Geol. Soc. Malaysia, Bulletin, 11, Dec. 1979; pp. 209–237.

Geology of the Cornubian Tin Field 'A Review'

N.J. JACKSON[1]

Abstract: Mainstage mineralisation is spatially related to the roof and border zones of several high level, post-kinematic, geochemically specialised, Permian granites. The following types of mineralisation phenomena are recognised and described; 1) pervasive, postmagmatic metasomatisms and alterations 2) hydrothermal breccia pipes 3) metallised and non-metallised pegmatites 4) metallised vein systems 5) metallised replacements. These mineralisation phenomena show definite space-time patterns within the batholith and its environs. Five spatial environments are recognised each, characterised by a particular style of mineralisation at any point in time. Mainstage mineralisation is considered to have been emplaced in four distinct phases, which broadly comprise 1) metasomatisms, pegmatites and hydrothermal breccias 2) early veins of quartz-wolframite-cassiterite, arsenopyrite, alkali feldspar, tourmaline 3) veins and replacements of quartz-cassiterite and cassiterite-sulphides 4) late veins of sulphides.

The main factors which controlled the distribution of mineralisation were; 1) magmatic-hydrothermal history of the intrusive 2) degree, location and nature of fracturing 3) location and nature of meteoric hydrothermal convection systems 4) physico-chemical conditions within the vein environment.

INTRODUCTION

The Cornubian tin field occupies an area of 3800 km^2 which, as a first approximation, coincides with the axial trace of the Cornubian granite batholith. The tin field was one of the earliest to be exploited and during its history it has become a classic area for the description of mineralisation phenomena.

Production figures for the province, based on Dines (1956) are as follows: tin 2×10^6 tons, copper 1.3×10^6 tons, lead 3.5×10^5 tons, arsenic 2.5×10^5 tons, zinc 1×10^5 tons, tungsten 1.2×10^3 tons. In addition small amounts of Au, Ag, Sb, U, Ni, Co, Fe, Bi, Mo, F and Ba have also been recovered. The present favourable economic climate has produced a phase of renewed academic and industrial interest in the metal potential of the province. Three mines are currently in production and several prospects are being re-examined.

This review outlines the regional geological setting of the Cornubian tin field and attempts to classify mainstage ore-deposits according to their structural—time relationships within the batholith.

LITHOSTRATIGRAPHY

The Cornubian tin field is confined to two major lithological units within the Cornubian peninsula of S.W. England: a Devonian-Carboniferous volcano-sedimentary sequence and a Lower Permian granite batholith.

The Devonian-Carboniferous sedimentary succession is lithologically variable throughout the peninsula. Three distinct stratigraphical successions can be recognised (Reading, 1973), in south Cornwall, south Devon and north Cornwall, and in north

---

[1] Institute of Applied Geology, King Abdul Aziz University, P.O. Box 1744, Jeddah, Saudi Arabia.

Devon. All three areas show evidence of underlying continental crust, represented by pre-Devonian metamorphic and shallow water facies sedimentary rocks in south Cornwall, and by Lower to Middle Devonian continental and shallow marine clastic sediments in south and north Devon.

In south Cornwall the Lower Devonian (?) argillaceous, Mylor beds are overlain by turbidites of the Middle Devonian Gramscatho beds and breccia conglomerates of the Veryan Series. The latter contains abundant exotic blocks of Ordovician quartzites and Silurian to Middle Devonian limestones and cherts within Upper Devonian black shales and pillow lavas. In north Devon the sedimentary succession consists of interbedded Lower to Middle Devonian continental and shallow marine clastic rocks representing an epicontinental depositional environment. In south Devon and north Cornwall late Middle Devonian and Lower Carboniferous sedimentation is represented by reef limestones, thin condensed sequences of limestone chert and pelite and thicker beds of pelite, chert and coarse clastics. This sedimentary regime probably represents sedimentation in restricted, fault bounded basins. Middle Carboniferous sedimentation is represented by thick turbiditic sandstones and fluviatile clastic sediments, probably representing a flysch-molasse relationship.

Volcanic and hypabyssal igneous rocks (known as greenstones) are concentrated in the Middle Devonian and Lower Carboniferous of S.W. England. They are predominantly basaltic in nature and form massive and pillowed flows, intrusive sheets and small stocks. Although often spilitised and metamorphosed in the greenschist facies, Floyd (1972) suggests that sufficient primary chemical features are preserved to indicate continental alkaline parentage for most of these rocks. Volcanicity appears to have increased in intensity throughout the Devonian and culminated in the Lower Carboniferous with the development of K-rich trachytes and keratophyres in addition to the spilitised basalts. K-rich lamprophyroid rocks are also present in limited amount throughout the Devonian and Carboniferous.

THE GRANITE BATHOLITH

Mineralisation is spatially related to the roof and border zones of a series of high level, post kinematic granite plutons, which together form the Cornubian batholith (fig. 1). The granites occur as six major and several minor masses, and together with their associated dykes and sheets were emplaced partly passively, by cauldron subsidence and block stoping, and partly forcefully, into a deformed Upper Palaeozoic volcano-sedimentary sequence. Each pluton is roughly circular or ellipsoidal in plan, contacts with the surrounding rocks are sharp and discordant, and the larger masses are composite in nature often showing a complex history of magmatic emplacement and insitu metasomatism. The main plutons and stocks vary in texture and composition from fine-grained biotite microgranites to coarse-grained, porphyritic two-mica granites and adamellites, and medium-grained quartz-feldspar granite porphyries (Exley and Stone, 1964; Hall, 1974, Hawkes and Dangerfield, 1978). The sheets are often leucogranite or aplite-pegmatite and the dykes are predominantly quartz-feldspar rhyolite or granite porphyries (Hall, 1970; Henley, 1974a). Locally, in the roof and marginal zones of the main plutons banded aplite-pegmatite and leucogranite become dominant (Stone, 1975). The general sequence of emplacement in the main plutons is coarse-grained porphyritic biotite granite 1) lithionite granite and fine-grained biotite granite 2) granite prophyry stocks and dykes 3) sheets of aplite—pegmatite, rhyolite porphyry and microgranite. Many of the granites have been extensively recrystallised and in many instances metasomatised (Stone and Austin, 1961; Exley and Stone, 1964).

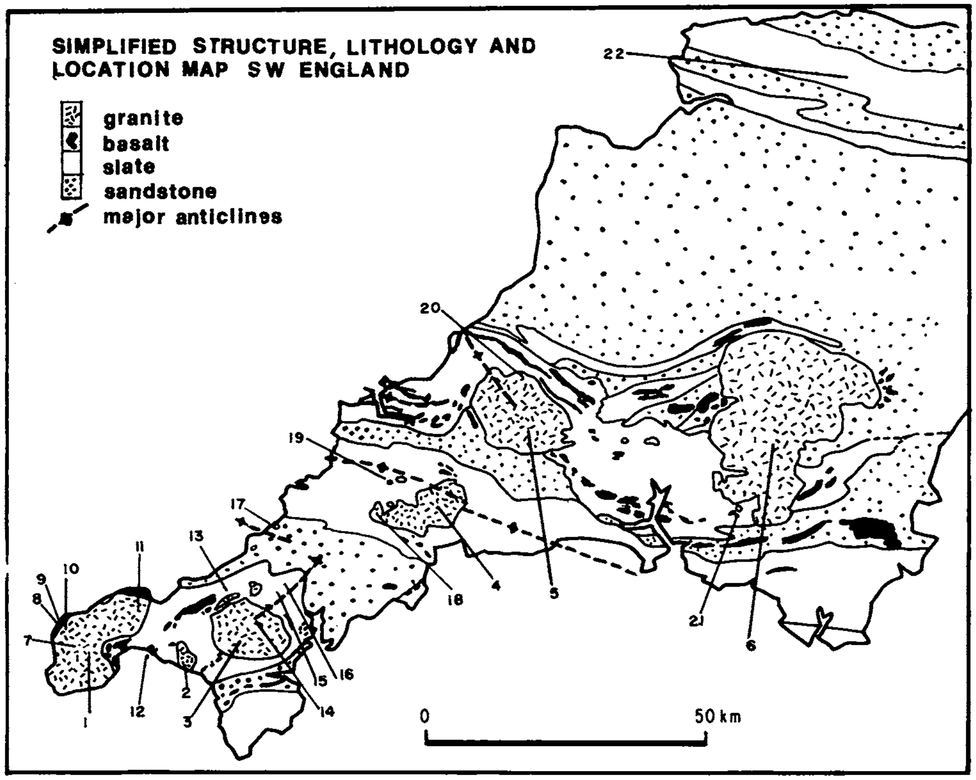

Fig. 1. Lithological map of the Cornubian peninsula. Locations mentioned in text—1) Land's End pluton 2) Tregonning-Godolphin pluton 3) Carnmenellis pluton 4) St. Austell pluton 5) Bodmin Moor pluton 6) Dartmoor pluton 7) Bostraze clay pit—Balleswidden Mine 8) Grylls Bunny Mine 9) Levant Mine 10) Geevor Mine 11) St. Ives Consols 12) St. Michaels Mount 13) South Crofty Mine 14) Halvosso and Trolvis quarries 15) Mount Wellington Mine 16) Wheal Jane 17) Cligga Head 18) Parka Mines 19) Castle-an-Dinas Mine 20) Buttern Hill 21) Hemerdon Ball 22) North Devon ore-field

The granites are composed of quartz, plagioclase (An_{0-40}, usually An_{10-20}), perthitic orthoclase/microcline, often as large megacrysts, biotite, muscovite and sometimes a lithium mica, tourmaline, apatite, topaz, flourite, zircon, sphene, ilmenite, rutile, anatase, brookite, cordierite, anadalusite, garnet, sulphides and cassiterite. They are enriched in B, Li, F, Cl, As, Pb, Zn, Sn, U, Rb, Cs, & Th (Hall, 1971; Floyd, 1972; Wilson, 1972; Edwards, 1976; Moore, 1977; Wilson and Jackson, 1977), compared to the average value for low Ca granite given by Turekian and Wedepohl (1961). Ba and Sr, and K/Rb ratios are low, and Sn, B, F & Li increase in the younger intrusives. Nb, Zr and Y are low (Pearce and Gale, 1977), which may indicate a back arc origin. An important chemical feature of the granites is the negative correlation between Na and K. This has been attributed to large scale metasomatism caused by the migration of K-rich aqueous fluids (Exley and Stone, 1964). The total chemistry of the plutonic granites is considered to reflect some degrees of magmatic differentiation e.g. increase of LIL elements in the younger intrusives, and the superimposed effects of internal alkali (K) metasomatism and contamination from the envelope, indicated by the irregular distribution of such elements as Mg, Fe, K, Ni, Cr, As, and Cu within individual plutons.

In spite of all these processes many of the plutonic granites plot close to the ternary minimum for a water pressure of 1000 bars (Exley and Stone, 1964; Hall, 1971; Wilson, 1972; Stone, 1975; Moore, 1977) in the normative quartz-orthoclase-albite triangular variation diagram of Tuttle and Bowen (1958).

Rhyolite porphyry dykes occupy dilatant extensional fractures created by the emplacement of the batholith (Moore, 1975). They are mineralogically similar to the main plutonic granites and often display flow foliation and brecciation structures (Goode, 1973). Their chemistry is also similar to the main plutonic complex ie. high Si, K, Cl, Cu, Zn, Pb, As, Sn, Rb, Cs, Th and U (Henley, 1974a), compared to the average value given by Turekian and Wedepohl (1961). They are depleted in Na, Mg, Ca and Ba, and enriched in K compared to the plutonic granites.

