Discordant calc-silicate bodies from the St. Just aureole, Cornwall

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SUMMARY. Several discordant, garnet-bearing bodies are described from the St. Just part of the Land's End granite aureole, Cornwall. It is suggested that these formed by a combination of metasomatic replacement and dilation with concomitant precipitation. Other Ca-Fe aluminosilicates (containing large amounts of Zn, Sn, B, and Be) are also present in the bodies. The chemical, petrographic, and field evidence suggests that the introduced material was transported by hydrothermal fluids. These fluids could well be related to the intrusion of the granite and the earliest phases of ore mineralization. Chemical analyses of garnets, calcic amphiboles and one apatite, epidote, diopside, and axinite are given.

THE heterogeneous, basaltic hornfelses adjacent to the Land's End granite have often been cited as examples of large-scale contact metasomatism (Tilley, 1935; Reynolds, 1947; Floyd, 1965). More recently a metasomatic origin for some of the hornfelses has been questioned and the suggestion made that pre-metamorphic alteration must be the prime factor for determining the unusual rock compositions (Vallance, 1967; Chinner and Fox, 1974). The object of this account is to describe a group of calcium-rich assemblages that occur as discordant bodies within the hornfelses. A mechanism for their development is discussed.

Geological setting

The St. Just portion of the Land's End metamorphic aureole forms a narrow coastal strip, about 5 km long, on the NW flanks of the granite pluton (fig. 1). The Devonian aureole rocks consist of a metasedimentary unit of pelitic hornfelses, interbedded with a volcanic sequence of basaltic hornfelses (Jackson, 1976).

The volcanic rocks occur as massive or pillow lavas and intrusive sheets. Primary features, such as pillows, amygdales, and flowbanding, are relatively common. Although the basalts were metamorphosed in the greenschist and lower hornblende hornfels facies they can be matched chemically with similar greenstones from the Cornubian province (Floyd, 1976; Jackson, 1976). The basaltic lavas are often interbedded with, or pass laterally into, banded amphibolites. This banding is caused by variations in amphibole and feldspar content and is particularly marked in areas of intense deformation and shearing. The field evidence and similarity in chemistry (Table II) suggest that the amphibolites developed from the metabasalts (Jackson, 1976). The basaltic rocks were subjected to low-grade regional metamorphism and intensive shearing during the Hercynian orogeny. This produced a variety of mineral assemblages: albite, epidote, calcite, magnetite-ilmenite, actinolite, chlorite, and quartz.

Two 'exotic' assemblages can be recognized in the aureole. The first is the mineralogically heterogeneous, cordierite–cummingtonite–anthophyllite hornfelses (Tilley and Flett, 1930). The most recent studies suggest that these have developed by isochemical metamorphism of the previously degraded basalts (Vallance, 1967; Chinner and Fox, 1974). The second variety consists of a typical skarn assemblage, in which garnet, epidote, calcite, diopside, hornblende, and magnetite are particularly prominent. Floyd (1965, 1975) considers that these calc-silicate hornfelses were formed by the metasomatic introduction of calcium into the metabasalts.

Thermal metamorphism during the emplacement of the Hercynian granite pluton produced assemblages in the hornblende hornfels facies. The basaltic rocks are now predominantly represented
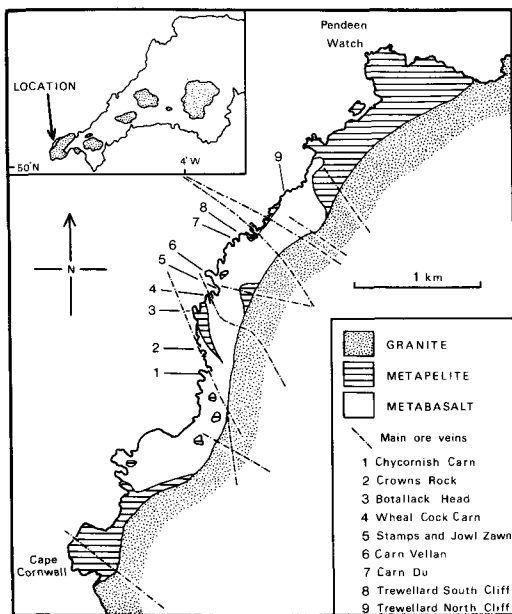
FIG. 1. Simplified geological map of the St. Just area, showing sample localities.

by plagioclase–amphibole hornfelses, as well as by the 'exotic' hornfelses mentioned previously. During the later stages of granite emplacement, the granite roof and its hornfels envelope were fractured and vigorous hydrothermal activity ensued. The circulation of such fluids promoted large-scale transfer of material within the aureole and produced the abundant vein and replacement ore deposits of tin and copper (Dines, 1956).

