A REVIEW OF THE GEOLOGY OF PRIMARY TIN DEPOSITS WITH EMPHASIS ON THE FACTORS THAT CONTROL GRADE AND TONNAGE

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CONTENTS

1. INTRODUCTION

The traditional approach to tin mining has been the intermittent development of 'small workings', usually in total ignorance of the exact scale and range of mineralisation present. Many tin mines have begun production without efficient evaluation and consequently maintain production on a precarious hand to mouth basis with virtually no blocked out ore reserves. The reason for this is that the geological controls on primary* tin mineralisation and grade and tonnage relationships are very complex and not always well understood so that generally very little effort is made to utilise them in evaluation. Clearly, this state of affairs should no longer exist. Exploration and evaluation are certainly fraught with difficulties but many viable deposits fail to reach production because of an inadequate standard of systematic evaluation. It is unlikely that South Africa is an exception to this.

The location of tin deposits and the characteristics of ore distribution are not haphazard but are closely controlled by geological factors. Careful and efficient evaluation can only be carried out if these factors are thoroughly understood. Only in this way will the high risk involved be reduced and production commenced with a degree of confidence.

The purpose of this dissertation is therefore to review the economic geology of primary tin deposits and the geological factors that control grade and tonnage. The work concludes with a discussion of the implications of these geological controls on evaluation. Exploration for primary tin deposits is not part of this study but is referred to in a number of publications, notably Garnett (1967), Hosking (1974), Crocker and Callaghan (1979) and Taylor (1979).

* primary tin deposits are those that form in igneous and sedimentary rocks by magmatic and hydrothermal processes. They do not include sedimentary placer concentrations (secondary deposits).

2. BACKGROUND TO TIN DEPOSITS

Metallic tin is soft, malleable, chemically inert, non-toxic and has a low melting point. Because of these properties, tin metal is of considerable consumer, industrial and strategic importance. Although it is not a rare metal, its distribution is confined to a small number of tin fields, Figure 1. Excluding Sino-Soviet sources, tin production is from Malaysia 39%, Bolivia 15%, Indonesia 12%, Thailand 11%, Australia 6%, Nigeria 1%, Zaire 1% and minor amounts from S.W. England and South Africa (Taylor, 1979). Approximately 80% of world production is from secondary alluvial sources in S.E. Asia whilst 200 000 tonnes of tin are consumed a year. In recent years there has been a declining production from secondary sources despite the increasing demand for tin. This is because of expanding industrial and consumer applications and the important stability induced by the International Tin Council (Fox, 1974; Hoare, 1974). Thus an increased emphasis must be placed on bringing new primary deposits into production especially as large tonnage/low grade potential is now recognised (Taylor, 1976).

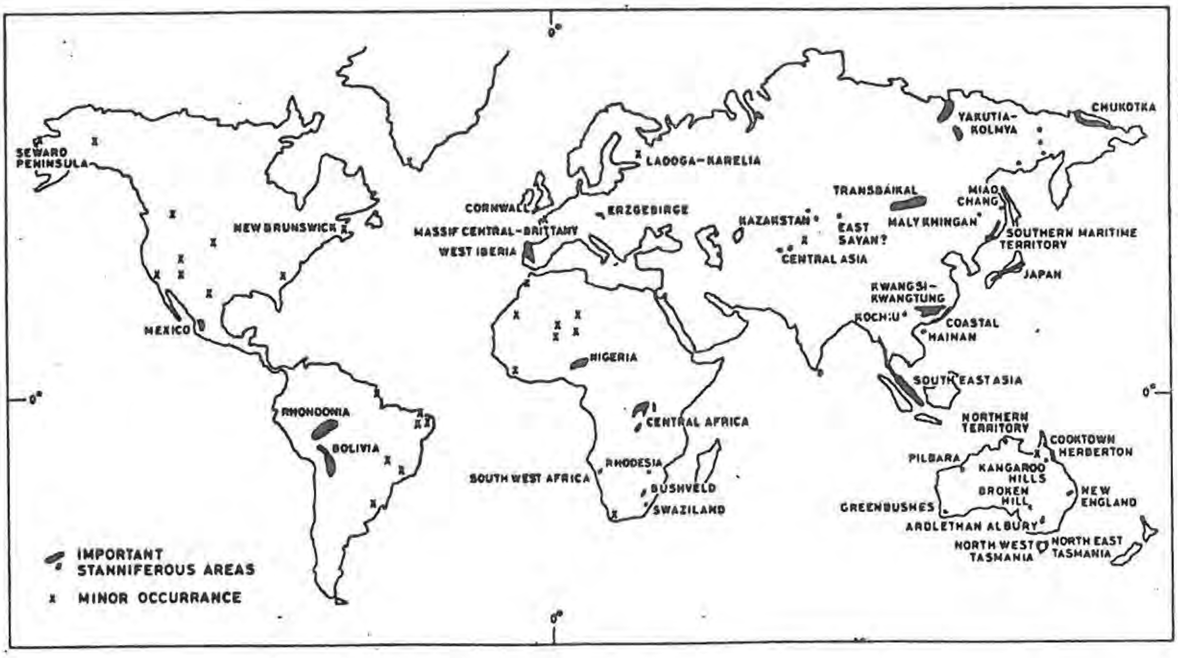


Fig. 1. Stanniferous areas of the world (Taylor, 1979)

CHARACTERISTICS OF TIN BEARING GRANITOIDS.

Primary tin deposits are genetically related to granitoids emplaced in continental crust. Granitoids are defined as a group of intermediate to acid rocks of granitic composition (granite to grandiorite) and texture (Flinter, 1971). Most tin granites* are biotite granites but some may be biotite-muscovite granite or quartz monzenite, or the subvolcanic and volcanic equivalents of these. There is a wide range in texture from fine grained to coarse grained and porphyritic.

Tin granites are generally the latest differentiates of larger composite igneous complexes or intrusions. For example, the Blue Tier Batholith of N.E. Tasmania is a composite high level intrusive that was emplaced as part of a sequence from early mafic granodiorites to late leucocratic granites (Groves, 1972). The batholith consists of a least eleven separate intrusions. The host to tin mineralisation is a biotite-muscovite granite that occurs as small sheetlike bodies intruding at a high level a pluton of porphyritic biotite granite. The biotite-muscovite granite represents a highly fractioned rock that crystallised from a small volume of ultimate residual fluid preferentially enriched in tin. Their position in a composite suite may be the critical factor that distinguishes tin granites from other high silica granites.

However, not all granites of the appropriate compositional range are necessarily tin bearing. Also, of two adjacent granites in the same complex, one may be mineralised and the other may be barren, Figure 2. These features have been recognised for some time so that considerable research has been carried out in an attempt to find criteria or to define the essential chemical characteristics that will distinguish tin-bearing granites from tin-barren ones. Similarly, research has been in progress to relate the tin content of granites and constituent minerals to compositional variations in the granites and minerals; for example, because tin can substitute isomorphously for elements such as Fe^{3+} and Li^{+} in minerals, then the changing composition of that mineral may reflect the tin potential of the granitoid. The diversity of opinions and contradicting conclusions is documented in Flinter

* a 'tin granite' is here defined as a granitoid with which primary tin deposits are genetically related.

(1971), Hunter (1973) and Taylor (1979).

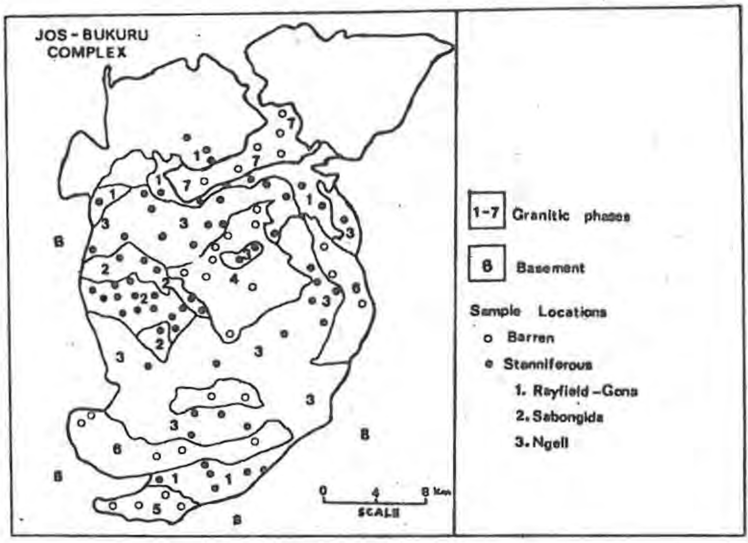


Fig. 2. Nigerian granite complex showing adjacent stanniferous and barren intrusions (Olade, 1980)

It was originally thought that a granitoid might be characterised by distinguishing features of mineralogy or major and trace element specialisation[*]. However, all of the studies to date indicate that there is no unique distinguishing feature of major element specialisation, other than a general but not universal trend towards excess silica and potassium. Flinter (1971) indicates that calcium may be important for fixing tin in some cases.

Investigations into trace element specialisation of the associated elements Sn, F, Cl, Li, B, Rb, W, Nb, Be, Ta, show that all the observed tin provinces have geochemically specialised granitoids and minerals of one sort or another, but the amount and type varies from province to province. Flinter (1971) concludes that the observed patterns of trace element specialisation are due to local conditions pertaining in that particular complex and cannot be applied elsewhere. In addition, although anomalous concentrations of the trace elements may indicate the presence of tin mineralisation, an absence does not indicate that tin mineralisation is not present. Flinter et al (1972) point out that high geochemical values generally occur in mineralised host rocks but mineralisation can also occur in rocks with low values.

[*] if a rock is anomalously enriched in a given element, it is said to be geochemically specialised in that element

Tischendorf (1977) reviews the subject of geochemical characteristics of granites associated with rare element mineralisation in some depth. He indicates that a high volatile content is necessary for the concentration of trace elements in granites so that volatiles such as fluorine must be present in elevated amounts. The importance of fluorine in tin granite forming processes is strongly stressed. It must be noted that patterns of trace element distribution are also due to inherent geochemical differences in sucessive phases of composite intrusions and this no doubt has lead to misleading conclusions in poorly controlled studies (Taylor, 1979).

THE AGE AND TECTONIC SETTING OF TIN BEARING GRANITOIDS

Tin mineralisation occurs in granitoids of all ages from Precambrian to Tertiary, but the largest and most important are Mesozoic and younger in age. It is often argued (e.g. Hunter, 1973) that granitoids of younger age are more likely to produce tin mineralisation because they may be second cycle melts of former granites which have previously suffered repeated fractionation. This would produce a greater incidence of deposits in more highly fractionated younger granites.

There is a significant grouping of deposits around the major periods of crustal orogeny, such as the Caledonian, Variscan, Kimmurian and Alpine (Taylor, 1979). The most important groups of tin deposits are those related to younger orogenic zones where tectonic activity probably involves the assimilation of previously fractionated granitic crustal material (Hunter, 1973). Hosking (1970) advocates a multi-phase granite intrusion mechanism for the generation of primary tin deposits of S.E. Asia.

Tin mineralisation is often preferentially located in the highest apical parts of granitoids and therefore older deposits at high levels are more likely to have been eroded. At the present erosion level, the most significant are those of Mesozoic age. Figure 3 illustrates how the erosion level affects the accessibility of different types of deposit through time.

Some authors, however, dispute that tin mineralisation is more likely in younger rocks. Hunter (1973) believes that although the level of erosion is a critical factor in removing older high level deposits, there seems to be little evidence that tin mineralisation is in fact time dependent. The important implication is that exploration should not be confined to younger granitoids alone. This is borne out by the presence of tin mineralisation in the Precambrian Bushveld granites.

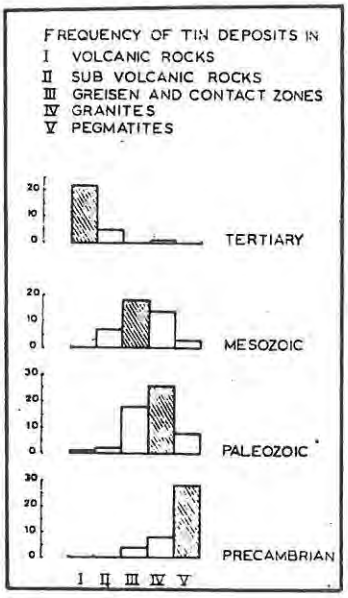


Fig. 3. Frequency of tin deposits (Schuiling, 1967)

ENVIRONMENTS OF TIN BEARING GRANITOIDS

Tin enrichment can only occur in granitoids that have been subjected to significant and prolonged fractionation. For this reason, the prescence of thick crust is a critical prerequisite. Tin bearing granitoids are emplaced in continental rather than oceanic crust and can occur in most tectenic settings, Table 1. The classification of environments of tin granitoid emplacement is difficult because they form a continuous overlapping spectrum. The reader is referred to Taylor (1979, Chapt. 3) for a comprehensive review of the main features of deposits in different environments.

In orogenic settings, emplacement can range from deep plutonic to subvolcanic. The important tin deposits of Australia and Tasmania are related to highly silicic and potassic granites which are late phases of composite granitoids emplaced in the orogenic stage of the Tasman Geosyncline. Similarly, tin-silver mineralisation in Bolivia is associated with acid volcanic rocks and quartz porphyry stocks related to subvolcanic activity in the Andean orogenic zone (Sillitoe et al., 1975).

TABLE 1. ENVIRONMENTS OF TIN DEPOSITS (adapted from Taylor, 1979)

ENVIRONMENT	FORM AND COMPOSITION OF ASSOCIATED IGNEOUS ROCKS	ECONOMIC SIGNIFICANCE	EXAMPLES
1 FOLD BELT TYPE: granitoids showing close relationship to major orogeny. Late stage emplacement.			
1a) Sn associated with extrusives and pyroclastics	lavas, tuffs, volcanic breccias;	very minor	Mexico
1b) Sn associated with intrusive complexes + terrestrial extrusives	small stocks, pipes, irregular intrusives + dyke swarms, sills, breccias etc; generally porphyritic from granite to granodiorite; rhyolites and andesites	primary ores: major to minor secondary ores: minor	Bolivia (southern part) = "porphyry tin" Ardlethan-Albury, Aust.
1c) Sn associated with intrusive complexes of mixed nature: deepvolcanic to high plutonic	small stocks to large intrusive complexes, complex major batholiths. Active repeated intrusion; diverse composition: granites and graniodiorites	primary ores: major to minor secondary ores: intermediate to minor	Herberton, Aust. New England, Aust. Chukotka, U.S.S.R. Transbakal, U.S.S.R. New Brunswick, Can.
1d) Sn associated with intrusive complexes of plutonic character. Extrusives absent	intermediate to large scale intrusive complexes. Relatively passive environment; granites and granodiorites, pegmatites common	primary ores: major to minor secondary ores: major to minor	Bolivia (northern part) Erzgebirge Cooktown, Aust. N.E. Tasmania Massif Central, France Seward Peninsula, Alaska
2 ANOROGENIC TYPE: granitoids emplaced via major zones of fracturing in cratonic shield areas. Not associated with major periods of folding.	small intrusive ring complexes, minor stocks, minor volcanics: strong linear alignment; granite, microgranite and rhyolite; alkali granites in Nigeria	primary ores: very minor secondary ores: major	Nigeria Rondonia, Brazil
granitoid members of layered mafic intrusives in cratonic terrain. Stable environment. Unique to Bushveld complex	stratiform granitic sheets associated with felsitic extrusives and pyroclastics; granite.	primary ores: minor secondary ores: very minor	Bushveld Complex, S.Afr.
3 PRECAMBRIAN PEGMATITE TYPE pegmatites in ancient metamorphic terrains	wide range of intrusive forms e.g. batholiths, domed complexes, stocks, sills etc; granites with minor alaskites; pegmatite phases	primary ores: minor secondary ores: minor to intermediate	Central Africa Pilbara, Aust. Greenbushes, Aust. Brazil shield Nigeria shield Kamativi, Zimbabwe Namibia

In terms of world production:

Group 1:	a) negligible	Group 2. 2.5%; all alluvial
	b)	Group 3. 2-5%; mostly alluvial
	c) 90-96%; mostly alluvial	Group 4. Negligible
	d)	

Major lineament control

It is highly significant that granitoid emplacement is almost universally controlled by major fracture-suture zones or deep-seated lineaments. This is an important regional control with obvious exploration implications. In the Herberton tin province of North Queensland, the granitoid is situated in a zone characterised by a major lineament and fractures which evidently controlled, the emplacement of the batholith, Figure 4.