The granites are all enriched in O^{18} (Sheppard, 1977) relative to the H_2 group of subsolvus granites (Taylor, 1968) due to partial melting, assimilation and/or exchange with argillaceous sediments. Rb-Sr and K-Ar age determinations (Miller and Mohr, 1964; Harding and Hawkes, 1971; Hawkes, 1975) indicate that the batholith was emplaced approximately 290–300 m.y. ago with an initial Sr^{87}/Sr^{86} ratio of 0.7096 ± 34 (St. Austell granite). Co-magmatic quartz-porphyry dykes followed at 278 ± 8 m.y. with similar initial ratios.

Emplacement of the batholith was probably within 2–4 km of the Permian surface (Floyd, 1971; Halls, and others, 1977) and parts of the batholith may have been subvolcanic in nature. There is some evidence for coeval rhyolitic volcanism (Cosgrove and Elliot, 1977). Latite, alkali basalt and minette volcanics to the east of the Dartmoor granite have been dated by K-Ar at 280 m.y., (Miller and others, 1962).

MINERALISATION

Hydrothermal activity within the batholith has expressed itself in the following phenomena:

1) pervasive, postmagmatic alterations, including potassium and boron metasomatism, and phyllic-argillic alterations inside the batholith, and calcium, iron and boron metasomatism in the hornfelsed envelope.
2) hydrothermal breccia pipes.
3) metallised and non-metallised pegmatites.
4) metallised sheeted vein systems.
5) polymetallic, polygenic fissure veins.
6) metallised replacements.

These mineralisation phenomena show definite space-time patterns within the batholith and its environs. This review is based on the recognition of five environments within the batholith, each of which hosts a particular style of mineralisation at any one point in time. The five environments recognised are: the internal zone, internal contact zone, contact zone ,external contact zone and porphyry stocks and cupolas (fig. 2). Mainstage mineralisation is considered to have been emplaced during four phases which broadly comprise I) metasomatisms, breccia pipes and pegmatites II) early fissure veins and sheeted vein systems III) late fissure veins IV) late sulphide metallisation. These different phases may not have developed simultaneously or to the same extent throughout the batholith (Alderton and others, in prep.), but each major pluton usually displays most of the mineralisation spectrum.

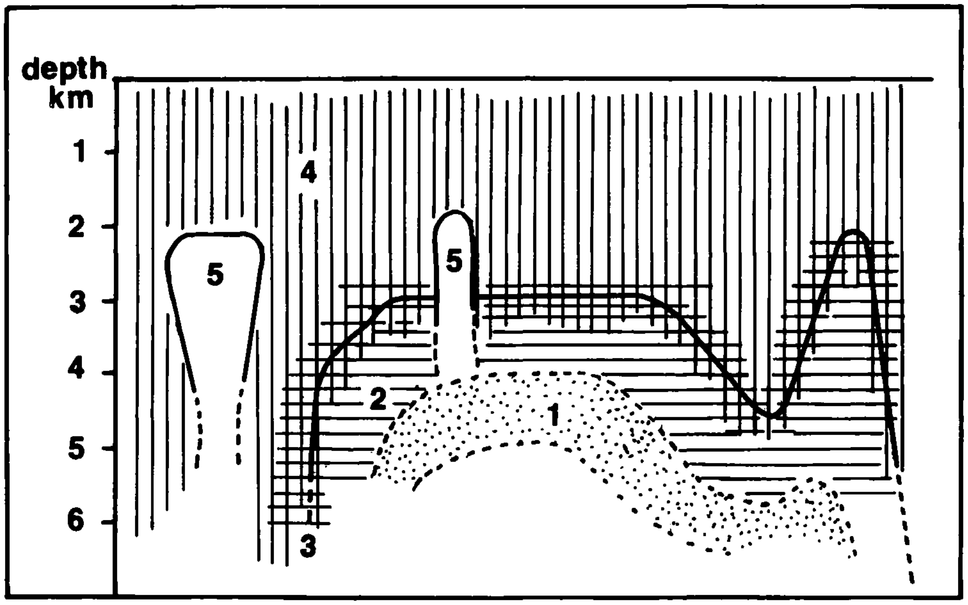

Fig. 2. Ore depositional environments: 1) internal zone 2) internal contact zone 3) contact zone 4) external contact zone 5) porphyry stocks and cupolas.

DISTRIBUTION OF METALS

Tin Occurs in all lithologies as vein or replacement deposits. It occurs mainly in the form of cassiterite and stannite, and rarely as stokesite, woodtin, varlomoffite, malayite and garnet (Hosking, 1969). Average Sn values in Cornubian lithologies are as follows:

metasediments—	10ppm (Hosking, 1964), 17ppm (median value, Henley, 1974b), 10ppm (Wilson and Jackson, 1977).
metabasalts—	14 & 16ppm (Floyd, 1968a) 11ppm (Wilson and Jackson, 1977).
granite—	58ppm (Ahmed, 1971), 40ppm (Hall, 1971), 17ppm (Wilson, 1972), 21ppm (Wilson and Jackson, 1977).

These values indicate that all major lithologies in the province are enriched in Sn relative to the average crustal values (Table I) given by Turekian and Wedepohl (1961). Cassiterite, as a primary accessory mineral in granite, is extremely rare. The first formation of Sn species appears to be in rare metallised pegmatites eg. Halvosso Quarry (Jackson, 1978) and pre-lode axinite veins in the St. Just district (Alderton and Jackson, 1978). Although economic quantities of tin were first emplaced during the formation of sheeted vein systems and some early veins, the main phase of tin emplacement occurred during major fracturing of the batholith. There is thus an increase in the amount of tin emplaced from the pegmatitic stage, through the early veins to the late veins.

The distribution of major Sn and Sn-W metallisation (fig. 3a & b after Dines 1956) shows that ≃70% of all the main tin producing areas occur within a granite intrusive or within ≃2 km of one.

TABLE 1

metal	lithology	mean values min — max (p.p.m.)	world average (p.p.m.)
Sn	granite	17 — 58	3 (low Ca granite)
	metasediment	10 — 17	6 (shale)
	metabasalt	11 — 16	1.5 (basalt)
W	granite	20 — 30	1.5
	metasediment	4 — 5	1
	metabasalt	— — —	1
Cu	granite	4 — 9.5*	10
	metasediment	30 — 59	45
	metabasalt	33 — 58	87
As	granite	26 — 65	1.5
	metasediment	12 — 30	13
	metabasalt	— — —	—
Pb	granite	13 — 44	19
	metasediment	14 — 51	20
	metabasalt	10 — 50	6
Zn	granite	39 — 63	39
	metasediment	112 — 245	95
	metabasalt	66 — 347	105

*excluding the average of values of Hall (1971).

Summary of mean metal values for Cornubian lithologies based on the average values given in the text. World average values are based on Turekian and Wedepohl (1961)—Sn, Cu, Pb and Zn; Onishi (1970)—As, and Krauskopf (1969) for W.

Tungsten Occurs in all rock types as vein deposits of wolframite with rare scheelite. However, most economic and sub-economic concentrations are directly associated with granite intrusives. Fig. 3b shows that ≃86% of all the major W occurrences either occur within a granite intrusive or within ∼1 km of one. The few data available for W values in Cornubian lithologies are as follows:

metasediments— 5ppm (Hosking, 1964), 4ppm (Hosking, 1973).
granite— <30ppm (Hall, 1971), <20ppm (Wilson, 1972).

These data indicate that the Cornubian rocks are enriched in W relative to the average crustal values (Table I) given by Krauskopf (1970).

Wolframite is rare in pegmatites. The main phase of tungsten emplacement was in the early veins and sheeted vein systems, particularly those associated with granite porphyry stocks and cupolas. Minor wolframite was emplaced in some of the late veins during the cassiterite-sulphide stage of metallisation (Kettaneh and Badham, 1977). It is thus apparent that most of the tungsten was emplaced at an early stage in the metallogenic history of the batholith.

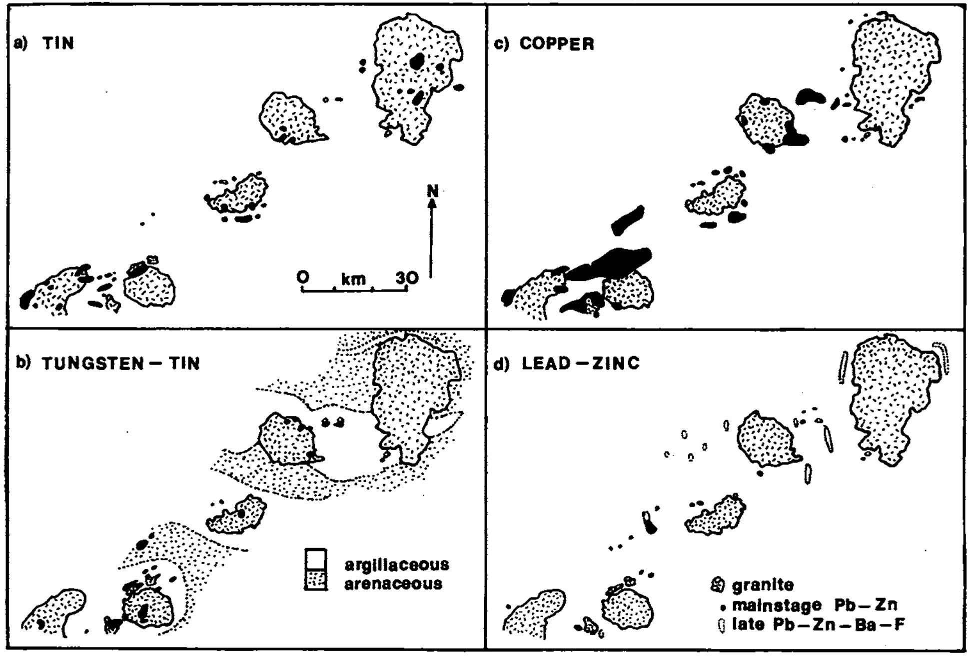

Fig. 3. Distribution of mainstage mineralisation in the batholith. The effects of Tertiary strike slip faulting have been removed (after Dearman, 1964).

Copper Occurs in all rock types as vein and replacement deposits. However, most economic concentrations occur in metavolcano-sedimentary host rocks. The main hypogene copper bearing phases are chalcopyrite and chalcocite with minor bornite, tetrahedrite, tennantite and bournonite, but extensive hypogene and supergene reworking of the ores has produced a great variety of mineral species. Average Cu values in Cornubian lithologies are as follows:

metasediments—	59ppm (Hosking, 1964) ,44ppm (median value, Henley, 1974b), 43ppm (Wilson and Jackson, 1977), 30ppm (Ahmad, 1977).
metabasalts—	56ppm (Floyd pers. comm. in Edwards, 1976), 85ppm (Floyd, 1968b), 33ppm (Wilson and Jackson, 1977), 58ppm (Ahmad, 1977).
granite—	99ppm (Ahmed, 1971), 108ppm (Hall, 1971), 9.5ppm (Fuge, 1974), 7ppm (Wilson, 1972), 4ppm (Wilson and Jackson, 1977), 21 ± 9ppm and 73 ± 18ppm (Ahmad, 1977).

These data indicate that the granites are depleted in Cu compared to their host rocks and also to average world values (Table I) for low Ca granites (Turekian and Wedepohl, 1961). Only minor copper was emplaced in the early veins, the main phase of copper emplacement occurring in the late veins, during and after cassiterite emplacement. The metal distribution map (fig. 3c) shows that ~80% of the main areas of Cu mineralisation lie outside the granite and the rest occur at, or near, the granite contact.