Calc-silicate bodies

The skarn assemblages typically occur either as sheets or as veins of varying size. The main sheet-like horizons outcrop at two localities, Crowns Rock and Carn Vellan. In addition small horizons occur at Carn Du, Trewellard North Cliff, Trewellard South Cliff, Botallack Head, Grylls Bunny, and Chycornish Carn (fig. 1). The occurrence of similar material around the disused mines of Botallack and Wheal Edward indicates that more horizons occur at depth. This was confirmed during a recent exploration programme in Levant Mine, which revealed the extensive development of calc-silicate horizons to depths of 400 m below the surface. These horizons tend to have an irregular shape; they are up to 15 m in thickness and dip gently (20°) towards the NW. The predominant minerals are garnet and magnetite, with lesser amounts of diopside, epidote, hornblende, calcite,

chlorite, and sphene. Although a definite conclusion regarding their mode of emplacement is not possible, the irregular form and diffuse contacts with the host hornfelses suggest an origin by metasomatic replacement. Two features appear to be associated with their development: the close proximity of highly folded and sheared, banded amphibolites; and the presence of more impermeable horizons, usually hornfelsed pelites. The significance of this association is discussed later.

Narrow ($<$ 1 cm) veins of garnet, axinite, and tourmaline are common throughout the St. Just part of the aureole and have also been described from the Tater-du region, to the SE of the granite (Floyd, 1965). They tend to be near vertical in attitude and cut across all other hornfels types, including the calc-silicate, sheet-like horizons.
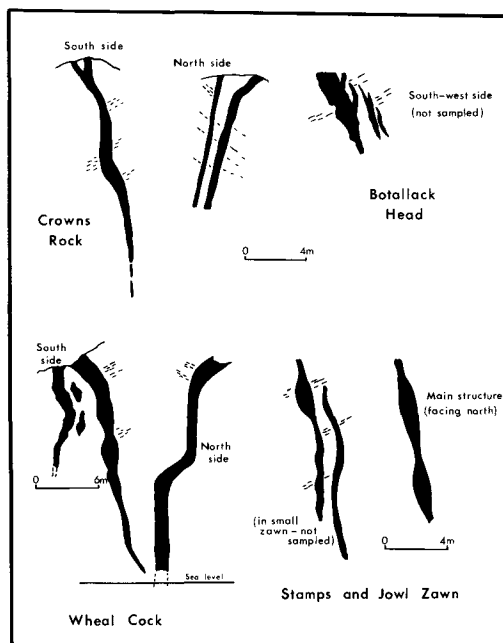

FIG. 2. Diagrammatic representation of the size and form of some typical calc-silicate veins.

Larger veins, up to one metre in width, also occur and these have a dyke-like appearance (figs. 2 and 3). Such veins cut the other hornfels types but are themselves cut by the tin and copper-bearing lodes. The veins trend towards the N or NE and dip steeply ($>$ 70°) towards the E. They have a slightly irregular form and inclusions of the host rocks are sometimes noted (fig. 4). The contacts of the bodies with the host rocks vary in character. In the case of the Crowns vein, where the host is a garnet-

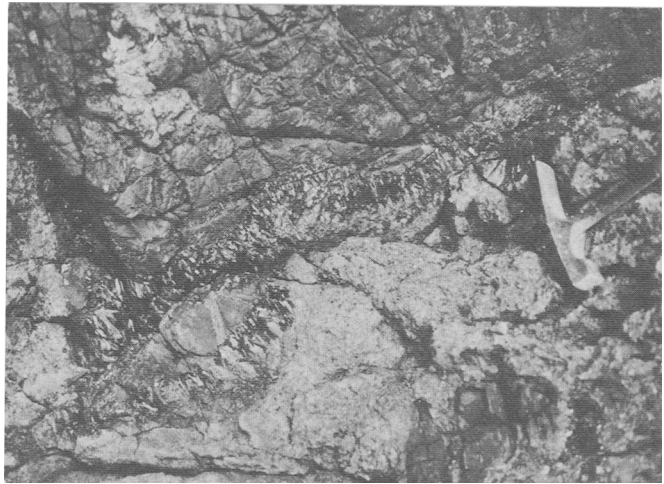FIG. 3.   FIG. 4.

FIG. 3 (*left*). Calc-silicate vein at Crowns Rock. The vein trends from the top right to lower left of the plate and has concentrations of tourmaline near its margins. The host is a banded, calc-silicate sheet horizon. FIG. 4 (*right*). Contact between calc-silicate vein (below) and host hornblende hornfelses (above) at Wheal Cock Carn. Note the profusion of coarse amphibole crystals at the contact. Note also the hornfels xenolith in the vein which appears to have suffered some 'digestion' and rotation.

magnetite skarn, the contacts are sharp (fig. 3). The vein at this locality has all the appearance of having formed by dilation with concomitant precipitation from a solution. The vein at Wheal Cock Carn on the other hand is situated in hornblende hornfelses. Here the contact is more irregular and some replacement of the hornfelses is indicated. Indeed, some parts of this vein, and the hornfels inclusions, have selvedges of coarse, green amphibole (fig. 4). This mineral appears to have formed by reaction between the introduced material and the hornblende hornfelses. The inclusion in fig. 4 shows a rotation relative to the adjacent hornfelses, suggesting that a small amount of fracturing and movement of the wall-rocks took place. It is therefore proposed that the veins formed by precipitation within a fissure with consequent marginal replacement of the wall-rocks. However, it must be noted that the presence of sharp junctions does not preclude an origin by replacement (e.g. King, 1948). Thus the relative importance of precipitation versus replacement cannot be gauged until critical features, such as the relationship to earlier structures, can be deduced.

