Chapter 31 Contact metamorphism of the Cambrian dolomites and limestones

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The rocks of the Cambrian Calcareous series have undergone important alterations, both in Assynt and in Skye, as a result of the intrusion of igneous rocks. In Assynt the effects are due to the granite, quartz-syenite, augite-syenite, nepheline-syenite, and borolanite, which together make up the plutonic complex of Cnoc na Sroine; in Skye they are due to igneous rocks of Tertiary age. The following account of this metamorphism has reference mainly to the phenomena seen in the Assynt district, but, as those of Skye are similar, some reference to that locality will also be made.

The marbles of Assynt have attracted the attention of many previous writers on the geology of the district. The fullest description of them which has hitherto appeared is that by Dr. Heddle in his papers on the Geognosy and Mineralogy of Scotland<ref>*Mineralog. Mag.,* vol. iv., p. 242, and vol. v., p. 271.</ref>, to which reference has been made in Chapter 29. This author gave particulars as to their distribution, structure, and composition, and arrived at the conclusion that the marble is a metamorphosed dolomite — a conclusion which the detailed mapping of the ground by the Geological Survey has fully confirmed. He also observed that " the localities where the marble occurs lie round, and nowhere at much greater distance than a mile from, the quartz-porphyry of Cnoc na Sroine or from the spurs of that hill; but he does not draw the obvious conclusion that the marbles are the direct result of the action of this rock upon the dolomite. In his second paper he gave a detailed description of a peculiar variety of the marble showing structures which were identified by Dr. Carpenter as being similar to those of the Canadian specimens of eozoon. Calculating the lime and magnesia soluble in "moderately strong acid with gentle heat" as carbonates, the matrix of the rock showing the structure in question was found to contain 46.307 of carbonate of lime and 37.632 of carbonate of magnesia. The insoluble residue amounted to 14.408 per cent., and consisted, according to Dr. Heddle, of "rounded crystals of malacolite, with small quantities of serpentine, quartz, margarodite, and magnetite". In view of the facts to be stated subsequently, it is highly probable that the rounded crystals were in part at least forsterite, not malacolite, and the presence of quartz is somewhat doubtful; but the analysis clearly proves that the material contained a considerable amount of magnesia in the form of carbonate, no doubt present as dolomite. Another specimen analysed by Dr. Heddle gave 55.562 per cent. of carbonate of lime and 39.942 per cent. of carbonate of magnesia, along with 4.238 per cent. of insoluble residue, said to consist entirely of granules of malacolite. An analysis of the marble of Ledbeg by Dr. Anderson gave the following result:

Carbonate of Lime	91.32
Carbonate of Magnesia	4.74
Alumina, Ferric Oxide, &c.	0.2
Silica	4.34
	100.60

It will be noted that Dr. Anderson's specimen contained much more carbonate of lime than the two specimens analysed by Dr. Heddle. In his description of the microscopic sections of the rock showing eozoonal structure, Dr. Heddle records the presence of a fibrous mineral which he somewhat doubtfully refers to as wollastonite, and a partially serpentinised ovoidal mineral which he regards as malacolite. The fibrous mineral was probably brucite and the ovoidal mineral forsterite. The results of the examination of the Survey specimens will now be given.

Minerals of the altered rocks

The altered rocks of Assynt which have been invaded by thd plutonic complex, described in the foregoing chapter, contain the following minerals: Calcite, dolomite, brucite, diopside, forsterite, serpentine, mica, and tremolite. The same minerals occur in the corresponding rocks from Skye, together with a violet spinel. Mr. Harker has also observed idocrase and garnet in the immediate neighbourhood of the Tertiary igneous rocks of the Broadford district.

In the microscopic examination of the altered rocks it has been found impossible to distinguish between Calcite and Dolomite in any other way than by the Lemberg staining test. This, however, is decisive and therefore invaluable. Both

minerals are usually present, but in very different proportions in different cases.