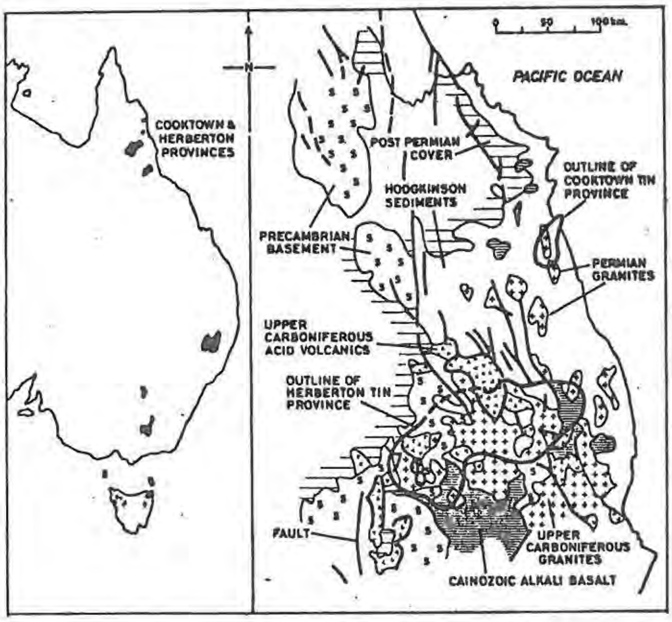
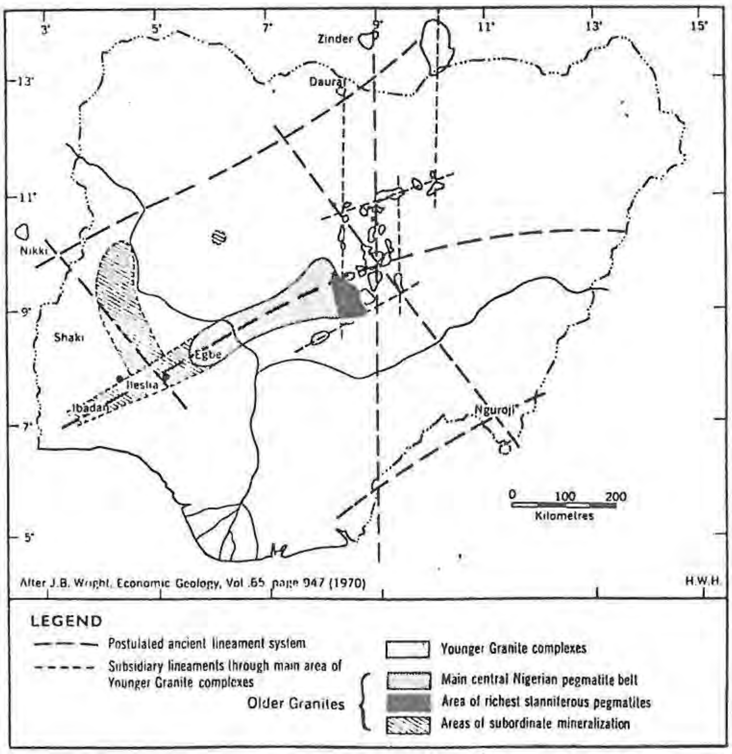


Fig. 4. Lineament control of batholith emplacement, Herberton tinfield, Tasmania (Taylor, 1979)

In an orogenic setting granitoids are emplaced in major zones of fracturing or vertical graben tectonics in stable cratonic shield areas. In the Nigerian tin province, distribution of stanniferous pegmatites of the basement, and the younger granite ring complexes is related to an ancient lineament system (Figure 5) which may be part of a failed limb of a triple junction. In a similar fashion, intersecting lineaments control the distribution of tin mineralisation in the Bushveld Complex (Hunter, 1973). The third group of deposit comprise small swarms of pegmatites associated with Precambrian cratonic granitoids which form stable shield areas. Associated igneous rocks show a variety of forms, such as batholiths, domed complexes, stocks and sills. Regional structural controls are likely to be major fractures.

However, tin provinces of all ages have developed similar types of deposit to varying degrees so that the critical tin concentrating processes must be similar irrespective of age or tectonic setting. Tectonism of any type may result in granitic material which is fractionated to produce enrichment of the incompatible elements in a residual melt. The geochemical processes that produce tin concentration in the anorogenic Precambrian Bushveld granite are the same as those that operate in younger orogenic granites (Groves and McCarthy, 1978). The different characteristics of individual tin provinces are controlled by the type and nature of the batholith and the level of emplacement within different country rocks. The important features of Australian tin deposits are reviewed by Taylor (1979) according to this criterion.

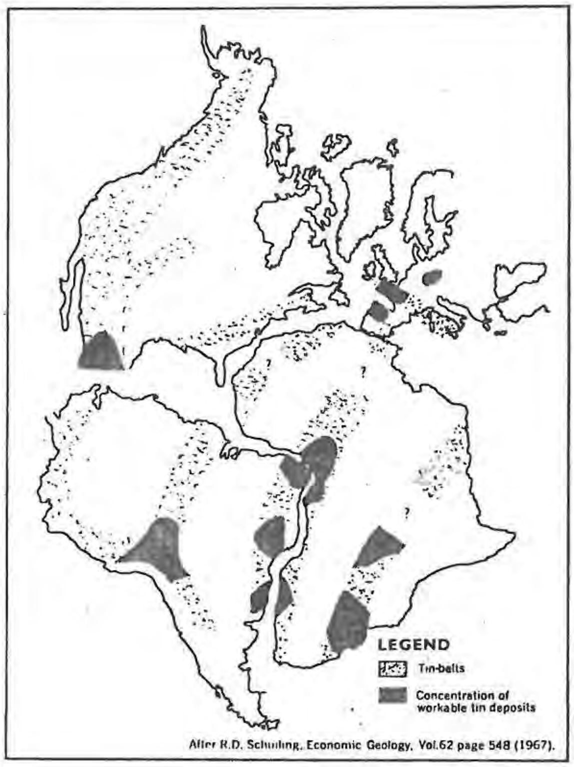


After J.B. Wright, Economic Geology, Vol.65 page 947 (1970)

Fig. 5. Control of lineament system on granites of the Nigerian tin province (Wright, 1970)

THE SOURCE OF TIN

The source of tin is a major point of debate and there is much speculation concerning the involvement and relationship of crustal and mantle processes (Taylor 1979, p. 35). Many hypotheses have been proposed to explain why tin is concentrated in certain magmas and these include melting of tin rich sediments and melting of crustal granitic rocks (Pearce and Gale, 1977). The important point however, is that in the tin concentrating process, the source of the tin is of no consequence. One school of thought believes that the distribution of tin in the crust is a reflection of an original irregular distribution; Schuiling (1967) concludes that the critical factor is that enhanced concentration of tin will occur where favourable geological processes affect those parts of the crust in which there was a primary preferential enrichment of tin. Figure 6 shows the position of the tin belts prior to Mesogoic drifting. The source of tin must have been located in the crust or attached parts of upper mantle in order to be carried along by the continents. Major concentrations may occur where two belts intersect and this is evidenced by the Bolivian tin province (Schuiling, 1967). As an alternative, Tauson et al. (1968) believe that tin is concentrated in intrusives where either slow differentiation took place or where there was a rich concentration of volatiles at high levels of emplacement. This implies that all granites have sufficient tin which may be concentrated if the appropriate crystallisation conditions are attained.



After R.D. Schuiling, Economic Geology, Vol.62 page 548 (1967).

Fig. 6. Position of tin belts on continental reconstruction (Schuiling, 1967)

To conclude, it is evident that if sufficient tin is present, then no matter how or where it originates, and no matter how or where the associated granitoid is emplaced, then continued fractionation will produce tin concentration if favourable conditions operate. Subsequent precipitation and deposition of tin is controlled by physical and chemical conditions in the different environments.

CLASSIFICATION AND DESCRIPTION OF TIN DEPOSITS

Primary tin deposits constitute a complex and highly heterogeneous group. A compact classification that satisfactorily incorporates mineralogy, morphology and environments of formation has not evolved because of the wide range and overlap of tin deposit types in different environments. Hosking (1965) however, has captured the essence of environments of primary tin deposits by illustrating all the deposit types in their correct geological setting, Figure 7.

Because tin deposits are ultimately derived from a granite magma, their genesis must be intimately related to the geochemical or petrochemical processes that are peculiar to granite generation. For this reason it is practical to use a classification that is based on the spatial position of the deposit relative to the host granitoid and country rock. This, in turn, is a reflection of the successive stages in the evolutionary processes which took place during formation of the deposits. The ore forming process involves fractionation of a granite magma with concentration of a tin rich residual fluid and its subsequent migration away from the site of concentration. Deposition may take place at a number of favourable sites ranging from within the granitoid (endogranitic) to within country rock beyond the granitoid (exogranitic), and a complete spectrum exists between these end members. Endogranitic deposition may be syngenetic or epigenetic whilst exogranitic deposits must be epigenetic.

The following scheme is suggested and is used as a basis for discussion in the ensuing work.

A. Those deposits that occur within the granitoid to which they are genetically related
    1. magmatic disseminations
    2. mineralised pipes
    3. high level, subvolcanic deposits (tin porphyry)

B. Those deposits that occur close to the granitoid contact, or span the contact; these are proximal to A.

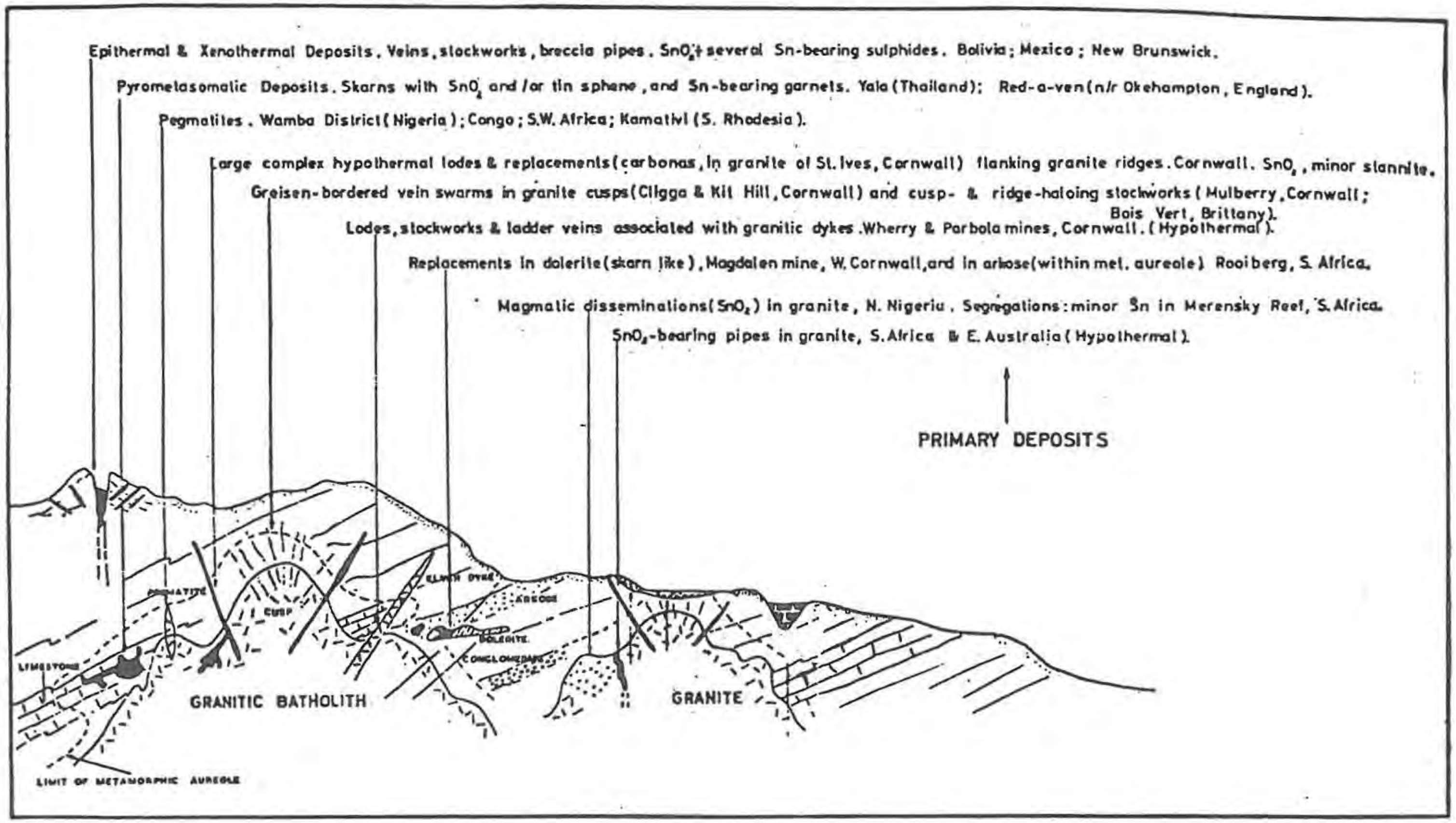


Fig. 7. Primary tin deposits (Hosking, 1965)

4. pegmatite and dyke deposits
5. greisen associated deposits
6. skarn associated deposits

- the tin prophyry domain includes both A and B

C. Those deposits that occur in country rock; these are 'distal' to A.

7. fissure lodes and replacement bodies
8. stockwork deposits

D. Epithermal deposits of the Mexican type associated with volcanic rocks.

E. Possible volcanogenic or volcano sedimentary exhalative deposits.

Types of primary tin deposit

i. magmatic disseminations

Endogranitic syngenetic mineralisation occurs if grains of cassiterite are present as comagmatic accessory minerals in a granitic host. This type of deposit is rare, but is well developed at Zaaiplaats in the Bushveld Complex; here, deposits are located in the roofs of stocks of miarolitic granites that intrude the Bushveld Granites.

At Zaaiplaats the Main Granite consists of a series of granitoids grading from coarse grained mesocratic granite at the base up to granophyric granite and granophyre. The Main Granite has been intruded by a coarse grained red miarolitic granite (Bobbejaankop Granite) whose upper contact is defined by an aplitic sheet (Lease Granite). This, in turn, is overlain by a thin pegmatite zone. The cassiterite zone forms a flat ore body with an average width of 30 m, and this may split into separate zones or lenses. This zone lies 50 m below the Lease granite and is some 120 m below the roof of the stock (Hunter, 1976) Figure 8. Cassiterite

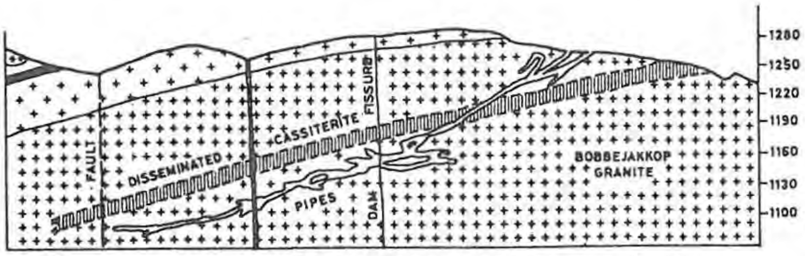


Fig. 8. Disseminated cassiterite zone at Zaaiplaats (Taylor, 1979)

occurs interstitially to quartz and feldspar and is oaasociated with fluorite, commonly in vugs in chloritised and sericitised granite. Grade varies from trace to 1% cassiterite and is gradational to barren granite. Slightly higher grade shoots are present within this (Crocker & Callaghan, 1979). The disseminated ore zone is characterised by an enrichment of disseminated scheelite on the upper and lower contact zones. An average of 4% scheelite is recovered at Zaaiplaats (Mine manager, pers. comm.).

ii. mineralised pipes (Crocker and Callaghan, 1979).

The best known endogranitic pipes occur at Zaaiplaats in the Bushveld Complex, Figure 8. The dposits are developed in the upper portions of the Bobbejaankop and Lease Granites. Pipes are concentrically zoned and consist of a core, an outer ring and a zone of metasomatically altered red granite. The core is commonly sericitised and may contain as much as 60% cassiterite. A second type consists of a core with a zone of red feldspar with fluorite, calcite, quartz, chalcopyrite, pyrite and minor sphalerite, scheelite, arsenopyrite and molybdenite. This is always surrounded by a layer of black tourmaline and quartz. Crocker and Callaghan (1979) report one example that changed rapidly with depth into copper ore consisting of bornite and chalcocite.

Pipes are long, roughtly cylindrical bodies with average dimensions of 1-2 m but often pinch and swell up to about 12 m. Length varies from 7 m up to 1000 m and they range from horizontal to vertical with a highly tortuous character. They are closed at both ends but widen out into flat lenticular bodies where the pegmatite zone of the Lease Granite acts as an impermeable barrier.

iii. high level subvolcanic deposits.

Deposits of this type are associated with apical zones of high level intrusives. The main forms are veins, stockworks, pipes and breccias which often appear to be intrusive hydrothermal products. Ores are typically polymetallic and may comprise tin, tin-silver or tin-zinc. They are sulphur rich with complex sulpho-salts such as teallite, franckeiite and stannite together with many sulphides. Mineralogy is typically very complex; mineral zones are frequently telescoped and are xenothermal.

Sillitoe et al. (1975) recognise that the geological features of deposits of this type within the southern Bolivian tin province are similar to those of typical porphyry copper deposits and thus propose the term 'porphyry tin' deposits, Figure 9. In southern Bolivia, the deposits are associated with passively emplaced high level Tertiary stocks of average area 1-2 km^2; they are of intermediate composition with stockwork, disseminated and breccia-filling cassiterite mineralisation associated with extensive sericite alteration. This alteration grades outwards to propylitic alteration and silicification, and some deposits have a pyrite halo. Host rocks are fractured and altered prior to the formation and filling of the vein systems with the tin and tin-silver polymetallic minerals.

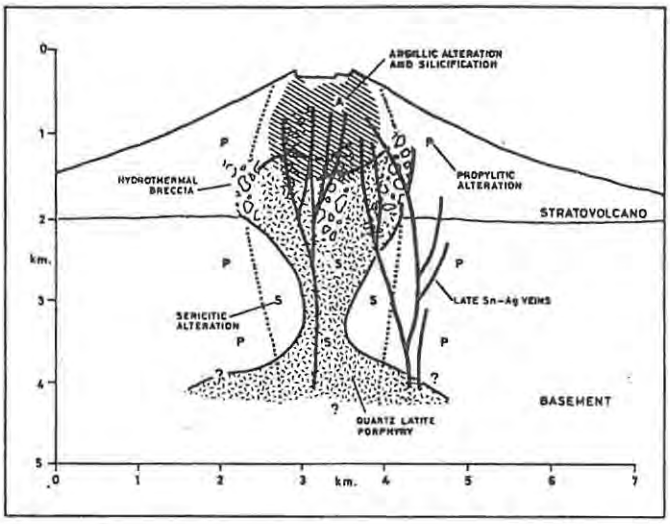


Fig. 9. Characteristic features of porphyry tin deposits (Sillitoe et al., 1975)

The deposits are undoubtedly of hydrothermal origin but are included at this stage of the classification because of their position within the porphyry stocks that produce them.

iv. pegmatite and dyke related deposits

Pegmatite deposits, occasionally with associated quartz cassiterite veins, generally occur in Precambrian shield areas. Most occurrences are small and have a limited and erratic cassiterite concentration and distribution; grade seldom exceeds 0.3% Sn (Taylor, 1979). A common characteristic, is that in a pegmatite field some pegmatites may be barren, whilst others are mineralised.

