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Beryllium minerals in Cornwall and Devon: helvine, genthelvite, and danalite.

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Summary. Helvine and genthelvite are recorded for the first time in Britain; of the former, three occurrences in Cornwall and one in Devon, and of the latter, one occurrence in Cornwall, are described. British danalite has hitherto been represented by two old specimens with the vague locality 'Redruth', Cornwall; occurrences at four Cornish localities are described, and a further Cornish locality is provided by two old specimens previously labelled as garnet. Partial chemical analyses for the helvine, genthelvite, and danalite specimens are presented; helvine and genthelvite occur in pyrometasomatic-hydrothermal deposits in metamorphosed calcareous sediments and, in one instance, in greenstone; danalite in hydrothermal deposits or lodes in metamorphosed greenstone; the parageneses of the three minerals are discussed.

THE helvine group of minerals, $(Mn,Fe,Zn)_4Be_3Si_3O_{12}S$, comprises helvine, genthelvite, and danalite, which are the manganese-, zinc-, and iron-rich members respectively of a three-component system. None of the pure end-members is known to occur in nature; iron and manganese appear in all the recorded analyses, whereas zinc appears in about half of them although probably present in the remaining specimens in trace amounts.

A comprehensive account of occurrences of helvine and danalite at Iron Mountain, New Mexico, U.S.A., together with a review and discussion of the whole helvine group, has been given by Glass, Jahns, and Stevens.[1] As shown in their paper, and in subsequent records, helvine has been found more widely than danalite, its environments including granite- and syenite-pegmatites (rare), hydrothermal veins,[2] and—more frequently—in contact-metamorphic deposits, skarns and tactites.

[1] J. J. Glass, R. H. Jahns, and R. N. Stevens, Amer. Min., 1944, vol. 29, p. 163.
[2] See also H. Neumann, Norsk Geol. Tidsskr., 1950, vol. 28, p. 234 [M.A. 11-511].

Danalite has been found in granite, but mainly in contact-metamorphic skarns and tactites. Genthelvite has only been found in pegmatites hitherto, and but five occurrences, three of them as single crystals, have been recorded.

Minerals of the helvine group are frequently associated with members of the garnet group, and the two may easily be confused in the field and in the hand specimen. Not only do both helvine and danalite, and genthelvite to a smaller extent, show similar variations of colour, mainly yellow and red shades but occasionally greyish or greenish, to those of garnets occurring in similar calcareous environments, but their crystals also can be of modified octahedral or dodecahedral habit. Only when in simple tetrahedra can they be readily recognized, but they are more frequently massive, or in anhedral grains embedded in the matrix; like garnet they are isotropic, and have refractive indices in the grossular range. In the past, the recognition and identification of minerals of the helvine group has, for these reasons, been by no means easy; J. W. Gruner,[1] however, more recently devised a simple and rapid staining test for members of the helvine group, which may also be used for detecting even one or two minute grains in a large amount of crushed material or in a hand specimen; the identification may then be completed by X-ray powder-photograph or by partial chemical analysis.

Previous occurrence of danalite in Cornwall.

Danalite is the only member of the helvine group hitherto recorded from Britain, and of two specimens in the British Museum mineral collection, one, B.M. 39955, was bought from R. Talling, the Cornish mineral dealer, in 1864 as 'Garnet, large tetrahedrons with quartz and mispickel, Redruth, Cornwall', and was described by Miers and Prior[2] in 1892. A second specimen, B.M. 74451, is closely similar in appearance and was bought from F. H. Butler in 1894;[3] according to Miers, the locality is also 'Redruth', Cornwall, and fragments from this specimen have been examined by Glass *et al.* (loc. cit.). Miers and Prior also described some small yellow tetrahedra, and one partly red and partly yellow, occurring in cavities in the red danalite, and suggested that this

[1] J. W. Gruner, Econ. Geol., 1944, vol. 39, p. 444.

[2] H. A. Miers and G. T. Prior, Min. Mag., 1894, vol. 10, p. 10.

[3] Talling had died shortly before this, and F. H. Butler, who was his son-in-law, had taken over all his stock of minerals; from the similarity of the two specimens, there is little doubt that they were both originally acquired by Talling and from the same source.

indicated the presence of both red danalite and yellow helvine; re-examination of the specimen has failed to reveal any of these crystals, although some parts of the larger crystals have a yellowish appearance, but they may well have been simply colour-variations of the danalite. Yellow varieties of danalite were not known in 1892, but have since been described by Glass *et al.* It is unfortunate that the locality 'Redruth' is so vague; as used by Talling it covered an area of some 30 square miles, and so it is virtually impossible to assign the specimen to a particular mine, especially as, at the time it was collected, there were probably nearly a dozen mines working in the Camborne–Redruth area from which, with the knowledge now gained from the new occurrences, it might have come. Four other specimens of Cornish danalite, from old Cornish collections and previously labelled as garnet, are now known and are described below (pp. 932–3).

New occurrences of helvine, genthelvite, and danalite in Cornwall and Devon.

The two large specimens of danalite in the British Museum collection, despite the absence of locality detail, have always suggested that more of the mineral existed originally and might still be found. I felt sure, from recent accounts of the more usual environments of both danalite and helvine, that there were a number of localities and areas in Cornwall and Devon where these minerals might be discovered; it also seemed probable that danalite, in particular, might have been mistaken in other cases for reddish-brown garnet, by no means uncommon in the Camborne–Redruth area and elsewhere, and that helvine might have been mistaken for scheelite or yellow garnet.

My investigations at a number of possible localities, together with a re-examination of several unidentified specimens that I had collected over a number of years, have now resulted in four new finds of helvine, one of genthelvite, and four of danalite; a fifth new locality for danalite is provided by two old specimens in Sir Arthur Russell's collection.

