

*The contamination of a gabbro by Carboniferous
Limestone at Carlingford, Co. Louth*

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Summary. Amongst the layered basic rocks of the Carlingford complex, is a gabbro which has been contaminated by a limited amount of Carboniferous Limestone. The clinopyroxene ($\text{Ca}_{49}\text{Mg}_{33}\text{Fe}_{18}$) produced in the gabbro is similar to that found in teschenitic gabbros. Such features as the instability of olivine distinguish this contaminated tholeiitic gabbro from true alkaline types. The production of aluminous augite is discussed, and comparison is made with the basic rocks of Scawt Hill and Gunnedah. Analyses of the contaminated gabbro and contained pyroxene are given.

ON the south-east slopes of Slieve Foye, and one mile west of the town of Carlingford, Co. Louth, Eire, there is a gabbro of unusual appearance amongst other gabbros of more normal appearance. The normal gabbros which have already been described (Le Bas, 1960) are medium to coarse-grained ophitic rocks formed of black and white crystals. They are part of the Carlingford complex of Tertiary age.

The anomalous gabbro forms a patch 230 yards long by 60 yards wide (see fig. 1) near the base of layer 1 of the normal gabbros. The contact between this gabbro and the normal gabbros varies. Sometimes it is simply gradational. More often one rock type is streaked into the other giving interbanding of the two rock types, the preponderance of one over the other gradually changing as one traverses the contact zone. The banding dips westward at 35° to 40° . In hand specimen, the anomalous gabbro has two characteristics: the green colour of the clinopyroxene giving a rock of green and white appearance, and the very variable grain size even within a hand specimen. Occasionally this greenish gabbro contains clots of half a dozen or so large pyroxene crystals each up to 0.5 cm across. These features suggest that this is a contaminated gabbro. A small exposure of similar rock type, but completely enclosed in normal gabbro, has also been recognized 1000 feet due west of the main locality. A third locality is on the south-east flanks of Barnavave in hybridized normal gabbro near the junction with granophyre (see fig. 1). The varied geological environments of the three