Large sized exceptions do however occur such as the Manono pegmatite in Zaire which is some 5 km long (Taylor, 1979). Mineral assemblages are varied and range from simple to complex, and include minerals such as quartz, feldspar, micas, lepidolite, cassiterite, beryl, tourmaline, columbite, tantalite and monazite. They may be zoned or unzoned; zones of mineral assemblages are arranged concentrically in successive shells around a quartz core. Cross cutting fractures may also contain minor mineralisation.

In the Nigerian tin fields pegmatites and aplites occur within the Older Granite basement (Wright, 1970). The pegmatites consist of quartz, feldspar, biotite, muscovite and tourmaline. Superimposed upon this paragenesis is a complex later mineralisation associated with intense albitisation. The more richly mineralised pegmatites are those associated with an initial quartz, microcline and muscovite mineralogy; the important economic minerals here are cassiterite and columbite/tantalite. The pegmatites occur in long narrow tin belts, as is the case in the Damara Belt in Namibia.

Mineralisation may be localised in granite dykes and may occur within them as shoots of greisenised granite or as small swarms of veinlets or stockwork. In the S.W. England tin province, the stockwork mineralisation occurs in acid porphyry dykes or 'elvans' which are cut by stanniferous veinlets which originate as small fractures (Hosking, 1969). The fractures tend to terminate against the country rock contact and local enrichment of cassiterite occurs here, and also where veins cross each other. The fracture fillings are simple in mineralogy and usually consist of quarts and cassiterite.

v. greisen associated deposits

Greisen consists of an aggregate of quartz and mica which generally occurs along fractures and in apical zones of granitoids below impermeable country rock. Greisen deposits consist essentially of two varieties which are really end members of a series; these are massive greisen and greisen bordered veins.

Massive greisen deposits are endogranitic and consist of disseminated cassiterite together with wolframite, fluorite, tourmaline and arsenopyrite. Fracture planes within the greisen may contain rich concentrations of tin and where several occur close together may result in large tonnage - low grade deposits (Taylor, 1979). Similarly large tonnage-low grade ore bodies may result when the apices of some cupolas are completely greisenised. At the Anchor tin mine in Tasmania, cassiterite deposits are associated with irregular sheet-like bodies of greisenised granite located in the domed apical region of intrusions of biotite-muscovite granite. The mineralised zone is some 250 m X 650 m in extent and comprises a series of subhorizontal lenticular sheets of varied dimension, with an average grade of 0.2% Sn (Groves and Taylor, 1973).

Greisen bordered vein swarms typically consist of a host of sub-parallel quartz veinlets with walls of greisen or selvages of chlorite, tourmaline, feldspar and fluorite (Bowie et al., 1978; Hosking, 1969). The central quartz vein ranges in size from a few millimetres to 15 cms, but carries most of the ore minerals of cassiterite, wolframite, arsenopyrite, chalcocite and stannite. Vein swarms of this type are common within granites but may extend for a limited distance into the exogranitic environment. Generally they are related to the roof form of the granite and are often located in crests of granite cusps.

Perhaps the best example of greisen-associated tin deposits occurs in the Erzgebirge province of Central Europe (Baumann, 1970). In this region a major batholith is developed with some 15 to 20 outcropping apical stocks and complexes. Younger granite complexes are specialised in F,Sn,Rb,Li. Major concentrations of Sn,W ± Mo,As,Fe,Cu,Bi,Zn are developed in massive greisens with associated quartz veins, Figure 10.

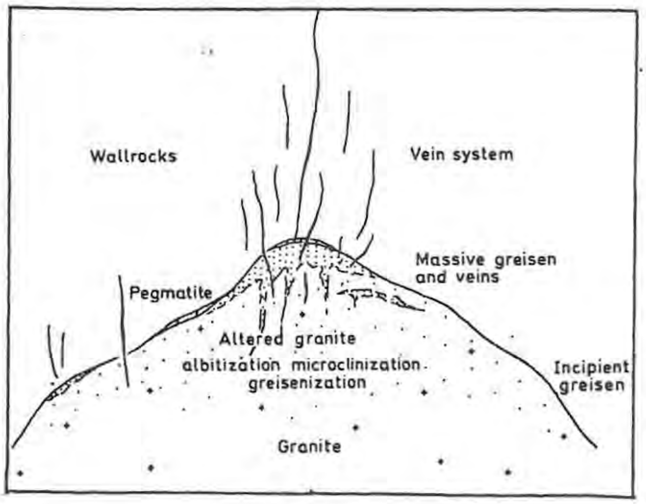


Fig. 10. The greisen environment. (Taylor, 1979)

Scherba (1970) discusses the greisen environment in some detail. He emphasises that the process of greisenisation is part of the pneumatolytic-hydrothermal system. This extends outwards from the endogranitic environment into country rocks and propagates a host of related mineralisation and alteration products.

vi. skarn associated deposits

Skarn associated deposits are pyrometasomatic and develop within the metamorphic aureole of granitoids. Hydrothermal fluids impinge upon reactive country rock such as carbonates to form typical skarn mineral assemblages. A complete spectrum exists from skarn deposits (high temperature calc-silicate minerals) to carbonate replacement deposits (low temperature alteration minerals).

Skarns can be divided into those containing iron oxides and those containing sulphides. Tin values in iron oxide skarns are usually low but deposits may be large. For example, the Lost River, Alaska deposit contains 33 million tonnes at 0.27% Sn and 15.6% fluorite. Sulphide rich skarns consist of a late sulphide phase including cassiterite and stannite.

Skarn deposits in general are usually small with erratic metal contents and complex mineral assemblages; in certain skarns most of the tin is locked into silicates such as malayaite. Other than one or two deposits such as Lost River, they are not of significance as a source of cassiterite.

vii. fissure lodes and replacement bodies

Fissure lodes and replacement bodies are economically the most important source of cassiterite. They are pneumatolytic-hydrothermal deposits that form at any favourable site from within the endogranitic environment to the distal exogranitic environment. Generally they are related to apical roof zones of granitoids and either emanate from the cupola or lie on the flanks of cupolas. As a group they are extremely diverse in shape and highly variable in metal concentration and distribution. A single structure can appear as fissure, breccia and replacement veins in different places along its course.

Fissure veins vary in shape from tabular bodies to cylindrical pipes formed at the intersection of two fractures; they are likely to change rapidly along their course and often assume the form of disconnected pods and irregular bulging zones. They frequently change character at lithological boundaries and often switch from one fracture to another. In the S.W. England district fissure veins or lodes are generally tabular and less than 2 m wide, but are known to extend to depths of 900 m and along strike for 6 km (Bowie et al., 1978). Fissure lodes are associated with conjugate fracture systems and display multiple phases of mineralisation. Their attitude varies from radial to concentric with respect to the granite contacts. The veins are either fissure fillings, breccia veins or replacement veins. Most fissure veins have a complex banded and braided structure caused by polyphase deposition and repeated opening fractures. Banded structures are often discontinuous and vary widely in mineralogy, grain size and texture and they usually include barren portions such as baryte and fluorite bands. For example, an early quartz cassiterite vein can be reopened and filled with quartz, chlorite and chalcopyrite, and late fractures can be sealed by fluorite. One cited example of a replacement vein from S.W. England extends for 6 km along strike and 1 km downdip (Bowie et al., 1978). It consists of tourmalinised and silicified granite with disseminated cassiterite and sulphides surrounding a quartz-tourmaline leader; widths of 1.3 to 4.5 m were mined. Tin values decrease outwards together with tourmalinisation.

Breccia veins consist of fragmented wall rock recemented by ore and gangue minerals; these occur frequently in faults and fractures. Polyphase deposition is common and mineralisation often consists of an interconnecting network of veinlets.

Replacement bodies develop where fractures intersect horizons such as shale or carbonate that are susceptible to replacement. Deposits of this type may form large economic deposits, such as at Mt. Bischoff, Cleveland and Rennison Bell in Tasmania, Figure 11. (Knight, 1975; Ransom and Hunt, 1975; Newnham, 1975).

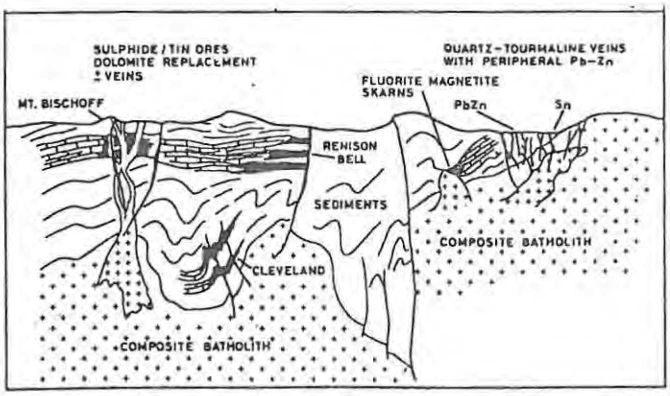


Fig. 11. Replacement style deposits in west Tasmania (Taylor, 1979)

viii. stockwork deposits

Stockwork deposits are vein swarms that comprise networks of ramifying mineralised veins; these occur in any host rock and may be found well into the exogranitic environment. For example, at the Union Tin Mine in the Transvaal mineralisation is located in fissures in felsites and in an inter-bedded shale horizon. Secondary bedding-plane shear and thrust lodes form a dense ramifying pattern of stockworks. The fractures are often little more than hairline cracks but adjacent wallrock is altered and they contain chlorite, sericite, vein quartz, tourmaline and calcite together with cassiterite and a variety of sulphides.

Stockworks often develop in the hanging wall of major lodes or where a vein enters a fracture zone or different lithology. Thus, stockworks are frequently found when a fissure lode enters a dyke, for example.

ix. epithermal deposits associated with volcanic rocks

Deposits of this type are rare and are found in lava flows and pyroclastics. The type locality is Mexico where mid-tertiary deposits contain low grade disseminated cassiterite in pipes and tabular zones in brecciated rhyolite (Ypma and Simons, 1969). More commonly, mineralisation is characterised by small veinlets which are fissure fillings of silica with ubiquitous specular haematite. Tin occurs as incrustations of cassiterite and wood tin. The tin distribution is erratic and grade is generally low.

x. possible volcanogenic or volcanosedimentary deposits

The stratabound, cassiterite bearing, massive pyrrhotite bodies at Mt. Bischoff, Cleveland and Renison Bell in Tasmania overlie discordant fault-fracture controlled and siliceous ore; they are traditionally regarded as replacement bodies. Hutchinson (1979) however, has reviewed the geology of these deposits and concludes that they in fact represent exhalative sea floor massive sulphide deposits similar to volcanogenic base metal sulphides.

3. GEOCHEMISTRY

THE CRYSTAL CHEMISTRY OF TIN

Tin, together with germanium and lead, belong to group IVB of the periodic table. These elements are characterised by having a ns^2 np^2 electron configuration and they form tetrahedral bands associated with sp^3 hybridisation. The electron configuration of tin is $4d^{10}$ $5s^2$ $5p^2$; it has an atomic number of 50 and atomic weight of 118.70 with 10 stable isotopes between mass numbers 112 and 114; this is the largest number of stable isotopes for any element.

Minerals that contain tin belong to three groups depending on the crystal chemistry of tin. These groups are: the elementary state, compounds with oxidation numbers of 2 (i.e. Sn^{2+}), and compounds with oxidation number of 4 (i.e. Sn^{4+}). Sn(II) as an oxidation state is relatively unstable compared to Sn(IV). Tin crystallises in two forms: α-tin ('grey tin') and β-tin ('white tin'). Only white tin occurs as a mineral due to a low transformation rate which occurs at about 18°C and 1 bar pressure.

α-tin has the ideal diamond structure, but in β-tin the co-ordination tetrahedron is flattened, and each atom recieves two additional neighbours at a greater distance to produce a deformed tetrahedron, Figure 12. At 25°C, β-tin transforms to a body centred tetragonal structure at about 94 k-bars, and probably transforms to a hexagonal close packed structure above 100 k-bars, Figure 13. Native tin occurs only in very rare cases and is generally thought to be the result of natural smelting. In addition,

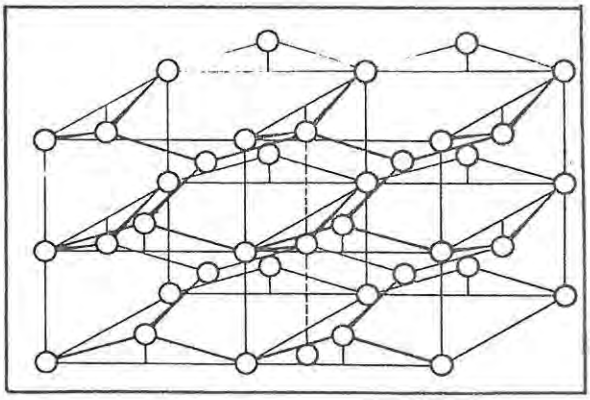


Fig. 12. The structure of α-tin (white tin) (Taylor 1979)

a complex family of stannides occurs in the platinum group, and native tin could form in this environment.

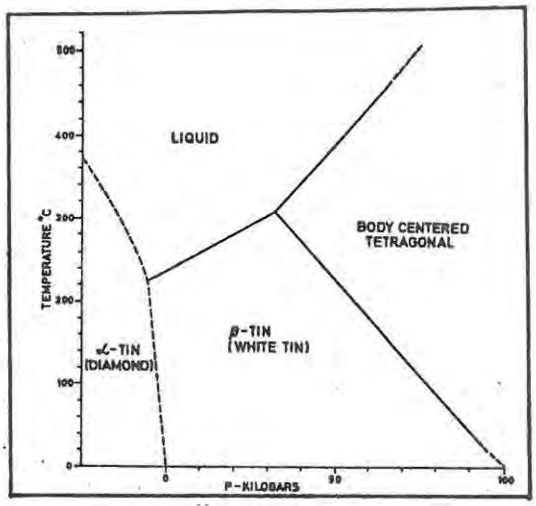


Fig. 13 . The phase diagram for tin (Taylor 1979)

In the bivalent state, Sn(II), tin forms pyramidal co-ordinations due to the electron configuration of the Sn(II) ion. This is illustrated in the crystal structure of herzenbergite, SnS, Figure 14 . Tin(II) bonding: The $5s^2$ $5p^2$ configuration at ground state permits the formation of covalent Sn(II) bonding by using the unpaired p-electron.

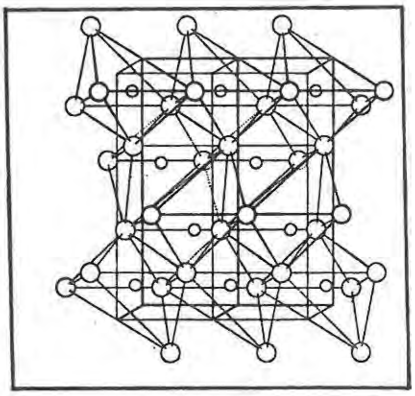


Fig. 14 . The crystal structure of herzenbergite, Sn S. Small circles Sn, large circles S. (Wedepohl, 1970)

In the tetravalent state Sn(IV), tin forms only a few minerals, the most important of which is cassiterite. An isomorphous series exists between SnO^2 and TiO_2 above 1350°C. In the Sn(IV) state, tin forms an octahedral co-ordination polyhedron which is occasionally distorted as in cassiterite, Figure 15. (Tin IV) bonding: The $5s^2$ $5p^2$ orbitals are likely to form four tetrahedral covalent bonds which is common in tin compounds. In octahedral environments, the 5d orbitals close in energy to the 5s 5p orbitals are used to form $Sp^3 d^2$ hybrid orbitals for covalent bonds. Tin does not form $p\pi$ multiple bonds, but in some cases, expecially with O, there is multiple bonding involving an orbital overlap ($d\pi$-$p\pi$ bonding).

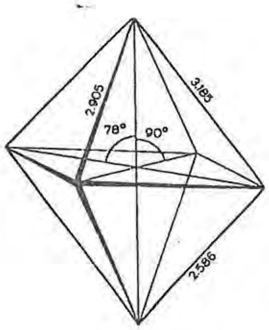


Fig. 15. Octahedral co-ordination polyhedron around Sn, cassiterite (Wedepohl, 1970)

Finally, Sn(IV) may substitute into tetrahedral holes, as in stannite, $Cu_2 Fe Sn S_4$.

The density, melting point and boiling points of tin are compared with those of the other Group IV elements in Table 2.

TABLE

PHYSICAL PROPERTIES OF GROUP IV ELEMENTS

Element	Density g. cm^{-3}	Melting Point °K	Boiling Point °K
C	3.51 (Diamond) 2.25 (Graphite)	3820	5100
Si	2.33	1690	2970
Ge	5.36	1210	3100
Sn	5.77(α) 7.29(β)	505	2540
Pb	11.34	600	2030

Table 2. (Taylor, 1979)

The distribution of tin in igneous rocks can be explained by the rules of substitution based on ionic charge and radius, together with the tendency to form covalent bonds. These are known as Goldschmidts Rules:-

1. if two ions have the same radius and the same charge, they will enter a given crystal lattice with equal facility.
2. if two ions have similar radii and the same charge, the

smaller ion will enter a given crystal lattice more readily.

3. if two ions have similar radii and different charges, the one with the higher charge will enter a given crystal lattice more readily.

(Krauskopf, 1979)

Cations with small radius and high charge such as Sn, W, U, Th, Be, B, Nb, etc are concentrated at the felsic end of the differention series because they are incompatible elements. This means that their size and charge do not allow them to substitute readily for major ions in common silicate rocks. For this reason, tin is usually segregated in late residual solutions. For tin to crystallise in a mineral of its own as a major component, the first requirement is that it must be present in a sufficient quantity. If only a limited amount is available, then these can be taken into silicate crystal structures as a replacement or as an inclusion. The amount that can be taken up depends on the characteristic of the Sn ion.