Good examples of these veins can be seen at the localities mentioned in Table I.

Petrography of the veins. Whilst the majority of the calc-silicate bodies contain the typical skarn minerals already mentioned, the larger veins have a more varied mineralogy. Approximate modal compositions of some typical veins are given in

TABLE I. *Approximate modal content of some calc-silicate veins*

	I	2	3	4	5
Garnet	80	30	60	80	—
Axinite	tr	40	10	—	10
Epidote	tr	tr	10	5	40
Hornblende	tr	15	10	—	35
Diopside	tr	5	10	—	—
Tourmaline	10	tr	—	—	10
Sulphides	tr	tr	—	5	tr
Apatite	—	3	—	—	tr
Calcite	tr	tr	—	10	—
Sphene	tr	tr	—	—	tr
Quartz	—	tr	tr	—	—
Chlorite	—	tr	—	—	—
Zeolite	—	—	tr	—	—

tr: trace   —: not present   Values in %

1. Crowns Rock.   2. Wheal Cock Carn.   3. Carn Vellan.   4. Stamps and Jowl Zawn.   5. Chycornish Carn.

Table I. The dominance of garnet is clear, but other Ca, Fe, and B-rich phases are also abundant.

All the minerals in these veins are characterized by a relatively large crystal size—the garnet (rhombdodecahedra with {110} up to 4 cm in length), amphibole (up to 7 cm), and apatite (up to 5 cm), being especially distinctive in the Wheal Cock

vein. Thin section studies reveal the presence of zoning in almost all mineral phases. This is strikingly displayed by the tourmalines, most of the garnets (which also exhibit sector twinning), and the axinites (which show a slight purple to colourless pleochroism). Similar anisotropic garnets have been figured by Murad (1976) and Lessing and Standish (1973).

In the Wheal Cock vein it is clear that the garnet, amphibole, and pyroxene are the earliest minerals to have formed. These minerals are extensively replaced by axinite. Chlorite, calcite, epidote, and sphene occur in all the veins as retrogressive products of the earlier formed silicate minerals. The axinite, tourmaline, and sulphides appear to be related to a later phase of hydrothermal activity as these minerals also occur as infillings in the numerous voids.

Fluid inclusions are present in the apatite, axinite, and pyroxene from the Wheal Cock vein. The primary and pseudo-secondary inclusions in these minerals are two-phase systems (liquid plus water vapour), which homogenize into a liquid phase on heating. Salinities of the fluid phase are less than 26 % (equivalent weight NaCl) and uncorrected homogenization temperatures for the apatite are between 360 and 380 °C. These results are uncorrected for the pressure during mineral formation; assuming a 10 % salinity and a pressure of 1 kb, an additional c. 100 °C is envisaged (Lemmlein and Klevtsov, 1961). Although the apatite may not be cogenetic with the other minerals, it seems reasonable to suggest that the vein formed at a temperature close to 500 °C. The minerals were therefore deposited from hot, presumably saline fluids that had broadly similar characteristics to those associated with the earliest Sn-Cu lodes of the district (Jackson, 1976).

General geochemical considerations. Representative chemical analyses of the calc-silicate horizons, the veins, and their host rocks are given in Table II, p. M60. The samples were first dissolved in a mixture of hydrofluoric and perchloric acid (the solution B of Riley, 1958). This solution was used for determining the majority of the major elements whilst the trace elements were determined on a more concentrated solution. Atomic-absorption spectrophotometry was used for the determination of Al, total Fe, Ca, Mg, Mn, Be, Co, Cr, Ni, Cu, Pb, Sn, Zn, and Li. Na and K were determined by emission flame photometry. Large concentrations of Ca and Mg were checked by titration with EDTA (Bennett and Reed, 1971). Detection limits for the same trace element vary slightly because the samples were analysed during a period in which new equipment was acquired. The Sn values were confirmed by X-ray spectrography, using cadmium acetate as an internal standard. Si was determined by the classical gravimetric technique of Washington (1930) with the later modification involving coagulation by addition of polyethylene oxide (Bennett and Reed, 1971). Fe^{2+} was determined by addition of ammonium metavanadate and titration with ferrous ammonium sulphate (Wilson, 1955). Water was determined by the Penfield tube method (Washington, 1930). P, Ti, F, and B, were all determined colorimetrically: P by the molybdenum blue method (Riley, 1958); Ti by the addition of hydrogen peroxide (Riley, 1958); F by the alizarin fluorine blue method (Hall and Walsh, 1969); and B by a modification of the curcumin method (Grinstead and Snider, 1967). Cl was determined gravimetrically by precipitation as silver chloride and CO_2 by non-aqueous titrimetry (Read, 1972).