Next to carbonates, Brucite is perhaps the most common mineral. It is present in several specimens both from Assynt and Skye. The specimen selected for the determination of this mineral came from the Ledbeg River (S9208) [NC 244 138], about half a mile S.E. of Loyne shepherd's house. The rock is of medium grain, nearly white, and effervesces freely with dilute acid. The weathered surface is extremely rough, owing to the projection of small crystals of dolomite. The fractured surface when examined with a lens discloses the presence of light-coloured more or less rounded grains (1 to 2 mm) in a mass of white carbonate. Under the microscope these rounded grains are seen to consist of fibrous or scaly aggregates, which often show a kind of plumose arrangement, and give, between crossed-nicols, the colours of the first order. This substance has all the characters of a pseudomorph. The larger grains above referred to are generally without form, but smaller grains (0.1 to 0.2 mm), occurring in the same slide and evidently composed of the same substance, give square, triangular, and hexagonal outlines such as are characteristic of octahedra.

An attempt to isolate the mineral from the carbonates by the action of dilute acid failed, for it was dissolved as readily as dolomite, and almost, if not quite, as readily as calcite. A perforated cover *glass* placed over the slide, so as to expose a portion of one of the larger grains, allows the action of dilute acid on the substance to be studied. Sometimes it fades away without effervesence, and sometimes one or two bubbles make their appearance when the acid is first applied; but there is no continuous effervescence during the solution of the mineral. The solution gives an abundant precipitate of the characteristic ammonio-magnesic phosphate when tested on a slide for magnesia in the manner recommended by Behrens. The mineral may be isolated in a state of tolerable purity by the aid of any heavy solution which does not act on carbonates. This has been done by Dr. Pollard. It floats in a solution of bromoform of sp. gr. 2.41. The grains, when treated on a slide with dilute hydrochloric acid, behave in the same manner as those in the slide. There is almost always a slight effervesence at first, but afterwards the mineral fades quietly away. Sometimes the effervesence can be distinctly traced to specks of calcite included in the mineral. As a similar mineral occurring in the predazzite of the Tyrol has been referred to hydro-magnesite (O. Lenecek: Ueber Predazzit and Pencatit., *Min. Mitth.* XII.. 1891, 429–456), it was desirable to remove all doubt as to its nature. The substance (0.2388g) isolated in the manner above described was accordingly analysed by Dr. Pollard with the following results

SiO_2	0.4
Al_2O_3/Fe_2O_3	1.4
MgO	60.0
CaO	0.8
Loss on Ig.	31.2
	99.8

Calculating the loss as water, this gives a ratio of MgO: H_2O as 1:1.06, and leaves no doubt that the bulk of the substance analysed was brucite. The amount of carbonic acid present was not estimated, but qualitative experiments proved that it must have been very slight. Brucite occurs in several specimens from Ledbeg River, and also from Kilchrist in Skye. The specimens from the latter locality bear the most striking resemblance in general appearance and microscopic character to specimens of the typical predazzite from the Tyrol.

In the paper by Lenecek above referred to, the so-called hydromagnesite is regarded as a pseudomorph after periclase; no unaltered periclase has been found in the metamorphosed dolomites of Assynt and Skye, but the octahedral form of the smaller grains in the rock from the Ledbeg River is unmistakeable, and the brucite is therefore very probably a pseudomorph after this mineral.

The normal Pyroxene of the altered rocks is a colourless Diopside. It is often aggregated in patches, which suggest that it has been formed at the expense of the cherts occasionally found in the dolomite ((S6738) [NG 625 207], Skye). The individual grains are allotriomorphic with respect to each other, but often more or less idiomorphic with respect to the carbonate. The prismatic faces are then well developed, and the clino-pinacoid has also been identified. The characteristic cleavages are strongly marked, and repeated twinning has been observed. It is worthy of note that the normal diopside (CaO, MgO, $2SiO_2$) can be formed from dolomite (CaO, MgO $2CO_2$) by the substitution of silica for carbon dioxide. The presence of quartz or chert in the original rock will therefore supply the necessary constituents for

the formation of diopside in a dolomite. Moreover, the formation of diopside in a dolomite does not involve dedolomitisation.