The electronegativity and ionic radius of Sn are compared with those elements for which it commonly substitutes in Table 3.

IONIC RADII AND ELECTRONEGATIVITY OF IONS SIMILAR TO Sn^{2+}, Sn^{4+}

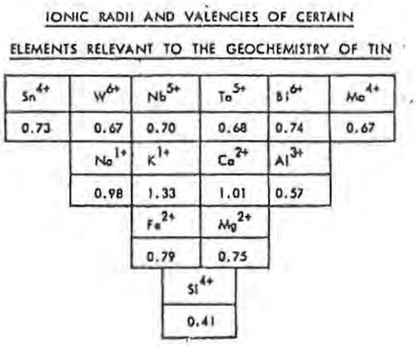
Ion		Coordination and ionic radius (Å)			Electronegativity
		4	6	12	
Sn^{2+}		-	0.93	-	1.80
	Ca^{2+}	-	1.00	1.35	1.00
	Cd^{2+}	0.80	0.95	1.07	1.70
	In^{3+}	-	0.79	-	1.70
	Fe^{2+}	0.63	0.61 (L)* 0.78 (H)*	-	1.80
Sn^{4+}		-	0.69	-	1.90
	Fe^{2+}	0.63	0.61 (L) 0.78 (H)	-	1.80
	Fe^{3+}	0.49	0.55 (L) 0.64 (H)	-	1.90
Mg	Mg^{2+}	0.58	0.72	-	1.20
	Sc^{3+}	-	0.74	-	1.30
	In^{3+}	-	0.79	-	1.70
	Ti^{4+}	-	0.60	-	1.60
	Nb^{4+}	-	0.69	-	1.60
	Nb^{5+}	0.32	0.64	-	1.60
	Ta^{5+}	-	0.64	-	1.50

* The letters (L) and (H) refer to the low spin and high spin states respectively.

Table 3. (Taylor, 1979).

Because of the similarity to other common metallic ions, tin may proxy for them in common minerals, or they may form tin analogues. This crystal chemical affinity of tin to replace Ti^{4+}, Fe^{3+}, Mg^{2+},

Ca^{2+} explains the preferential entry of tin into biotite, hornblende and sphene. Thus, ferromagnesian minerals will have a greater concentration of tin compared to minerals such as quartz and feldspar which contain Na, Ni, Ca, Si (Table 4). Biotite is especially well known to contain high amounts of tin (Table 5) and postulated reasons for this are the isomorphic replacement of cations occupying octahedral latice sites in biotite (i.e. substitution of Sn^{4+} for Fe^{3+}, Ti^{4+})or the presence of tin bearing accessory minerals occuring as inclusions. Small amounts of tin can be incorporated into corundum to produce nigerite, $(Al, Fe)_{12}$ (Sn, Fe, Zn) Mg_3 O_{22} $(OH)_2$, into spinel to produce limaite $(Al, Zn, Sn)_3$ O_4 and into galena to produce franckeite.



IONIC RADII AND VALENCIES OF CERTAIN ELEMENTS RELEVANT TO THE GEOCHEMISTRY OF TIN

Sn^{4+}	W^{6+}	Nb^{5+}	Ta^{5+}	Bi^{6+}	Mo^{4+}
0.73	0.67	0.70	0.68	0.74	0.67
	Na^{1+}	K^{1+}	Ca^{2+}	Al^{3+}	
	0.98	1.33	1.01	0.57	
		Fe^{2+}	Mg^{2+}		
		0.79	0.75		
		Si^{4+}			
		0.41			

Table 4.
(Hosking, 1965)

TABLE

TRACE ELEMENT ANALYSES (ppm) OF BIOTITES AND MUSCOVITES FROM THE ANCHOR MINE DISTRICT, BLUE TIER, NORTH EAST TASMANIA

(From Groves, 1972)

	Sn	Sc	Rb	Sr	
1) Biotite muscovite granite					
Biotite	635	38	6795	4	
Biotite	680	43	6940	8	
Biotite	450	9	6810	8	Tin bearing
Biotite	505	74	7570	15	
Biotite	435	45	6790	4	
Biotite	630	104	7520	3	
Average	556	52	7070	7	
Muscovite	340	-	2370	10	
Muscovite	130	-	2400	13	
2) Porphyritic biotite Granite/Adamellite					
Biotite	60	74	1935	21	
Biotite	67	68	1550	3	Tin barren
Biotite	58	74	1685	4	
Biotite	65	74	1520	18	
Biotite	72	73	1840	21	
Average	64	73	1705	13	

Table 5.
(Taylor, 1979)

THE MINERALOGY OF TIN

There are approximately 50 naturally occurring mineral species that contain tin as a major component, (Table 6) and more are being discovered. Of these however, the only economically important tin bearing minerals are cassiterite, SnO_2, and stannite, $Cu_2 Fe Sn S_4$. At low temperatures, the affinity of tin for sulphur increases, but at intermediate to high temperatures it occurs exclusively in oxygen bearing compounds. The predominance of the oxide, cassiterite, is thus explained because tin is concentrated in high temperature magmatic and hydrothermal systems. Any minor amount of residual tin that escapes to the low temperature regime will only then become fixed in sulphides.

Stannides	
Niggliite	$PtSn$
Stannopalladinite	$(Pd, Cu)_3Sn_2$ (?)
Sulfides	
Stannite	Cu_2FeSnS_4
Hexastannite (stannoidite)	$Cu_5(Fe, Zn)_2SnS_8$
Mawsonite	$Cu_7Fe_2SnS_{10}$
Kösterite	$Cu_2(Zn, Fe)SnS_4$
Colusite	$Cu_3(As, Sn, V, Fe)S_4$
Cernyte	Cu_2CdSnS_4
Herzenbergite	SnS
Ottemannite	Sn_2S_3
Berndtite	SnS_2
Teallite	$PbSnS_2$
Montesite	$PbSn_4S_5$ (?)
Franckeite	$Pb_5Sn_3Sb_2S_{14}$
Oxides	
Cassiterite	SnO_2
Varlamoffite (hydrocassiterite ?)	$(Sn, Fe)(O, OH)_2$
Nigerite	$(Zn, Mg, Fe)(Sn, Zn)_2(Al, Fe)_{12}O_{22}(OH)_2$
Ixiolite	$(Ta, Nb, Sn, Mn, Fe)_2O_4$ (orthorhomb.)
Wodginite	$(Ta, Nb, Sn, Mn, Fe)_{16}O_{32}$ (mon.)
Yttrotantalite	$(Y, Fe, U, Ce, Zr)(Ta, Nb, Ti, Sn)O_4$
Rijkeboerite	$Ba(Ta, Nb)_2(O, OH)_7$
Thoreaulite	$Sn(Ta, Nb)_2O_6$
Borate, silicates	
Nordenskiöldine	$CaSn[BO_3]_2$
Malayaite	$CaSn[O\|SiO_4]$
Pabstite	$Ba(Sn, Ti)[Si_3O_9]$

Table. 6 . The more important tin minerals. (Wedepohl, 1970)

The mineralogy of tin in various systems is reviewed in detail by Taylor, 1979 (Chapt. 10) so that only the minerals of economic significance will be discussed here. In addition, mineralogical features that are likely to influence sampling and recovery are briefly mentioned.

The tin-oxygen system

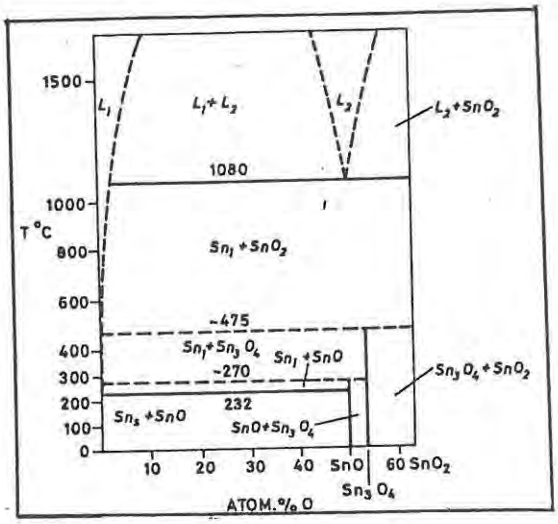


Fig.16. The tin-oxygen system (Taylor, 1979)

Cassiterite is the only mineral of economic significance in the tin-oxygen system (Figure 16) and it is the most common and important of all tin minerals. The tin content of cassiterite is 78.6% Sn. It is often associated with minerals of W, Fe, Bi, Bi, Ag, Mo, Li such as wolframite, tourmaline, lepidolite and fluorite, and occurs in pneumatolytic and high temperature hydrothermal veins or metasamatic deposits.

Cassiterite belongs to a family of compounds which are dioxides of quadrivalent metals and fluorides of divalent ions with small atomic radii such as Co, Fe, Mg, Mn, Ni, Pt, Zn. The parameters of its structure are shown in Table 7, which demonstrates why certain elements can be easily incorporated into the cassiterite structure.

VALUES OF THE CELL PARAMETERS a AND c AND THE POSITIONAL CO-ORDINATE u FOR SOME RX_2 STRUCTURES OF THE CASSITERITE (RUTILE) TYPE. (Adapted after Wychoff, 1963)

Compound	a in Å	c in Å	u
GeO_2	4.395	2.859	0.307
IrO_2	4.49	3.14	
MnO_2	4.396	2.871	0.302
MoO_2	4.86	2.79	
NbO_2	4.77	2.96	
OsO_2	4.51	3.19	
PbO_2	4.946	3.379	
RuO_2	4.51	3.11	
SnO_2	4.73727	3.186383	0.307
TaO_2	4.709	3.065	
TeO_2	4.79	3.77	
TiO_2	4.59373	2.95812	0.3053
WO_2	4.86	2.77	

Table 7.
(Taylor, 1979)

The incorporation of trace elements into cassiterite is governed by factors such as relative abundance, ionic radii, electronegativities, site compatability and site preference energy. Substitutions may take place into lattice sites for tin or oxygen and into interstitial positions whilst impurities may occur as absorbed species on surfaces or as discrete phases. The trace elements most similar to Sn^{4+} are Ti, Zr, Sc, Nb, Ta, W and In. Thus W may substitute for Sn^{4+} and be incorporated intq the cassiterite lattice or it may occur as exsolution bodies. The behaviour of these elements, and Ag, Pb, F, within cassiterite is discussed by (Taylor, 1979. Chapt. 10).

Cassiterite is ditetragenal in its crystal form and ranges widely in habit from bipyramidal to long hair-like fibres. The variability and nature is of importance in recovery. For example late stage cassiterite is often both strongly prismatic and acicular. In addition, it often occurs in different habits of different generations at the same site. It seems that certain crystal habits may be preferred in specific environments, Hosking (1965) for example, indicates that "true pegmatite cassiterite consists of squat dipyramids (101) and (111)". At high temperatures, cassiterite tends to occur as short prismatic crystals, whereas in lower temperature environments they are elongate prismatic, acicular or rolloform. Taylor (1979), however, concludes that although there are some relationships between crystal habit and environment of deposition, these can only be considered as generalisations.

Cassiterite is chemically inert and insoluble and has a high specific gravity of 6.8 to 7.1. These properties allow the mineral to be readily separated by gravity methods. However, cassiterite is brittle with a conchoidal fracture. The mineral is resistant to weathering and will concentrate in the oxidised portions of lodes, especially if it is associated with easily decomposable material such as calcite or sulphides.

It is traditionally regarded as being non-magnetic and treatment processes frequently rely on this property. However, it is now becoming evident that some cassiterite is magnetic. Magnetism may result from small magnetite inclusions or the presence of iron in the crystal lattice or iron impurities occuring as finely divided superparamagmatic material (Taylor, 1979).

Cassiterite is usually brown to black, although there is a wide range of possible colours. A wide colour variation is especially prominent in greisen environments. If it can be established that a particular colour is diagnostic of a specific environment, then colour may possibly be a useful prospecting aid in tracing the source from alluvial concentrations.

Wood-tin is the common name for the rare, concentric or radial, colloform-botryoidal-globular or oolitic forms of cassiterite. The mode of formation is not known but it seems to prefer high level environments and is found in particular in epithermal or xenothermal deposits such as Mexico, Japan and Bolivia. Wood-tin tends to occupy cavities and is therefore most likely of late stage, low temperature origin. It occurs well below the oxidation zone so that it cannot be of supergene derivation. Methods of formation may be cavity infilling by complex SiO_2 - SnO_2 gels, differing degrees of supersaturation resulting in preferential layered deposition or rapid nucleation promoted by highly saturated solutions.

The tin-sulphur system

The important minerals in this system are stannite, $Cu_2Fe SnS_4$, and herzenbergite, SnS. Herzenbergite is an orthorhambic phase (β Sn) which is stable below $6000^{\circ}C$, (Figure 17) and usually occurs intimately associated with cassiterite, pyrite and quartz.

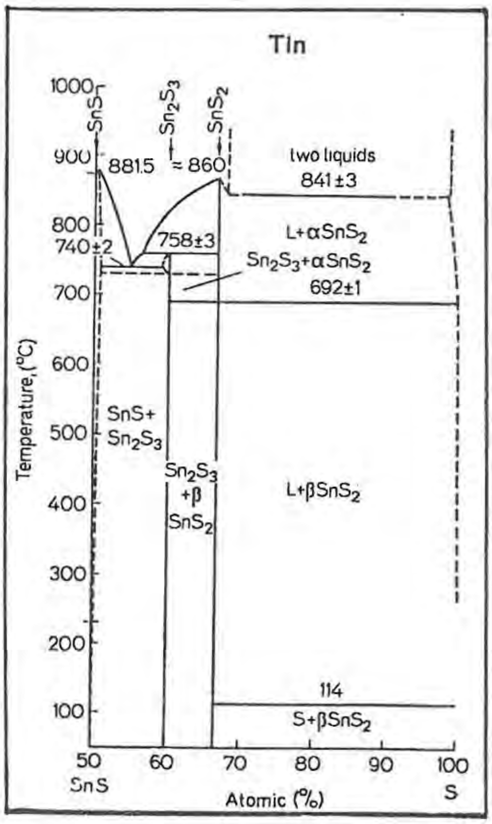


Fig. 17. Phase relations in the tin Sn S - S portion of the Sn - S system (Wedepohl, 1970)

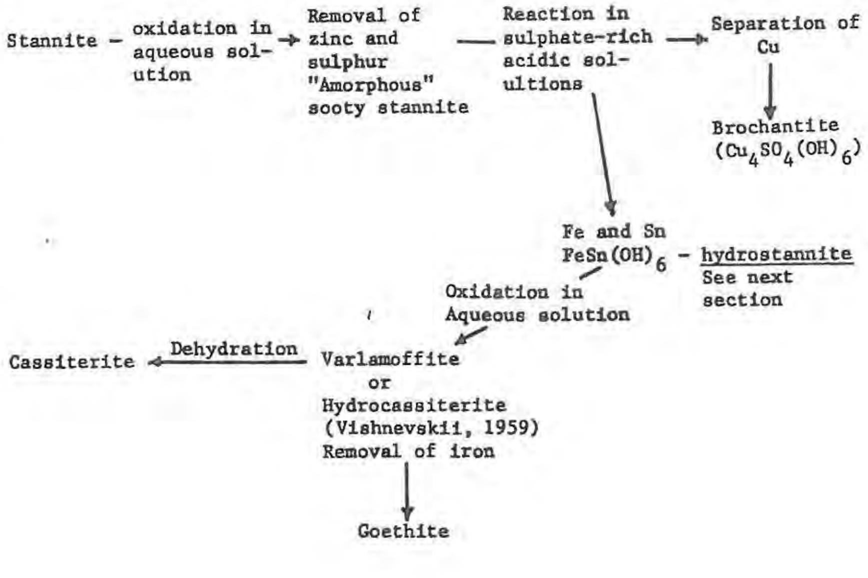
There is a distinct lack of sulphides in most deposits and as yet no reason has been found to account for this. For tin-sulphide, SnS, to occur, it seems that iron oxides and copper or copper iron sulphide must be absent (Taylor, 1979). If they are present, then tin will report into stannite. As they are usually present in tin deposits, then simple tin-sulphide SnS is rare. Tin sulphide has a limited stability range and rapidly fluctuating polyphase ore precepitation processes may not be favourable for its formation.

Stannite, with 27,5% Sn, is the most important economic tin sulphide mineral. It occurs in tin bearing veins and is associated with chalcopyrite, sphalerite, tetrahedrite, pyrite, cassiterite, wolframite and quartz. Stannite may form under a wide range of temperatures. It occurs in a number of forms ranging from massive lumps to small exsolutions. It oxidises to a series of complex products known as varlamoffite.

Other sulphide minerals which are only important in the Bolivian tin-silver province are canfieldite ($Ag_8\ SnS_6$), cylindrite ($Pbz\ Sn_4\ Sb_2\ S_{14}$), Teallite ($Pb\ Sn\ S_2$) and franckeite ($Pb_5\ Sn_3\ Sb_2\ S_{14}$).

Oxidation products of stannite : varlmoffite

The oxidation products of tin sulphides are important as they will influence any assays taken from the oxidation zone of stannite-bearing deposits. The oxidation product most likely to be met is varlamoffite which is the general name for a complex mixture of phases of amorphous and semi-amorphous hydrated tin compounds. It generally occurs as a yellow powder and is most likely formed by the attack of meteoric water on stannite:-



(Taylor, 1979)

Other oxidation products are known but are unimportant compared with varlamoffite. These include yellow brown hydrous tin dioxide (hydro-cassiterite), green hydrated copper iron stannate, copper iron hydro-stannates and tin chloride hydroxides.