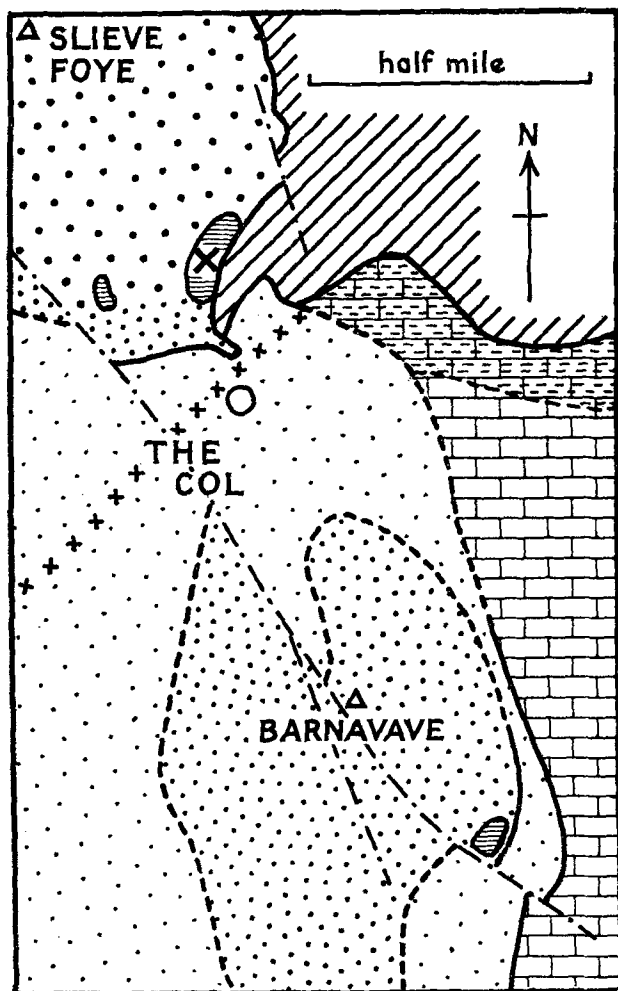


FIG. 1. Map of the Slieve Foye-Barnavave region showing the areas of the contaminated gabbros (horizontal ruling) and the locality of the analysed specimen 80b (X). Heavy dots—normal gabbro; more closely spaced dots—gabbro hybridized by granophyre; fine dots—granophyre; oblique ruling—Silurian sediments; bricking—Carboniferous Limestone; bricking with dashes—Basal Carboniferous conglomerate; circle—large xenolith of marble (now quarried away); XXX—
inferred former position of Silurian-Carboniferous unconformity.

localities (near gabbro-Silurian greywacke contact; in middle of gabbro; near gabbro-granophyre contact but not far from Carboniferous Limestone) suggest that the contaminated gabbros do not result from present environmental factors, but have a common origin elsewhere.

The textural variations are most marked at the main locality north of The Col. The various types sometimes occur as bands, each 10 centimetres to 1 metre wide. The bands dip westward at 35° to 40° which is the regional dip of the normal gabbros in this part of the lopolith in the Carlingford complex. Thus these contaminated gabbros form an integral part of the normal gabbros.

Petrographic and chemical evidence presented below suggests that the contaminated gabbro must have assimilated limestone picked up during the intrusion of the gabbroic magma, and that the contamination remained localized. The occurrence south-east of Barnavave could also be explained as a contact reaction between gabbro and Carboniferous Limestone, though these are now separated by a later granophyre intrusion (see fig. 1). Fig. 2 shows the probable extent of the Carboniferous Limestone under the gabbroic lopolith before the intrusion of the granophyre. No fragments of Carboniferous Limestone are found in the volcanic vent agglomerates of the area.

Petrography of the contaminated gabbro

The gabbro is essentially composed of clinopyroxene and plagioclase with occasional partly resorbed olivine crystals. Small amounts of sphene, magnetite, spinel, actinolite, calcite, and apatite occur. An analysis is given in table I, A. Sometimes the texture is granular; sometimes the pyroxene bears a subophitic relation to the plagioclase; and sometimes the pyroxene is idiomorphic, particularly in the pyroxenic clots (see fig. 3). It is similar to the augite-diorites of Camphouse and Rudha Groulin, Ardnamurchan (Richey, 1930, p. 153 and p. 293). Agrell has since shown (1950) that the Camphouse rocks were produced by limestone assimilation.

Plagioclase. The plagioclase is often zoned, especially in the coarser-grained rocks. The cores, when present, are bytownite (R.I.s indicate An_{82}), and show some evidence of resorption. Forming a discontinuous zone around them, and also as discrete crystals, is labradorite (R.I.s indicate An_{65}). This is zoned continuously through andesine to oligoclase. In a few thin sections, small bytownite crystals also occur as inclusions in the pyroxenes. It appears that the introduction of limestone to the magma temporarily inhibited the formation of plagioclase,

in the rock. An analysis of the dolomitic Carboniferous Limestone from Carlingford is given in table IV, N. The above reaction is preferred to that given by Tilley for the resorption of olivine at Scawt Hill and Camas Mòr (1952, p. 538 and p. 540) since there is no evidence of nepheline being stored up in the liquid at Carlingford. This may result from the fact that the initial magma at Carlingford was tholeiitic (Le Bas, 1960), unlike that at Scawt Hill and Camas Mòr.