Some rocks of exceptional character and apparently of compound origin occur in the Ledbeg River about 400 or 500 yards north-east of Ledbeg (four and a half miles south of Inchnadamlf). The calcareous members of the series from this locality ((S9203) [NC 244 138] to (S9205) [NC 244 138]) contain two varieties of pyroxene; the one a colourless diopside similar to that already referred to, the other a green mineral identical with the mgirine-augite of the augitesyenites. The green pyroxene sometimes forms a distinct and sharply-defined border to the colourless variety (S9205) [NC 244 138]. As both field and microscopic evidence suggest interaction between the igneous and sedimentary rocks, the green pyroxene *was* isolated from its matrix of calcite (S9203) [NC 244 138] and analysed by Dr. Pollard with the following result:

SiO_2	53·58	0.8871
TiO_2	tr.	—
Al_2O_3	1·32	0.0129
Fe_2O_3	9·46	0.0591
FeO	3·36	0.0467
MnO	0.31	0.0043
CaO	16·82	0.3003
MgO	11.67	0.2891
K_2O	0.20	0.0021
Na_2O	3·31	0.0533
Li_2O	tr.	—
Ignition	0.73	0.0405
	100·76	

Sp. gr. above 3·28; 0.5032gr. taken for main analysis, 0.5g. for alkalies, 0.329g. for FeO. Ratio of CaO: MgO —1.04 : 1.

Assuming the following molecules to be present, we have:

$(NaK)_2$, Fe_2 Si_4 O_{12}	25.76
Fe Fe_2 Si4 O_{12}	1.76
Fe Al_2 Si O_6	3.03
Ca Mg Si_2 O_6	62.73
Ca Mn Fe SiO_2	5.99
SiO_2	0.76
H_2 O (Ig.)	0.73
	100.76

This analysis reveals the presence of over 25 per cent. of the characteristic vegirine-molecule, and leaves no doubt that material has passed from the igneous to the metamorphic rock. But, although there has undoubtedly been some interchange of material such as that emphasised by Mr. Johnston Lavis, this interchange, so far as the rocks under consideration are concerned, appears to be limited to the immediate neighbourhood of the junction.

Forsterite and Serpentine derived from this mineral are both common in the altered dolomites of Skye and Assynt, but there is a doubt as to whether all the serpentine has been so formed. In the specimens from Assynt forsterite always occurs in ovoidal grains, which often suggest the form of olivine, but never possess sharp angles. The mineral is quite colourless in thin sections, and frequently shows the characteristic alteration to serpentine along irregular cracks. It was isolated from a rock occurring on the borders of the Once na Sroine mass (S3099) [NC 25 12], and analysed by Dr. Pollard with the following result:

SiO_2	42.2
Al_2O_3	0.8
Fe_2O_3	0.5

CaO	0.3
MgO	57.0
Ignition	0.3
	101·1

Ratio of MgO : SiO_2 = 2.02 : 1.

It is important to note that the formation of forsterite in a dolomite must, if the bases be retained, be accompanied by the development of calcite. The forsterite in question was embedded in a matrix of calcite. In the above analysis the state of oxidation of the small amount of iron present was not determined, and it is therefore quoted as Fe, 0_3. An exceptional variety of forsterite occurs in a rock about half a mile west by north of the outlet of Loch Lonachan, south of Broadford, in Skye (S6743) [NG 625 195]. The mineral is here developed as thin tables bounded by planes, often meeting in sharp angles. The large flat planes are at right angles to the positive bisectrix, and correspond, therefore, to the macro-pinacoid, on the assumption that the optic orientation is the same as that of normal forsterite. The plates measure from 1 to 3 mms. across, and are somewhat elongated in the direction of the vertical axis, but not markedly so. Their thickness is only about 0.1 mm They are much broken up by cracks, and readily disintegrate on the application of the slightest pressure. In addition to the macro-pinacoid (100), which is the dominant form, the basal plane (001), the brachydome (021), and the prism (110) probably occur, but have not been identified with absolute certainty.