Arsenic Occurs in all lithologies as vein and replacement deposits of arsenopyrite. However, most economic concentrations occur in metavolcano-sedimentary host rocks. Data on the primary distribution in Cornubian lithologies is sparse, average values are as follows:

metasediments—	12ppm (Hosking, 1964), 30ppm (median value, Henley, 1974b).
granite—	65ppm (Hall, 1971), 33ppm (Wilson, 1972), 26ppm (mean of 7 granites, Jackson, 1976b)

These data indicate that the granites are enriched in As (Table 1) compared to published average values (Onishi, 1969). Some arsenopyrite was emplaced at an early stage eg. Tremearne aplite-pegmatite sheets. It is also a common phase in the early veins. However, most of the arsenic was emplaced in late veins during the cassiterite-sulphide and sulphide stages of mineralisation.

Lead Occurs in all rock types as vein deposits of galena. However, occurrences in granite are rare and all the main deposits (fig. 3d) occur in metavolcano-sedimentary host rocks well removed from granite. Average Pb values in Cornubian lithologies are as follows:

metasediments—	49ppm (Hosking, 1964), 51ppm (median value, Henley, 1974b), 14ppm (Wilson and Jackson, 1977).
metabasalt—	50ppm (Floyd pers. comm. in Edwards, 1976), <10ppm (Floyd, 1968a), 19ppm (Wilson and Jackson, 1977).
granite—	44ppm (Ahmed, 1971), 35ppm (Hall, 1971), 15ppm (Wilson, 1972), 13ppm (Wilson and Jackson, 1977).

These data indicate that all Cornubian lithologies are enriched in Pb compared to the average values (Table I) of Turekian and Wedepohl (1961). It is probable that there are two phases of lead—zinc mineralisation in the Cornubian ore-field. Alderton (1978) suggests that an initial, relatively minor phase of Pb-Zn mineralisation was emplaced during mainstage mineralisation but most of the economic concentrations of Pb and Zn were emplaced much later, in north-south trending fractures (cross-courses). These deposits are often associated with fluorite and baryte. Fluid inclusion populations in fluorite coeval with Pb-Zn minerals are different to those found in the earlier stage of Pb-Zn metallisation.

Zinc Occurs in all rock types as vein deposits of sphalerite. However, all economic concentrations occur in the metavolcano-sedimentary host rocks. Average Zn values in Cornubian lithologies are as follows:

metasediments—	245ppm (Hosking, 1964), 162ppm (median value, Henley, 1974b), 112ppm (Wilson and Jackson, 1977).
metabasalts—	347ppm (Floyd pers. comm. in Edwards, 1976), 66ppm (Wilson and Jackson, 1977).
granite—	63ppm (Ahmed, 1971), 103ppm (Hall, 1971), 45ppm (Wilson, 1972), 39ppm (Fuge, 1974), 47ppm (Wilson and Jackson, 1977).

These data indicate that all lithologies are enriched in Zn compared to the average world values (Table 1) of Turekian and Wedepohl (1961). Some zinc was emplaced during the pegmatitic stage eg. Halvosso, but most of the mainstage zinc mineralisation was emplaced during cassiterite-sulphide and sulphide stages of mineralisation. Most economic concentrations of zinc were emplaced much later and are not genetically related to batholith emplacement (Alderton, 1978).

To summarise, these data indicate that compared to the average values given by Turekian and Wedepohl (1961) and Onishi (1969), the granites are enriched in Sn, As, Pb and Zn but not Cu, the metasediments are enriched in Sn, Pb, Zn and As but not Cu.

DISTRIBUTION OF MINERALISATION

The following discussion is an attempt to describe the main types of mineralisation based on the space—time distributions shown in fig. 4. The various mineralisation phenomenon are described in their relative chronological sequence.

Phase I

Metasomatisms—large scale metasomatisms occurred within and adjacent to the batholith (fig. 4a) immediately before the emplacement of tin mineralisation. Potassium metasomatism (Stone and Austin, 1961) occurred throughout the whole of the upper portion of the batholith but was particularly intense in the roof and contact zones. K metasomatism probably overlapped the emplacement of aplite-pegmatites in the roof zone and in some instances it predated aplite dyke emplacement (Exley and Stone, 1964). Metallisation is not recognised to be associated with this phase of metasomatism but it undoubtedly marks the first stage in the mass transfer of material, by aqueous fluids, in the batholith.

Simultaneously, in the host rock envelope, internal metasomatism within suitable lithological units was in progress. The most responsive units were the metabasalts. Floyd (1965) described extensive metasomatism at Tater-Du and Jackson (1976b) described similar metasomatisms in the St. Just aureole. In both localities plagioclase, hornblende/actinolite hornfelses are replaced by garnet-magnetite assemblages, indicating an internal redistribution of Ca and Fe. The St. Just metasomatites contain up to 560ppm Sn and similar horizons along the northern margin of Dartmoor eg. Belstone Consols, contain disseminated arsenopyrite—pyrite—chalcopyrite mineralisation (Dines, 1956). In both the above cases the time of metal emplacement is not known.

These early metasomatisms were followed by extensive boron metasomatism both inside and outside the batholith. Contact zones were particularly susceptible to this type of metasomatism. It is also possible that quartz—tourmaline intrusive bodies were emplaced coevally with this activity. In Ca rich horizons, calc-silicate assemblages were produced, some of which show definite enrichment in Sn and Be. At St. Just discordant axinite—garnet veins contain up to 2050ppm Sn and 68ppm Be and represent the first evidence of Sn mineralisation in the district. This early phase of boron metasomatism may have been the immediate precursor to widespread Sn mineralisation.

Breccia pipes—Halls and others, (1977) have recognised a breccia pipe at Wheal Remfry clay pit in the St. Austell pluton. The elongate NNW trending 60×250m pipe is exposed for a vertical distance of 80m and is located at the intersection of NE and NW trending sheeted quartz—tourmaline vein systems. The polymictic breccia

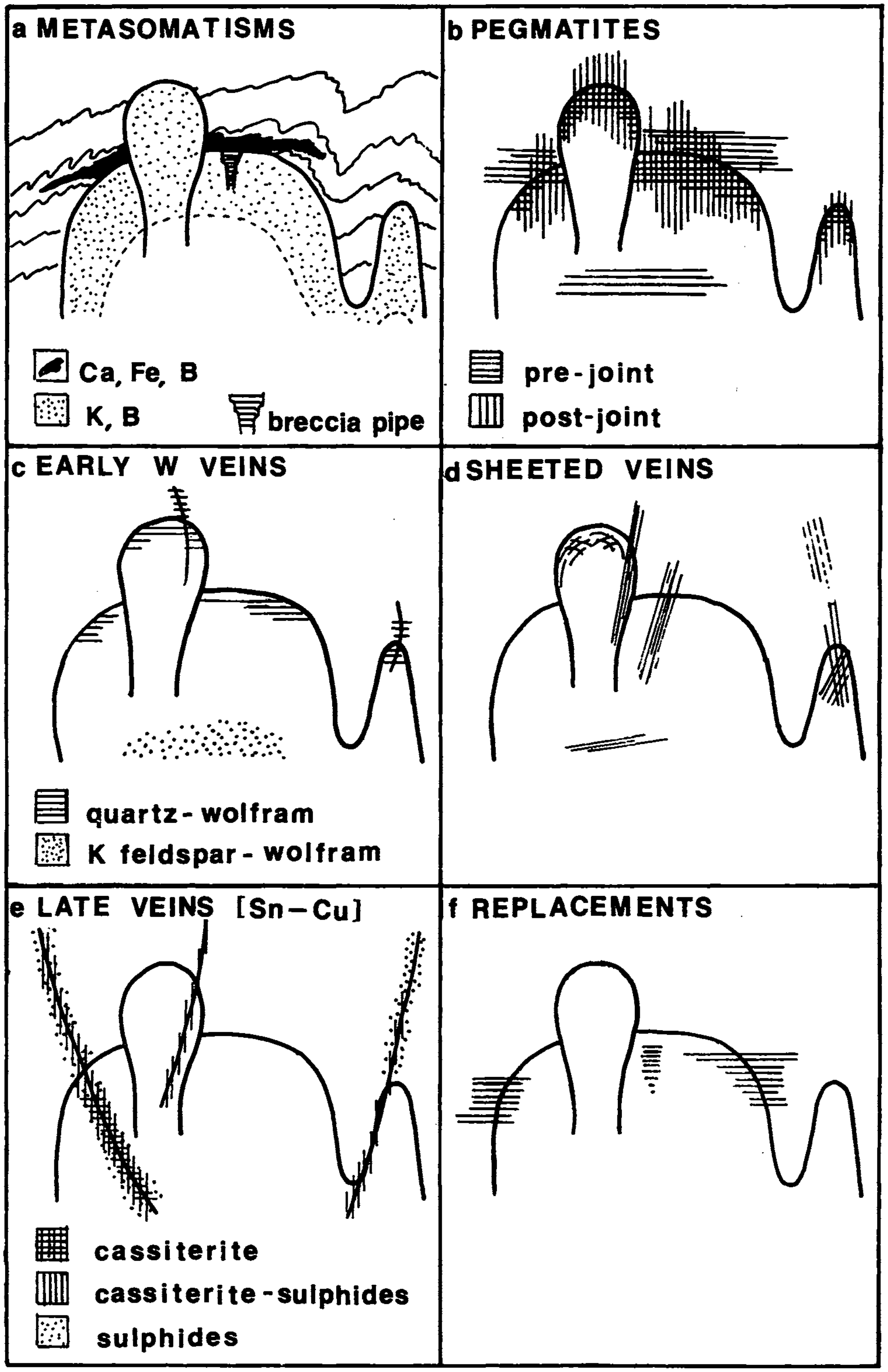

Fig. 4. Distribution and relative chronology of mainstage mineralisation phenomena.

consists of tourmalinised, kaolinised and silicified clasts of granite and hornfelsed pelite in a matrix of mineral and lithic fragments. Depth of emplacement was considered to be of the order of 1—1.5km.

The pipe closely resembles tourmalinised hydrothermal breccias associated with tin-bearing subvolcanic eruptives in the Bolivian eastern Cordillera (Sillitoe and others, 1975; Grant and others, 1977), and it is interpreted to represent the explosive release of volatiles during the transition from magmatic to hydrothermal stages of evolution in the pluton. The intense tourmalinisation associated with the pipe suggests that it is probably related to the boron metasomatisms of Phase I, and the structural control exerted by the intersecting sheeted vein systems suggests that these also formed during this phase.

Pegmatites—two types of pegmatite can be recognised in the batholith, early pre-joint pegmatites often associated with aplite, and post-joint pegmatites. Pre-joint pegmatites are confined to marginal sheets. eg. Tremearne (Stone, 1969) or the roof zone of a major pluton eg. Tregonning—Godolphin pluton (Stone, 1975). They comprise banded and comb-layered bodies composed of quartz, alkali feldspar, muscovite, biotite, Li mica, tourmaline, topaz, apatite and flourite. The Tremearne pegmatites are thought to have grown in the solid state by the metasomatic replacement of aplite (Stone, 1969).

Post-joint pegmatites occur in the margins and roof zones of several plutons. They usually comprise small podiform or lenticular bodies whose distribution is controlled by primary igneous cooling joints. The pegmatites may be monomineralic eg. the tourmaline pegmatites of Cape Cornwall, or multimineralic eg. the quartz, alkali feldspar, mica, tourmaline pegmatites in the same area. In the Carnmenellis granite, Penryn area, pegmatites in the Trovlis Quarry (Hosking, 1964) contain quartz, alkali feldspar, tourmaline, muscovite, Li mica, topaz, apatite, flourite, betrandite, chlorite, stilbite and chalcedony. Nearby, at Halvosso, pegmatites containing a similar silicate mineralogy also contain cassiterite, stokesite, sphalerite and pyrite (Jackson, 1978).

Although pegmatites in S.W. England are enriched in F, B, Li, Be and Sn no economic deposites are known.