TABLE I. Analyses and norms of contaminated gabbros

| | A | B | | A | B | |
|--------------------------------|--------|-------|--------|----------------------------------|-------|-------|
| SiO ₂ | 47.98 | 48.17 | or | 2.06 | 2.22 | |
| TiO ₂ | 0.82 | 0.49 | ab | 12.58 | 12.05 | |
| Al ₂ O ₃ | 18.09 | 18.18 | an | 41.42 | 41.98 | |
| Fe ₂ O ₃ | 2.66 | 2.63 | di | CaSiO ₃ | 12.76 | 10.98 |
| FeO | 5.01 | 6.77 | | MgSiO ₃ | 8.40 | 6.40 |
| MnO | 0.12 | 0.07 | | FeSiO ₃ | 3.43 | 3.96 |
| MgO | 6.86 | 6.87 | hy | MgSiO ₃ | 8.15 | 9.40 |
| CaO | 15.58 | 14.03 | | FeSiO ₃ | 3.24 | 5.54 |
| Na ₂ O | 1.50 | 1.44 | ol | Mg ₂ SiO ₄ | 0.31 | 0.84 |
| K ₂ O | 0.33 | 0.39 | | Fe ₂ SiO ₄ | 0.14 | 0.61 |
| H ₂ O ⁺ | 0.56 | 0.49 | mt | 3.94 | 3.71 | |
| H ₂ O ⁻ | 0.09 | 0.07 | sphene | 1.96 | 1.18 | |
| P ₂ O ₅ | 0.01 | tr | cc | 0.90 | — | |
| CO ₂ | 0.40 | nd | | | | |
| | 100.01 | 99.60 | | | | |

- A. Pyroxene-rich gabbro no. 80*b* produced by contamination with Carboniferous Limestone. 2,800 feet S. 36° E. of Slieve Foye summit, at 1100 feet O.D. Analyst: M. J. Le Bas. (No. 63748 in Harker Collection of the Department of Mineralogy and Petrology, Cambridge University). Mode: plag. 39 %, cl. pyrox. (core) 30 %, cl. pyrox. (zoned margin) 30 %, accessories 1 %.
- B. 'Dark doleritic variety' of gabbro. SE. side of Barnavave (Nockolds, 1938, p. 471, II). Besides being contaminated by Carboniferous Limestone, this rock has also been slightly hybridized by granophyre.

The olivine has a composition of about Fa₂₅ which is similar to that in the adjacent normal gabbros. It is frequently replaced by serpentine and bowlingite.

Pyroxene. Clinopyroxene forms 60 % of the contaminated gabbro, whereas it forms only 40 % of the normal gabbros. The pyroxene is zoned, the pleochroic scheme for the core being: α pale brownish-green, β yellow-brown, γ pale green; also $\gamma \wedge c 44^\circ$, $\gamma - \alpha 0.020$, weak dispersion. That for the zoned margin is: α brownish-green, β brown, γ grey-green, $\gamma \wedge c 48^\circ$, $\gamma - \alpha 0.018$, moderate dispersion. It is estimated that half the bulk of the pyroxene is in the core and half in the zoned margins.

An analysis of the core pyroxene is given in table II, C. It was

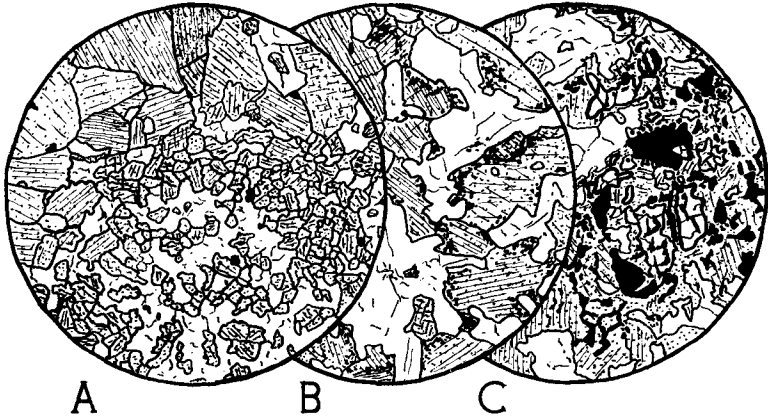


FIG. 3. Contaminated gabbros; $\times 20$, p.p.l., Slieve Foye.

