feldspars were noted in the sodic rims which supports the optical determination of normal zoning in these plagioclase feldspars.

Ore Mineral

An ore mineral appears to crystallise in time between the pyroxene and the hydrous titaniferous minerals. There is no indication of coarse exsolution lamellae either optically or using the electron microprobe. The mineral has a 1:1 ratio of $F^{2+}:Ti^{4+}$ and is therefore ilmenite. The only minor element of any importance is MnO which has a maximum value of 1.88%.

Bulk rock chemistry

The petrochemical character of the Wolf Cave dyke has been ascertained from 5 analyses made on the samples described above
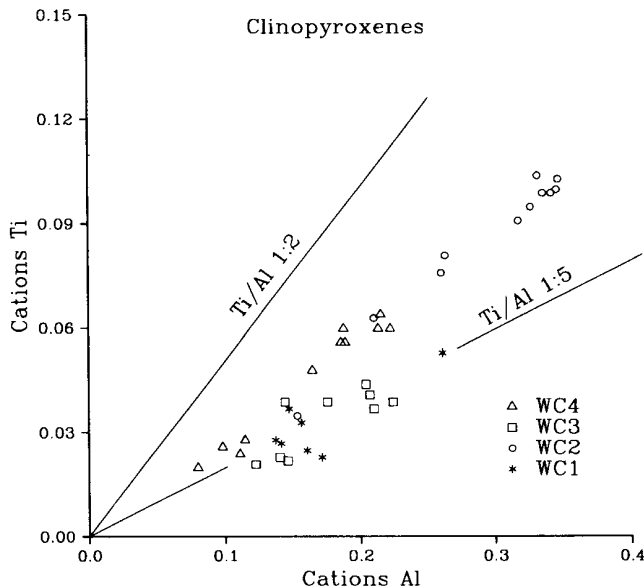

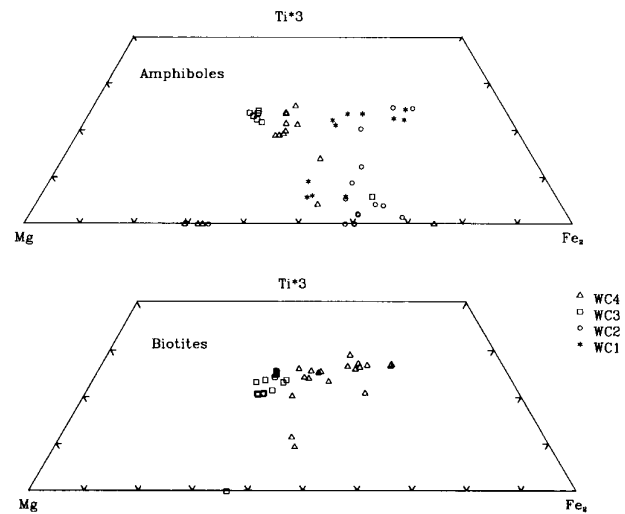Figure 4. Compositional variation of clinopyroxenes from Wolf Cave Dyke. Binary plot of the minor components Ti^{4+} and Al^{3+}.