In all these cases, except for two of Sir Arthur's old specimens, preliminary examination by Gruner's staining test established the minerals as members of the helvine group; this was followed by X-ray powder-photograph study and, in most cases, by spectrographic examination, carried out by Dr. S. Ross Taylor, to whom my thanks are due. Through the courtesy of the Keeper of Minerals, Dr. G. F. Claringbull, partial analyses, to obtain where possible the iron-, manganese-, and zinc-contents of the various specimens, have been carried out in the Mineral Department of the British Museum (Natural History), to whom the specimens have now been handed over; my thanks are especially due to the Keeper, to Mr. P. G. Embrey, and to Mr. D. I. Bothwell by whom the analyses were actually

made. Particulars of the figures obtained are given in table I below, together with relevant figures obtained for the two British Museum specimens by Mr. Bothwell and by Miers and Prior.

Helvine from Red-a-ven Brook mine, Meldon, Okehampton, Devon. This locality[1] is situated about ½ mile south-south-east of the large British Railways quarry at Meldon, and lies on the northern bank of the Red-a-ven about ½ mile upstream from its confluence with the West Okement river, and some ⅔ mile from the granite margin. The country-rocks consist of metamorphosed Culm-measure sediments, and the mine, which was little more than a trial, lies in the narrow outcrop of a series of impure limestones and calcareous shales of Lower Culm age, which have been intensely folded and overturned and now dip very steeply to the north. Two shafts were sunk, evidently on mineralized bands in the calcareous series, and small dumps adjoining them contain skarn-assemblages of hedenbergite, diopsidic pyroxenes, green and brown garnet, idocrase, wollastonite, calcite, some fluorite, and chloritic minerals; through this are disseminated much pyrrhotine and löllingite, traces of arsenopyrite, as well as chalcopyrite and blende, a little galena, and some scheelite. The latter occurs at other, similar metamorphic deposits in this area, as at Ramsley mine (where it has also been found by Sir Arthur Russell), at Ford mine, South Tawton, and at Meldon Limestone quarry, but its occurrence in the Okehampton district has not been previously recorded.

Helvine has been found in some skarn material collected in 1948 at Red-a-ven Brook mine, as minute grains or occasionally tetrahedral crystals (up to 1 mm.) of a very pale primrose-yellow colour, in granular intergrowths of dark-brown blende, calcite, garnet, and a little colourless fluorite. This material was the first of the various new occurrences to be re-examined, and I detected the helvine by Gruner's staining test; its identity was confirmed by a spectrogram, and by X-ray powder-photograph which showed almost exact agreement with those of bright sulphur-yellow tetrahedra of helvine from Schwarzenberg and from Breitenbrunn, both in Saxony, from specimens (O.U.M. 20590 and O.U.M. 11353 respectively) in the Oxford University collection. Compositional data of the Red-a-ven Brook helvine are given in table I.

Helvine from Wheal Cock, St. Just, Cornwall. In 1949 I found very small amounts of a pale yellow waxy mineral, suggestive of scheelite, in some massive, rather decomposed chloritic material on the dumps

[1] It was briefly referred to, as an exploration of Black Down in line with Wheal Forest, by Warington Smyth in Trans. Roy. Geol. Soc. Cornwall, 1878, vol. 9, p. 40.

adjoining the two main shafts immediately south of Wheal Cock Zawn; other minerals found in the same matrix, at the same time, include phenakite, bertrandite, herderite,[1] and apatite. The pale yellow, waxy mineral has proved to be helvine, but the quantity present has, unfortunately, not been sufficient to allow of a partial analysis being made; spectrographic and X-ray examination, however, have shown that it is a manganese-rich member. Only a few grains, mostly rather decomposed, are present, scattered here and there through the matrix, and closely resemble scheelite, which has since been found here by Dr. K. F. G. Hosking, of the Camborne School of Mines, and by myself, as pale yellow, bipyramidal crystals (up to 6–7 mm.) in massive chlorite.

Wheal Cock lies entirely in metamorphosed greenstone, and material on the dumps includes not only sulphide-bearing quartz-chlorite and other veinstone from the lodes, but also much country-rock with, *inter alia*, massive chlorite, axinite, garnet, calcite, magnetite, arsenopyrite, and metamorphic skarn-type assemblages. The matrix of the helvine is more characteristic of the metamorphic material than that of the lodes, and in view of the occurrence of phenakite and herderite in the same matrix, it may be significant to note that C. Palache[2] found phenakite as an alteration-product of danalite at Gloucester, Massachusetts. The bertrandite is unquestionably derived from alteration of the phenakite, and here also this latter may be an alteration-product of helvine; the herderite, a calcium beryllium phosphate, could have formed during one or other of these later, hydrothermal stages. The occurrence of phenakite, with adularia-habit orthoclase, quartz, cassiterite, and scheelite, was recorded by Sir Arthur Russell[3] in some vein-material from a lode that outcrops in Stamps and Jowl Zawn, 200 yds. to the north, in the northern part of the mine. In this latter occurrence, all the associated minerals are of characteristic hydrothermal lode formation, and have been found in other lodes in the area. The association is, moreover, distinct from those now described, which are almost certainly of pyrometasomatic origin. It may be noted that both here and at other nearby mines, rhodochrosite, much manganiferous calcite, and other manganese minerals were present, which explains the formation of the manganese-rich member, helvine, in the environment of the greenstone.

Helvine from Wheal Betsy, Tremore, Lanivet, Cornwall. Some 250 yds.