- A. Pyroxene-rich gabbro of variable texture, lower half—granular pyroxene and plagioclase, top left—anhedral pyroxene, top right—subophitic pyroxene and plagioclase. Specimen No. 405A, (Harker collection No. 63750) from same locality as No. 80b.
- B. Pyroxene-rich gabbro with subophitic texture and zoned pyroxenes. Specimen No. 80b.
- C. Pyroxene-rich gabbro with partially resorbed olivine. The olivine crystals are all in optical continuity, and are wholly enclosed by pyroxene and ore. They represent the relic of an originally large single crystal of olivine. Specimen No. 405c from the same locality as No. 80b.

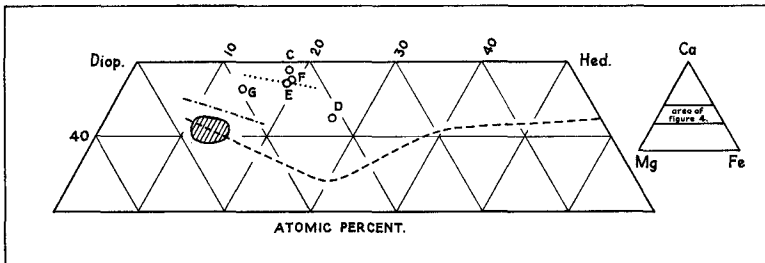


FIG. 4. Plot of clinopyroxenes on Ca-Mg-Fe diagram. trend from alkali-basalt magmas (Wilkinson, 1957); - · - · - trend from normal gabbros of the Carlingford complex (Le Bas, 1960); - - - - - trend from Skaergaard and other tholeiitic magmas (Brown and Vincent, 1963); oblique ruling indicates the field of augites produced by contamination of Carlingford gabbros by Silurian argillaceous material. C, D, E, F, and G refer to analyses given in table II.

TABLE II. Analyses, formulae, and optical data of pyroxenes

| | C | D | E | F | G | Metal atoms to 6 oxygens | | | | | |
|---------------------------------|-------------|--------|-------------|--------|-------|--------------------------|-------|-------|-------|-------|-------|
| | | | | | | Si | C | D | E | F | G |
| SiO ₂ | 48.72 | 46.88 | 48.12 | 47.25 | 49.31 | Si | 1.844 | 1.799 | 1.829 | 1.783 | 1.835 |
| Al ₂ O ₃ | 4.51 | 4.69 | 3.58 | 5.36 | 4.60 | Al in Z | 0.153 | 0.192 | 0.148 | 0.224 | 0.170 |
| TiO ₂ | 0.97 | 2.08 | 2.42 | 3.45 | 1.26 | Al in Y | 0.048 | 0.021 | 0.011 | 0.016 | 0.031 |
| Fe ₂ O ₃ | 3.39 | 3.89 | 1.80 | 2.04 | 2.38 | Ti | 0.028 | 0.060 | 0.067 | 0.097 | 0.036 |
| FeO | 7.83 | 10.67 | 9.45 | 9.06 | 5.57 | Fe ²⁺ | 0.096 | 0.111 | 0.051 | 0.059 | 0.067 |
| MnO | 0.18 | 0.05 | 0.20 | 0.18 | — | Fe ²⁺ | 0.246 | 0.341 | 0.301 | 0.283 | 0.172 |
| MgO | 10.87 | 10.40 | 11.58 | 10.85 | 14.02 | Mn | 0.006 | 0.002 | 0.006 | 0.007 | — |
| CaO | 22.64 | 19.78 | 22.09 | 21.44 | 22.71 | Mg | 0.613 | 0.595 | 0.653 | 0.613 | 0.778 |
| Na ₂ O | 0.62 | 0.79 | 0.70 | 0.65 | — | Ca | 0.918 | 0.816 | 0.899 | 0.866 | 0.906 |
| K ₂ O | 0.12 | 0.58 | 0.12 | nil | — | Na | 0.045 | 0.060 | 0.051 | 0.045 | — |
| H ₂ O ⁺ | 0.07 | 0.49 | 0.19 | 0.18 | — | K | 0.006 | 0.028 | 0.006 | — | — |
| H ₂ O ⁻ | 0.16 | — | tr. | nil | — | Z | 1.997 | 1.991 | 1.977 | 2.007 | 2.005 |
| | 100.08 | 100.30 | 100.25 | 100.46 | 99.85 | WXY | 2.008 | 2.032 | 2.044 | 1.986 | 1.990 |
| Fe ^{cat} /Mg wt. ratio | 1.3 | 1.8 | 1.3 | 1.2 | 0.8 | Ca | 49.0 | 42.6 | 47.0 | 47.4 | 46.4 |
| ±2V | 56° | — | 49°-59.5° | — | — | Mg | 32.7 | 31.0 | 34.1 | 33.5 | 39.6 |
| α | 1.690-1.690 | ±.003 | 1.699-1.707 | — | 1.698 | Fe | 18.3 | 26.4 | 18.9 | 19.1 | 14.0 |
| β | 1.697 | — | 1.704-1.711 | — | — | Per cent. Al in Z | 7.7 | 9.6 | 7.5 | 11.2 | 8.5 |
| γ | 1.710 | 1.722 | 1.725-1.732 | — | 1.730 | | | | | | |
| γ∧c | 44° | 55° | 42°-45° | — | 43° | | | | | | |