Figure 5. Compositional variations of amphiboles and biotites from Wolf Cave Dyke. Trinagular plots of Mg^{2+} - $Ti^{4+}*3$ - Fe^{2+}. Upper diagram - amphiboles; lower diagram - biotites.
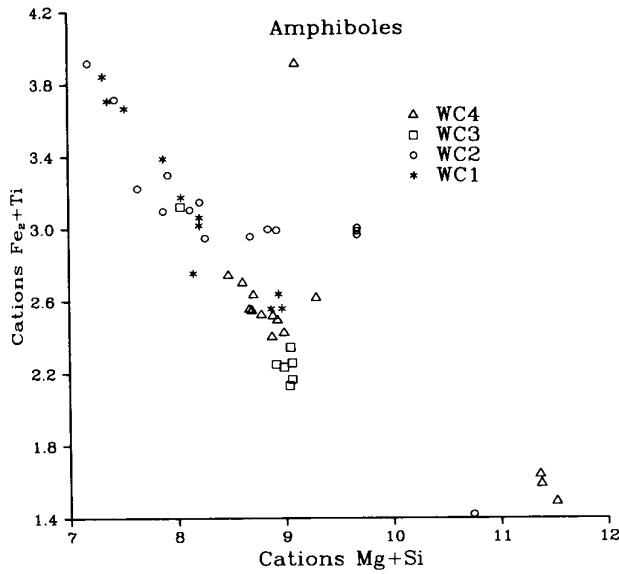
Figure 6. Compositional variations of amphiboles from Wolf Cave Dyke. Binary plot of the coupled substitution $Fe^{2+}+Ti^{4+}=Mg^{2+}+Si^{4+}$.
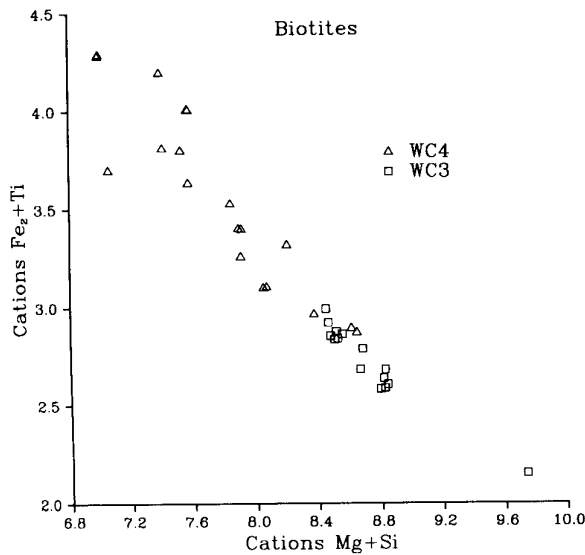

Figure 7. Compositional variation of biotites from Wolf Cave Dyke. Binary plot of coupled substitution $Fe^{2+}+Ti^{4+}=Mg^{2+}+Si^{4+}$

(Table 2). The SiO$_2$ content of the dyke is tightly constrained, varying only by some 3%, even though WC-4B is of leucocratic vein material. The mean value (45.93%), with the enhanced MgO and Fe$_2$O$_{3(TOT)}$ contents, indicates a basaltic composition. In contrast to the behaviour of SiO$_2$, the relative variation in Al$_2$O$_3$ is much greater, showing a steady decrease towards the dyke centre. Fe$_2$O$_{3(TOT)}$ and the incompatible oxides TiO$_2$ and P$_2$O$_5$ show small decreases inward, but MgO shows a marked increase towards the dyke centre. CIPW-normative feldspar content decreases inward while those of the mafic minerals clinopyroxene and olivine show distinct increases. The norms indicate that the bulk of the dyke is olivine-normative, lying close to the Ol-Di tie-line in the normative basalt trapezohedron (Thompson et al. 1983). However, the vein and the mafic material marginal to it are nepheline-normative.

In the binary total alkalis v SiO$_2$ Plot (Kuno 1968), the Wolf Cave dyke samples fall in the alkaline field, at the extreme low- SiO$_2$ end. The dyke is sodic in nature, with Na:K ratios between 2.1 and 3.9. This sodic nature is reflected in high K:Rb ratios of c.190 to 320. However, though the K$_2$O and P$_2$O$_5$ contents seem enhanced, the

overall level of incompatible elements is low, in accord with the high mafic mineral content.