As this habit is so different from that of the forsterite usually found in altered rocks from Assynt, Skye, Vesuvius, and elsewhere, the mineral was isolated and analysed by Dr. Pollard:

SiO_2	42.6
Al_2O_3	1.2
Fe_2O_3	1.2
CaO	0.6
MgO	51.2
Ignition	3.1
	99.9

The total iron is given as Fe_2O_3, but the state of oxidation was not determined. The ratio MgO : SiO_2 = 1.8 : 1. Fluorine was looked for but not found.

The Serpentine (S9211) [NC 295 087] is greenish-yellow in colour, and, like the forsterite from which it is in most, if not in all, cases derived, is invariably associated with calcite. In the course of the examination of these rocks a doubt arose as to whether some of the serpentine may not have originated from diopside. A rock from Skye (S6783) [NG 579 198] in which this appeared to be possible, and which contained cores of the parent mineral, was accordingly selected for chemical examination. The comparatively unaltered substance was found by Dr. Pollard to possess the following composition:

SiO_2	41.5
Al_2O_3	0.9
Fe_2O_3	1.4
CaO	0.3
MgO	55.6
Ignition	1.2
	100.9

Ratio of MgO: SiO_2 = 2: 1.

The other minerals do not call for detailed description. Mica when present is in the form of light-coloured, silvery scales, and is uniaxial. It is rare, and has been noticed only in one or two specimens. Tremolite is also comparatively rare. It occurs as slender prisms associated with calcite.

Petrographical characters of the altered rocks

The minerals above mentioned are mixed in very different proportions in the different rocks. Those in which brucite occurs are of special interest, because they belong to a type hitherto unrecognised in the British Isles, though long known as predazzite, from the neighbourhood of Predazzo in the Tyrol. A typical specimen of this rock from the Ledbeg River (S9208) [NC 244 138] is a medium-grained, nearly white rock composed of brucite, calcite, and dolomite.

The brucite aggregates vary in size from about 0.1 to above 1 mm in diameter. The larger grains are mostly rounded in outline, but the smaller ones often give square, triangular, and hexagonal sections, which strongly suggest the conclusion that the material is a pseudomorph after periclase. The carbonates occuras irregular individuals of a somewhat larger size than the brucite. They consist of calcite and dolomite in about equal proportions.

Another specimen, also from the Ledbeg River (S3096) [NC 244 135], is a dark-grey crystalline rock composed of calcite, dolomite (scarce), brucite, and a few grains of serpentine probably after forsterite. The corresponding rocks from Skye occur at Kilchrist. They are very fine-grained or compact, and are sometimes flecked with black patches. The compact white or cream-coloured varieties exactly resemble specimens of predazzite from the Tyrol in the Museum of Practical Geology. The constituents are the same as in the rocks from Assynt, the principal differences being due to a fine-grained texture, and the occasional presence of unaltered forsterite. The specimens come from the upper quarry, Kilchrist (S6801) [NG 622 201] and (S6802) [NG 622 201]; from a point 200 yards south-east by east of this quarry (S7084) [NG 613 200]; from a quarry close to the south angle of the glebe-fence, Kilchrist (S7082) [NG 617 202]; and from a point 500 yards W.S.W. of Kilbride (S7083) [NG 588 209].

Rocks mainly composed of calcite and forsterite, with a varying admixture of dolomite, sometimes with none at all, occur both in Assynt and Skye. A specimen (S3099) [NC 25 12] from the former district is a fine-grained, nearly white rock composed of calcite and forsterite in about equal proportions. The forsterite occurs in colourless, more or less rounded grains, which vary in size from about 0.2 up to 1 mm in diameter. The calcite occurs in large ophitic plates, and forms the matrix in which the grains of forsterite are embedded. The forsterite of this specimen has been isolated and analysed. The slight loss on ignition (3 per cent.) shows that but little change to serpentine has taken place, a fact fully supported by the microscopic evidence.

Another type of rock composed of calcite, dolomite, and forsterite is represented by a specimen (S6743) [NG 625 195] collected by Mr. Clough, from a point half a mile west by north of the outlet of Loch Lonachan in Skye. In this case the forsterite occurs in the form of thin tables. The matrix is a crystalline-granular aggregate of carbonates, the individuals of which measure from 0.1 to 2 mm in diameter. Calcite and dolomite cannot be distinguished from each other in the ordinary microscopic slide, but after staining they are easily separable. It is then found that the calcite grains are grouped around the forsterite-crystals, while the dolomite occupies the interspaces. This relation can be explained if we assume that the original rock was a dolomite containing some silica, either in the form of chert or quartz, and that the forsterite has been formed by taking the magnesia from the dolomite in its immediate neighbourhood.