C. Unzoned core of diopsidic augite from contaminated gabbro No. 806 (analysis A, table I). Analyst: M. J. Le Bas.

D. Bulk composition of zoned augite from gabbro contaminated by limestone and slightly hybridized by granophyre. East side of Barnavave (Nockolds, 1938, p. 472 and p. 477, V).

E. Bulk composition of pyroxene from differentiated teschenite 500 feet above lower contact, Gunnedah, New South Wales (Wilkinson, 1957, p. 124, III (H8)).

F. Pyroxene from alkali olivine-basalt, west side of Fishmish Peninsula, Mull (Tilley and Muir, 1962, p. 210).

G. Pyroxene from pyroxenite, near contact of dolerite with chalk, Seawt Hill, Co. Antrim (Tilley and Harwood, 1931, p. 451).

separated using an isodynamic separator from the analysed gabbro 80*b* (table I, A). The pyroxene is lime-rich, $\text{Ca}_{49}\text{Mg}_{33}\text{Fe}_{18}$, and differs considerably from that found in the normal gabbros of Carlingford (see fig. 4). Other features by which it differs are its lower SiO_2 and higher Al_2O_3 contents, giving $\text{Al}_z = 7.7$ instead of the normal 5; its greater TiO_2 content; and its higher proportion of Na_2O , 0.6 % instead of the normal 0.4 %.

TABLE III

| | H | K | L | M | |
|-----------------------------|-------|-------|-------|--------|-------|
| SiO_2 ... | 47.98 | 14.61 | 48.07 | | |
| TiO_2 ... | 0.82 | 0.29 | 0.77 | or | 2.43 |
| Al_2O_3 ... | 18.09 | 1.35 | 24.12 | ab | 16.78 |
| Fe_2O_3 ... | 2.66 | 1.02 | 2.36 | an | 57.45 |
| FeO ... | 5.01 | 2.35 | 3.83 | hy | 14.28 |
| MnO ... | 0.12 | 0.05 | 0.10 | ol | 6.03 |
| MgO ... | 6.86 | 3.26 | 5.19 | sphene | 1.72 |
| CaO ... | 15.58 | 6.80 | 12.65 | cc | 1.31 |
| Na_2O ... | 1.50 | 0.18 | 1.90 | | |
| K_2O ... | 0.33 | 0.03 | 0.43 | | |
| CO_2 ... | 0.40 | — | 0.57 | | |