The trace element patterns are consistent with the major element trends. The incompatible elements Nb, Zn, Y, Zr, with Cr, V and Sr, show a steady decrease from margin to centre of the dyke, while Rb behaves erratically. Incontrast, Ni shows a marked increase inward, mimicking MgO. The mafic central material (WC-4A) adjacent to the felsic-rich leucocratic vein (WC-413)-is somewhat anomalous in its content of certain trace elements. Ni content is much lower than in WC-3, while Rb and Zr are higher. Cr, V, and Sr contents are the highest of any of the mafic types analysed as are the major element oxides TiO$_2$, CaO and Na$_2$O. However, the V, Sr, Zr and possibly Rb contents are even higher in the felsic vein material, while both Ni and Cr are severely depleted. It could be that WC-4A in many ways resembles a composition intermediate between those of WC-3 and WC-4B. The major element oxide compositional trends would seem to support such a contention, while the content of the ratio of the coherent element pair of LIL elements K:Rb is the same in both WC4A and WC-4B, perhaps indicating diffusion of mobile elements beyond the confines of the vein.

The chondrite-normalised REE patterns of the marginal and central zones of the Wolf Cave dyke (WC-1 and WC-3) are subparallel, with a steady enrichment from Lu to La (Fig. 8a); the La:Yb ratios (un-normalised) are 8.07 and 7.89 respectively. The significant points about these profiles are: (a) the central zone sample WC-3 has consistently lower values than those of the marginal WC- 1; (b) compared with the envelope of REE contents for the albite- dolerites of
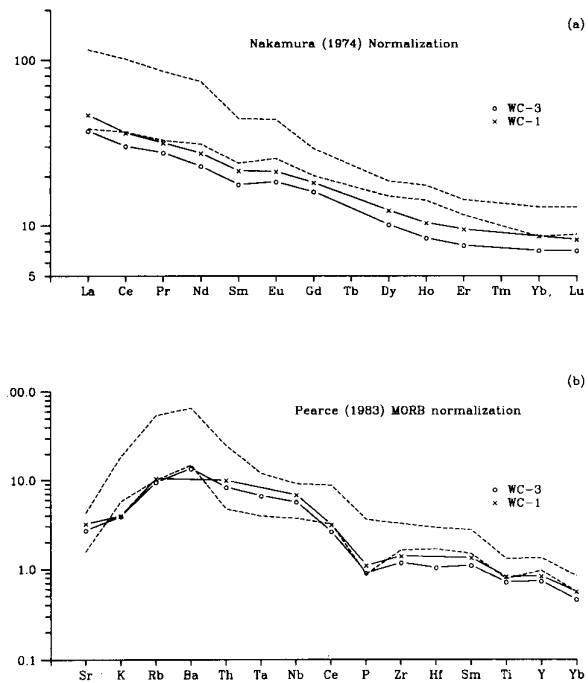

Figure 8. Trace element variation trends in the Wolf Cave Dyke, with the envelope of the albite-dolerites of Guernsey for comparison: (a) Chondritenormalized REE plot (after Nakamura 1974); (b) MORB - normalized incompatible element diagram (after Pearce 1983).

Guernsey (Lees et al. 1989), the REE contents of both the Wolf Cave dyke samples are again consistently lower. The MORB-normalised multi-element 'spidergram' (Fig. 8b) for the two sample WC-1 and WC-3 shows a similar pattern of steady enrichment with increasing incompatibility, again with remarkable parallelism of trends. For most elements the Wolf Cave dyke rocks lie close to the lower margin of the compositional envelope of the Guernsey albite dolerites. However, Th and the coherent element pair Ta and Nb are relatively significantly enriched, plotting in the middle of the envelope. The difference is confirmed in a Nb v Zr binary plot where the Wolf Cave rocks occupy a completely subparallel path. Incompatible elements

ratios (Table 2) are often considered indicative of the composition of the parent magmas (Pearce and Norry 1979). The values of Zr:Y and Y:Nb accord well with those of the Guernsey albite-dolerites, but the Zr:Nb ratios differ significantly.