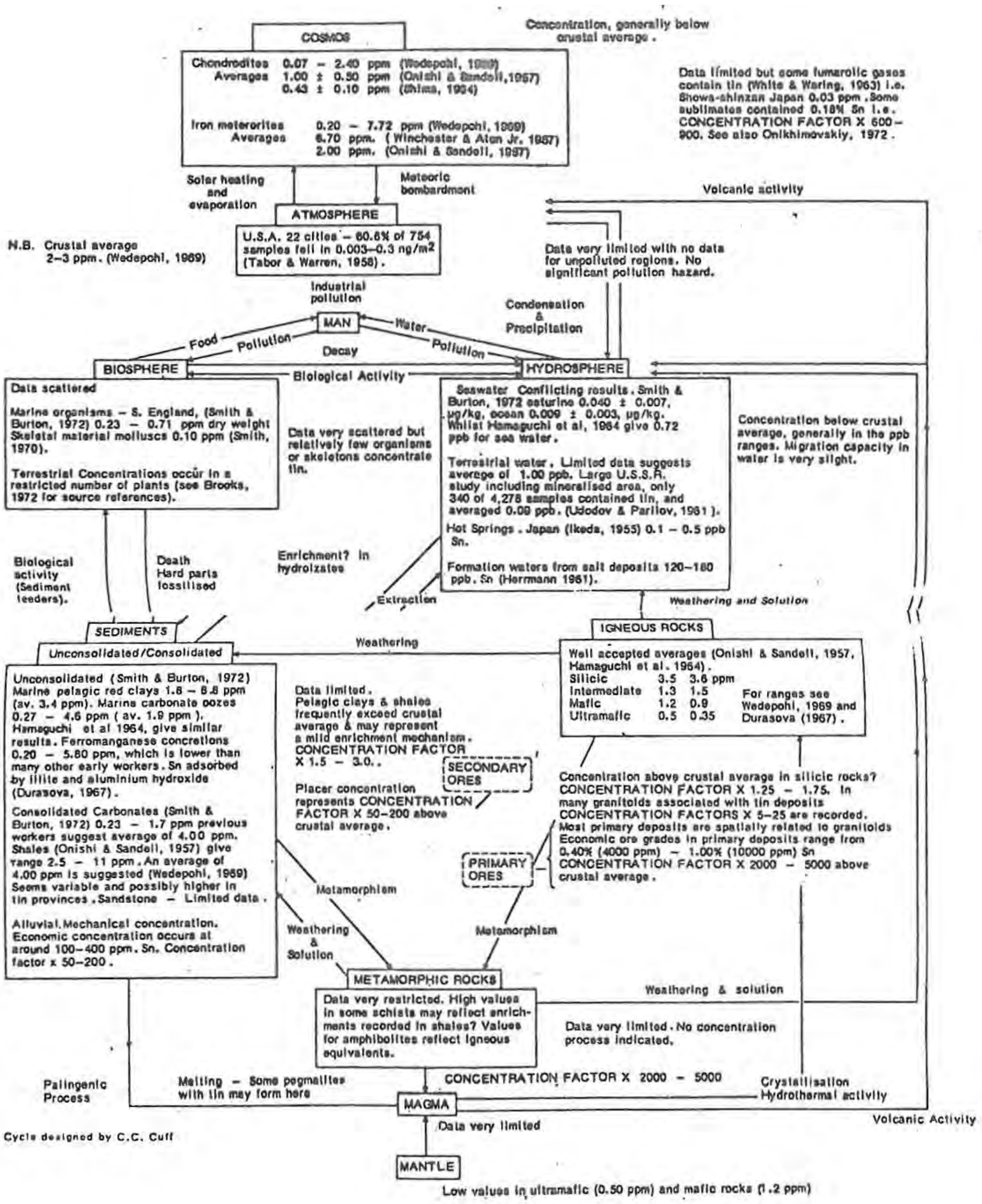
Tin silicate minerals

Malayaite ($Ca SnO Si O_4$) is the tin analogue of sphene and is generally confined to skarn deposits. Here it is associated with wollastanite, grossularite, diopside, etc. which may also be tin rich. It can usually be identified by pale yellow green fluorescence under ultraviolet light.

THE ABUNDANCE AND DISTRIBUTION OF TIN IN THE GEOCHEMICAL CYCLE.

Tin has an average crustal abundance of 2-3 ppm and is particularly enriched in acid igneous rocks. The average content of granitoids is 3.5-3.6 and this is illustrated as part of the geochemical cycle in Figure 18.

Cassiterite is a resistate mineral that is resistant to chemical weathering. The mechanical release and concentration of tin, together with a high specific gravity of 6.8-7.1 results in the formation of important placer deposits under favourable conditions. Although tin is essentially insoluble, some very fine grained particles may act as colloidal particles and some may even pass into solution; the behaviour is governed by physico-chemical parameters such as Eh-pH conditions. In particular, the behaviour in fluid is determined by the oxidation state: Sn(II) has an ionic potential of 2.6 and therefore passes into solution as cations. Sn(IV) has an ionic potential of 5.14 and consequently precipitates as hydrolysates. Because natural conditions are unfavourable for Sn(II), Sn(IV) is the only stable ionic species in the weathering environment. Figure 18 demonstrates that the hydrosphere contains very low concentrations of tin, and this is due to its low migration capacity. Tin is poorly concentrated in sedimentary rocks although some clay minerals may be able to remove tin from solution by absorbtion and base metal exchange. Tin does, however, become enriched in aluminium rich resistates such as bauxites. The reason for this is that tin will only go into solution to a limited degree and therefore remains as a residue.



Chondrodites 0.07 – 2.40 ppm (Wedepohl, 1969)
Averages 1.00 ± 0.50 ppm (Onishi & Sandell, 1957)
0.43 ± 0.10 ppm (Shima, 1964)

Iron meterorites 0.20 – 7.72 ppm (Wedepohl, 1969)
Averages 6.70 ppm. (Winchester & Aton Jr. 1957)
2.00 ppm. (Onishi & Sandell, 1957)

Concentration, generally below crustal average.

Data limited but some fumarolic gases contain tin (White & Waring, 1963) i.e. Showa-shinzan Japan 0.03 ppm. Some sublimates contained 0.18% Sn i.e. CONCENTRATION FACTOR X 600–900. See also Onikhimovskiy, 1972.

N.B. Crustal average 2–3 ppm. (Wedepohl, 1969)

U.S.A. 22 cities – 60.6% of 754 samples fell in 0.003–0.3 ng/m2 (Tabor & Warren, 1958).

Data very limited with no data for unpolluted regions. No significant pollution hazard.

Data scattered

Marine organisms – S. England, (Smith & Burton, 1972) 0.23 – 0.71 ppm dry weight Skeletal material molluscs 0.10 ppm (Smith, 1970).

Terrestrial Concentrations occûr in a restricted number of plants (see Brooks, 1972 for source references).

Data very scattered but relatively few organisms or skeletons concentrate tin.

Seawater Conflicting results. Smith & Burton, 1972 esturine 0.040 ± 0.007, µg/kg, ocean 0.009 ± 0.003, µg/kg. Whilst Hamaguchi et al, 1964 give 0.72 ppb for sea water.

Terrestrial water. Limited data suggests average of 1.00 ppb. Large U.S.S.R. study including mineralised area, only 340 of 4,278 samples contained tin, and averaged 0.09 ppb. (Udodov & Parilov, 1961).

Hot Springs. Japan (Ikeda, 1955) 0.1 – 0.5 ppb Sn.

Formation waters from salt deposits 120–180 ppb. Sn (Herrmann 1961).

Concentration below crustal average, generally in the ppb ranges. Migration capacity in water is very slight.

Unconsolidated (Smith & Burton, 1972) Marine pelagic red clays 1.8 – 6.8 ppm (av. 3.4 ppm). Marine carbonate oozes 0.27 – 4.6 ppm (av. 1.9 ppm). Hamaguchi et al 1964, give similar results. Ferromanganese concretions 0.20 – 5.80 ppm, which is lower than many other early workers. Sn adsorbed by illite and aluminium hydroxide (Durasova, 1967).

Consolidated Carbonates (Smith & Burton, 1972) 0.23 – 1.7 ppm previous workers suggest average of 4.00 ppm. Shales (Onishi & Sandell, 1957) give range 2.5 – 11 ppm. An average of 4.00 ppm is suggested (Wedepohl, 1969) Seems variable and possibly higher in tin provinces. Sandstone – Limited data.

Alluvial. Mechanical concentration. Economic concentration occurs at around 100–400 ppm. Sn. Concentration factor x 50–200.

Data limited. Pelagic clays & shales frequently exceed crustal average & may represent a mild enrichment mechanism. CONCENTRATION FACTOR X 1.5 – 3.0..

Placer concentration represents CONCENTRATION FACTOR X 50–200 above crustal average.

Well accepted averages (Onishi & Sandell, 1957, Hamaguchi et al. 1964).

Silicic	3.5	3.6 ppm
Intermediate	1.3	1.5
Mafic	1.2	0.9
Ultramafic	0.5	0.35

For ranges see Wedepohl, 1969 and Durasova (1967).

Concentration above crustal average in silicic rocks? CONCENTRATION FACTOR X 1.25 – 1.75. In many granitoids associated with tin deposits CONCENTRATION FACTORS X 5–25 are recorded.

Most primary deposits are spatially related to granitoids Economic ore grades in primary deposits range from 0.40% (4000 ppm) – 1.00% (10000 ppm) Sn CONCENTRATION FACTOR X 2000 – 5000 above crustal average.

Data very restricted. High values in some schists may reflect enrichments recorded in shales? Values for amphibolites reflect igneous equivalents.

Data very limited. No concentration process indicated.

Cycle designed by C.C. Cuff

Low values in ultramafic (0.50 ppm) and mafic rocks (1.2 ppm)

Fig. 18. The geochemical cycle of tin (Taylor, 1979)

Data from Sainsbury et al. (1968), Figure 19, indicates that tin is preferentially concentrated in the granite and that heavy minerals contain the greatest concentration of tin. Tin is also concentrated in the contact zones and in all minerals from the tin and beryllium deposits. Similarly, soils and plants over the deposits are enriched, but the authors do not indicate in what form. Hosking (1965) notes that in areas containing tin skarns, the tin content of soils is due to the presence of sphene, andradite, grossularite etc. and also to secondary decomposition products.

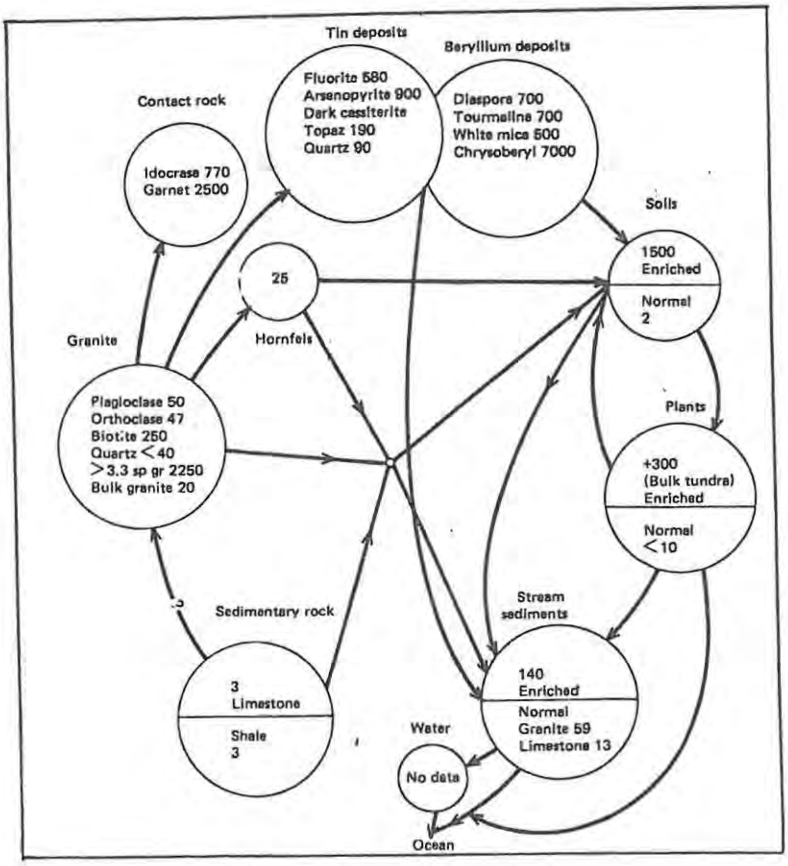


Fig. 19. Geochemical cycle of tin, western Seward Peninsula, Alaska. Numbers are ppm (Sainsbury et al., 1968)

Weathering has a different effect on the different types of deposit and this depends on the gangue and associated sulphides present. Sulphide rich deposits are likely to oxidise easily and thus release cassiterite, whilst quartz cassiterite deposits will be more durable. Similarly, greisen deposits will weather rapidly but endogranitic types will be relatively resistant. Tin is only likely to be released into solution if the weathered deposit contains tin bearing sulphides and ferromagnesian minerals which oxidise easily.

Supergene and hypogene enrichment does not occur in tin deposits due to the low chemical mobility of tin. This is in contrast to many base metal sulphide deposits such as copper.

4. THE GENERATION OF PRIMARY TIN DEPOSITS

The genesis of primary tin deposits is related to the fractional crystallisation of residual liquids that crystallise from the final portion of granite magmas. The initial magma is differentiated during emplacement and this results in multiple phase intrusions. During the fractional crystallisation process, volatiles and incompatible elements are concentrated in residual fluids that separate from the rest liquid. These are consequently associated with the youngest members of the granitoid suite. Concentration of the elements is governed by the crystal chemistry of the elements involved. The fluids so formed generate the evolving hydrothermal system that transports and deposits tin in both endogranitic and exogranitic environments.

Tin deposits comprise a continuous spectrum that ranges from endogranitic through pyrometasomatic and hypothermal to distal xenothermal. The transport and concentration of tin can therefore be considered in terms of the successive stages in the evolutionary process which took place during ore formation.

THE TRANSPORT AND CONCENTRATION OF TIN

The processes of transport and concentration of tin are highly complex and by no means understood. Because different patterns of tin distribution and element specialisation occur in nature, it is evident that a diversity of processes operates, Figure 20. These processes may be distinguished as those that concentrate and transport tin in the orthomagmatic melt phase, and those that concentrate and transport tin in subsequent postmagmatic hydrothermal fluid phases. Hesp and Rigby (1972) believe that postmagmatic processes are by far the most important mechanisms.

The transport and concentration of tin in the orthomagmatic melt phase

The tin from the primary source is concentrated through the processes that operate during magma solidification. It may pass directly into orthomagmatic cassiterite or it may be concentrated as isomorphous replacements for other metals in host minerals such as biotite, hornblende, sphene and to a lesser extent, feldspar and quartz. In the orthomagmatic environment, concentration and transport processes occur together (Taylor, 1979). They consist of: fusion and incorporation of the tin rich source material, enrichment by progressive late stage differentiation, and selective enrichment by diffusion.

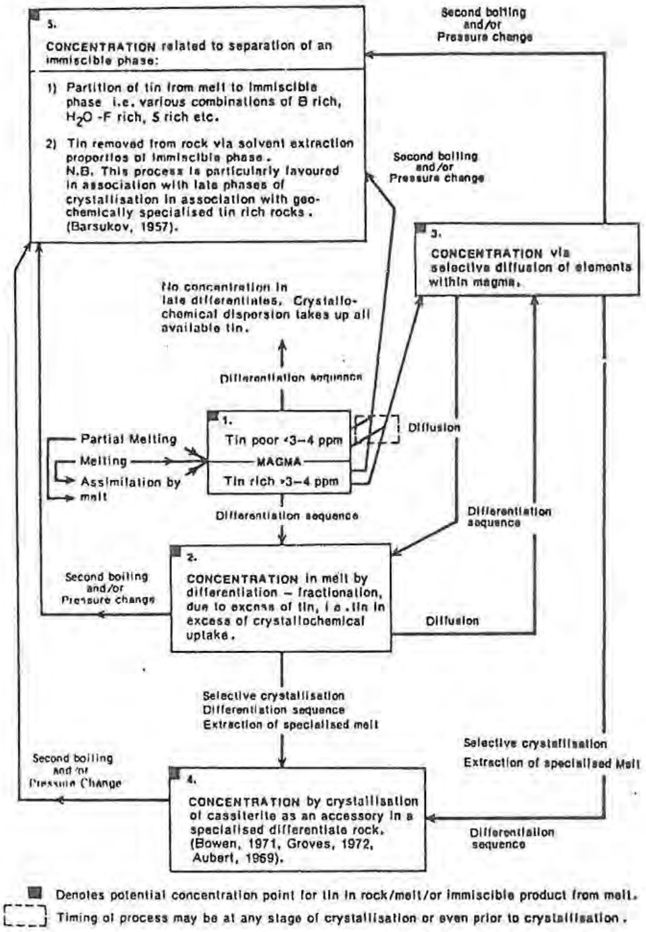


Fig. 20. Concentration mechanisms for tin in the igneous environment (Taylor, 1979)

Selective diffusion occurs by migration through intergranular pore fluids, along grain boundaries and internal boundaries and through multi-component magmatic fluids. The mechanisms are poorly understood but it seems possible that trace elements may be concentrated during the melt phase, prior to differentiation (Taylor, 1979).

Differentiation or fractional crystallisation is the most important control on tin concentration in the orthomagmatic environment. A magma that is more highly fractionated will concentrate a greater amount of tin. For this reason the most highly fractionated and silicic granitoid intrusives are optimal for tin concentration. Within the granitoid, fractional crystallisation increases towards upper levels so that the roof zones are the preferred sites of concentration.

The chemical behaviour of Sn in orthomagmatic processes is not clearly known. However, tin may occur in the melt as free Sn^{4+} or as stanno-alumino-silicate complexes. It may substitute isomorphously for Fe^{2+}, Mg^{2+}, Li^{+} in ferromagnesian minerals because of its crystal chemistry or it may concentrate in residual silicate melts. In the silicate melt, Sn^{4+} behaves as a "network former" (Stemprok, 1969) so that tin-oxygen compounds accumulate in residual magma until concentration is sufficient for cassiterite to precipitate. Environmental conditions such as oxygen fugacity and partial pressure of CO_2, Cl_2, F etc., affect the partitioning of tin into the solid phase.