H. Pyroxene-rich gabbro no. 80*b* quoted from table I, A.

K. Clinopyroxene from gabbro no. 80*b* (table II, C) reduced to 30 %.

L. Rock remaining after subtraction of K from H, recalculated to 100 %.

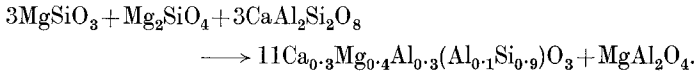
M. Norm of L. For interpretation of norm, see text.

Such a pyroxene is similar to those in alkaline basaltic rocks, particularly those from Gunnedah and Fishnish, which are reproduced in table II, E and F. There are, however, certain distinguishing features. Its titania is not as high as that usually found in pyroxenes from alkali basic rocks (see table I in Le Bas, 1962), and the value of Al_z (7.7) is rather low for a pyroxene of such high lime (compare fig. 3 in Le Bas, 1962, p. 278). These features help to confirm the field and petrographic evidence that these rocks have been contaminated.

A similar pyroxene (table II, D) is that described by Nockolds (1938, p. 472) from the gabbros of Barnavave. Besides having been hybridized by granophyre, the gabbros were also contaminated by the Carboniferous Limestone with which they were once in contact. The higher iron content of the pyroxene is probably the result of the granophyric hybridization.

Since pyroxene C in table II represents only the core of the zoned pyroxene, a calculation is made in table III to determine the composition of the zoned margin. The core pyroxene analysis is subtracted from the rock analysis (column L) and the norm of the remainder is

calculated (column M). This, however, does not correspond to the mineralogy as seen under the microscope, since no hypersthene and only very little olivine are present in the rock. The anomaly can be overcome by combining the hypersthene and olivine with some anorthite to give aluminous augite and a little spinel. The following illustrates the style of combination:



The calculated mineral composition then corresponds to the observed mineralogy, and it is deduced that the zoned margin of the pyroxene is highly aluminous.

Whilst the Ca content of the pyroxene is high and remains so throughout its crystallization, it is only enriched in alumina from about half-way through its crystallization history. This enrichment probably coincides with the reprecipitation of plagioclase which caused a relative impoverishment in silica in the magma, the effect of which has already been discussed (Le Bas, 1962). During all this, the Fe/Mg ratio remained constant; Fe/Mg wt. ratio is 1.3 ± 0.1 for both core and margin of the pyroxene. Hence the zoning observed optically must be due to the large increase in alumina and perhaps also titania. Though the deepening in colour may be caused by titania, the decrease in birefringence and increase in extinction angle and dispersion are probably due to the increasing alumina content. This is in keeping with the properties of the aluminous augite fassaite (Deer, Howie, and Zussman, 1963, p. 165).

This aluminous pyroxene is comparable in many ways to the colourless pyroxene, rich in alumina, described by Nockolds (1937, p. 128) at the junction between Carboniferous Limestone and syenite at Barnave.

Accessories. Very little iron-ore exists in these Carlingford gabbros, a feature found in the pyroxene-enriched rocks at Scawt Hill, but not at Camas Mòr which is richer in ore (Tilley, 1952, p. 535). Numerous small crystals of what appears to be deep brown to black spinel occur associated with iron-ore. Anedral crystals of sphene and apatite are usually present in small quantities. Interlocking crystals of epidote, amphibole, and calcite occur interstitially and are considered to be deuteric or secondary in origin.