The calc-silicate assemblages as a whole have a similar chemistry and show a marked concentration of Ca. Local enrichments of P and B are also noted in apatite and axinite-rich samples. Where replacement is envisaged, elements such as Ca, Mn, P, and B must have been introduced into the host metabasalts, with the consequent removal of Si, Mg, Na, and K. Precipitation from a solution necessitates the introduction of all the components listed in the analyses. In either situation a large amount of Ca must have been introduced. As the wall-rocks adjacent to these bodies show no marked depletion in this element (Table II, nos. 8 and 9, p. M60) it must have been derived from deeper tectonic levels rather than by lateral secretion.

The reaction that caused the recrystallization of the wall-rock to the coarse amphibole in the Wheal Cock vein is close to isochemical (Table III, no. 7 and Table II, nos. 7, 8, and 9, p. M60). However, some exchange of alkalis appears likely.

Large amounts of certain trace elements are present in some of the rocks (Table II, p. M60). Several of these, e.g. Cu, Co, Cr, and Ni, are typically present in substantial quantities in basic volcanic rocks (Prinz, 1967). There are particularly high concentrations of Zn in the St. Just rocks but contents in the range 100 to 200 ppm are not unusual for basaltic rocks (Wedepohl, 1972). It is probable therefore that the presence of these elements in the calc-silicate assemblages can be related to the original content of the host volcanics. Elements such as Sn, Be, and B have, however, probably been introduced from an external source and deserve special mention as they are typically associated with granitic rocks.

Studies by Floyd (1968) and Alderton and Jackson (1974) have revealed that there are several factors controlling the distribution of tin in the aureole of the Land's End granite. First, there appears to be a chemical control, since the tin is

concentrated in the more Ca-rich environments. Thus the following sequence reflects both the average content of tin and calcium: calc-silicate veins > calc-silicate sheets > hornblende hornfelses > cordierite cummingtonite-anthophyllite hornfelses. Not all the Ca-rich phases have high tin contents, however (Table III, p. M60). The above sequence is also one of decreasing ferric iron values and it is therefore possible that this element may control tin distribution as well.

Secondly, there is a regional control, as the area between Crowns Rock and Carn Vellan contains the more tin-rich, calc-silicate assemblages and has the majority of the tin lodes (fig. 1). Other parts of the St. Just aureole, and the Tater-du to Newlyn region, contain fewer tin lodes and have calc-silicate assemblages with much lower tin contents. It is thus a possibility that the hydrothermal activity responsible for ore deposition is related to the formation of the calc-silicate assemblages. The increasing concentration of elements such as Sn, Be, and B in these fluids can be gauged from the fact that the later individual phases and the veins themselves have higher contents of these elements. This temporal influence is a third control on the tin distribution.

Mineral chemistry. Eleven minerals were separated from the calc-silicate assemblages by heavy liquid and magnetic methods. They were analysed chemically by the methods outlined previously, and all the analyses have been recalculated on the basis of no H_2O^-. The minerals consisted of five garnets, two amphiboles, one apatite, one axinite, one epidote, and one pyroxene. The purpose of analysing these minerals was twofold: to discover if their major element chemistry was controlled by the immediate geological environment; and to see whether their trace element contents could elucidate the origin of the fluids that formed the bodies.

All the garnets have a similar major element chemistry (Table III, p. M60). They all contain over 90% of the grossular and andradite molecules, in the range $Gr_{71\cdot0} An_{20\cdot8}$ (Crowns vein) to $Gr_{62\cdot8} An_{31\cdot5}$ (Crowns sheet). Only a minor amount of hydrogrossular is present ($\leqslant 1\cdot1\%$). These garnet end-member molecules were calculated using the procedure suggested by Rickwood (1968), with the exception that almandine was derived before grossular. Although the cations (particularly Ti) were not wholly used up, over 96% were allotted and the recalculations are thus considered acceptable. If the vein garnets alone are considered, there appears to be a difference between the Crowns garnet and the three specimens from further north (Wheal Cock, Carn Vellan, Stamps and Jowl). This difference is no doubt due to the Crowns

vein being situated in a calc-silicate sheet horizon whilst the other three are in hornblende hornfelses (and may in fact all be part of the same vein). The garnet from the host calc-silicate horizon at Crowns (no. 2) is generally similar but has a lower grossular:andradite ratio. The only trace element present in substantial amounts appears to be tin. The Crowns vein garnet contains over 2000 ppm Sn, whilst the others contain between 100 and 400 ppm. No cassiterite was visible in thin section and the tin was assumed to be in solid solution in the garnet.