The specimens containing calcite and forsterite are connected with the ophicalcites by transitional forms. If the specimens from Skye are considered along with those from Assynt, a fairly continuous series can be made out among the combined examples. The specimen from the base of Cnoc na Sroine (S3099) [NC 25 12], already referred to, is a good example of a rock essentially composed of calcite and forsterite; a second, from the shore north of Camas Malag, Loch Slapin, in Skye, shows forsterite in various stages of alteration to serpentine; a third, from a small quarry south-east of Kilchrist (S6804) [NG 616 200], is composed of alternating layers of white calcite and greenish-yellow serpentine with cores of unaltered forsterite; and a fourth, from near the Loch Ailsh road, east of Aultnagallagach, Assynt (S9211) [NC 295 087], is a true ophicalcite composed of calcite and yellowish-green serpentine, which shows by its form and microscopic structure that it has been derived from forsterite.

A specimen from a quarter of a mile south-east of Suardal Farm, Skye (S6788) [NG 612 227], illustrates another type of rock. It consists of more or less rounded lumps of white diopside, measuring one or two inches in diameter, embedded in a dark-bluish crystalline matrix. The forms of the nodular patches suggest that they are due to the presence of chert in the original dolomite. Under the microscope the constituents are seen to be diopside, dolomite, calcite, forsterite, and

tremolite. The ¯diopside of the nodules is idiomorphic with respect to dolomite, which is seen to be directly moulded upon it. The matrix is mainly composed of dolomite, but contains also calcite, forsterite, and tremolite; moreover, the calcite is directly associated either with tremolite or forsterite. Thus the patches of calcite either surround crystals of forsterite or are penetrated by prisms of tremolite.

This association of minerals accords with the view that the metamorphism has been accompanied by dedolomitisation, for the development of forsterite (2MgO, SiO_2) and tremolite (CaO, 3MgO, $4SiO_2$) in a siliceous dolomite must be accompanied by the formation of calcite, if the alteration is brought about by simple interchange of constituents with the loss of carbonic acid. In addition to the types above described, the series of specimens from Assynt and Skye includes rocks in which the principal constituents (calcite, dolomite, brucite, forsterite, tremolite, and diopside) are mixed in different proportions. Some are banded, so that the relative proportions of the different minerals may vary in a hand specimen or even in a microscopic slide.

Some exceptional rocks occur in the immediate neighbourhood of the contact with borolanite and augite-syenite in the Ledbeg River ((S9203) [NC 244 138], (S9204) [NC 244 138], (S9205) [NC 244 138], (S9206) [NC 244 138], (S9207) [NC 244 138]. In addition to colourless diopside, mica. and carbonates, mainly calcite, these rocks contain a green augite identical with that occurring in the augite-syenite. The green pyroxene is aggregated in lumps and patches in a matrix of calcite either by itself (S9203) [NC 244 138] or in association with the round colourless diopside (S9205) [NC 244 138]. In the latter case it forms a border to the colourless variety. One specimen of the series deserves special attention (S9206) [NC 244 138]. It is a mottled dark-green and white rock composed of calcite, orthoclase, and an aegirine-augite. One portion of the specimen consists of aagirine-augite and orthoclase, the other of the same augite in a matrix of calcite.

There is absolutely no difference in form,., size, or colour between the pyroxene associated with the calcite and that associated with the orthoclase. The only way in which such a rock can have been formed is by a most intimate blending of the igneous and sedimentary material accompanied by some interchange of constituents. The pyroxene-orthoclase aggregate is coarse-grained, so that there is no sign of chilling at the contact of the igneous rock with the marble.