Hesp and Rigby (1972) consider that the ability to form cassiterite in the orthomagmatic environment depends on the composition of the magma, the mechanism of fractional crystallisation, the original concentration of tin and geological/structural factors. In particular, the content and nature of volatiles is critical. Water and halogen compounds are especially important as these may be largely responsible for tin transport. These authors propose that three main routes are availible for cassiterite formation during rock solidification:

i) pneumatolytic (vapour phase) transport of tin as volatile halides; residual melts containing tin in the presence of halogens may give rise to volatile tin halides (SnF_4 and $SnCl_4$) which move as vapour to apical regions where they react with wall rocks to hydrolyse and precipitate cassiterite

ii) extraction of tin from country rock as sodium stannate; Smith (1947) proposed this as an alternative to the pneumatolytic transport theory. He indicates that tin concentrates as Na_2SnO_3 which is stable in melts above 700°C and soluble in water at low (100-200°C) temperatures. On heating, sodium stannate hydrolyses to produce cassiterite above 300°C. This is therefore a mechanism by which tin may transport at low temperatures.

iii) the direct crystallisation of cassiterite from a magma; although orthomagmatic cassiterite deposits have been reported, for example in the Bushveld Complex (Hunter and Lenthall, 1971), it seems more likely that these are in fact of epigenetic postmagmatic origin because of the presence of associated hydrothermal alteration. Taylor (1979) is doubtful about the presence of orthomagmatic cassiterite in tin deposits and believes that most of the tin reports to ferromagnesian minerals and accessories. This is a reasonable thesis as most descriptions of orthomagmatic deposits (Strauss, 1954) note the presence of some form of associated alteration which is indicative of hydrothermal postmagmatic activity. The important feature, according to Taylor, is that the tin content of ferromagnesian minerals becomes available for later release and concentration by postmagmatic hydrothermal fluids.

The transport and concentration of tin in postmagmatic hydrothermal fluid phases

Figure 21 demonstrates that hydrothermal fluids result from a variety of sources and that the interacting system is highly complex. The possible mechanisms of transport are numerous and likely to be different in various fluids and their combinations under different conditions. Transport may occur in either the gas or the aqueous phase but more likely a combination of the two. In addition, transport mechanisms may be genetically related to host rock leaching and other alteration processes that liberate tin (Taylor, 1979).

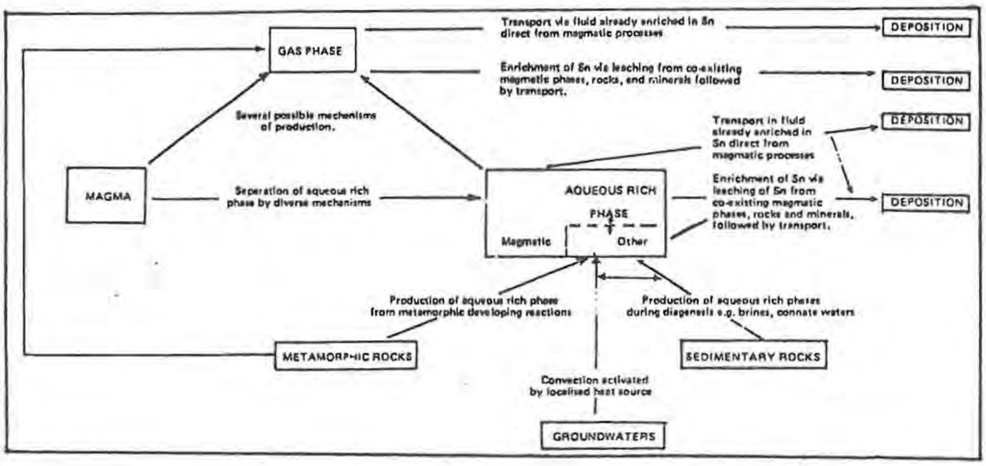


Fig. 21. The concentration and transport of tin in aqueous rich fluids (Taylor, 1979)

The large number of alternatives proposed are reviewed by Taylor (1979, Chapt. 11) who concludes that each may be applicable in different circumstances. In the gaseous phase, tin may be transported as chlorides and halides, where the transport ability is a function of the boiling point. Alkaline solutions may leach tin from the granitoid and trasport it as oxyfluoro stannates; similarly ammonium chloride may be an efficient leaching and transporting agent. In aqueous solution, tin may travel as $Na_2(Sn(OH)_6)$, $Na_2(SnF_6)$ and $Na_2(Sn(OH_1F)_6)$ and a variety of other complexes.

Flourides are often quoted as an important transporting agent (Pearce and Gale, 1977; Tischendorf, 1973). Pearce and Gale (1977) indicate that tin has a strong affinity for fluorine and that the partitioning of tin into late fluids increases with increasing fluorine concentration. According to Tischendorf (1973), tin-fluorine specialisation is compulsory in tin granitoids of the Erzgebirge and there is a definite minimum activity of fluorine for tin mineralisation. An increasing concentration of fluorine is necessary for intensification of hydrothermal processes and the increasing solubility of tin which is transported as the fluorohydroxy stannate complex. Similarly boron-rich fluids may act as concentrating agents. This is because tin partitions strongly into an immiscible B_2O_3 rich phase in the system $CaO-B_2O_3-2SiO_2$ (Durasova and Barsukov, 1973).

However, fluorine and boron are not associated in all deposits which demonstrates that other complexes are equally significant in different circumstances. Groves and McCarthy (1978) suggest that the most likely form of transport is as anionic oxy- or hydroxy complexes. Concentrated chloride brines may transport tin, but usually there is a lack of chlorine bearing minerals associated with tin deposits. Kelly and Turneaure (1970) nevertheless conclude that the fluids of the southern Bolivian tin deposits are Na Cl rich brines.

Hesp and Rigby (1972) believe that postmagmatic metasomatism is the most important process in generating tin deposits. Thus, tin is released from host minerals by hydrothermal solutions and under favourable conditions they hydrolyse to form cassiterite. Tin may be removed from biotite and other tin bearing minerals as the oxyfluoro complex (Barsukov, 1967). In alkaline solutions of pH 8-11 containing Na^+, K^+, Cl^-, SiO_3^{2-} and F^-, oxyfluoro stannates of the type $Na_2(Sn(OH)_xF_{6-x})$ are soluble in aqueous fluids and may therefore transport tin. Cassiterite precipitates when the pH is reduced by wall rock reaction to 7.5-8. Hesp and Rigby point out that 1 km^3 of rock at 1ppmSn contains 5000 tons of cassiterite.

ENDOGRANITIC TIN DEPOSITS

If the tin rich fluids are restrained within the granitoid by an impermeable barrier or lack of fractures, then endogranitic crystallisation results in the formation of either syngenetic or epigenetic mineralisation. In the first case, magmatic disseminated deposits may form. In the latter, the hydrothermal fluids may migrate upwards through the semi-crystallised magma at a late stage to produce mineralised pipes. The hydrothermal fluids may react with the enclosing granitic material to produce alteration effects such as greisenisation and albitisation. If the hydrothermal fluids are impounded, then extensive greisenisation associated with disseminated mineralisation will result in greisen hosted disseminated deposits. Because of the mobility of hydrothermal fluids, they tend to travel upwards so that greisenisation and mineralisation are frequently concentrated at the highest apical parts of intrusions. Alternatively, they may occur as laterally extensive sheets if the roof zones are less irregular anf flatter (Groves and Taylor, 1973).

Residual liquids separate from the magma during fractionation. Groves and McCarthy (1978) indicate that the starting composition of the melt is not a controlling factor. What is most important is the manner of crystallisation of the host magma. In particular, the style of crystallisation dictates the degree of separation of the residual liquids from the cumulate phase. This is critically important as the degree of enrichment of tin is reduced by the amount of intercumulus melt that remains in previously separated cumulates (McCarthy and Hasty, 1976).

The trace element composition of the granitoid is controlled by the nature of crystallisation processes or modes of crystallisation. McCarthy and Hasty (1976) recognise two end members of a continuum of conditions. At one end, the entire solid phase remains at all times in equilibrium with the melt to form perfect equilibrium crystallisation. At the other end, perfect fractional crystallisation occurs when only the surfaces of the crystals are in equilibrium. Between the end members partial equilibrium between solid and melt is known as incremental equilibrium crystallisation. The trace element distribution is controlled by crystallisation within this range. In the very late stages of crystallisation, perfect fractional crystallisation predicts the extreme concentration of all trace elements with partition coefficients less than one, and extreme depletion of those trace elements with partition coefficients greater than one. Incremental equilibrium crystallisation controls a finite trace element composition according to how much intercumulus melt is trapped. The effect of trapped intercumulus melt is to suppress the degree of enrichment of trace elements in late solids and liquids and therefore the amount of tin available for concentration, Figure 22.

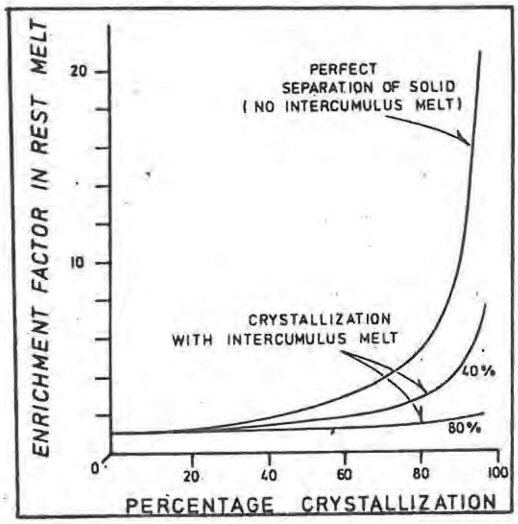
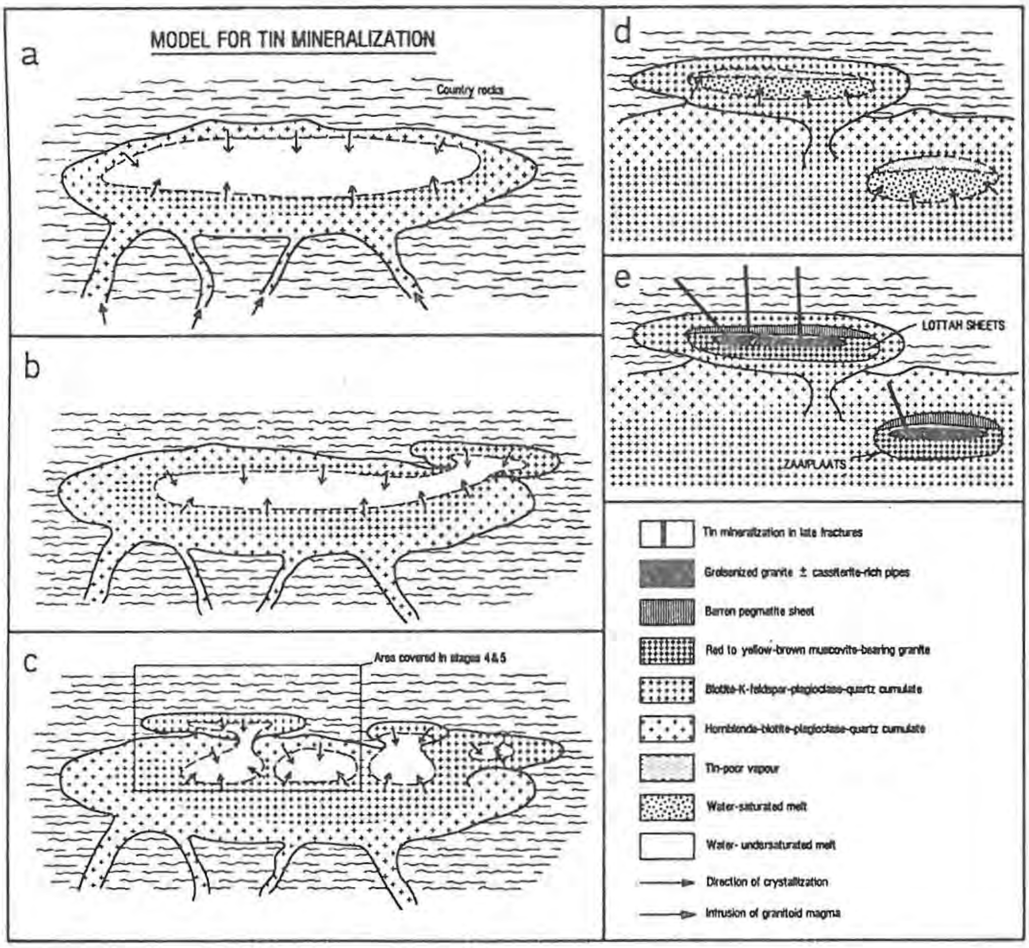


Fig. 22. The enrichment of an incompatible trace element in the melt with progressive fractional crystallisation; 0,40%, 80% trapped intercumulus melt. (McCarthy and Hasty, 1976)

Many tin bearing granitoids have a number of common features such as in-situ fractional crystallisation, the accumulation of late melt in roof sheets, the presence of associated barren pegmatites and aplites and the presence of cassiterite rich sheets with greisenisation effects. Consideration of these features enabled Groves and McCarthy (1978) to formulate a general model for tin mineralisation that is illustrated in Figure 23. The authors state that "a crustally-derived granitoid magma is emplaced and undergoes fractional crystallisation from the margins inwards, with bottom crystallisation dominating. Disruption of earlier formed solids by rest liquid commonly occurs. Continued fractional crystallisation causes enrichment in volatiles and incompatible elements in the late rest melts, which have a sheet-like habit. The efficiency of enrichment of incompatible elements is critically dependent on the degree of separation of melt from solids throughout crystallisation. An early, tin-poor vapour may separate after initial water saturation of the magma is achieved, and this collects under the roof, commonly forming an impermeable barrier (ie. pegmatite) to later tin-bearing fluids. Continued fractional crystallisation on the floor further enriches incompatible elements, and at a very late stage a Sn-rich vapour separates within the intercumulus phase and becomes concentrated by progressive crystallisation of the intercumulus melt. At a late stage of solidification, this vapour loses equilibrium with the earlier formed feldspars and greisenisation ensues, accompanied by the crystallisation of cassiterite and other ore minerals. Dependent on the permeability of the roof, various styles of mineralisation may develop". Large low-grade deposits are more likely to form under an impermeable roof.



Proposed model for tin mineralization: vertical scale exaggerated. a. Initial crystallization of granitoid magma intruded with hornblende, biotite, plagioclase and quartz on liquidus (need not be developed). b. Continued crystallization of magma with progressive change in cumulus mineralogy; disruption of early crystallizates by rest melt forming hornblende-free body. c. Further disruption of early crystallizates during continuing crystallization. d. Continuing crystallization with rest melt attaining water saturation; no roof crystallization but early separation of a tin-poor vapour that collects in structural highs under crystallized roof and forms barren pegmatite sheet at d/e. e. Water-saturated melt crystallizes red or yellow-brown, miarolitic muscovite-bearing granite; Sn-, F- and/or B-rich vapours in late intercumulus liquid cause greisenization beneath roof zone; cassiterite-rich pipes may develop adjacent to greisenized granite; mineralization may occur along late fractures

Fig. 23. (Groves and McCarthy, 1978)

Endogranitic pipe deposits that are not fracture related, such as the Zaaiplaats type, may also be explained by this model. At the stage of concentration of the tin rich vapour, an immiscible low density aqueous, phase separates from the silicate melt and travels upwards through semi-solid crystallising material. Because of the presence of volatiles, extensive alteration occurs so that pipe deposits are frequently fourmalinised and greisenised. This elongate bubble trail (Taylor, 1979) eventually becomes entrapped by crystallising rock before it escapes through a suitable plumbing system. In the Bushveld examples, the pipes reach the impermeable barren pegmatite and spread out laterally to form a series of flat lenticular bodies of disseminated cassiterite which are connected to the underlying pipes.

Groves and Taylor (1973) discuss the role of 'second boiling' as a mechanism for tin precipitation. At the Anchor tin mine, Blue Tier province, Tasmania "greisenisation and mineralisation are related to processes involving a delicate balance between crystallisation of the melt and the development of an aqueous tin rich phase during second boiling". 'Second boiling' is caused when continued cooling results in an increase of crystallisation of anhydrous phases so that the H_2O content of the remaining melt is increased. When the pressure of the H_2O rich phase exceeds total confining pressure, second boiling begins. This causes the aqueous phase to separate as discrete bubbles which rise through the remaining melt in an irregular pipelike column.

ALTERATION PROCESSES IN ENDOGRANITIC ENVIRONMENTS

Hydrothermal fluids react with enclosing rock to produce a variety of alteration effects that are an intimate part of mineralisation. Alteration involves irreversible chemical exchange between hydrous solutions and adjacent wall rock in an attempt to achieve equilibrium under new conditions. The detailed chemical process is not clearly understood and it is apparent that the final result is due to a complex series of events. Components are selectively leached from wall rock whilst other components are removed from fluids to be selectively precipitated, either as a replacement or as a coating. The process depends on the composition of wall rock and fluid, physical conditions at the rock/fluid interface and on the volumes of fluid and rock involved. For this reason the alteration effects vary rapidly at different sites in the system.

The most common alteration types encountered in tin forming environments are sericitisation, chloritisation, tourmalinisation, silicification and greisenisation. These affect the surrounds of fractures and veins for up to 7-8 m (Taylor, 1979) and are often zoned, Figure 24.