The other mineral analyses are also presented in Table III, p. M60. The apatite from Wheal Cock (no. 6) is a fluorapatite with a low content of H_2O, Cl, and CO_2. Some trace elements appear to be present in quite large amounts, e.g. Sr, Co, Cu, and Zn.

The amphibole from the Wheal Cock vein (no. 7) is pleochroic in thin section (α = light yellow-green, β = dark green, γ = blue green). The composition (Table III, p. M60) corresponds to a potassian magnesian hastingsite while the amphibole from the Chycornish Carn vein (no. 8) is a magnesio-hornblende (Leake and Winchell, 1978). Both the amphiboles are enriched in Sn (990, 780 ppm) and Zn (200, 250 ppm). Large amounts of Zn are common in amphiboles (Wedepohl, 1972) but high contents of Sn are unusual.

The 'epidote' from the Chycornish Carn vein (no. 9) is midway between epidote and clinozoisite. As with the garnets, Sn is the main trace element present (1200 ppm).

In thin section the pyroxene appears turbid due to incipient alteration and this is confirmed by the high water content in the analysis (no. 10). The optical characteristics suggest that it is diopside and this is confirmed by the recalculation of the chemical analysis. Large concentrations of Zn and Cr are present in the pyroxene (150 and 115 ppm).

A partial analysis of the axinite from the Wheal Cock vein (no. 11) reveals that Co, Ni, Sn, and Zn, are all present in substantial amounts (> 1000 ppm). It also contains more Be than any other mineral phase analysed (43 ppm). Axinite quite often contains appreciable amounts of Be (see Hellwege, 1956, and MacKenzie, 1972). The high Mn content of the axinite (4·2% MnO) indicates that a large proportion of this element in the veins is located in this mineral (the garnets also contain Mn; typically 1% MnO).

The minerals analysed in this study are typical skarn minerals enriched in Ca and Fe^{3+}. Many are also enriched in Sn and Zn. Zinc seems to be preferentially enriched in those phases that contain more Fe^{2+}, as might be expected from the similar ionic radii and electronegativities of these two

elements. However, Zn does seem to be enriched in the aureole rocks (Table II, p. M60) and high Zn concentrations are not unusual in such environments (Wedepohl, 1972).

From published analyses of the Sn content of rock-forming silicates (Hellwege, 1956; Hamaguchi and Kuroda, 1969) it appears that Sn concentrations greater than 100 ppm are rather unusual and are generally associated with tin-rich regions. High Sn concentrations in silicate phases have been noted by several authors (Hellwege 1956; Dadák and Novák, 1965; Mulligan and Jambor, 1968; McIver and Mihálik, 1975). These authors described high Sn concentrations in garnet, axinite, epidote, and pyroxene. El Sharkawi and Dearman (1966) also reported the presence of substantial Sn concentrations in garnets from skarns in the Meldon area, Devonshire, as well as the tin-bearing analogue of sphene (malayaite). Various suggestions have been put forward as to the structural position of the Sn but as andradite-rich garnets commonly have these high contents the substitution of Sn for Fe^{3+} (rather than Fe^{2+}, Ca, Ti, or Si) is most favoured.

The large concentrations of Sn found in the veins indicate that other tin-bearing phases are present. No cassiterite or tin-bearing sulphide has been found in any of the garnet-rich veins. Stokesite (a silicate of Ca and Sn) was first discovered in the immediate vicinity by Hutchinson (1900) and more recently by Couper and Barstow (1977), and is thus a possible candidate. The presence of malayaite is also possible.

The Wheal Cock vein in particular contains measurable amounts of Be. Much of this is located in the axinite, but the respective values do allow the possibility of other Be-bearing phases being present. Kingsbury (1961) found helvine in the adjacent mine dumps of Wheal Cock and in places this was altered to herderite (a Ca-Be phosphate). This correlates with the association of axinite and apatite, especially as Kingsbury noted that the helvine contained substantial amounts of Zn and Mn. It therefore seems likely that other Be-rich phases could be found in these veins, especially as danalite and phenakite can occasionally be found on some of the mine dumps.

Origin of the calc-silicate bodies. The morphology of these bodies indicates widespread introduction of material into the hornfelses. The larger, sheet-like horizons appear to replace rocks of basaltic origin. Their association with sheared amphibolites and impermeable pelites suggests that pronounced foliation aided fluid migration whilst the impermeable horizons acted as structural barriers.