Origin of the rocks

The field relations of the marbles of Assynt and Skye leave no doubt that they are the result of the metamorphism of the "Durness limestone series" in contact with intrusions of various igneous rocks. This calcareous series in the typical locality of Durness includes both dolomites and limestones, but the former appear to predominate both in Assynt and in Skye. Most of the specimens examined accord with the theory that they are metamorphosed dolomites containing a variable amount of silica in the form of chert or quartz, and it will be interesting to consider the facts from this point of view.

Diopside (CaO, MgO, $2SiO_2$) may be formed from dolomite (CaO, MgO, $2CO_2$) by the simple substitution of silica for carbon dioxide, and in accordance with this interchange we find diopside often in direct association with dolomite. Forsterite (2 MgO, SiO_2), on the other hand, cannot be formed in a dolomite, by simple interchange of constituents, without dedolomitisation, and in every ease in which this mineral occurs it is associated with calcite. Moreover, there is at any rate a rough general agreement between the amount of forsterite present and the amount of assumed dedolomitisation. In extreme cases no dolomite is left; in others there is only partial dedolomitisation, and the distribution of minerals in the slide accords with the view that the dedolomitisation is due to the development of forsterite. Thus calcite is found surrounding the crystals or crystalline grains of forsterite, while dolomite occurs in the interspaces. The serpentinous rocks illustrate the same principle. The serpentine is mainly if not entirely due to the alteration of forsterite, and is invariably associated with calcite. This suggests the possibility that most of the ophicalcites, includi$_{ng}$ the eozoonal limestone, are altered dolomites.

Tremolite is another mineral invariably associated with calcite in the rocks under consideration, and this fact also accords with the dedolomitisation hypothesis, for the ratio of CaO : MgO is 1 : 3 instead of 1 : 1 as in dolomite and diopside.

It follows as a necessary consequence of the above hypothesis that the contact metamorphism of a siliceous dolomite will not disturb the ratio of CaO : MgO in the mass as a whole; so that if a sufficiently large specimen be taken in the

preparation of the sample for the bulk analysis, this ratio should be 1 : 1. To test this a specimen collected about half a mile W.N.W. of the outlet of Loch Lonachan, Skye (S6744) [NG 627 197], was selected and partially analysed by Dr. Pollard with the following results:

SiO_2	15.96
Al_2O_3	0.70
Fe_2O_3	0.70
CaO	32.17
MgO	21.43
Ignition	29.22
	100.22

This gives CaO : MgO=1.08 : 1, agreeing with dolomite. The rock is a white saccharine marble containing calcite, forsterite, and a little mica. It was selected not because the relative pro portions of the different constituents appeared to be most favourable to the theory but because the constituents, though distributed in bands, were not concentrated in patches or nodules. It is right, however, to add that it would be possible to select specimens from the series in which the amount of lime would be in excess of that required by the theory. Such specimens may indicate either that the original rocks were not true dolomites or that the migration of magnesia has in some cases proceeded to considerable distances.

So far we have been discussing the theory of dedolomitisation consequent on the development of magnesium-silicates. Such a process requires the presence of silica in the original rock, and this is frequently found as chert in the dolomites of Assynt and Skye. But dedolomitisation appears also to be produced in non-siliceous rocks by the formation of periclase or brucite. Both in Skye and Assynt rocks are to be seen composed of brucite and calcite, with a varying admixture of dolomite, forsterite, and serpentine. These rocks are identical with the so-called predazzite which was supposed for some time to be a definite mineral in consequence of the constancy in the ratio of $CaCO_3$ to H_2MgO_2 — a constancy equally well accounted for on the theory that the predazzite is an altered dolomite. The evidence that brucite in the rocks from Skye and Assynt is a pseudomorph after periclase has been already referred to. If it be accepted it brings these rocks into close relation with the aggregates of periclase and calcite found amongst the ejected blocks of Monte Somma, which include also eozoonal limestones and other petrological types having affinities with the altered Durness dolomites. The general conclusions arrived at are that the marbles of Assynt and Skye are, for the most part, altered dolomites, and that the alteration has been accompanied by dedolomitisation due either (1) to the development of magnesian silicates such as forsterite and tremolite, or (2) to the formation of periclase or brucite.