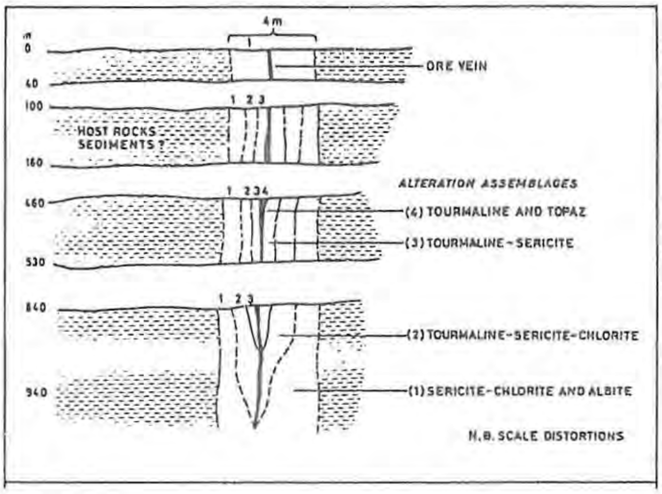


Fig. 24. Vertical wallrock alteration zoning (Tolak and Fedchin, 1970)

Alteration effects are concentrated in apical zones along with mineralisation. This is a result of the trapping of the vapour phase which reacts with partly consolidated cumulates to produce greisenised granite sheets and apophyses, Figure 25. Vein systems may be associated and these may extend beyond the confines of the granite. Greisen is essentially a white mica and quartz assemblage that results from breakdown of feldspar. Occasionally, white mica-topaz assemblages occur, with varied amounts of fluorite, haematite, tourmaline, scheelite, wolframite, molybdenite and bismuthite. The chemical process involves removal of Na and K from the original granite and the addition of OH, F, W, Sn, B to the greisen. This occurs as a result of the increased acidity of the solutions, and takes place when environmental conditions change. The decrease in temperature and the appearance of the liquid H_2O phase lowers the stability of high temperature complexes. This results in decomposition of acid complexes that are stable in supercritical high pressure solutions, and consequently releases anions of strong acids. Greisenisation is a response to this increased acidity of the solutions.

Other alterations such as feldspathisation, sericitisation and muscovitisation occur with greisenisation and invariably grade into each other, Figure 26. Feldspathisation usually

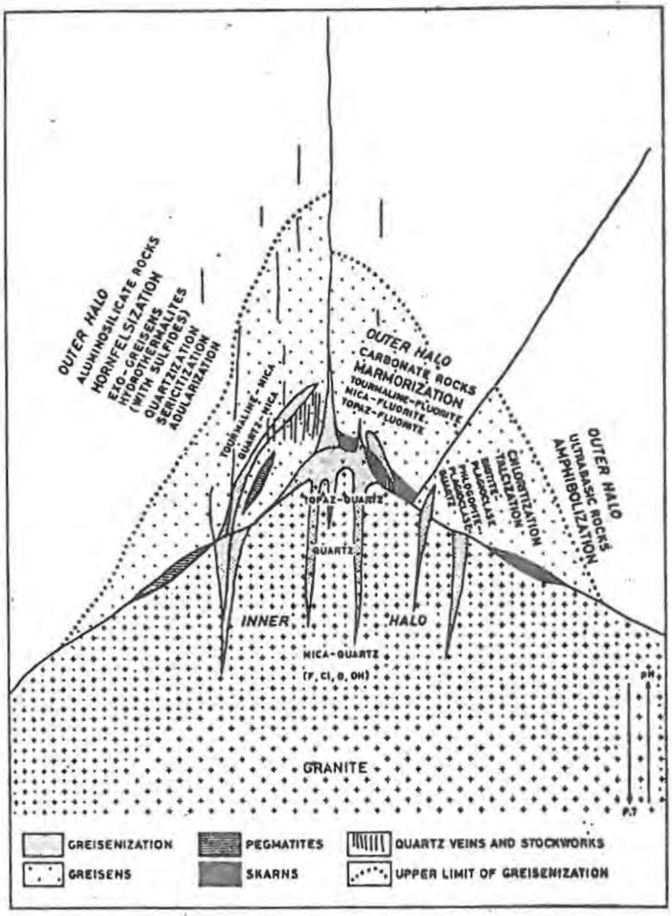


Fig. 25. The greisen environment (Scherba, 1970)

predates greisenisation and involves the conversion of feldspar into secondary albite and microcline. Groves and Taylor, (1973),

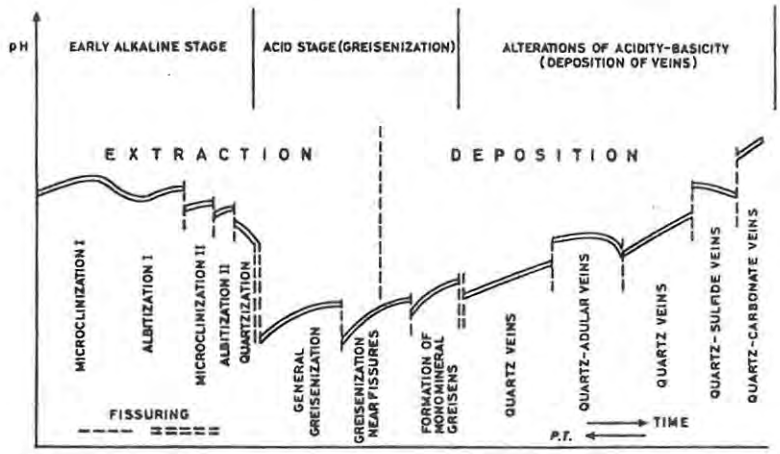


Fig. 26. Postmagmafic alteration sequence in greisen environments (Shcherba, 1970)

note that during conversion of granite to greisen, the following enrichments occur : Sn(x16), Cu(x6), Zn(x3), Ag(x3), Mo(x2), W(x2) whereas Ba is decreased by (x50), Ti(x10), Sr(x4). The first stage of alteration involves the formation of topaz from K feldspar which indicates an acid fluid with a high F content and low K^+/H^+ ratio. This process continues by removal of H^+ ions and addition of K^+ ions to the fluid until muscovite remains as the stable phase. The degree of alteration depends on the rate of removal of fluids from the system. In a closed system with no renewal (i.e. the zones of greisenised granite), equilibrium is reached with the solid phases present. Here alteration takes place as a result of in-situ reaction between residual fluids and crystals. On the other hand the subhorizontal greisen veins are more strongly greisenised with a much higher Sn content, and this indicates renewal of fluids passing through an open system as in Figure 27. The authors conclude that the system contains a delicate balance between a rising aqueous phase and crystallisation of the residual melt. This results in complex variations in shape and composition of the greisen and greisenised granite.

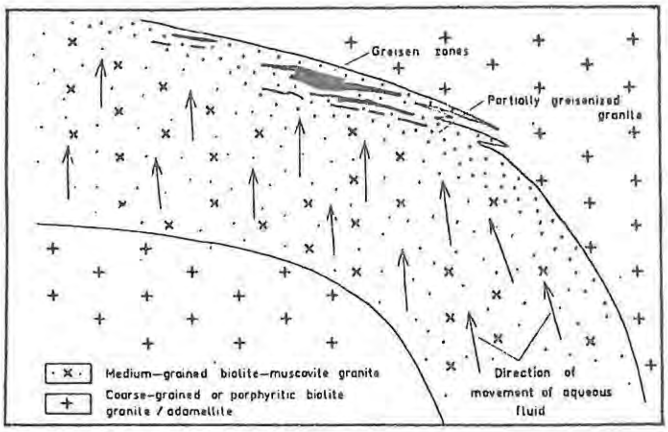


Fig. 27. Possible movement of aqueous fluids derived from crystallising granite producing concentrations of greisenisation and mineralisation along upper contact of intrusion (Groves and Taylor, 1973)

Processes of postmagmatic alteration may be active in leaching tin from tin rich minerals into hydrothermal fluids (Barsukov, 1967). Hosking (1965) maintains that the muscovitisation of brotite releases large amounts of tin, and that subsequent silicification of the muscovite mobilises the tin into the system. This has an important implication in that tin may be derived in part from micas of the granitoid and in part from the tin rich residuum, Figure 28.

TRAPPING MECHANISMS AND SUBSEQUENT FRACTURING

The important constraint on the endogranitic ore forming process is that a trapping mechanism of some sort must exist in order to impound the upward migrating magmatic and hydrothermal fluids. The most favourable sites for concentration are apical roof zones of granites, particularly cupolas, cusps and ridges.

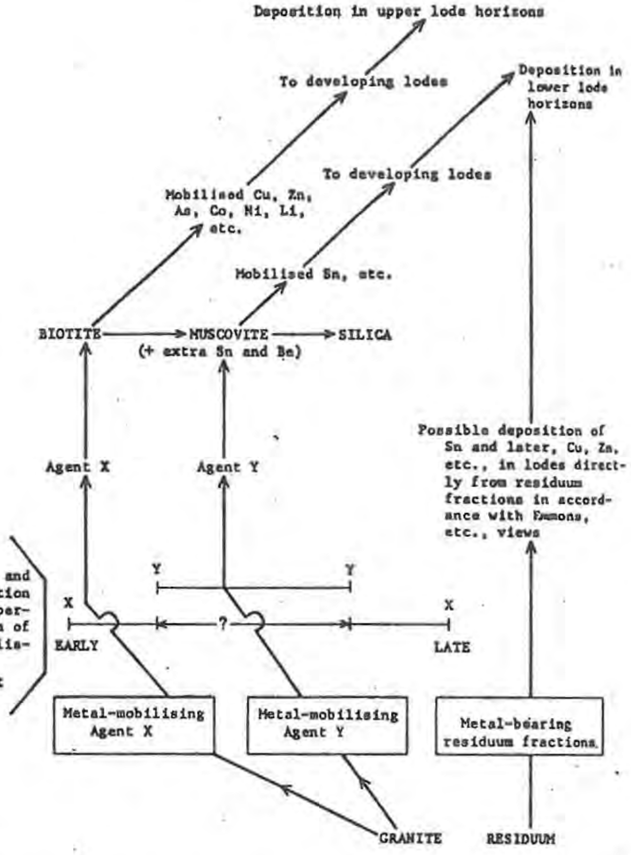


Fig. 28. Postulated genesis of tin deposits: metals derived partly from micas and partly from residuum (Hosking, 1965)

If undisturbed the overlying strata may form an impermeable seal. Often, the impermeable horizon is provided by the previously crystallised granitoid above the roof zone of the mineralised granite. For optimal concentration there must be a total absence of fracturing. Under these conditions tin poor aqueous fluids may collect in structural highs to form an impermeable layer of barren pegmatite, as at Zaaiplaats.

Fractures may eventually develop and facilitate the escape of mineralised fluids to the exogranitic environment. The fracture system produced results in vein networks, fissures and faults that are available for mineralisation. Where these cross reactive lithologies, replacement and skarn deposits can result. Endogranitic fissures may be used by fluids to produce pipelike deposits whilst apical zone vein swarms may be greisenised and mineralised to form greisen-bordered vein swarms.

PEGMATITE AND DYKE RELATED DEPOSITS.

Pegmatites and dykes may result if fracturing occurs at an early stage when the residual liquid is still partly granitic.

Pegmatites are produced during crystallisation of a magma at a stage when the alumino-silicate residuum has extremely low viscosity due to the increasing concentration of volatiles. The relationship between pegmatites and granitoid shows that the main part of the crystallisation of the magma was complete at the time of formation of the pegmatite. More volatile fractions which are markedly enriched in rare elements may separate out as independent gaseous phases, especially if there is a local reduction of external pressure. Under these conditions, cassiterite crystallises together with minerals such as topaz, tourmaline, flourite and wolframite. Pegmatites derived from in situ-metasomatic alteration, i.e. 'sweat-outs', do not produce mineralisation because of the absence of rare element enrichment.

Pegmatites generally solidify late in igneous activity and are especially associated with plutonic hypabyssal intrusives in deep seated high pressure environments. For this reason, they are typically associated with Precambrian basement areas where erosion has exposed deeper levels of the system. They are less common in younger granites; for example, in the S.W. England district they are only of minor significance.

Pegmatites may be simple, although tin mineralisation is dominantly associated with complex varieties that have a varied mineralogical assemblage. During formation, quartz and feldspar are the first minerals to precipitate and subsequent mineral deposition is controlled by the passage of solutions of varying composition. There is often a pronounced zonation in complex pegmatites that results from differential in-situ crystallisation. In the simple case, the metallic minerals are usually concentrated in the intermediate zone. Late, progressively changing fluids however, often induce changes in the composition of early minerals and this results in a complex polyphase paragenesis. Hunter and Lenthall (1971) conclude that tin is introduced during a replacement phase late in the crystallisation of a pegmatite and is associated with replacement phases such as albitisation and muscovitisation. Some finely disseminated cassiterite may have crystallised earlier but does not contribute towards economic concentration. This accords with the views of Hosking (1970) who believes that in the pegmatites of S.E. Asia, the cassiterite is introduced by replacement in fractures and joints after consolidation of the pegmatite itself. In the Kamativi deposit of Zimbabwe (Rijks and van der Veen, 1972) the last major stage of crystallisation was a muscovite-quartz stage which partly replaced all earlier formed minerals. Volatiles such as CO_2, H_2O, HF, HCl were carriers of the Na, Li, K ions which caused alteration. Along with these, concentrations of Sn, Ta, Be, B crystallised to form cassiterite, beryl, apatite, columbo-tantalite and tourmaline.

Granitic dykes are simply late phases of hydrous magma that escape along suitable pathways. The dyke material is not a primary carrier of tin; mineralisation is preferentially located in dykes because they are brittle, fracture easily, and thus allow passage of fluids.

Both dykes and pegmatites are formed in fracture and fissure systems within and adjacent to granitoids. Dykes are important because they demonstrate areas of local crustal weakness which are centres of concentrated fissure development (Rayment et al., 1971). As such, they are useful exploration guides for fissure lode systems. Pegmatites are important because although of minor economic significance, they are transitions between ordinary intrusive granitoid masses and vein systems of hydrothermal fluids. On this basis, pegmatites should grade into hydrothermal deposits but actual examples are extremely rare (Park and MacDiarmid, 1975).

SKARN DEPOSITS

During evolution of the hydrothermal system, fluids continue to react with host rocks to produce a variety of wall rock alteratiosn types. If the host rock is highly reactive, then replacement may occur to produce replacement and skarn type deposits. Skarn deposits are the result of reaction between an intrusive granitoid and reactive calcareous rocks, generally within the metamorphic aureole. The most common rocks are limestones, dolomites and to a lesser extent basic igneous rocks. The skarn forming process is one of replacement which can also occur at more distal sites in vein systems to form replacement veins and bodies. Replacement deposits generally form with vein systems and will therefore be considered with them.

The process begins (Barnes, 1979) with shallow intrusion of granitic magma at 900-700° C into carbonate rocks. Contact metamorphism occurs at about 700-500° C during magma crystallisation. Reaction will occur with dolomite but only slightly with limestone. Hosking (1970) states that there is a lack of skarn deposits in S.E. Asia simply because the limestones are too pure; only impure limestones contain the necessary 'ingredients'. These impurities react to give calc silicates + CO_2 + H_2O. The loss of these volatiles causes a net volume loss resulting in increased porosity; this acts a ground preparation for later skarn and ore deposition. At temperatures of 600-400° C and lower, metasomatism and iron-rich skarn formation takes place with contributions from hydrothermal fluids and possibly meteoric ground water. This fluid becomes enriched in sulphur and metal with time. Skarn formation proceeds outwards into the country rock but calcium concentrated by the fluid may alter the granite to produce 'endoskarn'. Diffusion gradients operate adjacent to fractures and lithological contacts to produce alteration zones which progressively migrate outwards. If the fluids arrive when temperature is too low or pressure too high, then a replacement body may form. Oxides are amongst the first mineral precipitated but at 500-300° C they are followed by sulphides. Following this is late hydrothermal alteration of early skarn minerals at 400-200° C. This takes place together with continued ore deposition which is a consequence of acid neutralisation.

Smirnov (1976) indicates that 'superimposed' mineralisation is usual and that the skarns act as hosts for the deposits. This accords with Hosking (1965) who states that in S.E. Asia, cassiterite was deposited during a late hydrothermal stage. In addition much of the cassiterite was derived from degradation of early formed and early skarn silicates such as malayaite.

Barnes (1979) concludes that the dominant controls on skarn formation and ore deposition are the structure and stratigraphy of the deposit.

FISSURE LODES AND STOCKWORK DEPOSITS

Volatile tin rich hydrothermal fluids migrate into elevated roof portions and escape through well fractured rocks into the fissured country rock environment. Here they form exogranitic vein deposits by open space fillings and replacement. Favourable horizons may be replaced in part to produce replacement deposits. Because they represent open space filling, the location and morphology of vein systems are controlled by structural and lithological factors which are discussed in the following section.

The origin and transport of tin in hydrothermal systems has been reviewed. The subsequent deposition of tin as it migrates in fluids away from the granitoid is controlled by changes in the chemical equilibria that occur in the fluid in response to changing conditions. The spatial position of the vein deposit relative to the host granitoid and country rock is a reflection of these successive changes. Although the physical and chemical factors that cause precepitation vary widely under different circumstances, they result generally in similar mineral paragenesis which is reflected in mineral zoning. The relationship of reactions between metal ions and chemically active sulphur and oxygen is significant (Smirnov, 1976). The concentration of active sulphur ions increases as the hydrothermal system evolves. Thus, initial low-sulphur compounds at the high temperature stage are replaced by later high-sulphur ones at low temperatures. For this reason, oxygen compounds such as cassiterite, scheelite and wolframite predominate in early stages.

In high level subvolcanic deposits such as those in Bolivia, xenothermal or telescoped deposits are formed. These result when high temperature fluids are expelled into shallow low pressure environments. Here pressure and temperature gradients are exceptionally steep so that fluids cool very rapidly with sudden pressure losses. Consequently, the minerals are deposited over a short distance with a confused paragenesis; lower temperature minerals such as silver sulphosalts are virtually coprecipitated along with high temperature cassiterite, wolframite, magnetite etc.