[1] A. W. G. Kingsbury, Min. Mag., 1958, vol. 31, p. 816.
[2] C. Palache, Amer. Journ. Sci., 1907, ser. 4, vol. 24, p. 252.
[3] A. Russell, Min. Mag., 1920, vol. 19, p. 19.

north of Tremorebridge, 2 miles west of Lanivet, and on the east side of the stream, there is a large, now disused, quarry in part of the main outcrop of a belt of metamorphosed calcareous sediments to which the name 'calc-flintas' was given by the Geological Survey. This belt extends round the northern fringe of the St. Austell granite from near Lostwithiel westwards to St. Columb; the rocks have been much folded and now dip very steeply to the north. In addition to being thermally metamorphosed, these upturned rocks have, in many places, been fractured or faulted along the bedding-planes, affording channels up and along which pyrometasomatic and hydrothermal agents have given rise to further alteration and mineralization. In a number of instances, highly inclined mineralized bands or beds such as these have erroneously been described and referred to as 'lodes'. Mineralization phenomena in this area in general, and in these altered calcareous rocks in particular, had suggested that it was one of the most likely in which minerals of the helvine group might occur; four such occurrences have, in fact, now been found.

This quarry at Tremore was referred to by Barrow and Thomas[1] in an account of metamorphic minerals in calcareous rocks in the Bodmin area, and they mentioned the occurrence, *inter alia*, of yellow garnet and, 'in the refuse from an old pit sunk in a copper-vein at the southern end of the quarry', of certain 'pneumatolytic' minerals, massive chalcopyrite, fluor, well-crystallized 'talc', zinc-blende, and masses of 'peculiar' chlorite in the form of 'peach'. Though little is known or recorded about it—and some of the data are certainly erroneous—a small mine, known as Wheal Betsy, was at one time worked here. Two east–west 'lodes', a few feet apart in the 'calc-flintas', were said to have been opened up by adits, driven east from near stream-level, and by a shaft, probably on the northern 'lode', on the valley side.[2] The site of this shaft, which is not specifically mentioned, as such, by Barrow and Thomas, is still visible just outside the southern edge of the quarry, but a short distance to the west of it, nearly at stream-level, there is an old overgrown pit, which may be that to which they referred. In and around this pit, mineralized calc-flinta occurs with massive granular chlorite, traces of fluorite, chalcopyrite, and blende, and among this material I collected a specimen of pale grey-green, scaly, crystallized chlorite with quartz and calcite, in which were implanted several small, bipyramidal,

[1] G. Barrow and H. H. Thomas, Min. Mag., 1908, vol. 15, p. 113.

[2] Compare the account in Memoirs of the Geol. Survey; the Metalliferous Mining region of South-West England, 1956, vol. 2, p. 513.

pale wax-yellow crystals of scheelite. This scaly chlorite may be the 'talc' mentioned by Barrow and Thomas; the pit, from its position, appears more likely to have been caused by a collapse of one of the adits, which must have been quite shallow.

Just below the site of the shaft there is a small, overgrown dump containing similar material to that round the 'pit'; both the calc-flintas and the dark, granular chlorite, however, contain rather more disseminated chalcopyrite, blende, and fluorite, with the addition of pyrite and calcite, and Dr. Hosking informs me that, on the only occasion he visited this locality, he also found traces of scheelite. Examination of a large amount of material, obtained on the surface and by digging into the dump, yielded several specimens and fragments of a yellowish mineral which here and there showed small crystals closely resembling tetrahedra; this mineral has now proved to be helvine. Though rather iron-stained, the helvine is mainly wax-yellow in colour, some parts being slightly more brownish-yellow and translucent, and except for the small, characteristic tetrahedral crystals, might readily be mistaken for yellow garnet or scheelite. A partial analysis is given in table I.

It seems clear from an examination of the locality that there are no true lodes at all, and that the mineralization consists of bands, of pyrometasomatic and hydrothermal origin, adjacent to fractures in the highly inclined 'calc-flintas'.

Helvine from Bodmin Wheal Mary, Lanivet, Cornwall. About ⅔ mile north of Lanivet, and some 250 yds. south of Hooper's Bridge, there are old mine-workings, on both sides of the stream, formerly known as Bodmin Wheal Mary. The main, or Wheal Mary, section lies on the east side of the valley, and was worked from an engine-shaft and two adits; the other section, later known as Wheal Ding, lies about 300 yds. to the west on the other side of the valley and was worked from two shafts and some opencast workings in Bodwannick Wood.

Wheal Mary section lies at or near the junction between slaty killas and part of the main outcrop of the 'calc-flintas', here striking east–west and again dipping very steeply to the north; Wheal Ding section appears to lie almost entirely in the 'calc-flintas'. The Survey Memoir (op. cit., vol. 2, p. 515) gives a short account of the mine, and refers to a main east–west quartz-pyrite lode crossing the river and showing, in Wheal Ding, a quartz leader in association with fluccan[1] at the hanging wall, south of which the calc-flintas were impregnated with small crystals of

[1] Flucan, fluccan, or flookan—a stiff clay found in faults and especially in 'cross courses'.

blende. This account is difficult to reconcile with the field-evidence present at the locality, and in examining the evidence the author appears to have overlooked the essentially metamorphic character of the main mineralization.

The locality was very fully examined in 1958; near the engine-shaft at Wheal Mary, a few small piles of iron-stained quartz were found, but these are entirely barren, and from the chalcedonic and other characteristics of the quartz it is evident that they came from a much later infilling, almost certainly in a fault. The occurrence of fluccan, due to renewed movement along the fault, would be further evidence of this, and it is unlikely that mineralization from this vein could have impregnated the calc-flintas in the manner shown *in situ* and by the material on the rest of the dumps.