Phase II

The earliest economic metallisation in the province comprises quartz-K feldspar-wolframite-arsenopyrite, quartz-K-feldspar-arsenopyrite ± cassiterite and quartz-wolframite ± cassiterite veins and sheeted vein systems associated with intense phyllic, or more rarely K feldspathic or tourmalinitic alteration haloes. Most of the tungsten was emplaced during this phase.

This style of mineralisation was emplaced at all structural levels in the batholith but was mainly restricted to small porphyry stocks and the contact zones of major plutons (fig. 4c & d). Mineralisation was structurally controlled by primary and secondary joint systems and occassional pre-batholith fissures.

The following ore-bodies are considered to represent this style of mineralisation at various structural levels in the batholith.

INTERNAL, AND INTERNAL CONTACT ZONES

Complex lode, South Crofty Mine—is a 2—5m wide, steeply dipping, lenticular body consisting of quartz-K feldspar-wolframite-arsenopyrite with associated phyllic and K feldspar alteration. The ore-body is differentiated into upper wolframite-arsenopyrite rich and lower wolframite-arsenopyrite poor zones. Subsequently cassiterite pyrite, chalcopyrite, stannite, scheelite (after wolframite) chlorite and carbonates were emplaced into the same ore-body (Hosking, 1964).

3A, B & C zone, South Crofty Mine—comprises numerous flat dipping, sub-parallel narrow veins containing a quartz-K-feldspar-wolframite-arsenopyrite assemblage with associated phyllic alteration (Hosking, 1964; Taylor, 1966).

Geevor Mine—numerous early fissure veins, in the deeper parts of the Geevor Mine vein system (—300m below surface), contain a vein paragenesis of quartz-K feldspar-arsenopyrite ± cassiterite associated with phyllic and, locally, K feldspar alteration eg. Coronation Lode, 14 level.

CONTACT ZONE

Buttern Hill Mines—the northern flank of the Bodmin Moor pluton contains several small tungsten prospects. One of them comprises a pegmatite vein containing quartz, K feldspar, topaz, muscovite and wolframite, with associated phyllic alteration (Dines, 1956).

Castle-an-Dinas Mine—exploited a 1m wide, NE trending, subvertical vein containing an assemblage of quartz-wolframite-tourmaline and associated with tourmalinised wallrocks. The vein is confined to metasediments, the base of it being truncated by a small granite cupola (Dines, 1956). Numerous granite veins (quartz-muscovite-topaz greisens) cut the lode. This vein is one of the few well documented examples of metallisation emplaced before the emplacement of the granite (Davison, 1919; Dines, 1956).

Balleswidden Mine—located in the roof zone of the Lands End pluton, exploited a group of NW trending fissure veins within a steep dipping sheeted vein system, and several irregularly shaped replacement bodies (Rowe & Foster 1887; Dines, 1956;). The narrow veins contain an assemblage of quartz-tourmalinefluorite-arsenopyrite-cassiterite-wolframite and are associated with intense phyllic alteration. The replacement ore-bodies comprise irregular shaped masses of greisen containing veinlets and disseminations of cassiterite-wolframite with minor arsenopyrite and pyrite.

PORPHYRY STOCKS AND CUPOLAS

Cligga Head Mine—exploited a complex, east-west trending, sheeted vein system located within a small (600 × 300m), granite porphyry stock (Scrivenor, 1903; Dines, 1956). Well developed, curved, primary flat lying joints, and to a lesser extent diagonal igneous joints and tectonic a-c joints, controlled the emplacement of quartz-wolframite-cassiterite-stannite-arsenopyrite-pyrite-chalcopyrite veins (Moore and Jackson, 1977) and associated phyllic-argillic alteration (Hall, 1971). The total vertical extent of mineralisation is 150m and most of the veins are confined to the stock.

Phase III

This phase represents the main stage of economic Sn (and Cu?) metallisation in the province. During this phase vein and replacement ore-bodies of quartz-cassiterite ± tourmaline or hematite and quartz-cassiterite-sulphides ± tourmaline, chlorite, hematite, flourite and alkali feldspar, associated with moderate phyllic, tourmalinitic, chloritic, hematitic, silicic or feldspathic alteration, were emplaced. Veins (lodes) are usually between 10cm–5m wide and occupy subvertical (60–90° dip) or occassionally low angled (50° dip), tensional or shear fractures, produced during or soon after batholith emplacement by the enlargement and dislocation of pre-existing joints and fractures. Veins often display, compositional variations along strike and dip, and internal structures such as crustification, symmetrical banding, vugs, brecciation and slikensides indicate that most veins had a complex tectonic history comprising alternating phases of dilatancy and shear. Economic tin mineralisation occurs over strike length of up to 2km and a dip length of up to 1km.

The following ore-bodies are considered to represent this style of mineralisation at various structural levels in the batholith.

INTERNAL, AND INTERNAL CONTACT ZONES

Main Lode, Dalcoath Mine—has been the most productive vein in the province (Dines 1956). The NE trending, vertical to 50° dipping, structure can be traced along strike for 1.5km and contains economic tin mineralisation for a dip length of over 1km. The vein varies in thickness from 0.3–12m and comprises highly brecciated granite veined by quartz, tourmaline and cassiterite in the deeper levels, and comby quartz, containing pyrite and chalcopyrite in the upper levels. Wallrocks are intensely brecciated and altered to an assemblage of quartz, sericite, tourmaline and chlorite. Longitudinal sections (Dines, 1956) distinguish upper copper rich and lower tin rich zones.

Simms Lode, Geevor Mine—trends NW, is usually less than 1m wide, dips steeply NE and is developed for a strike length of 1500m and a dip length of 250m. The sequence of mineralisation is as follows (Mr M. Mount. pers. comm.) quartz-tourmaline-cassiterite, quartz-hematite-cassiterite, quartz-carbonates-flourite-hematite. The associated alteration assemblage is quartz-sericite-tourmaline-hematite (Wilson, 1972).

B Lode—Wheal Jane Mine—occupies a shear zone in slates on the footwall of a quartz porphyry dyke (Rayment and others., 1971). The development and nature of the ore is structurally controlled by irregularities in the shape of the dyke, which are in turn controlled by pre-emplacement structures in the slates. The emplacement of the ore-body was complex, the most notable feature being the close relationship between cassiterite and sulphides. A typical lode assemblage comprises cassiterite, wolframite, arsenopyrite, pyrite, chalcopyrite, sphalerite, chlorite and flourite, associated with chloritised, silicified and tourmalinised wallrocks. Other parts of the ore-body comprise zones of massive pyrite and sphalerite.

REPLACEMENT MINERALISATION

In addition to fissure vein ore-bodies, numerous replacement deposits were formed in the granite and its envelope. Two morphological types of replacement can be recognised: pipes and sheets. Pipes are cylindroidal bodies of intensely altered rock with a maximum diameter of 20m and up to 200m in length. They may be vertical, inclined or horizontal and they are usually associated with a mineralized fissure. Sheets are much more lode-like in character. They are planar bodies of intensely altered rock usually on the footwall of a fault, below the intersection of two fissures or confined to a specific lithostratigraphical unit. They may be subvertical or subhorizontal, with dimensions up to 20m in width and 200m along dip and strike. Favourable sites for the development of replacement deposits occur a) in the roof of the pluton within a vertical ore-shoot b) at the margins of the pluton within an inclined ore-shoot c) outside the pluton at the intersection of a favourable lithological horizon eg. granite sheet, basalt flow etc. and the ore shoot. The ore assemblage is usually cassiterite in association with pyrite, chalcopyrite and arsenopyrite. Flourite, tourmaline, chlorite and quartz are the common gangue minerals. The associated alteration is variable but intense. The following assemblages have been recognised in replacement deposits: quartz-tourmaline,, quartz-sericite, albite-tourmaline-flourite, quartz-chlorite-tourmaline-alkali feldspar.

Great Carbona, St. Ives Consols—this irregular pipe shaped body in granite branched off the south wall of the Standard Lode and pitched SE at ~20° (Henwood, 1865; Collins, 1912; Dines, 1956; Hosking, 1969). Its maximum length was 238m and its diameter varied between 1–20m. Mineralisation comprised quartz, alkali feldspar, tourmaline, chlorite, flourite, cassiterite, chalcopyrite, pyrite, arsenopyrite associated with quartz-chlorite-tourmaline-alkali feldspar alteration.

Carbona, Levant Mine—an irregular shaped zone of replacement ~10m × 10m × 50m occurs at the intersection of a mineralised fissure vein with a granite sheet (Jackson, 1975). Mineralisation comprises disseminated cassiterite-sulphides (pyrite, chalcopyrite, arsenopyrite) and massive cassiterite and sulphides associated with intense alteration, albite, quartz, chlorite, tourmaline and flourite.

Grylls Bunny Mine, Botallack—a 20° dipping, metabasalt-pelite horizon, ~35m thick × 75m × 75m, contains several discontinuous lenticular mineralised horizons (Hawkins, 1820; Collins, 1912; Jackson, 1974). Four discontinous flat lying lenticular ore-bodies, each 1–4m thick are exposed. Each ore-body consists of an upper 0.3–1m thick bed of tourmaline–quartz-cassiterite and a lower <1m thick zone of chloritised amphibolite containing disseminated cassiterite.

Parka Mines—the ore-body comprises lenticular replacements of cassiterite 2–3m thick × 15m × 20m, within steeply dipping (60–70°) pelites. Mineralisation consists of quartz-cassiterite and the host rocks are extensively tourmalinised (Collins, 1912).

Phase IV

This phase is the least known of all the phases of mineralisation in the province. During this phase vein deposits of sulphides (pyrite, chalcopyrite, arsenopyrite galena and sphalerite) were emplaced and, in addition, it is probable that earlier sulphide ores were reworked. The metal bearing fluids utilised existing fractures and consequently the sulphide ores were emplaced into and overprinted earlier vein assemblages. Sometimes the fissures which host this style of mineralisation were opened for the first time to metal bearing fluids. In general, the mineralisation was emplaced under retreating thermal gradients and therefore it is usually emplaced at comparatively deep structural levels ie., within zones in which earlier Sn and W ores were emplaced.

The following examples are considered to represent this style of mineralisation.

Geevor Mine—is characterised by vein systems in which early quartz-cassiterite and cassiterite-sulphide assemblages are overprinted by a sulphide only stage of mineralisation (Garnett, 1962; 1963). The sulphide assemblage, chalcopyrite, pyrite, chalcocite with minor bornite, sphalerite and galena, was emplaced into the base of the existing cassiterite-sulphide ore shoot, with the net result that the maximum copper content in the veins occurs below the maximum tin content.

Southern boundry fault, Cligga Stock—a major high angled reverse fault, which forms part of the southern margins of the Cligga granite stock (Moore and Jackson, 1976), contains an assemblage of pyrite and chalcopyrite. Mineralisation in the vein was emplaced at the same structural level as an earlier Sn-W phase.

A summary of the main ore and alteration assemblages associated with each phase of mineralisation is presented in table 2.

ALTERATION PATTERNS

Numerous studies of alteration haloes surrounding mainstage veins have been made (Webb, 1947; Rao, 1952; Garnett, 1962; Hall, 1971; Rayment and others, 1971; Wilson 1972; Cotton, 1973; Alderton, 1976; Jackson, 1976; Moore, 1977). These studies indicate that there are several, widely distributed, fundamental alteration patterns in the batholith. The significance of the alteration pattern is that it indicates the degree of fluid—wallrock interaction and therefore controls the level of activity of many components in the vein fluids, which in turn affect the stability of metal complexes being transported by the hydrothermal fluids.