Discussion

The Wolf Cave dyke is an intrusion of alkaline-olivine basaltic magma. Both mineralogical and chemical evidence support this even though the high mafic mineral content of the dyke precludes the enhanced incompatible element contents developed in more evolved suites. Its highly sodic nature (Na:K ratios c.3.10) is in marked contrast to the potassic nature of the JMDS (Na:K 0.53-2.62, with 90% of analyses below 2.0) (Lees 1990). Similarly the K:Rb ratio of c.270 compares with a very wide range of 93-310 (mean = 207) in the JMDS. Both differences would seem to obviate any genetic link between them.

The age of injection of the Wolf Cave dyke remains somewhat conjectural. Mourant (1977) reported the post-aplogranitic age of the southerly extension of the dyke. Recent remapping (Bland 1985; Salmon 1987) has shown the NW Jersey igneous complex to be composed of four major granitoid divisions. One, a pink aplogranite, forms the eastern margin of the pluton, outcropping from Sorel Point [61205710] (Salmon 1987) southwards. Bland (1985) obtained Rb:Sr isochron ages on three granite types; one of 426±14Ma on red granite. Assuming the red granite to be the marginal aplogranite, the upper age limit to injection of the Wolf Cave dyke and its extension must thus be Silurian.

N-S trending dykes of a similar nature and affinity form a considerable swarm in the coastal region of northern Brittany between St Malo and Morlaix (the subject of current study by G.J.L.). These have been shown to be contact metamorphosed by early Hercynian granite plutons (Velde 1970) and have been consequently assigned a tentative Dinantian age. It would thus seem reasonable to consider the intrusion of the Wolf Cave dyke to have taken place somewhere in the Upper Palaeozoic.

N-S basic dykes in Jersey are not common. Several outcrop in the NW Jersey igneous complex but their magmatic affinity is disparate - most would seem to be of calc-alkaline magmatic type and thus related to the JMDS. One or two in the south of the island seem to be transitional between the mature calc-alkaline magmas of the JMDS and more intraplate tholeiitic types. Another, cutting the SW granite complex in Portelet Bay [60254695] is thoroughly tholeiitic with a marked iron-enrichment trend. The only dyke which seems unequivocally of alkaline type is that from Cotte a la Chevre in the extreme NW [55305655], identified by Smith (1936) as a camptonite but an olivine-pyroxene-phyric alkaline dolerite. Its chemistry is similar to that of the Wolf Cave dyke.

Alkaline olivine basalt magmatism is not common in the Armorican Massif despite the abundance of basic volcanics and intrusives of a wide variety of ages and magmatic types. In Guernsey, the alkaline olivine basaltic magmatism that gave rise to the suite of albitedolerites (Lees *et al.* 1989) was one of the last magmatic events to take place, post-dating all effects of the Cadomian orogenic event, but pre-dating injection of the mica-lamprophyre suite. In Jersey no such definite evidence is available to delimit the lower age limit. The close compositional affinity of the albite dolerites and the Wolf Cave dyke, despite their being intruded into different stress regimes (the albite-dolerites were emplaced along ENE-WSW trends) points to a common origin. It is tempting to postulate further that they may both form a northern extension to the more extensive North Brittany swarm. If so, in the Upper Palaeozoic the cratonized Cadomian active continental margin of the Armorican Massif was being subjected to mild E-W extensional stress which resulted in the injection of magma of continental intraplate basalt from an enriched mantle source as NS trending dykes.

Petrographic and petrochemical evidence indicates that the Wolf Cave olivine-bearing dolerite dyke is heterogenous in composition in