Apart from some killas on the Wheal Mary dumps, the waste material in both sections consists wholly of calc-silicate rocks or assemblages; no trace of quartz lode-material could be found in Wheal Ding. The calc-silicate material comprises a great deal of fine-grained 'calc-flintas' but also includes large amounts of massive, compact to granular, pale green to yellow and brown garnet, green amphiboles, green and greyish-green pyroxenes, with smaller quantities of wollastonite, calcite, fluorite, axinite, magnetite, pyrrhotine, and chloritic minerals. Disseminated through the calc-flintas and these skarn assemblages, especially in the garnet, are much brown blende, some chalcopyrite, galena, and other sulphides, among which bornite and alabandine (MnS) have been identified from the Wheal Mary section. Rather more chalcopyrite and galena occur here than in Wheal Ding, where blende is predominant, and where a little scheelite also occurs. Much of the weathered material is stained by manganese oxides, and brown botryoidal rhodochrosite has been found investing some of it. No trace of the 'calamine' and 'franklinite' mentioned in the Survey Memoir could be found. This is only the second known locality in Cornwall for alabandine. These characteristic minerals and assemblages indicate clearly that there has been extensive pyrometasomatic-hydrothermal mineralization in the 'calc-flintas', no doubt along fractures in the highly inclined beds as at Wheal Betsy and elsewhere in this area.

Among these skarn assemblages in Wheal Ding, helvine has also been confirmed. The mineral is wax-yellow in colour, and closely resembles some of the yellow garnet; it forms a granular intergrowth with brown blende, calcite (largely corroded), traces of a green pyroxene, and a little galena and colourless fluorite. Where originally in contact with some of the calcite, small tetrahedra (up to 2 mm.) project from irregular surfaces of some of the helvine. The material formed a roughly lens-shaped pod in the mineralized 'calc-flinta' and came from a large, weathered block that was dug out of the dump by the upper shaft in Bodwannick Wood. The composition of this helvine is shown in table I.

Genthelvite from Treburland, Altarnun, Cornwall. An account of the old Treburland manganese mine was given by Sir Arthur Russell[1] in 1946, but within recent years the site has been ploughed up and obliterated.

The mine was primarily worked for the oxidized manganese ore present in two pockets which lay within a belt of calcareous sediments and associated greenstone intrusions, only about 120 yds. (at surface) from the margin of the Bodmin Moor granite. The two pockets had, no doubt, originally consisted of bedded deposits of iron and manganese carbonates, and metamorphism by the adjacent granite produced a complex assemblage of iron and manganese silicates and other minerals. A small dump, near one of the shallow adits by which the deposits were worked, consisted almost entirely of the hard unoxidized portions that had been rejected.

A short distance to the north of the small 'manganese' dump, and quite separate and distinct from it, a small pit had been opened, possibly in search of other pockets of ore. This pit, however, only exposed the country-rocks, in which metamorphism by the granite produced a different assemblage of minerals. The calc-silicate rocks exposed in this pit include streaks and bands of a dark grey to greyish-green colour, which almost certainly represent inclusions or veins of sheared, highly metamorphosed greenstone; within these rocks are other streaks, veins, bands, and inclusions of pink to cinnamon-coloured calcium-iron garnet, diopside, wollastonite, idocrase, axinite, calcite, chlorite, pyrite, pyrrhotine, and zeolitic minerals of later formation, with traces of arsenopyrite, galena, and molybdenite.

On a visit to Treburland in 1948, with Sir Arthur Russell and Dr. G. F. Claringbull, specimens of various minerals were collected, and while examining some of the exposures in the overgrown pit, my attention was drawn to a small band or vein-like inclusion in some of the darker material, which, in addition to cinnamon-coloured garnet, calcite, chlorite, and traces of galena and molybdenite, contained one or two small blebs of a mineral having a more distinct rhodonite-pink colour. Apart

[1] A. Russell, Min. Mag., 1946, vol. 27, p. 221.

from the difference in colour, and a more greasy lustre, there was little to distinguish this pink mineral from garnet. As many fragments and pieces of this inclusion as could be extracted were collected, and more recent examination of samples of it by Gruner's staining test showed that the small pink blebs gave the reaction for a helvine-group mineral. A powder-photograph showed a pattern similar to that of danalite, but with slightly different spacings, and from the results of a spectrogram, which showed a fairly high iron-content and low manganese, but a certain amount of zinc, it was provisionally considered to be danalite. Partial chemical analysis, however, has proved that zinc is, in fact, predominant, and that, as the figures in table I show, the mineral is an iron-rich genthelvite.

Danalite from the 'New Tolgus shaft', Redruth, Cornwall. The circumstances leading up to the sinking of this shaft[1] between the years 1923 and 1927, and its final abandonment at a depth of 2 000 feet, have been described in detail; during the sinking, a careful log was kept and details have been published, with a full section, by J. C. Davey.[2] Between 700 ft. and 1 000 ft. from surface, the shaft passed through a large body of metamorphosed greenstone some 278 ft. thick, which was considerably mineralized and carried much axinite in the upper parts and large amounts of red garnet in the lower parts, together with chlorite, arsenopyrite, pyrrhotine, chalybite, and other minerals. Another body of mixed greenstone and slate was encountered between 1 800 ft. and 2 000 ft., and a number of small mineralized veins were also cut at various horizons.

In 1937 I had visited the site of this shaft, when there was still a large amount of material on the dumps, and when, from its position relative to the shaft-head, it was possible to judge approximately from what depth it was obtained. Among large amounts of altered greenstone, the occurrence of axinite near the shaft and of much red garnet farther away suggested that this latter material originally came from the lower parts of the main body. Many large bodies of greenstone occur in this area, some of them having been encountered only during mining operations, and garnet is of common occurrence in them. It varies from cinnamon-colour to dark brownish red and is almost always massive, forming veins, lenticles, and often considerable masses. It is frequently

[1] The site of the shaft (now cemented over) is 700 yds. north of the western corner of the Redruth Union (Public Assistance) Building.