Alteration haloes surrounding mainstage veins in granitic rocks contain either quartz-sericite-illite, quartz-tourmaline, quartz-alkali feldspar, quartz-chlorite, quartz-hematite-limonite or quartz-kaolinite or combinations of these assemblages. Argillaceous wallrocks are altered to assemblages containing combinations of quartz, chlorite, sericite-illite, tourmaline, alkali feldspar, biotite, hematite-limonite, montmorillonite, kaolinite and calcite, while basaltic wallrocks are altered to assemblages of quartz, chlorite, tourmaline, axinite, sphene, biotite, alkali feldspar, calcite, epidote and hematite-limonite. Alteration envelopes are often polyphase in nature.

A complete discussion of wallrock alteration is beyond the scope of this review however, it is worth noting that throughout the batholith, mainstage veins are characterised by the ubiquitous development of quartz-sericite-illite (phyllic) alteration haloes. The significance of this type of alteration was noted by Wilson (1972a, b) who suggested that the main chemical process involved in producing the assemblage was hydrogen ion metasomatism involving an exchange of H^+ in the fluids for Na^+, K^+, & Ca^{++} in the wallrocks. The ubiquitous development of this assemblage also indicates that in general the cation /H^+ ratio in the vein fluids was below the permissible limits for the stability of alkali feldspar (Hemley and Jones, 1964).

Table 2 summarises the most characteristic alteration minerals associated with each phase of mainstage mineralisation. The following generalisations can be made;

Phase II	veins systems at high structural levels are associated with intense phyllic± tourmalinitic alteration, while deeper veins are associated with phyllic and/or K feldspar alteration envelopes.
Phase III	veins and replacements are associated with weak to moderate phyllic alteration with coeval tourmalinitic, chloritic, alkali feldspathic and hematitic alterations.

TABLE 2

MINERALISATION AND ALTERATION ASSEMBLAGES OF MAINSTAGE MINERALISATION

ab—albite, alk. fel—alkali feldspar, ap—apatite, ars—arsenopyrite, ax—axinite, be—beryl, bi—biotite, bt—bornite, cal—calcite, cas—cassiterite, ch—chalcocite, chl—chlorite, cp—chalcopyrite, diop—diopside, ep—epidote, fl—flourite, gal—galen, gnt—garnet, hem—hematite, ido—idocrase, ka—kaolinite, li. m—lithium mica, lim—limonite, mag—magnetite, mo—montmorillonite, mu—muscovite, or—orthoclase, py—pyrite, qtz—quartz, sch—schelite, se—sericite, sp—sphalerite, sph—sphene, stan—stanite, stk—stokesite, tm—tourmaline, wo—wolframite, zin—zinnwaldite.

MINERALISATION PHENOMENON	NATURE OF MINERALISATION	MINERALISATION ASSEMBLAGE	ALTERATION ASSEMBLAGE
PHASE I METASOMATISMS	Pervasive and fracture controlled K & B. metasomatism (granite) Ca, Fe & B metasomatism (aureole)	qtz, or, mu. qtz, tm±alk. fel. gnt, mag, cal, diop, ido, tm, ax,	
PEGMATITES	Pre and post-joint replacement and void fill	qtz, or, ab, tm, mu, bi, Li. m, ap, be, cas, wo, ars, sp, py, stk, to, fl, bt,	qtz, or, se.
PHASE II	Joint and pre batholith fracture controlled fissure veins	qtz, or, wo, ars. qtz, wo, tm±cas, qtz, or, cas, ars.	qtz, se. tqz, or, se.
EARLY VEINS	Joint controlled sheeted fracture systems	qtz, wo, cas±tm, to, zin, mu, mo stan, py, ars, cp, bi, be, ap, fl,	qtz, se/Li m±tm. qtz, zin, to,
PHASE III & IV LATE VEINS	Joint controlled major fractures displaying both dialational and shear features	qtz, or, ab, mu, tm, chl, fl, hem, lim, mag, cas, wo, sch, ars, py, pyr, stan, cp, ch, bn, sp, gal, Bi-Sb-Ag-Pb-Cu-As-Fe sulphosalts minor Au, Ag, Co, Ni, U phases	qtz, se, tm, chl, hem-lim, or, ab, mont, ka, (granite). qtz, se, tm, chl, hem-lim, cal, ka, or,ab, mont (pelite) qtz, tm, or, ab, chl, hem-lim, cal, sp, mont, bi,
REPLACEMENTS	Pipes, sheets and irregularly shaped zones of alteration and massive to disseminated mineralisation	qtz, wo, cas, py, ars, cp [granite] qtz, cas. py. cp. ars±cas [basalt] qtz, cas, py, cp, ars, sph, gnt [calc-pelite, limestone]	qtz, se. qtz, tm, qtz, chl, ab, fl, tm. qtz, tm. gnt, ax, amph, chl, sph, ep, cal. qtz, tm, cal, ax, sph, ep.

Phase IV veins are associated with weak phyllic and coeval chloritic and hematitic alterations.

CORNUBIAN KAOLINITE DEPOSITS

The debate concerning the origin of Cornubian kaolinite deposits has recently been revived (Sheppard, 1977; Exley, 1976; Badham and others, 1976; Bristow and Wilson, 1977).

The geometry and composition of most of the Cornubian kaolinite deposits are consistent with formation in a post magmatic plutonic environment. Typical characteristics are: conical or trough-like shape, pervasive alteration extending to depths of over 200m, sharp contacts with unaltered material, spatially associated with minealised fissures or sheeted joint systems, alteration assemblages containing a limited number of phases (quartz-kaolinite-illite-sericite ± montmorillonite), sometimes structurally overlain by unaltered granite.

In spite of these gross geological features Sheppard (1977) has argued convincingly in favour of a low temperature, supergene origin for these deposits, based on oxygen and hydrogen isotopic ratios in kaolinites. $^{18}O/^{16}O$ and D/H ratios in kaolinites fall within a very restricted range close to the kaolinite weathering line. These data are compatible with formation in a warm temperate weathering environment, possibly during the early Tertiary, at temperatures of $<20°C$.

Fluid inclusion studies of argillised granite support both hydrothermal and low temperature supergene origins (Charoy, 1975; Jackson, 1976b.). Faced with such conflicting geological evidence it seems probable that argillisation occured in two stages (Bristow, 1975); an initial phase of hydrothermal, pervasive, weak argillic phyllic alteration followed by a low temperature, supergene (?) phase of pervasive altealteration, whose distribution was controlled by the previous phase of alteration.

ZONING

The Cornubian ore-field has often been cited as a classical example of metal zoning on the district and local scales, Dewey, (1952), Davison, (1927) Hosking 1951 & 1964) and Dines (1956) all support the concept of Sn, Cu, Pb-Zn, Fe-(Mn, Sb) metal zones arranged sequentially around emmanative centres. This monoascendent pattern, although possibly correct for a single metallogenic event, is grossly oversimplified when a single fissure system or district is considered in detail. Many workers have recognised the polyphase nature of mineralisation in the province and the model proposed here subdivides the emplacement of mainstage metallisation into three distinct events. In addition, Mesozoic and Tertiary metallisation events, either superimposed on earlier vein parageneses or localised in separate structures, and the reworking of earlier ores during these later events, combine to produce a very complex metal distribution pattern on both local and district scales. However, although the simplistic zoning models are grossly oversimplified there is undoubtedly zoning on a district scale in terms of the style of mineralisation. The St. Just district is an example of this type of zoning (Jackson 1976b.) in which the nature of the ore body, the ore minerals and the alteration assemblages vary according totheir position in the vein system (fig. 5).

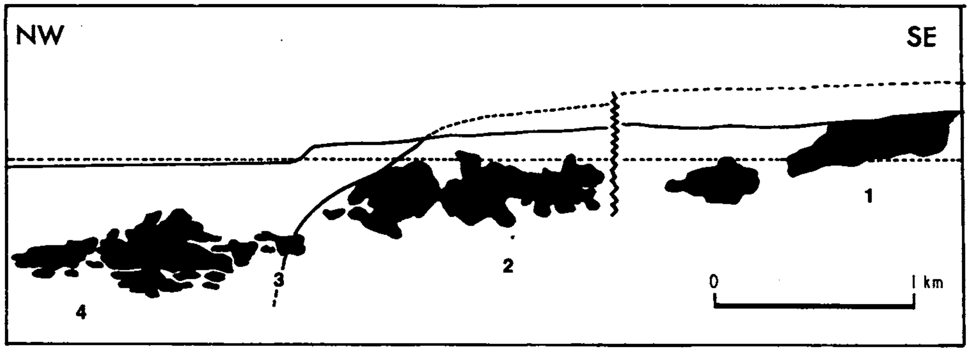

Fig. 5. Ore deposit zoning in the St. Just district (after Jackson 1976b.). A NW-SE composite longitudinal section through the Geevor-Levant-Balleswidden mine vein systems. Zones 1–4 are characterised by the following styles of mineralisation:

1) Sheeted vein systems and minor veins and replacements of quartz-cassiterite-wolframite associated with intense phyllic alteration.
2) Fissure veins of quartz-cassiterite, cassiterite-sulphides and sulphides associated with moderate phyllic, tourmalinitic, chloritic, feldspathic and hematitic alterations.
3) Fissure veins, stockworks and replacements of quartz-cassiterite, cassiterite-sulphides and sulphides associated with phyllic, feldspathic, chloritic, tourmalinitic alterations.
4) Fissure veins of quartz-cassiterite, cassiterite-sulphides and sulphides associated with weak phyllic and chloritic alterations.

LITHOLOGICAL CONTROLS

It is obvious from the preceding sections that metallisation is not uniformly distributed throughout the batholith. Figures 3 and 4 show that most of the metallisation, with the exception of the N. Devon ore-field, lies within 2 km of the roof and margins of the major and minor granite intrusives. But within this fundamental spatial framework there is a distinct lithological control on the distribution of metallisation. Essentially, there are four major lithologies in the peninsula; granite, argillite, arenite and basalt.

Without recourse to a statistical analysis it is apparent from fig. 1 and 3 that the arenaceous units are almost devoid of extensive mineralisation. Most of the tin-tungsten mineralisation is confined to granitie or occurs in argillaceous rocks close to the granite contact. Even in the Cligga Head-St. Agnes area where Sn-W mineralisation is emplaced in the predominantly arenaceous Gramscatho unit, the rocks which surround the intrusives and host the mineralisation are dominantly argillaceous. In addition, most of the copper mineralisation is confined to argillaceous horizons, and in particular, to sequences of interbedded argillite and basalt close to granite intrusives.

On the mine scale there are many examples of mineralisation being confined to a particular lithology. At Cligga Mine (Dines, 1956), fissures which are mineralised in granite become barren in the hornfelsed slates. Similarly at West Chiverton Mine (Dines, 1956), Pb-Zn-Ag ore is almost totally confined to argillaceous beds within an interbedded sequence of argillaceous and arenaceous rocks.

Such regional and local associations may be due to a number of factors such as: differences in response to brittle deformation, differences in the degree of chemical reactivity or even differences in the original metal content of the host rocks. These factors are discussed in more detail in the following sections.

FRACTURE SYSTEMS

The distribution of fracture systems exerted a fundamental control on the distribution of mineralisation. A majority of the fractures which host mineralisation are steep dipping and oriented parallel to the axis of the batholith (fig. 6, after Dines, 1956; and Hosking, 1964). Two families of hypothermal and mesothermal veins can be recognised: main lodes and caunter lodes. The strike of both sets of veins is approximately parallel but locally they intersect at acute angles. Subsurface exposures indicate that the main lodes are cut and displaced by the caunter lodes, and together they constitute a modified conjugate system of normal faults and extensional fractures. Both families of veins are cut and displaced by N-S trending strike slip fractures (cross-courses) which often contain epithermal Pb-Zn and Fe±U mineralisation.

Webb (1947) invoked Emmons (1934) theory, of explosive hydraulic fracturing within a N-S compressional stress field, to explain the origin of the vein systems.