The calc-silicate veins cut the earlier assemblages, including the sheet-like horizons. They therefore represent a second phase of hydrothermal re-mobilization, which was associated with the formation of tensional fissures. Similar veins containing garnet, epidote, axinite, etc. can be found at other localities where volcanics occur within the metamorphic aureole of a granite (Reid and Scrivenor, 1906; Firman, 1957; Floyd, 1965; MacKenzie, 1972). Anhydrous, grossular-rich garnets have been synthesized in the temperature range 500-600 °C (Mill and Kalinin, 1966; Shoji, 1974). This would thus correlate well with the fluid inclusion data and the suggestion by Floyd (1971) that temperatures in the immediate aureole of the granite during its intrusion were in the order of 500-600 °C.

It is suggested that the excess Ca in these bodies was derived from the basaltic rocks, as they contain large quantities of this element (Table II, p. M60). However, this does not preclude a significant contribution from the pelites (which contain up to 5 wt % CaO) or the granite (typically 1% CaO). Floyd (1965) discussed the formation of the Ca-rich hornfelses in the Tater-du region and suggested that the breakdown of hornblende and plagioclase would liberate large quantities of Ca. Now that pre-metamorphic, low-grade, hydrous degradation of the original basalts is envisaged, an alternative source for the Ca could be the calcite and epidote derived from such reactions (Floyd, 1975). It is worth noting that similar garnet-rich bodies occur in association with altered gabbroic and ultrabasic rocks (Bilgrami and Howie, 1960; de Waal, 1969; Easton *et al.*, 1977). One suggestion for the origin of rodingites in particular is that they were formed by the liberation and subsequent concentration of Ca during the hydrothermal alteration of pyroxene and plagioclase in these rocks.

Whereas a component like Ca could have been derived by 'internal metasomatism' of the basaltic rocks (Floyd, 1967), an external source for elements such as Sn, Be, and B is likely. Such a source could be the granite, which is enriched in these elements (e.g. Hall, 1971). The presence of these elements in the hypothermal ore veins of the area, and the similarity in fluid inclusion data, suggest that there may be an association.

The garnet-rich veins are thus the product of an early phase of hydrothermal activity, since they cut the other hornfels types, but are themselves cut by the NW-trending, hypothermal, Sn-Cu lodes (fig. 1). This has been substantiated by the K-Ar dating of the amphibole from the Wheal Cock vein at 280 Ma. The granite intrusion is dated at 280-290 Ma and the earliest ore mineralization at 270-280 Ma (Dr. A. Halliday, pers. comm.).

Stable isotope studies have shown that the hypothermal ore mineralization in the region was accomplished by fluids that had a large meteoric component (Sheppard, 1977). A stable isotopic

analysis of the amphibole from Wheal Cock revealed that $\delta^{18}O = +9 \cdot 0\%_{00}$ and $\delta D = -61\%_{00}$. Unfortunately, the isotopic systematics of the amphibole-water system are not at present accurately defined (Bottinga and Javoy, 1975; Suzuoki and Epstein, 1976). However it is possible to *estimate* the isotopic fractionation between the amphibole and water (bearing in mind the imprecise nature of the fluid inclusion data and the uncertainty in the effect of octahedral Fe^{3+}). In the temperature range 400–600 °C, water in equilibrium with this amphibole would have an isotopic composition in the range $\delta^{18}O = +10$ to $+11\%_{00}$, and $\delta D = -5$ to $-30\%_{00}$. These compositions lie outside the field for Cornubian magmatic waters ($\delta^{18}O = +10$ to $+13$, $\delta D = -40$ to -65; Sheppard, 1977). Thus the fluids associated with amphibole formation must have contained a substantial proportion of a non-magmatic (presumably meteoric) component (c.f. Taylor and O'Neil, 1977).

It seems likely that a large-scale circulation of fluids with a high meteoric component was initiated during the later stages of granite intrusion. Hot, saline fluids leached certain elements, e.g. Ca, from the degraded basalts through which they passed. This dissolved material was later fixed in minerals such as garnet during the formation of the sheet-like, skarn horizons.

Whilst this earlier phase of hydrothermal activity was of a pervasive nature, the later phase was restricted to well-defined, planar fissures. As the development of the bodies progressed, elements like Sn, Be, and B became concentrated in the later minerals, indicating that the fluids had gained increasing access to a reservoir rich in such elements —probably the granite. The hydrothermal activity culminated in the development of extensive economic deposits of tin and copper.