[2] J. C. Davey, Trans. Roy. Geol. Soc. Cornwall, 1927, vol. 15, p. 439; idem, ibid., 1948, vol. 17, part 7 (for 1947), p. 361 and section.

associated with bands or rims of green diopsidic pyroxene and occasionally with wollastonite.

From among some of this material, one specimen, *inter alia*, was collected primarily by reason of its rather unusual appearance; it consisted of a small piece, some 6 cm. long and 4 cm. wide, of a glassy, massive mineral, closely resembling the darker varieties of garnet, but having a peculiar, dark, mahogany-red colour, associated with it being some dark chlorite, and traces of arsenopyrite, pyrite, chalcopyrite, blende, calcite, and fluorite. It was clear that it had been derived from the greenstone, but the association suggested that it had almost certainly come from a mineralized vein. This dark-red mineral has now been proved to be danalite; its composition is given in table I.

Danalite from Levant mine, St. Just, Cornwall. The lodes in the well-known Levant mine passed westwards from granite, first into hornfelsed killas, and then into metamorphosed greenstone. Throughout the St. Just area, metamorphic minerals occur in large amounts, particularly in the altered greenstones, and include large amounts of axinite, garnet, epidote, amphiboles, pyroxenes, and various skarn assemblages, with magnetite and pyrrhotine. In addition to the normal quartz-chlorite veinstones, the lodes at Levant sometimes enclosed massive red garnet associated with chalcopyrite and pyrite. Examples of this and other varieties of garnet, with associated species, could at one time be found round the shafts and on the dumps adjoining Levant Zawn and Cockle Zawn. Disseminated white scheelite, together with calcite showing a pink fluorescence, occurs in some of this red garnet, and among specimens collected in 1948 were several with an unusual glassy appearance and darker, mahogany-red colour similar to that of the Tolgus material. Like much of the garnet, this darker red mineral contains disseminated chalcopyrite and pyrite, and it was also accompanied by a little chlorite, arsenopyrite, blende, and traces of fluorite; it also has been proved to be danalite and its composition is shown in table I.

Danalite from Tretoil mine, Lanivet, Cornwall. This mine is not far from Bodmin Wheal Mary, and is situated about 2 miles east of Lanivet and the same distance south of Bodmin. It lies just outside the margin of the eastern part of the St. Austell granite, in country-rocks consisting of hornfelsed killas and intrusions of greenstone. Two main lodes, coursing east-north-east, were worked and both of them cut through the greenstones in several places. The veinstone is principally quartz and chlorite, and the lodes carried a little cassiterite in depth, but mainly chalcopyrite and pyrite, with minor blende and galena and some arsenopyrite in places. Where the lodes cut the greenstones, chlorite is more abundant, and in some parts, especially in the south vein, there is much massive, fine-grained magnetite; garnet, specular hematite, ilvaite, and other metamorphic minerals have also been found during the course of numerous visits. On a visit in 1952, primarily in search of the rare yttrium phosphate, churchite,[1] I had concentrated on three particular shafts on the southern lode, all of which had been sunk through greenstone. In some of the material derived from William's shaft, 300 yds. north-north-east of Tretoil Farm, and the middle one of the three, I collected a specimen of chloritic veinstone that contained in addition to arsenopyrite, pyrite, chalcopyrite, quartz, and some blende, a small amount of a compact, massive, brownish-red garnet-like mineral. The outer parts of this mineral had a bleached, slightly yellowish, granular appearance, but internally it was more glassy and had a darker, columbine-red colour; where in contact with some of the chlorite, small triangular outlines suggested crystals of tetrahedral habit. This mineral has also been confirmed as danalite; it has a slightly higher zinc content than the others (table I).

Danalite from Wheal Maudlin, Lanlivery, Cornwall. Three specimens of danalite have been confirmed from this locality, which lies 1½ miles south-east of Tretoil and about 2 miles north-west of Lostwithiel. One of these specimens was collected by myself at the mine, on a visit there with Sir Arthur Russell; the other two are in Sir Arthur's collection, and had originally been labelled as garnet from Wheal Maudlin, one formerly having been in the collection of Philip Rashleigh[2] (1729–1811), of Menabilly, near Fowey, and the other in a collection at one time belonging to the Fox family, of Falmouth. Both these well-known collections dated back to the end of the eighteenth century.

Sir Arthur's two specimens came to light when I was showing him the danalite from Tolgus, Levant, and Tretoil early in 1958, during which he had remarked that he had in his collection some old specimens, labelled as garnet from Wheal Maudlin and another locality, which, as far as he could remember, were similar in appearance. He also mentioned that the red colour of the Wheal Maudlin specimens had puzzled him, as the garnet from there was otherwise always of brown to yellowish shades. On comparing these old specimens with my own new examples, there was no doubt as to their similarity, and they have been subse-

[1] See A. W. G. Kingsbury, Min. Mag., 1956, vol. 31, p. 282, for its rediscovery.

[2] For a short account, see Sir Arthur Russell, Journ. Roy. Inst. Cornwall, 1952, p. 1.

quently examined in the Mineral Department of the British Museum and confirmed as danalite.