Moore (1975) analysed the stress distribution during prophyry dyke and vein formation (fig. 6b) based on the assumption that dykes and veins occupy fractures produced by normal faulting during batholith emplacement. Comparisons of the vein lode stress trajectory pattern, with the theoretical models of Roberts (1970), indicate that the vein configuration resulted from the interaction of hydraulic stresses, exerted by the mobile cores of the major granitic plutons, with the regional confining stress field. The regional stress field was such as to control the emplacement of the batholith and induce strongly elongated fracture systems parallel to the E-W to NE-SW axis of the batholith. In the case of the Lands End pluton a crude radial fracture pattern was developed as a result of the internal hydraulic pressures overcoming the regional stress field.

The following important points emerge from this study:

1. Stress distribution during dyke and vein formation was similar.
2. The distribution of stress around individual plutons was such as to produce rupture in the flanks of the pluton rather than the roof. Once a sector failed it continued to rupture.
3. Other important structural traps occur in subsidiary or parasitic stocks and ridges situated on the flanks of the major intrusions. Fracture systems in these small bodies were usually related to the much larger subjacent ridges, although small stocks modified the regional stress field (Moore and Jackson, 1977).
4. The major plutons were mechanically independent as is evidenced by cross-cutting relationships of vein systems developed by different plutons.
5. The orientation of the stress field of each pluton varied both in space and time. Cross-sectional models indicate that although normal faults were developed at high structural levels, oblique and strike slip faults develop in the steep dipping flanks of the pluton at deeper structural levels.

Detailed field studies indicate that within granite intrusives primary joint systems often control the orientation and distribution of fissure veins. At Geevor Mine, Garnett (1962) concluded that WNW and NW trending, primary and secondary joints, formed within a predominantly horizontally oriented maximum compressive stress

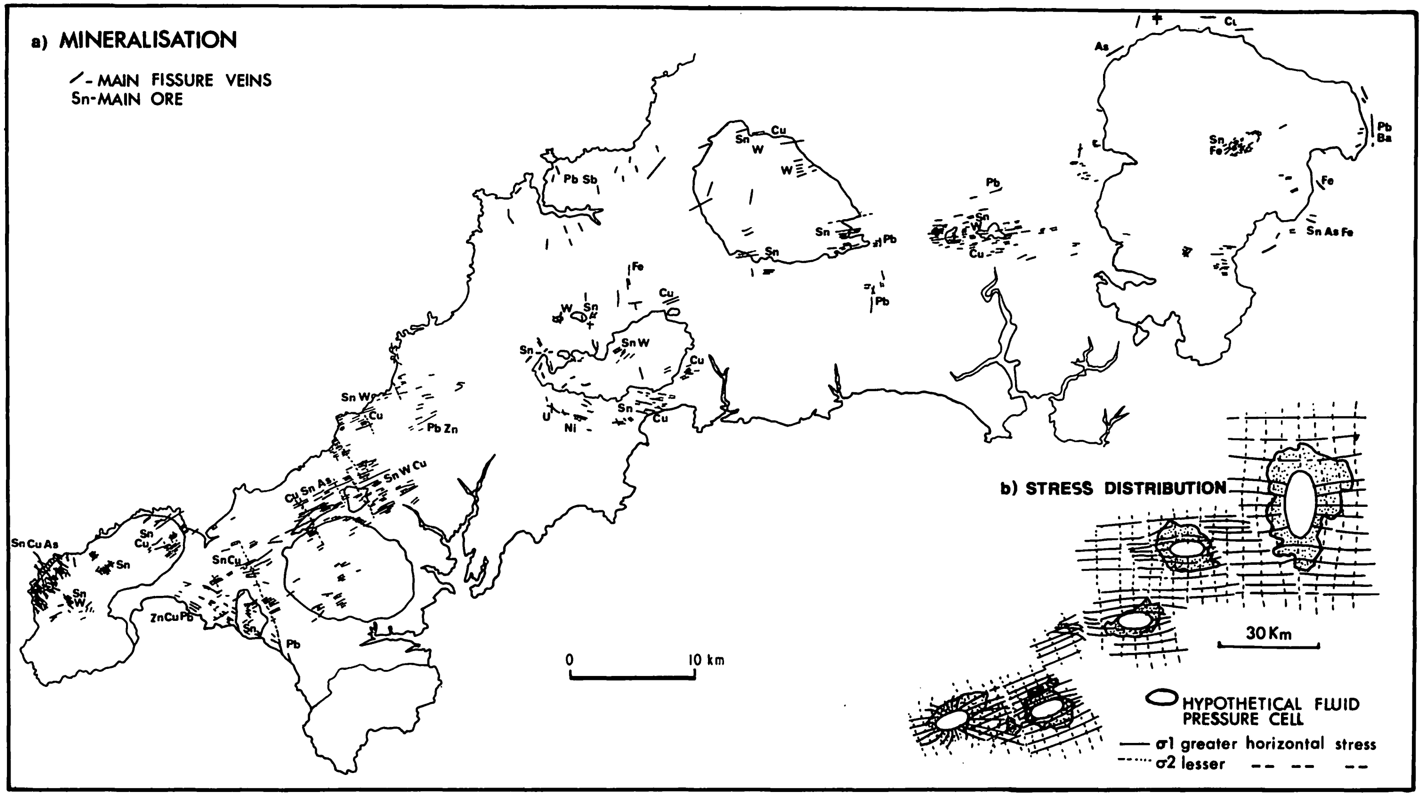

Fig. 6a. Distribution of main fissure veins (after Dines, 1956; Hosking, 1964)
Fig. 6b. Stress distribution during vein formation (after Moore, 1975)

field, were enlarged, dislocated and preferentially mineralised within a predominantly vertically oriented maximum compressive stress field. In the Cligga porphyry stock, E-W trending, curved primary, flat-lying joints were preferentially mineralised (Moore and Jackson, 1977).

Similarly, in the hornfelsed metavolcano-sedimentary envelope, joint systems, produced simultaneously with batholith emplacement, and often aligned parallel to primary igneous joint systems, controlled later fissure vein systems. Studies at Levant Mine (Jackson, 1976b) suggest that the Geevor Mine fissure systems were extended into the aureole by this mechanism.

Pre-emplacement structures in the aureole such as major lithological contacts, regional cleavages and foliations, and major fractures were locally important in controlling later fissure vein development, and they were often responsible for local irregularities in individual vein systems. Within an individual vein system or fissure the nature of the fracture itself ie., degree of fracturing, attitude of the fissure and nature of fissure intersections, exerted a fundamental control over the distribution of mineralisation (Garnett, 1966; Taylor, 1966). The reason for such a correlation between metal distribution and fissure structure is undoubtedly the direct effect such mechanical features had on promoting or restricting the flow of hydrothermal fluids through the vein system.

HYDROTHERMAL SYSTEMS

Numerous fluid inclusion studies (Little, 1960; Sawkins, 1966; Bradshaw and Stoyel, 1968; Alderton, 1976 and 1978; Jackson, 1976; Jackson and Rankin, 1976 and Jackson and others, 1977) and O & H isotopic studies (Sheppard, 1977); indicate the vein minerals were transported to their present location by hot, saline, aqueous meteoric fluids. Therefore, the disposition of hydrothermal systems within the batholith was also of fundamental importance in ore localisation.

The location and form of individual hydrothermal systems was controlled by such factors as the availability of meteoric groundwaters, rock permeability and pressure-temperature regimes in and around the intrusive body. Hydrothermal convection and mass transport of material will occur if there is a localised heat source and the environment is permeable and water saturated. The mineralised vein systems in the batholith indicate that these conditions were satisfied.

Mathematical models of hydrothermal convection cells, developed around and within fractured intrusives, have been produced by Elder (1976) and Cathles (1978). These theoretical models indicate that, for moderate sized intrusives (3km diameter), convection is concentrated at the periphery of the pluton, and in very large plutons fluid circulation may even be confined to the host rock envelope. The model of Cathles (1978) is considered to approximate the prevailing conditions during the emplacement of the Cornubian batholith. Fig. 7b shows the predicted flow conditions around a 3.4km diameter fractured intrusive emplaced at a temperature of 700°C and depth of 3km into water saturated permeable host rocks (permeability 0.25 md). The following points emerge from this model:

1. The convection cell is developed at the margins of the intrusive body.
2. The diameter of the cell is of the order of several kilometers (a larger intrusion will generate a much larger cell).

3. The pattern of flow within the cell is such that water is drawn into the lower flanks of the intrusive and expelled along subvertical to steeply inclined pathways through the flanks of the intrusive.

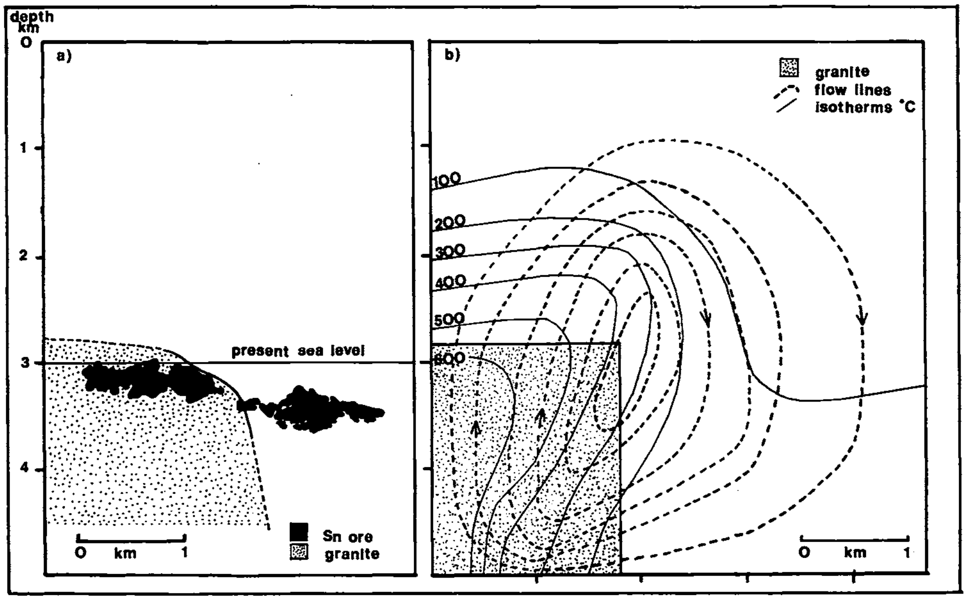

Fig. 7a. Distribution of economic tin mineralisation in the Geevor-Levant vein systems (after Garnett, 1962)

Fig. 7b. Flow patterns in a hydrothermal convection cell associated with a small intrusive (after Cathles, 1978)

For comparison with the theoretical model the distribution of Sn ore in the Geevor-Levant fissure vein system on the NW flanks of the Lands End pluton is shown in fig. 7a. Clearly, there are gross similarities between the size, shape and position of the cell relative to the intrusive, in the theoretical model, and the actual distribution of mineralisation in the Geevor-Levant area.

Assuming the individual plutons comprising the batholith were emplaced into a water saturated environment then the critical factor in producing a hydrothermal convection system would be local permeability ie., degree of local fracturing. Although no quantitative comparitive studies of the degree of fracturing in mineralised and unmineralised areas have been made, the stress distribution analysis of Moore (1975) predicts that the areas of most intense fracturing will occur on one or more of the steeply dipping flanks of an intrusive body. There is, therefore, a coincidence between the areas most likely to be fractured and the area in which an intrusive body is most likely to establish a hydrothermal convection cell.