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TABLE II. Chemical analyses of rocks from the St. Just aureole

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
SiO_2	31.85	34.07	37.70	33.75	39.52	35.49	40.22	39.42	42.50	34.99	33.32	45.28	1.82	48.70	42.39	47.53	1.57	50.00	45.30
TiO_2	1.42	4.00	1.34	0.38	3.58	0.42	1.37	4.95	5.03	1.93	1.69	2.52	0.67	3.96	0.98	2.29	0.58	2.99	1.15
Al_2O_3	13.47	15.26	16.09	15.06	14.25	16.68	11.25	10.61	15.77	16.36	15.23	17.62	2.63	23.14	12.40	16.53	1.84	18.24	13.66
Fe_2O_3	4.42	8.69	7.38	13.98	9.66	6.27	4.46	11.01	7.25	5.80	11.82	1.47	0.75	3.54	0.22	1.08	0.60	2.14	0.21
FeO	3.64	3.27	3.46	1.11	1.62	2.72	13.99	5.45	4.85	1.29	2.69	11.16	2.30	16.15	6.85	8.18	2.10	10.69	4.40
MnO	2.76	1.94	2.68	1.30	0.93	1.30	0.42	0.32	0.22	0.39	0.60	0.24	0.07	0.38	0.07	0.24	0.08	0.41	0.15
MgO	1.18	2.22	1.16	0.20	0.94	0.84	10.84	8.46	5.46	3.43	0.60	7.21	2.18	14.12	4.38	4.68	1.89	8.84	2.58
CaO	27.04	23.97	23.30	32.38	27.00	33.76	11.33	14.50	16.29	30.19	30.13	7.79	4.25	13.51	0.25	13.87	0.80	14.80	12.52
Na_2O	0.16	0.39	0.24	0.10	0.13	0.42	0.85	0.62	0.66	0.26	0.56	2.07	0.87	3.70	0.65	2.66	1.01	4.52	1.25
K_2O	0.12	0.28	0.12	0.13	0.16	0.34	0.40	0.71	0.30	1.97	0.17	2.40	1.31	5.43	0.55	0.86	0.66	2.50	0.28
P_2O_5	10.77	3.68	0.24	0.38	0.69	0.45	0.19	0.59	0.39	0.09	2.30	0.30	0.18	0.89	0.03	0.25	0.11	0.52	0.14
H_2O^+	1.06	0.75	1.18	0.69	0.81	0.34	3.12	1.94	0.87	1.89	0.44	1.63	0.78	3.48	0.43	1.17	0.30	1.47	0.56
H_2O^-	0.33	0.22	0.38	0.20	0.25	0.24	1.12	0.70	0.15	1.23	0.47	0.26	0.17	0.76	0.07	0.19	0.06	0.34	0.13
B_2O_3	2.11	1.03	4.42	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
F	0.52	0.42	0.10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
O≡F	0.22	0.18	0.04	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Total	100.63	100.01	99.75	99.66	99.54	99.25	99.56	99.28	99.74	99.72	100.02	–	–	–	–	–	–	–	–

Trace elements (ppm)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Be	68	32	43	<10	<10	<10	<10	<10	<10	–	–	–	–	–	–	–	–	–	–
Co	1500	50	35	45	35	30	100	1000	50	35	6	44	10	67	26	34	8	54	28
Cr	70	35	35	35	35	35	270	130	135	61	42	190	166	588	32	289	73	370	143
Cu	24	30	187	57	45	15	40	68	42	175	40	30	24	88	4	42	39	113	8
Li	25	46	41	18	53	35	169	92	101	91	20	101	56	241	15	44	26	103	15
Ni	580	30	30	30	50	25	100	250	60	35	14	88	108	489	24	147	52	250	59
Pb	118	36	36	63	42	65	35	68	42	15	21	15	9	36	4	25	16	54	8
Sn	902	859	945	160	631	2050	–	–	<10	58	430	<10	–	16	<10	<10	–	12	<10
Zn	217	214	188	65	143	70	400	700	25	226	171	68	24	116	<7	128	130	455	30

1. Apatite-rich sample of Wheal Cock vein. 2. Amphibole-rich sample of Wheal Cock vein. 3. Axinite-rich sample of Wheal Cock vein.
4. Garnet-rich sample of Stamps and Jowl Zawn vein. 5. Garnet-rich sample of Carn Vellan vein. 6. Garnet-rich sample of Crowns vein.
7. Hornfels inclusion in Wheal Cock vein. 8. Hornfels, immediately adjacent to Wheal Cock vein. 9. Hornfels, 2m from Wheal Cock vein.
10,11. Calc-silicate, sheet-like horizon, Crowns Rock. 12. Mean of 17 metabasalts. 13. Standard deviation of 17 metabasalts.
14. Maximum values for 17 metabasalts. 15. Minimum values for 17 metabasalts. 16. Mean of 8banded amphibolites. 17. Standard
deviation of 8 banded amphibolites. 18. Maximum values for 8 banded amphibolites. 19. Minimum values for 8 banded amphibolites.