Later that same year, Sir Arthur and I visited Wheal Maudlin together, and during an intensive search, I obtained a small specimen of danalite *in situ* in some lode material on the burrows adjoining one of the old shafts. Wheal Maudlin is a very ancient mine and lies just outside the granite margin; the country-rock is mainly killas, but in the northern part of the mine there is a large intrusion of greenstone, both killas and greenstone being metamorphosed. Records are very incomplete, but several veins, with a general east–west trend, were worked, and westwards they extended into the greenstone. The greenstone–killas contact passed through the Engine shaft, 300 yds. south-east of Maudlin Farm, about 50 fathoms below surface, and also through or close to Benson's or Whim shaft, 100 yds. south-west of Engine shaft. The mine was not a large producer, but the mineral assemblage was complex, and included cassiterite, scheelite, arsenopyrite, pyrrhotine, chalcopyrite, pyrite, blende, galena, fluorite, garnet, much chlorite, and quartz, and many other species.[1]

Our search was concentrated mainly on Benson's shaft, where the material on the burrows was almost entirely derived from the greenstone, and where, with the exception of cassiterite and scheelite, we found all the minerals mentioned above, and several others. Owing to long exposure, much of the material is weathered or superficially iron-stained, but internally most of it is remarkably fresh. During the course of examining many samples of the chloritic and other vein-stuff, removal of a corner from one of them revealed traces of a massive mineral with the characteristic, dark columbine-red colour, and further breaking of the matrix yielded, in two portions, a small mass of danalite, some 6 cm. by 5 cm. The chlorite associated with this specimen shows a curious dark, greenish bronze colour, and is present in other material found at this mine; a similar chlorite is found on some of the other specimens of danalite, and it has been found elsewhere where veins cut the greenstones. Other minerals associated with this danalite from Wheal Maudlin are pyrite, arsenopyrite, chalcopyrite, blende, quartz, and fluorite; the composition is shown in table I.

Danalite from Wheal Clinton, Mylor, Falmouth, Cornwall. This is the fifth distinct locality from which danalite has now been confirmed; two

[1] It was best known for some of the mineral specimens it produced, including, especially, those of chalybite, francolite, cronstedtite, and pseudomorphs of wolframite after scheelite.

old specimens, which are identical and were originally labelled as garnet from Wheal Clinton, were in Sir Arthur Russell's collection, both of them having formerly also been part of the Fox collection.

The specimens show the characteristic dark, columbine- to mahogany-red colour, but they are slightly decomposed, appearing cloudy and granular, and they contain a great many minute inclusions of a black substance; chlorite is associated with them but no sulphides are visible. In these characteristics they are somewhat distinct from all the other specimens.

Wheal Clinton is situated near Trefusis Point, Mylor, opposite Falmouth, and lies just within the metamorphic aureole surrounding the south-eastern part of the Carnmenellis granite. It was a little-known mine, worked for a short time between 1850 and 1858, primarily for lead, and of the two lodes present only one, the north lode, was said to be workable, the minerals occurring in it being recorded as galena and blende, with some chalcopyrite and calcite. This lode, trending north-east, lay partly in killas and partly in or against an intrusion of metamorphosed greenstone, where it was said to be disordered. The environment is thus the same as at the other danalite localities. The specimens have

TABLE I. Manganese-, zinc-, and iron-contents of helvine, genthelvite, and danalite from Cornwall and Devon.

Mineral.	Locality.	B.M. No.	FeO.	MnO.	ZnO.
Helvine	Red-a-ven Brook	1956,85	8·7	32·0	13·2
,,	Wheal Betsy, Tremore	1958,537	11·8	41·9	n.d.
,,	Bodmin Wheal Mary	1959,626	7·4	39·3	3·5
Genthelvite	Treburland	1959,627	19·8	4·4	25·9
Danalite	New Tolgus shaft	1958,534	38·8	7·1	4·9
,,	Levant mine	1958,533	37·3	6·7	n.d.
,,	Tretoil mine	1958,536	32·0	9·0	8·4
,,	Wheal Maudlin	1958,535	33·4	9·2	n.d.
,,	Wheal Clinton	—	39·5	6·7	5·6
,,	'Redruth'	74451	33·8	12·1	6·0
,,	'Redruth'	39955	32·1	7·8	5·2
,,	'Redruth'	39955	37·5	11·5	4·9
Helvine	Wheal Cock	—	Insufficient material was available for analysis, but a qualitative spectrographic determination showed major Mn, moderate Fe, trace of Zn.		

Analyses by D. I. Bothwell, except the last, which is from Miers and Prior (1894).
The first eight specimens were collected by the author; the Wheal Clinton specimen is from Sir Arthur Russell's collection; B.M. 74451 was bought from F. H. Butler and B.M. 39955 from R. Talling.

been identified as danalite in the Mineral Department of the British Museum, and the composition is shown in table I.

Consideration of the compositions in relation to the associations.

Apart from other factors in the environment that undoubtedly control the formation of helvine-group minerals, the availability and concentration of manganese, zinc, and iron are those upon which the formation of any particular member of the group depends. The beryllium-bearing solutions giving rise to these minerals in Cornwall and Devon may have carried, in some instances, some of the elements required, but it is clear that local conditions at many of the localities also had a direct influence on the mineral formed.

Three of the occurrences of helvine are in altered calcareous sediments that carry appreciable amounts of manganese, those at the nearby localities of Wheal Betsy (Tremore) and Bodmin Wheal Mary being somewhat richer in this element, and having a number of other manganese minerals associated with them. The helvine from Red-a-ven Brook mine shows the lowest manganese-content, 32·0% MnO, of those analysed, but a notably high zinc content, 13·2%; those from Wheal Betsy and Bodmin Wheal Mary have the highest manganese, 41·9 and 39·3 respectively, with little or no zinc; all of them have a moderate iron-content. As was indicated by Glass *et al.* (loc. cit.), in the pure helvine end-member of the group, the theoretical content of MnO is 51·12, and among all the specimens of natural helvine so far analysed, an example from Amelia, Virginia, with 51·64 MnO, shows the highest, while the helvine from Iron Mountain, with only 26·51 MnO, but with 18·02 FeO, shows the lowest. At the Wheal Cock occurrence, in greenstone, the conditions indicate that there was a local concentration of manganese, which seems to have been somewhat more readily available than iron, and though there was insufficient material for an analysis, the X-ray powder pattern and spectrographic examination, which showed major amounts of manganese, a good deal of iron, but only traces of zinc, indicated that the mineral was helvine rather than danalite.