The distribution of main stage mineralisation in SW England (fig. 3), indicates that there must have been several major convection cells located on the flanks of the major plutons. The disposition of the larger cells was as follows;

1. NW and NE flanks of the Lands End pluton.

2. A major NE trending cell centred on the Carn Marth-Carn Brea ridge and the northern flanks of the Carnmenellis pluton-extending SW to the NE flank of the Lands End pluton and NE to the Wheal Jane area.
3. A NE trending cell running through the Mounts Bay area—Godolphin granite and the southern flanks of the Carnmenellis pluton.
4. A NE elongated cell centred on the St. Agnes—Cligga Head area.
5. Minor cells on the northern and southern flanks of the St. Austell and Bodmin plutons.
6. An elongated cell centred on the Kit Hill—Hingston Down ridge.

Areas which are essentially devoid of mineralisation but which might be expected to fulfill the requirements needed to form a convection cell occur on the SE margins of the Carnmenellis pluton and the NE and SE flanks of the Dartmoor pluton.

Although the gross mineralisation pattern probably approximates to theoretical predictions for the shape and location of the hydrothermal cell, the actual distribution of mineralisation within individual vein systems was controlled by very localised physico-chemical conditions. The state of research into local fluid conditions during mineralisation is at such a preliminary level that very few meaningful comments can be made. However, fluid inclusion studies do indicate that temperature, pressure, salinity and fluid compositions varied in space and time. A more complete discussion of the nature of the hydrothermal fluids will be presented elsewhere (Alderton and others, in prep.) but the most critical fluid factors in localising metal distribution are temperature eg., most cassiterite was deposited in the range 300–500 °C, and salinity eg., most cassiterite was deposited in the range 5–25 equivalent wt. % NaCl. Boiling within the vein systems was not a common phenomenon and therefore was not a significant factor in localising ore.

The life span of an active hydrothermal system associated with a small intrusive is ~10–20,000 years (Elder, 1976; Cathles, 1978). This suggests that mainstage mineralisation would occur simultaneously with or soon after batholith emplacement (~280m.y. B.P) Field observations indicate that some of the early veins pre-date the emplacement of porphyry dykes and cupolas, and many early veins are localised in non-tectonic primary igneous joint systems. These indications, that the earliest phases of mineralisation were coeval with batholith emplacement, are supported by K-Ar age determinations (Miller and Mohr, 1964; and Alderton and others in prep.). However, most of the mineralisation was emplaced after the deep fracturing of the batholith (~270m.y. B.P.). In addition there were numerous hydrothermal rejuvenations throughout the Mesozoic and Tertiary (Pokley, 1964; Darnley and others, 1965; Mitchell and Halliday, 1976; Halliday, 1977).

ORIGIN OF ORE METALS

The problem of the origin of ore metals associated with acid intrusives is of course not confined to S.W. England. The ore metals could have been derived from the following sources.

1) the metals were derived by partial melting of crustal/mantle (?) rocks, transported to the upper crust along with the granite melt, concentrated in a residual granite melt and then emplaced hydrothermally.

2) the metals were derived by partial melting of assimilated upper crustal rocks, retransported into the upper crust along with late pulses of magma, concentrated in a residual magma and then emplaced hydrothermally.

3) the metals were derived by hydrothermal leaching of upper crustal rocks (granites, metasediments and metavolcanics).

Supporting evidence for a direct genetic link between the acid intrusives and the ore metals is the metal rich nature of the intrusives themselves. The granites are geochemically highly specialised and enriched in Sn, F, B and Li. In addition there is some evidence for increased metal enrichment in the late acid intrusives, an indication that the residual magmatic fractions were being enriched in incompatible trace metals. The close spatial association of cassiterite-wolframite ores with *small* porphyry stocks also suggests a genetic relationship between ores and intrusives. However, even if the ore metals were concentrated in a residual magma it seems likely that they were transported to their present positions by meteoric hydrothermal fluids.

Another possibility is that the metals were derived by partial melting of stoped upper crustal rocks, Ahmad (1977) suggested that this mechanism could have produced the copper ore-bodies. If an assumption is made that 25% of the granite magma was derived by hostrock assimilation then 4681.5km^3 of granite was produced in this way. Assuming a pelite/basalt ratio of 25:1 with average copper contents of 30 and 50ppm respectively, with 100% efficiency of Cu extraction, 395430×10^3 tons of copper could have been produced. An amount 300 times greater than the total recorded recovery of copper from the whole province.

A similar estimate for the amount of tin that could have been derived in the same way, based on the assumption that all the tin from 4494km^3 of pelite with an average Sn content of 15ppm was liberated and concentrated, gives a value of 182007×10^3 tons. An amount 90 times greater than the total recorded recovery.

Alternatively the metals could have been derived by hydrothermal leaching of upper crustal rocks. Similar order of magnitude calculations to those above suggest that this may be a valid mechanism for producing large amounts of the required ore-metals. For example a small cylindrical convection cell 5km in diameter and 5km long could leach 98.2km^3 of rock. If the cell is located on the periphery of an intrusive and leaches a volume of rock comprising 1/3 granite (density 2.6, average 15ppm Sn and 10ppm Cu) and 2/3 pelite (density 2.7, average 17ppm Sn and 40ppm Cu) then with 100% efficiency 4281×10^3 tons of Sn and 7916×10^3 tons of Cu could be liberated.

These order of magnitude calculations clearly indicate that the metals could have been derived from one of several sources; possibly different metals being derived from different sources. The specialised nature of the intrusives themselves does however suggest a magmatic origin for at least the Sn-W ores. It therefore seems likely that both magmatic and hydrothermal processes contributed to the formation of the ore-bodies.

CONCLUSIONS

Each major intrusive displays its own spectrum of mineralisation phenomena suggesting that each had the potential to develop mineralisation independently. The distribution of mainstage metallisation was controlled by three major factors.

1) magmatic-hydrothermal evolution of each major intrusive
2) structural evolution (brittle deformation) of each intrusive and its metamorphic envelope
3) development and evolution of hydrothermal systems in and around each intrusive.

The essential structural and compositional features of the mineralisation phenomena suggest that mainstage mineralisation was accomplished in four distinct phases.

I) Pervasive K and B metasomatisms and emplacement of mainly barren pre and post-joint pegmatites and rare hydrothermal breccias.

II) Emplacement of quartz-wolframite ± cassiterite, quartz-Kfeldspar-wolframite-arsenopyrite ± cassiterite veins and sheeted vein systems, associated with intense phyllic, K feldspathic and tourmalinitic alterations. Veins controlled by primary igenous cooling joints, early secondary tectonic joints and rarely by pre-batholith faults.

III) Emplacement of quartz-cassiterite ± tourmaline, hematite, and quartz-cassiterite-sulphides ± tourmaline, chlorite, fluorite and alkali feldspar veins and replacements, associated with weak to moderate phyllic, tourmalinitic, chloritic or feldspathic alterations. Veins controlled by dislocated and enlarged primary and secondary joints.

IV) Emplacement of sulphides, pyrite-chalcopyrite-galena-sphalerite. Mineralisation was often localised in the earlier vein systems but was emplaced at varying structural levels relative to the earlier phases of mineralisation.

Metallisation is unevenly distributed throughout the batholith, a majority of all types being confined to granitic or argillaceous lithologies. All the main lithologies are enriched in Sn, Pb and Zn but not Cu, compared to published average values.

The actual distribution of mineralisation on the local scale was probably the result of the interaction of many factors, structural, genetic and physico-chemical. The principal ones were as follows;

1) magmatic-hydrothermal history of the intrusive
2) degree, location and nature of fracturing
3) location and nature of meteoric hydrothermal convection systems
4) physico-chemical conditions within the vein environment
5) original metal content of the various lithologies (?)

The distribution of vein controlled mineralisation closely approximates the theoretical models for the development of fractures and hydrothermal convection systems around small intrusive bodies.

Wallrock alteration assemblages suggest that the net result of fluid-wallrock interactions was the exchange of H^+ ions for base cations. However locally, fluid-wallrock interactions were dominated by cation exchange reactions.

Order of magnitude calculations indicate that Sn and Cu ores could have been derived by either hydrothermal leaching or partial melting of upper crustal rocks.

ACKNOWLEDGEMENTS

This review has benefited considerably from many discussions with friends and colleagues and in particular with Dave Alderton, Alex Halliday, John McMoore, Simon Sheppard and Ian Wilson. I am indebted to these and many other people who have helped me during my involvement with Cornubian geology.

I would also like to thank Mr Saleem Kazi who helped prepare the manuscript.

REFERENCES

AHMAD, S.N., 1977. The Geochemical distribution and source of copper in the metalliferous mining region of southwest England. *Min. Deposita,* 12, 1–21.

AHMED AWAD KARIM, M.A., 1971. *The distribution of some major and trace elements in the granites of W. Cornwall. Unpub.* MSc. thesis, Camborne School of Mines, Camborne.

ALDERTON, D.H.M., 1976. *The geochemistry of mineralisation at Pendarves Mine and other Cornish areas.* Unpublished Ph.D. thesis, London Univ.

ALDERTON, D.H.M., 1978. Fluid inclusion data for lead-zinc ores from south-west England *Trans. Instn. Min. Metal.* Sect. B, 87, B132–135.

ALDERTON, D.H.M., and JACKSON, N.J., 1978. Discordant calc-silicate bodies from the St. Just aureole, Cornwall. *Min. Mag.,* 42, 427–434.

ALDERTON, D.H.M., HALLIDAY, A.N., JACKSON, N.J., and SHEPPARD, S.M.F., Evolution of hydrothermal activity in the Cornubian batholith of southwest England. (in prep.).

BADHAM, J.P.N., STANWORTH, C.W. & LINDSAY R.P., 1976, Post-emplacement events in the Cornubian batholith. *Econ. Geol.,* 71, 534–539.

BRADSHAW, P.M.D., and STOYEL, A.J., 1968, Exploration for blind orebodies in southwest England by the use of geochemistry and fluid inclusions. *Trans. Instn. Min. Metal.,* Sect. B, B144–152.

BRISTOW, C.M., 1975. Diagnostic characteristics which can be used in the field to differentiate types of kaolinising process. In the *Proceedings of the Kaolin Symposium.* Exeter 1974.

BRISTOW, C.M., & WILSON, I.R., 1977, Post-emplacement events in the Cornubian batholith. A reply. *Econ. Geol.,* 72, 307–310.

CATHLES, I.M., 1978, An analysis of the cooling of intrusives by groundwater convection which includes boiling. *Econ. Geol.,* 72, 804–826.

CHAROY, B., 1975, Ploemeur kaolin deposit (Brittany): an example of hydrothermal alteration. *Petrologie,* 1. No. 4. 253-266.

COLLINS, J.H., 1912, Observations on the west of England mining region. *Trans. R. Geol. Soc. Corn.,* 14.

COSGROVE, M.E., & ELLIOT, M.H., 1977, Supra—batholithic volcanism of the south-west England granites. *Proc. Ussher Soc.,* 3, 391–398.

COTTON, M.T., 1973, *Mineralisation and wallrock alteration in west Cornwall, with particular reference to Mount Wellington Mine.* Unpub. Ph.D thesis, London Univ.

DARNLEY, A.G., ENGLISH, T.H., SPRAKE, O., PREECE, E.R. & AVERY, D., 1965. Ages of uraninite and coffinite from southwest England. *Mineral Mag.,* 34, 159–176.

DAVISON, E.H., 1919. On the geology of Castle-an-Dinas and Belowda Beacon, *Trans. Roy. Geol. Soc. Corn.,* 14, 269–285.

DAVISON, E.H., 1927. Recent evidence confirming the zonal arrangement of minerals in the Cornish lodes. *Econ. Geol.,* 22, 475–479.

DEARMAN, W.R., 1964. Wrench faulting in Cornwall and south Devon. *Proc. Geol. Ass. Lond.*, 74, 265–287.

DEWEY, H., 1925, The mineral zones of Cornwall. *Proc. Geol. Assoc.*, 36, 107–135.