History of crystallization. During intrusion, the magma began by crystallizing normally, bytownite plagioclase being precipitated first, followed by olivine. When Carboniferous Limestone was assimilated by

the magma, these two minerals ceased to appear. Instead a lime-rich clinopyroxene formed. When half the pyroxene had been precipitated labradorite plagioclase began crystallizing also, causing a relative deficiency of silica in the magma. As a result, the rest of the pyroxene which was co-precipitated with increasingly sodic plagioclase, became highly aluminous (compare Chinner and Schairer, 1962, p. 630). Neither acmite nor nepheline were developed, partly due to the limited nature of the contamination, and partly due to the tholeiitic nature of the original magma.

TABLE IV. Analyses of Carboniferous Limestone

| | N | O | P | Q | R |
|----------------------------------|--------|--------|--------|--------|-------|
| SiO ₂ | 5.98 | 4.26 | 4.25 | 4.93 | 38.68 |
| Al ₂ O ₃ | 3.43 | 1.18 | 0.72 | 0.80 | n.d. |
| Fe ₂ O ₃ * | | 3.14 | 0.32 | 0.42 | n.d. |
| MgO | 17.66 | 17.91 | 1.76 | 0.74 | n.d. |
| CaO | 30.84 | 29.01 | 53.29 | 51.44 | n.d. |
| H ₂ O ⁻ | 0.37 | 1.08 | 0.08 | 0.60 | 0.23 |
| CO ₂ | 42.09 | 42.70 | 40.02 | 40.62 | 2.39 |
| | 100.37 | 100.60 | 100.59 | 100.54 | |

* Total iron as Fe₂O₃.

- N. Carboniferous Limestone, a dark dolomite. Shore due S. of Whites Town, 1 mile NW. of Cooley Point, Carlingford Peninsula, Co. Louth (analyst M. J. Le Bas).
- O. Carboniferous Limestone, the Castlecary Limestone, a ferriferous dolomite. Cariehall old mine, 1 mile W. of Culross, Fife (Muir *et al.*, 1956, p. 61, SL 120). Analysis includes Na₂O 0.15, K₂O 0.24, TiO₂ 0.07, P₂O₅ 0.31, MnO 0.24, FeS₂ 0.31.
- P. Carboniferous Limestone xenolith (inner zone) in 'syenite'. E. side of Barnavave, Carlingford Peninsula (Nockolds, 1937, p. 130, I). Analysis includes H₂O⁺ 0.15.
- Q. Carboniferous Limestone, the Dockra Limestone, a fine-grained limestone. Hessilhead Quarry, Lugton, Ayr (Muir *et al.*, 1956, p. 46, SL 109). Analysis includes Na₂O 0.09, K₂O 0.05, TiO₂ 0.05, P₂O₅ 0.07, MnO 0.16, FeS₂ 0.57.
- R. Carboniferous Limestone xenolith in gabbro, 10 feet from contact, a calc-silicate rock, 1100 yards S. 5° W. of Barnavave, Carlingford (analyst M. J. Le Bas).

The Limestone causing the contamination

In order to have a check on the chemical constituents added to the gabbro during the contamination, the chemical composition of the Carboniferous Limestone at Carlingford was determined. The result and some comparable analyses are given in table IV. Together with thin-section observations, they indicate that the limestone assimilated by the gabbro was dolomitic, ferriferous, and had 5–10 % argillaceous impurity.

It is calculated that the addition of between 10 and 13 % of Carboniferous Limestone (such as analysis N in table IV) to normal gabbro for that part of the layered basic complex concerned (analyses 79, 504, and 1071 in table III, Le Bas, 1960), would give the contaminated gabbro described in this paper (table I, A).

Limestone has also been assimilated in other parts of the Carlingford complex (see fig. 2) giving limestone xenoliths or their calc-silicate products (Nockolds, 1947). The gabbros in contact with these xenoliths differ from the contaminated gabbro described in this paper. They are rich in aegirine-augite and sphene, and closely resemble the rocks of Scawt Hill. They evidently result from the assimilation of an unlimited amount of limestone in contrast to the example on the south-east slopes of Slieve Foye.

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