The genthelvite from Treburland, while showing a predominance of zinc, has a rather high iron-content and, surprisingly, only a small amount of manganese. The calcareous sediments in the country-rocks, among which the mineral occurred, are low in manganese and contain no manganiferous minerals other than axinite, in contrast to the high concentration of manganese minerals in the two deposits, or pockets, close by, which were worked in the old mine. The high iron-content, however, can almost certainly be attributed to the influence of the metamorphosed greenstone intermixed with the calcareous sediments, and with which the genthelvite was intimately associated. In this part of the locality, blende, which is present in small amounts in the manganese deposits, is notably absent, and whatever zinc there was appears to have been introduced at a relatively late stage in sufficient concentration to have been more readily available for the formation of the genthelvite, in spite of the influence of the greenstone. The occurrence of the zinc-rich member of the group under the conditions at Treburland is, therefore, the more remarkable. Pure genthelvite should contain 54·54% ZnO, and of the few analysed specimens, the original single crystal from Colorado contains the highest amount, 46·2% ZnO, with 6·8% of FeO. In two of the recent new records of genthelvite, one from the Kola Peninsula (E. M. Eskova, Min. Abstr. **14**–53) was a manganese-rich variety, with ZnO 40·0 and MnO 10·21, and the other, from Northern Nigeria (O. von Knorring and P. Dyson, Amer. Min., 1959, vol. 44, p. 1294) was also an iron-rich variety, with ZnO 40·56, FeO 11·73, and MnO 1·72. Both these occurrences, however, were in pegmatites.

The most marked influence of the local conditions is shown by the Cornish occurrences of danalite, all of which are in veins intimately associated with greenstones. Though the figures in table I show slight variations from locality to locality, the specimens are all consistently high in iron and there can be no doubt that this is due to the availability and influence of the iron in the greenstones. The pure danalite end-member should contain 51·44% of FeO, and hitherto (see Glass *et al.*) the highest iron-content of analysed natural examples has been given as that found by Miers and Prior for the old specimen from 'Redruth', B.M. 39955, namely 37·53% FeO. In the new Cornish occurrences, as is shown in table I, FeO ranges from 32·0% at Tretoil (where zinc reaches 8·4%) to 38·8% in the Tolgus material and 39·5 in that from Wheal Clinton. The figures recently obtained for the two old specimens in the British Museum differ from those given by Miers and Prior; in the case of B.M. 39955, they are somewhat low, but Prior's figures for iron, manganese, and zinc together amount to 53·93, which, on the face of it, is rather high. It is possible, however, that different parts of the specimen may show variations due to alteration.

In spite of the absence of details of the occurrences of the two old specimens of danalite from 'Redruth', there is now little doubt that they also originally came from a lode or deposit in one of the greenstones in the Camborne–Redruth area.

A summary of the environments and localities is given in table II.

TABLE II. Summary of environments and localities of helvine, genthelvite, and danalite in Cornwall and Devon.

Environment.	Mineral.	Locality.	Associated granite.
Pyrometasomatic deposit in metamorphosed calcareous sediments	Helvine	Red-a-ven Brook mine, Meldon, Devon	Dartmoor
	Helvine	Wheal Betsy, Tremore	St. Austell
	Helvine	Bodmin Wheal Mary, Lanivet	St. Austell
Pyrometasomatic deposit in metamorphosed greenstone (manganese locally present)	Helvine	Wheal Cock, St. Just	Land's End
Pyrometasomatic deposit in mixed calcareous sediments and greenstone	Genthelvite	Treburland, Altarnun	Bodmin Moor
Hydrothermal veins or lodes in metamorphosed greenstone	Danalite	New Tolgus Shaft, Redruth	Carn Brea
	Danalite	Levant mine, St. Just	Land's End
	Danalite	Tretoil mine, Lanivet	St. Austell
	Danalite	Wheal Maudlin, Lanlivery	St. Austell
	Danalite	Wheal Clinton, Mylor	Carnmenellis
Not known, but by analogy, almost certainly from a lode in metamorphosed greenstone	Danalite (B.M. No. 39955)	'Redruth'	Probably Carn Brea
	Danalite (B.M. No. 74451)	'Redruth' (almost certainly from the same locality as the preceding specimen)	do.

The associations of helvine, genthelvite, and danalite in Cornwall and Devon.

As the occurrences of these minerals described above show, the environments and associations are distinct from those of any other beryllium minerals occurring in the south-west. In contrast to the rare occurrences of beryl and other species in pegmatites and early greisen-bordered lodes in granite, and of phenakite and bertrandite in high-temperature, usually tin-bearing, lodes both in granite and in killas, where the assemblages are entirely different, the helvine-group minerals all occur in calcareous rocks, either impure limestones or greenstones. In all cases, these rocks have been metamorphosed and metasomatized by the adjacent granite, and carry skarn-type minerals such as idocrase, wollastonite, diopsidic pyroxenes, garnet (lime- and iron-bearing varieties, often with some manganese) and axinite, as well as scheelite, fluorite, calcite, chlorite, &c. Helvine and genthelvite are present in essentially pyrometasomatic deposits of hydrothermal origin, all except one in impure limestones, and are accompanied by sulphides such as löllingite, arsenopyrite, pyrrhotine, pyrite, chalcopyrite, molybdenite in one instance, blende, and galena. Danalite occurs in veins or lodes of hydrothermal origin where these cut or are associated with greenstones and in almost every case is accompanied by arsenopyrite, pyrite, chalcopyrite, blende, fluorite, calcite, and chlorite.