TABLE III. Chemical analyses of minerals from the calc-silicate horizons

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	37.40	38.61	37.60	37.87	37.40	0.00	38.86	46.76	37.76	5.19	–
TiO_2	0.00	0.57	0.87	0.72	1.12	0.12	0.39	0.39	0.24	0.51	–
Al_2O_3	17.83	14.36	16.20	15.71	15.80	0.07	14.65	7.62	28.27	2.08	–
Fe_2O_3	7.16	10.35	8.94	9.22	8.28	0.20^X	5.05	4.25	8.05	1.09	–
FeO	1.38	1.02	2.00	2.54	2.17	–	14.51	10.91	0.49	5.64	–
MnO	1.35	0.75	1.41	1.20	1.23	0.01	0.36	0.28	0.36	0.29	4.2
MgO	0.30	0.41	0.26	0.18	0.24	0.09	8.61	13.44	0.18	3.58	–
CaO	33.66	34.03	32.18	32.41	33.72	54.76	12.63	12.09	22.46	23.86	–
Na_2O	0.09	0.11	0.09	0.10	0.09	0.09	1.80	0.75	0.06	0.12	–
K_2O	0.03	0.05	0.03	0.05	0.04	0.03	1.53	0.28	0.02	0.01	–
P_2O_5	0.04	0.01	0.00	0.01	0.03	42.02	0.01	0.02	0.05	0.08	–
H_2O^+	0.25	0.00	0.00	0.07	0.11	0.42	1.91	2.38	1.59	1.38$^+$	–
F	–	–	–	–	–	3.4	0.24	0.65	–	–	–
-O≡F,Cl	–	–	–	–	–	1.47	0.10	0.27	–	–	–
Total	99.75*	100.27	99.58	100.08	100.23	99.74	100.45	99.55	99.53	99.83	–
Si	5.826	6.028	5.899	5.926	5.848	–	5.895	6.816	2.969	1.876	–
Al^{IV}	0.174	–	0.101	0.074	0.074	–	2.105	1.184	0.031	0.090	–
Al^{VI}	3.101	2.643	2.895	2.824	2.761	(0.014)	0.515	0.125	2.590	–	–
Fe^{3+}	0.839	1.216	1.055	1.086	0.974	0.025	0.576	0.466	0.476	0.030	–
Ti	–	0.067	0.103	0.085	0.132	0.015	0.044	0.043	0.014	0.014	–
Fe^{2+}	0.180	0.133	0.262	0.332	0.284	–	1.841	1.330	0.032	0.173	–
Mg	0.070	0.095	0.061	0.042	0.056	0.022	1.947	2.920	0.021	0.742	–
Mn	0.178	0.099	0.187	0.159	0.163	0.001	0.046	0.035	0.024	0.009	–
Ca	5.619	5.693	5.409	5.434	5.650	9.823	2.053	1.888	1.983	0.937	–
Na	–	–	–	–	–	0.029	0.528	0.212	–	0.009	–
K	–	–	–	–	–	0.006	0.296	0.052	–	–	–
P	–	–	–	–	–	5.956	–	–	–	–	–
OH	0.260	–	–	0.073	0.115	0.469	1.933	2.314	0.834	–	–
F	–	–	–	–	–	1.800	0.115	0.300	–	–	–
Cl	–	–	–	–	–	0.045	–	–	–	–	–
Anion basis	24	24	24	24	24	26	24	24	13	6	–
Gro.	71.0	62.6	64.6	63.5	65.9						
And.	20.8	31.5	26.4	26.9	25.0						
Pyr.	1.2	1.6	1.0	0.7	1.0						
Spess.	2.9	1.7	3.2	3.2	2.8						
Alm.	3.0	2.3	4.4	5.6	4.9						
Hyd.	1.1			0.3	0.5						
Sch.	–		0.4	0.4	–						

Trace elements (ppm)

	1	2	3	4	5	6	7	8	9	10	11
Be	<10	2	<10	<10	<10	<10	<10	17	<10	–	43
Co	17	<2	19	20	20	92	51	11	39	23	400
Cr	22	24	45	23	41	34	48	46	30	115	23
Cu	24	90	16	24	20	91	38	53	54	12	30
Li	10	8	12	14	19	4	55	49	3	16	10
Ni	<10	<2	<10	12	<10	64	40	<10	23	148	–
Pb	15	3	20	20	22	47	<15	15	18	<15	25
Sn	2233	391	144	226	267	<20	993	782	1223	–	973
Zn	45	14	42	43	58	75	246	196	49	150	218

1. Garnet from Crowns vein (*total includes 0.26% SnO). 2. Garnet from Crowns, calc-silicate sheet horizon. 3. Garnet from
Wheal Cock vein. 4. Garnet from Stamps and Jowl Zawn vein. 5. Garnet from Carn Vellan vein. 6. Apatite from Wheal Cock
vein (x:Fe as Fe₂O₃; %Cl = 0.16; %CO₂ < 0.05; Sr = 200 ppm). 7. Amphibole from Wheal Cock vein. 8. Amphibole from Chycornish
Carn vein. 10. Pyroxene from Wheal Cock vein (+:H₂O⁺ from loss on ignition; recalculation on water-free basis). 11. Axinite
from Wheal Cock vein. 9. Epidote from Chycornish Carn vein.