DINES, H.G., 1934, The lateral extent of the ore-shoots in the primary depth zones of Cornwall. *Trans. Roy. Geol. Soc. Corn.*, 16, 279–296.

DINES, H.G., 1956, *The metalliferous mining region of south west England.* Mem. Geol. Surv. U.K.· H.M.S.O., London 2 vols.

EDWARDS, R.P., 1976. Aspects of trace metal and ore distribution in Cornwall. *Trans. Inst. Min. Metal.*, Sect B, B83–B90.

ELDER, J.W., 1976. Model of hydrothermal ore genesis. In "*Volcanic processes in ore-genesis.*" Spec. pub. No. 7, Geol. Soc. Lond., 4–13.

EMMONS, W.H., 1934, On the origin of certain systems of ore bearing fractures. Tech. Pub. Am. *Inst. Min. Engrs.* No. 561, 26p.

EXLEY, C.S., 1976, Observation on the formation of kaolinite in the St. Austell granite, Cornwall. *Clay Minerals*, 11, 51–62.

EXLEY, C.S., & STONE, M., 1964. The granitic rocks of south-west England. In Hosking & Shrimpton (eds), *Present views of some aspects of the geology of Cornwall and Devon*, 131–184.

FLOYD, P.A., 1965. Metasomatic hornfelses of the Lands End aureole at Tatur-du, Cornwall. *J. Pet*, 6. 223–245.

FLOYD, P.A., 1968a Tin and lead in the Lands End aureole, Cornwall. *Proc. Ussher Soc.*, 2, 45–48.

FLOYD, P.A., 1968b Distribution of Cu in the basic hornfelses of the Lands End aureole, Cornwall and other chemically similar rocks. *Goechim. Cosmochim. Acta*, 32, 879–896.

FLOYD, P.A., 1971. Temperature distribution in the Lands End aureole Cornwall. *Proc. Ussher Soc.*, 2, 335–351.

FLOYD, P.A., 1972. Geochemistry origin and tectonic environment of the basic and acidic rocks of Cornubia, England. *Proc. Geol. Assoc.*, 83, 385–404.

FUGE, R., 1974. The distribution of zinc and copper in the granites of S.W. England and its relationship to the geochemistry of the halogens. *Proc. Ussher Soc.*, 3, 156–160.

GARNETT, R.H., 1962. *The geology and mineralisation of Geevor Tin Mine, Cornwall.* Unpub. Ph.D thesis, London Univ.

GARNETT, R.H., 1963. Local mineral zoning in Geevor tin mine, Cornwall. *Symposium on problems of post-magmatic ore-deposition.* 1, Prague 91-96.

GARNETT, R.H., 1966. Distribution of cassiterite in vein tin deposits. *Trans. Instn. Metal.*, Section B 75, B 245–273.

GRANT, J.N., HALLS, C., AVILA, W., and AVILA, G., 1977, Igneous geology and the evolution of hydrothermal systems in some sub-volcanic tin deposits of Bolivia. In "*Volcanic processes in ore-genesis.*" Spec. pub. No. 7, Geol. Soc. Lond., 117-126.

GOODE, A.J.J., 1973. *The mode of intrusion of Cornish elvans* I.G.S. Rept. No. 73/7.

HALL, A., 1970. The composition of cornish quartz-porphyry (Elvan) dykes. *Proc. Ussher Soc.*, 2, 205–208...

HALL, A., 1971. Greisenisation in the granite of Cligga head, Cornwall. *Proc. Geol. Ass.*, 82, 209–30.

HALL, A., 1974, Granite porphyries in Cornwall. *Proc. Ussher Soc.*, 3, 145–148.

HALLIDAY, A.N., 1977, *Isotopic age studies of mineralisation in western Europe*, Unpub. Ph.D thesis, University of Newcastle-upon-Tyne.

HALLS, C., RANKIN, A., FERRIDAY, I.L., BLAIN, C.F., BRISTOW, C.M., and GRONOW, C., 1977, A tourmalinised hydrothermal intrusion breccia at Wheal Remfry in the western part of the St. Austell pluton, Cornwall. *Trans. Inst. Min. Metal.*, Sect B, B 163.

HARDING, R.R., and HAWKES, J.R., 1971. *The Rb-Sr age and K/Rb ratios of samples from the St. Austell granite, Cornwall.* I.G.S. Rept. No. 71/6 H.M.S.O. London.

HAWKES, J.R., HARDING, R.R., and DARBYSHIRE, D.P.F., 1975. Petrology and Rb-Sr age of Brannel, south Crofty and Wherry elvan dykes, Cornwall. *Bull. Geol. Surv.* Great Britain No. 52, 27–42.

HAWKES, J.R., and DANGERHELD, J., 1978. The Variscan granites of S.W. England: A progress report. *Proc. Ussher Soc.*, 4, 158–171.

HAWKINS, J., 1820. On the stratified deposits of tin-stone, called tin floors, and on the diffusion of tin-stone through the mass of some primitive rocks. *Trans. Roy. Geol. Soc. Corn.*, 2, 30–48.

HEMLEY, J.J., and JONES, W.R., 1964. Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism. *Econ. Geol.*, 59, 538–569.

HENLEY, S., 1974a, Geochemistry and petrogenesis of elvan dykes in the Perranporth area, Cornwall. *Proc. Ussher Soc.*, 3, 136–143.

HENLEY, S., 1974b. Geochemistry of Devonian Sediments in the Perranporth area, Cornwall. *Proc. Ussher Soc.*, 3, 128–136.

HENWOOD, W.J., 1865, Observations on Providence Mines. *Trans. Roy. Geol. Soc. Corn.*, 7, 179–184.

HOSKING, K.F.G., 1951. Primary ore distributions in Cornwall. *Trans. R. geol. Soc. Corn.*, 18, 309–356.

HOSKING, K.F.G., 1964. Permo-Carboniferous and later mineralisation of Cornwall and south-west Devon. in Hosking & Shrimpton (eds), *Present views of some aspects of the geology of Cornwall and Devon.* 201–245.

HOSKING, K.F.G., 1969. The nature of the primary tin ores of the south-west of England. *A technical conference on tin: London. I.T.C.* 1157–1243.

HOSKING, K.F.G., 1973. The sesarch for tungsten deposits. *Bull. Geol. Soc. Malaysia*, 5, 70p.

JACKSON, N.J., 1974. Grylls Bunny, a 'tin floor' at Botallack. *Proc. Ussher Soc.*, 3, 186–188.

JACKSON, N.J., 1975. The Levant Mine carbona. *Proc. Ussher Soc.*, 3, 220–225.

JACKSON, N.J., 1976a. The Levant Mine Carbona, a fluid inclusion study. *Proc. Ussher Soc.*, 3, 427–429.

JACKSON, N.J., 1976b. *The Geology and mineralisation of the St. Just Mining District, West Cornwall.* Unpub. Ph.D thesis, London Univ.

JACKSON, N.J., 1978. The Halvosso pegmatites. *Proc. Ussher Soc.*, 4, 190–191.

JACKSON, N.J., & RANKIN, A.H., 1976. Fluid inclusion studies at St. Michaels Mount. *Proc. Ussher Soc.*, 3, 430–434.

JACKSON, N.J., MOORE, J. MCM., & RANKIN, A.H., 1977. Fluid inclusions and mineralisation at Cligga Head; Cornwall, England. *Journ. Geol. Soc. Lond.*

JACKSON, N.J., HALLIDAY, A.N., SHEPPARD, S.M.F., & MITCHELL, J.G., Hydrothermal activity in the St. Just mining district, West Cornwall. (unpublished data)

KETTANEH, Y.A., & BADHAM, J.P.N., 1977, Mineralogy and paragenesis at the Mount Wellington Mine. *Proc. Ussher Soc.*, 4, 3–4.

LITTLE, W.M., 1960. Inclusions in cassiterite and associated minerals. *Econ. Geol.*, 55, 485–509.

MILLER, J.A., SHIBATA, K., & MUNRO, M., 1962, The potassium argon age of the lava of Killerton Park, near Exeter. *Geophys. J.R. astr. Soc.*, 6, 394–396.

MILLER, J.A., & MOHR, P.A., 1964. Potassium-argon measurements on the granites and some associated rocks from south-west England. *Geol. J.*, 4, 105–126.

MITCHELL, J.G., & HALLIDAY, A.N., 1976. The extent of Triassic/Jurassic hydrothermal ore deposits on the North Atlantic margins. *Trans. Inst. Min. Metal.*, Sect B. 85, B 159–161.

MOORE, F., 1977. The occurrence of topaz rich greisens at St. Michael's Mount. Cornwall. *Proc. Ussher Soc.*, 4, 49–56.

MOORE, J. MCM., 1975. A mechanical interpretation of the vein and dyke systems of the S.W. England orefield. *Mineral Deposita*, 10, 374–388.

MOORE, J. MCM., & JACKSON, N.J., 1977. Structure and mineralisation in the Cligga granite stock. *QJGS*, 133, 467–80.

ONISHI, H., 1970, Arsenic. In Wedepohl (ed) *Handbook of Geochemistry*. Springer-Verlag. Berlin 11-2, 33B–M.

PEARCE, J.A., & GALE, G.H., 1977. Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks. In "*Volcanic processes in ore-genesis*". Spec. pub. Geol. Soc. Lond., 7, 14–24.

POCKLEY, R.P.C., 1964. Four new uranium-lead ages from Cornwall. *Mineral. Mag.*, 33, 1081–1092.

RAO, A.N., 1952. *Trace element variation in hydrothermally altered rocks associated with mineralisation.* Unpub. Ph.D thesis, London Univ.

RAYMENT, B.D., DAVIS, G.R., & WILLSON, J.D., 1971. Controls to mineralisation at Wheal Jane, Cornwall. *Trans. Inst. Min. Metal.*, Sect B, B 224–237.

READING, H., 1973. The tectonic environment of south-west England: Contributions to the discussion of a paper by P.A. Floyd. *Proc. Geol. Assoc.*, 84, 239–242.

ROBERTS, J.L., 1970. The intrusion of magma into brittle rocks. In Newall and Rast. (eds), *Mechanism of igneous intrusion*. Geol. Jl. Spec. issue 2, 286–338.

STONE, M.S., & AUSTIN, W.G.C., 1961. The metasomatic origin of the potash feldspar megacrysts in the granites of south-west England. *J. Geol.*, 69, 464–72.

TAYLOR, H.P., Jr., 1968. The oxygen isotope geochemistry of igneous rocks. *Contrib. Mineral. Petrol.* 19, 1–71.

TAYLOR, R.G., 1966. *Geology and structural controls to ore deposition at south Crofty tin mine*, Cornwall. Unpub. Ph.D thesis, London Univ.

TUREKIAN, K.K., & WEDEPOHL, K.H., 1961. Distribution of the elements in some major units of the Earth's crust. *Bull. Geol. Soc. Am.*, 72, 175–192.

TUTTLE, O.F., & BOWEN, N.E., 1958, *Origin of granite in the light of experimental studies in the system* $NaAlSi_3O_8$—$KAlSi_3O_8$—SiO_2—H_2O. Geol. Soc. Amer. Mem., 74. 153p.

WEBB, J.S., 1947, *The origin of the tin lodes of Cornwall.* Unpub. Ph.D thesis, London Univ.

WILSON, I.R., 1972. *Wallrock alteration at Geevor Mine, Cornwall and Ashanti Mine, Ghana.* Unpub. Ph.D thesis, Leeds Univ.

WILSON, I.R., 1972b. Wallrock alteration at Geevor Mine. *Proc. Ussher Soc.*, 2, 425–434.

WILSON, I.R., & JACKSON, N.J., 1977. Discussion on 'Aspects of trace metal and ore distributions in Cornwall. *Trans. Inst. Min. Metal.*, Sect B, B 61–62.