The occurrence of danalite in veins in greenstone and of helvine in the impure limestones reflects the ratios of the available Fe and Mn, the greenstones being in general rich in Fe (with the exception of Wheal Cock, St. Just, where a local, somewhat greater concentration of Mn was apparently available), the impure limestones being demonstrably richer in Mn. The rarity of genthelvite, both in Cornwall and elsewhere, is no doubt due to rocks with a high content of Zn being exceptional; the introduction of Zn generally takes place at a relatively late stage, as does the formation of blende, and to this the occurrence at Treburland conforms. It is clear that a concentration of Zn was introduced and was available for the formation of genthelvite, but the local deficiency in Mn in the impure limestones and the availability of Fe in the closely associated intruded greenstones are reflected in the low Mn-content and the relatively high Fe-content.

It appears to be significant that both the greenstones and the impure limestones in which the helvine-group minerals occur in Cornwall and Devon lie in close proximity to the granite and have been thermally and metasomatically altered; before, and probably during, the introduction of the beryllium-bearing solutions, whatever their original alumina content, the whole or the greater part of the available Al had been or was immobilized or 'fixed' in the formation of the skarn-type calcium silicates. While calcium, as such, may not necessarily have been essential for the formation of the helvine-group minerals, it had the effect of removing or neutralizing the alumina both in the permeating solutions and in the host-rock, thus giving rise to conditions of Al-deficiency, which were not congenial to the formation of beryl or other aluminous beryllium minerals, but more congenial to the formation of helvine-group minerals, depending on the other elements available. The sub-aluminous conditions produced in thermally metamorphosed and metasomatized limestones, consequent on the formation of skarn-type calcium-silicates, no doubt accounts for the virtual absence of beryl and other beryllium minerals in these rocks, in contrast to their presence in metamorphic aluminous schists. Beryl has been recorded in limestones, but very rarely, as in the classic occurrences in Colombia, where its formation has been attributed to pegmatitic or other hydrothermal solutions introduced under 'pneumatolytic' conditions; in Colombia the limestones were not thermally metamorphosed and no skarn silicates were formed, but albite was deposited, the solutions also giving rise to the calcite infilling in the veins, and the general conditions in which the beryl was deposited were aluminous, and not influenced, as in metamorphosed limestones, by the host-rock.

It has frequently been noted that conditions in granite cusps and bosses are more strongly influenced by high concentrations of various elements than elsewhere in a batholith. This is certainly the case in the granites of Cornwall and Devon, where the conditions and mineralization in general are exceedingly complex. This complexity is largely due to the many phases of mineralization that took place, apart from the fact, established by a number of recent investigations, that almost all the granite intrusions or bosses themselves are composite and comprise two and usually three distinct phases. Mineralization accompanied and succeeded many of these phases, some more than others, and while, in general, the main stages of hydrothermal lode formation followed the latest phase, there is evidence to show that earlier deposition followed earlier phases.

The granites of Cornwall and Devon are rich in beryllium, as has been shown in five cases investigated by J. R. Butler.[1] Though records of beryllium minerals in the south-west have up till now been somewhat restricted, recent investigations have indicated a wider and more varied distribution than hitherto suggested. With other volatiles, beryllium tends to migrate into pockets and structural traps towards the upper and outer margins of the intrusions and to be deposited, early, in pegmatites. Beryl, under these conditions, is relatively rare in Cornwall and Devon, though there are a number of the normally much rarer occurrences in early, mainly greisen-bordered, lodes. J. Phemister,[2] in 1940, drew attention to the apparent ease with which, under the complex conditions prevailing in Cornwall, beryl could be altered and transformed, and though this may, in part, explain the apparent rarity of beryl, the recorded and many recently confirmed occurrences of

[1] J. R. Butler, Geochimica Acta, 1953, vol. 4, p. 157.

[2] J. Phemister, Min. Mag., 1940, vol. 25, p. 575.

beryllium minerals, in both Cornwall and Devon, indicate that much of the beryllium has been introduced at a relatively late stage. This introduction is not confined to any one phase in the emplacement of a composite intrusion and may result in a variety of minerals being deposited in a variety of associations. In the case of the St. Austell granite intrusion, the eastern, phase 1, portion shows beryl (rare) in pegmatites (with herderite and bertrandite), phenakite as a late-formed mineral in pegmatites, and just outside the northern margin, danalite in veins in metamorphosed greenstone at Tretoil and Wheal Maudlin, and helvine in metamorphosed impure limestones at Wheal Betsy (Tremore) and at Bodmin Wheal Mary. In the central, second phase, beryl occurs in greisen-bordered veins with cassiterite, wolframite, &c. in granite, and phenakite as a late mineral in pegmatite in killas just outside the granite; in the more westerly, 'china-stone' area, the third and last phase, beryl also occurs in a greisen-bordered lode with cassiterite and löllingite. These occurrences illustrate clearly the variation in the minerals formed and their associations; comparable occurrences and associations occur at the many other localities.

In a preliminary account of the helvine at Iron Mountain, J. J. Glass[1] had suggested that beryllium-bearing minerals such as helvine might be limited to those parts of contact-metamorphic deposits that were of hydrothermal origin. In 1953 W. T. Holser[2] described an unusual association of beryl and helvine at the Victorio Mountains, New Mexico, the beryl occurring in a tungsten-bearing quartz-muscovite vein against a limestone, the helvine in metamorphic marble and tactite within the same limestone. After discussing the paragenesis and conditions for their formation, Holser suggested that the beryl and helvine could have been formed from solutions originally of identical Al-rich composition, but while in the fissure-vein the chemical conditions of the wall-rock would have had little effect, permeation of the solutions into limestone would have changed the composition of the whole system, excess aluminium being removed to form grossular and idocrase, causing the formation of helvine.

The pattern in Cornwall and Devon clearly follows that demonstrated by Glass *et al.* and by Holser.

[1] J. J. Glass, Trans. Amer. Geophys. Union, 1943, p. 253.
[2] W. T. Holser, Amer. Min. 1953, vol. 38, p. 599, where many references are given.