a way which is difficult to explain by *in situ* crystal fractionation of a basaltic magma. The presence of a porphyritic chilled margin and a porphyritic centre separated by an aphyric zone is a common phenomenon in vertical dykes (Platten and Watterson 1983) and has been ascribed to either flow differentiation (Drever and Johnston 1967; Komar 1972; Gibb 1968; Bhattacharji 1967), wall crystallization and accretion (Harker 1904), or a differential accretion (Platten and Watterson 1969) mechanism. Such variations in phenocryst content across dykes are much more common-in magmas containing phenocrysts of olivine than in those containing other phenocryst phases. Drever and Johnston (1967) noted that, not only do olivine phenocrysts increase in modal content from margins to the centres of picritic dykes, but their grain-size also increases. They ascribed this variation to multiple injection by magmas of slightly differing composition, whereas Gibb (1968) interpreted it as due to flow differentiation. Such a mechanism maybe invoked in magmas whose phenocryst concentrations are greater than 8%- certainly the case for the Wolf Cave magma - where grains strongly interact with each other when the fluid/phenocryst mixture is sheared by magma flow, causing the grains to repel each other, and thereby creating the condition of dispersive grain pressure (Komar 1972). Such interactions are capable of producing the variations of olivine grain size and modal content observed in the Wolf Cave dyke.

Modal and bulk rock petrochemical data indicate that olivine is the main mineral involved in the flow differentiation process in the Wolf Cave dyke. It is postulated that olivine crystals were present as suspended particles in the magma during flow. Thus the olivines in the chilled marginal facies should have the same core compositions as those in the centre of the dyke. This is demonstrated in Fig. 2; the core compositions of the olivine in the chilled margin are Fo_{75-79} while in the central zone there is no core composition greater than Fo_{80}. These compositions are very similar to those obtained from Hebridean picrite sills and dykes (Drever and Johnston 1967). If olivine crystallization had occurred during or after intrusion, cryptic variation could be expected. However in the Wolf Cave dyke, olivine compositions between Fo_{75} and Fo_{60} occur only on the rims of the crystals, a phenomenon also noted by Gibb (1968). Unfortunately microphenocrysts of plagioclase feldspar present in the chilled margin are altered so neither comparison nor comment can be made as to whether more than a small proportion of plagioclase was involved in the flow differentiation process postulated above.

A flow differentiation process is favoured over an accretion process such as that outlined by Platten and Watterson (1983) since core compositions of olivine could be expected to be different for different pulses of magma with consequent cryptic variation in Fo content.

It is interpreted that olivine was the dominant solid phase in suspension during possible laminar flow within the dyke and the crystallization of the other mafic and feldspar minerals has taken place subsequently.

Subsequent to intrusion, the olivines at the centre of the dyke underwent some reaction with the liquid to produce more iron-rich rims (e.g. Fo_{60}) while clinopyroxene of diopside composition started to crystallize. At this point ilmenite precipitated, depleting the remaining liquid in much of the titanium. Such a mechanism would explain why the amphibole compositions are titanoan ferroan pargasite rather than the more highly titaniferous kaersutite which is very common in basic dykes of this composition (e.g. Floyd and Rowbotham 1982). The biotites too are less titaniferous than expected.

Conclusions

The Wolf Cave Gabbro dyke has the following characteristics:
(1) it is the product of alkaline olivine basalt magmatism;
(2) it is post-Cadomian in age, most likely Upper Palaeozoic;
(3) the mineralogical evidence shows that discontinuous reaction has occurred between the mafic phases and the liquid;
(4) the mechanism of emplacement is thought to involve flow differentiation;

(5) a genetic link is postulated with the albite-dolerites of Guernsey and the N-S dolerite dyke swarm of North Brittany.

Analytical methods

Bulk rock chemical analyses were performed by XRFS using an ARL 8420 automatic sequential spectrometer at Keele. REE were determined mined using ICP-AE at RHBNC, London, by Dr J.N. Walsh, and lowlevel incompatible elements by INAA methods at URR Risley by Dr G.R. Gilmore. Mineral analyses were obtained using a Cameca (Camebax) microprobe at the University of Manchester, Department of Geology. Operating conditions were 15kV, 10^{-8}A, with a spot size of c.3µm, except for hydrous phases when the beam was defocussed. Calibration is against metals, oxides and silicates. An estimate of the accuracy of this technique is reported by Dunham and Wilkinson (1978).

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