Althourh the paragenesis of the southern Bolivian tin-silver deposits are telescoped, Kelly and Turneaure (1970) determined the following sequence of events which is probably applicable to the generation of tin vein systems in general:

a) early vein stage in which tin and tungsten are deposited
b) a base metal sulphide stage
c) hypogene alteration of pyrrhotite to pyrite, marcasite and siderite
d) late deposition of siderite, fluorite and hydrous phosphate

In the early vein stage, temperature was a maximum of 530° C and this decreased to about 70° C near the close of mineralisation. During early stages of mineralisation, boiling of the CO_2, NaCl brines occurred which forced CO_2 into the vapour phase whilst increasing the salt content of the brine. Early boiling precipitated quartz and cassiterite and resulted in a restricted vertical distribution of high grade ore. Sheets of rich cassiterite ore possibly mark the levels of boiling of the early fluids as they ascended into the vein systems. The entire series took place in a single extended period of mineralisation and not a hybridisation of different mineralisation events. Kelly and Turneaure also note that the tin deposits of the deeper level, north Bolivian province have a similar paragenesis due to gradual and systematic cooling of the fluids, Figure 29.

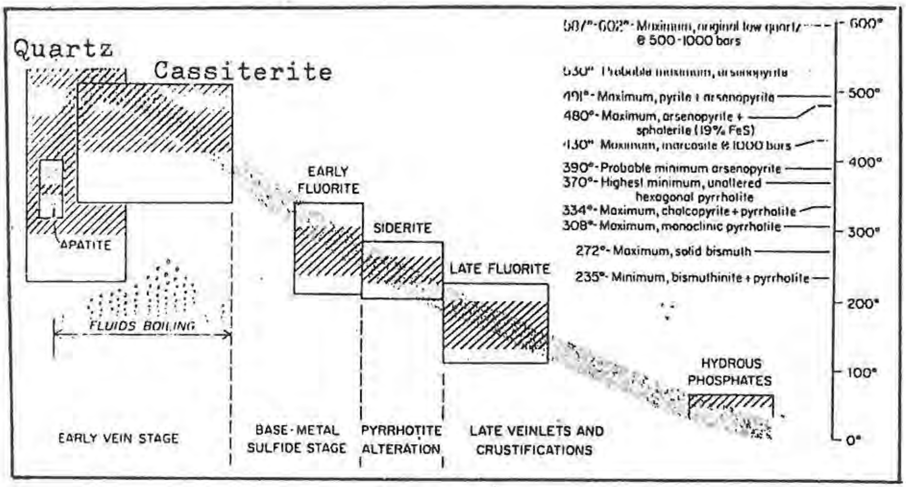


Fig. 29. Summary of temperature variation during formation of tin and tungsten deposits (Kelly and Turneaure, 1970)

The authors note that different mechanisms of cooling operate in combination and at different times. These involve conductive heat exchange, boiling and irreversible adiabatic expansion during early stages. At later stages, heat was lost by conduction from the fluids and by gradual mixing with ground water. They conclude that temperature is the major factor in controlling the paragenetic events, such as transition from oxide to sulphide stage.

Very little is known of the actual chemical mechanisms by which cassiterite precipitates. If tin is transported as fluoride, then the fluids may hydrolise to give cassiterite according to

$$SnF_4 + 2H_2O \rightleftharpoons 4HF + SnO_2\downarrow$$

Smith (1947) crystallised cassiterite from aqueous solutions with sodium stannate by

$$Na_2SnO_3 + H_2O \rightarrow 2NaOH + SnO_2\downarrow$$

As with transporting mechanisms, Taylor (1979) reviews a number of alternatives that may each be applicable under different circumstances.

REPLACEMENT DEPOSITS

Replacement deposits may be formed in three different ways: by the outward migration of ore bearing fluids from a narrow fissure to penetrate and replace wall rocks, by the total replacement of selected horizons within sediments or by the invasion and replacement of sheared host rocks in a shear zone. Veins and bodies of this type can form at any suitable site from proximal to distal from the granitoid. More extensive replacement however, can be expected closer to the granitoid because of higher temperatures and availability of mineralising fluids. Replacement reactions are common above 250°, but are rare at lower temperatures (Barnes, 1979).

Barnes (1979) states that "replacement is a major area of ignorance in understanding hydrothermal ore genesis". Very little is actually known about the reactions involved. The most common reactive rock types are carbonates, but thinly bedded shales may be affected. Deposition on first contact is probably caused by acid neutralisation, but deposition caused by fluids passing though the horizon is problematical. Some research has been conducted in the case of sulphide deposition in replacement processes but virtually none on oxides. It seems that the selective replacement process depends on mineral-chemical composition of host rock and fluids, optimum porosity and filtration effects which lead to concentration of ore below impermeable cap rock. Labuschagne (1970) indicates that complex replacement pockets at the Rooiberg tin mines result as a consequence of successive stages of mineralisation. He notes that the replacement process was selective: ankerite, pyrite, tourmaline and cassiterite replace feldspar, whilst chlorite replaces quartz. Because of this, arkosic layers are replaced in preference to shales and pure quartzite. Although chemical and mineralogical variations in a host rock are important, the overriding control is structural, and this will be discussed later (Stear, 1977).

Larger replacement deposits occur in Tasmania at Cleveland and Rennison Bell (Cox and Glasson, 1971; Newnham, 1975). Here, stratabound sulphide and cassiterite deposits occur as metasomatic replacements of finely layered calcareous shales and shaley limestones.

SUBVOLCANIC PORPHYRY TIN DEPOSITS

In subvolcanic environments such as southern Bolivia, different crystallisation and precipitation conditions are caused by the high level, low pressure environment of emplacement. Here, the hydrothermal system operates in permeable zones in brittle fracture domains and behaves much as the porphyry copper system (Sillitoe et al., 1975). This environment is characterised by complex vein systems within and peripheral to high level stocks, intrusive hydrothermal breccias, concentric alteration zones and telescoped deposition of complex polymetallic sulphide rich mineral assemblages. The shallow depth of emplacement is the important factor in causing rapid fluctuations in pressure and temperature and in allowing the influx of ground water into the magmatic hydrothermal system.

Deposits are formed when a body of undersaturated magma of quartz-latite to dacite composition becomes saturated with aqueous fluids as it intrudes into higher level environments. The magma begins to consolidate in the volcanic vent and becomes partly crystallised. As it does so the behaviour of the hydrothermal system is controlled by the balance between confining pressure and the fluid pressure of the hydrous residuum that concentrates in the highest part of the stock. When fluid pressure exceeds confining lithostatic pressure, retrograde boiling occurs and the fluids escape explosively to produce hydraulic fracturing, brecciation, alteration and the first generation of disseminated cassiterite mineralisation. There is thus an introduction of tin during the later stages of stock consolidation and prior to development of the vein system. Because of the shallow depth of emplacement it is likely that groundwater contributes to the fluid phase.

The Chorloque deposit is zoned with sulphide-rich intense sericite alteration surrounding a central zone of quartz tourmaline alteration with disseminated tin mineralisation. This is cut by a later cassiterite vein system. Fluid inclusion studies (Grant et al., 1977) show that the early fluid consists of a low density vapour phase and a very high density liquid phase coexisting at about 500°C. They are high salinity (up to 46 wt.% NaCl equivalent) Na-Ca-Cl brines that boil intermittently (Kelly and Turneaure, 1970), and there is a steady decline in temperature and salinity as the veins develop, Figure. 30. A depth of 1-2 kms is indicated and the maximum pressure under which boiling occurs is 360 bars; this boiling has the effect of increasing salinity.

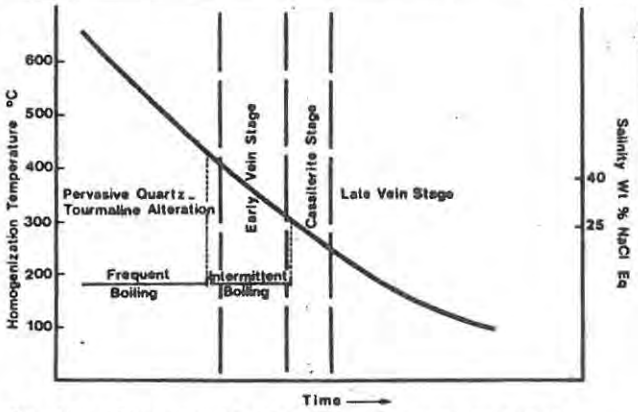


Fig. 10 Summary diagram of fluid inclusion data for Chorolque hydrothermal system illustrating very high initial temperature and salinity of the fluid during pervasive quartz–tourmaline alteration and their major decline prior to earliest cassiterite deposition

Fig. 30.
(Grant et al., 1977)

In addition, the process of quartz-tourmaline alteration liberates salts to the fluids and further increases salinity. In the peripheral zone, strong sericite-tourmaline alteration and metal sulphide deposition occurs in volcanics and underlying sedimentary rocks. Grant et al., (1977) suggest that mixing of high temperature highly saline fluid and groundwater produces the conditions leading to silicate alteration and sulphide/cassiterite precipitation.

Hydraulic brecciation of the solidified outer parts of the stock results in a pervasive stockwork whilst more explosive release produces hydrothermal intrusion breccias or 'crackle' breccias. Escape of fluids is followed by rapid congealing of the outer zones with a resultant porphyritic texture (Sillitoe et al., 1975), whilst multiple phases of boiling and explosion produce overlapping phases of mineralisation, alteraltion and brecciation.

As the hydrothermal activity decreases, the upper levels consolidate. Discrete vein systems are then produced that cut across and are superimposed upon early alteration, mineralisation and brecciation. These are the result of regional tectonic stresses that develop after the decline of the local magmatic/hydrothermal pressure system. The vein fluids were rapidly cooled and diluted with groundwater so that there is little resurgent high temperature activity or renewed hydrothermal brecciation.

EPITHERMAL VOLCANIC TIN DEPOSITS AND POSSIBLE VOLCANOGENIC EXHALATIVE DEPOSITS.

In rare circumstances, tin bearing hydrothermal fluids may enter the volcanic regime where tin is precipitated as disseminations and within narrow fissure veins and breccia zones of rhyolite lava flows. Veins occur in steeply flow banded plugs of vesicular rhyolite which probably represent eruptive centres. The tin is deposited close to the vents from low temperature (less than 150° C) hydrothermal fluids during the closing stages of volcanism (Sillitoe, 1979). Sillitoe notes that the mineralisation may be produced from a high temperature gas phase at above 500° C directly after deposition of the rhyolites. He further indicates that ore deposition in the near surface epithermal environment is dominantly from convecting circulating meteoric water and may represent the distal equivalent of slightly deeper level porphyry type mineralisation.

It seems that very little tin would be left by this stage because of the precipitation of tin in high temperature environments. Any tin, however, that has not precipitated, may possibly exhale onto the sea floor in hydrothermal exhalative fluids to form deposits similar to exhalative massive sulphides (Hutchinson, 1979). By this method, metals and silica are leached from underlying epiclastic rocks by deeply circulating strongly reudced CO_2-rich saline brines. The metalliferous brines rise up active faults to the sea floor. Below the sea floor, quartz, sulphides and gangue minerals precipitate in the feeder channels because of temperature reduction and increase in Eh,pH, or by the recrystallisation of the surrounding unconsolidated cherty sediments. The rising reduced brines mix with oxygenated connate calcium sulphate bearing sea water. Sulphide ions are produced from sulphate reduction and this causes precipitation of metal sulphides. Calcium oxide from reduced sulphate combines with CO_2 or F from the brines to form carbonates and fluorite, whilst fixing of F as fluorite reduces tin solubility to precipitate cassiterite. Greisen and epigenetic tin lodes are formed, according to Hutchinson, by remobilisation of tin and volatiles from the ore by Devonian quartz porphyry intrusions. Further evidence is given to this theory by the presence of volcanogenic massive base metal sulphide deposits in the same time-rock stratigraphic position just to the east of the tin deposits. Furthermore, tin is common in many massive base metal sulphide deposits such as Sullivan, and copper is recovered from the Tasmanian tin ores. Thus there may certainly be overlap between tin and base metal sulphide deposits under favourable conditions.

5. THE GEOLOGICAL CONTROLS OF MORPHOLOGY AND TONNAGE

The concentration of tin into an economic deposit is critically dependent on structure. Structure primarily controls the site of formation and attitude of the deposit, whether it is endogranitic or exogranitic. In any mineralised area the type of deposit shows a close relationship to structural features, with the availibility of channelways having a strong influence on the final shape. Within the granitoid, significant deposition can only occur if an impermeable barrier is present to prevent the escape of the mineralizing fluids. For hydrothermal fluids to escape, solutions must pass through a plumbing system; clearly, no deposition can take place if suitable channelways do not exist. The extent of mineralisation is controlled by the nature of the country rock, the degree of fracturing, the age of fracturing and the rate of flow as well as temperature-pressure conditions. Alteration may increase brittleness and makes the rock more susceptible to fracturing. Significant economic concentration can only occur if the channelways pass through a restricted volume. Geological structure controls this and the resultant morphology which consequently influences volume and hence tonnage. In vein systems, structural control determines where the deposits are formed, the length and thickness of the veins, the overall distribution of mineralisation, the final shape of the vein and the position of the ore shoots in the vein. Because structure controls the volume, a detailed structural knowledge is vital for accurate ore evaluation.

REGIONAL STRUCTURAL CONTROLS.

The regional tectonic framework is critical in controlling the emplacement of the apical zones of granitoids. In addition it controls the fracture system and thus the passageways of escaping hydrothermal fluids.

Tin deposits are located within and around apical roof zones such as steep sided cupolas, cusps and ridges. This is because migrating fluids travel upwards under the influence of the pressure gradient and are trapped in structurally high regions. If roof zones are flat, then this will contribute to dispersion of mineralisation.

If the roof zone is capped by an impermeable horizon, then fluids will be retained within the granite. This results in extensive alteration and mineralisation of the greisen type. Important lithologies that act as impermeable seals are pure unfractured carbonate rocks and shales (Hosking, 1970). Hosking notes that deeply buried pure marbles adjacent to granitoids behave as plastic bodies and they deform by stretching rather than brittle failure. If the tin granite is intruded into a slightly older overlying granite that is still relatively hot, then discrete cooling joints are less likely to form. The recognition of an impermeable cap rock is thus important to evaluation as mineralisation will consequently occur in the underlying restricted zone.

During granite emplacement, the structure of the invaded country rocks determine the disposition of the elevated areas of the granite (Hosking, 1965), Figure 31. Gentle domes and anticlinal structures are important in this respect together with the intersections of antiformal axes. The location of these structures is thus of prime exploration significance.

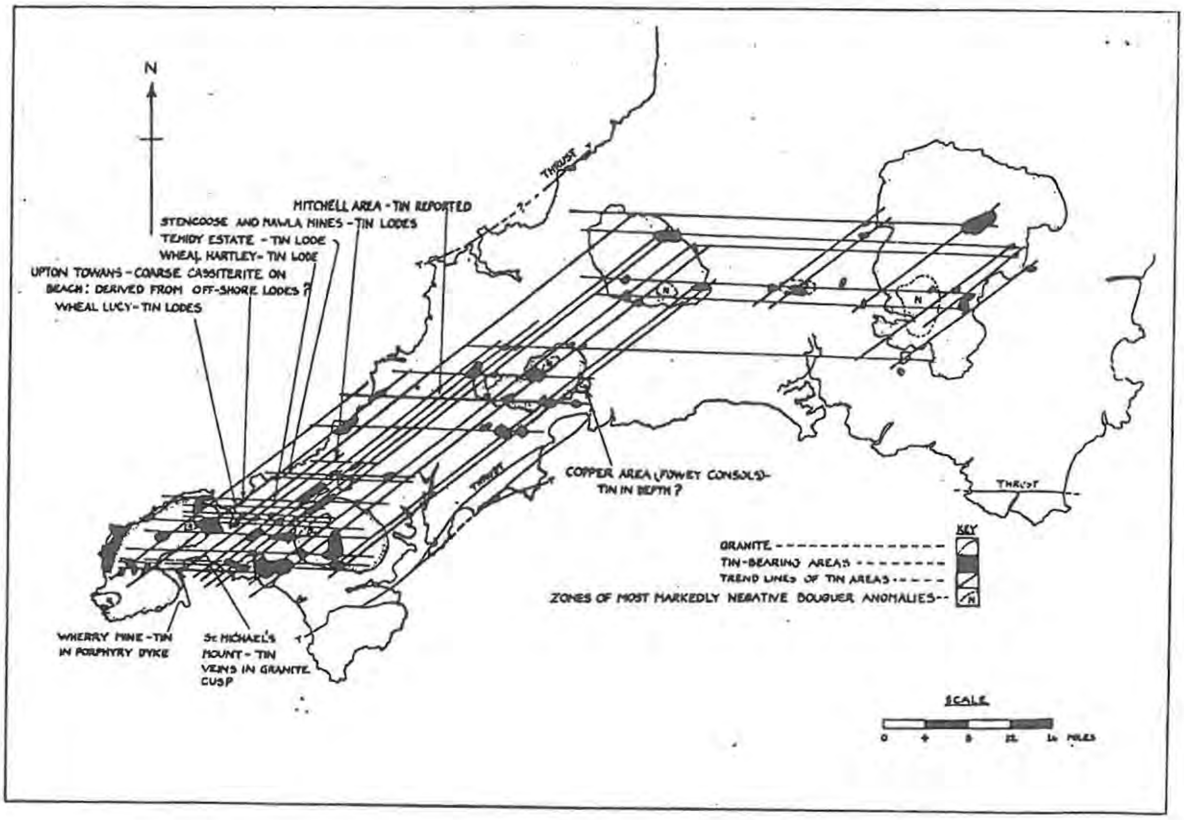


Fig. 31. The occurrence of cusp related tin deposits at the intersection of sedimentary strike lines in S.W. England. (Hosking, 1967)

ENDOGRANITIC TIN DEPOSITS

The form of the apical region controls the size and shape of massive greisen zones. These apical zones tend to be structurally simple. This is well exemplified in the examples of deposits from the Erzgebirge, Figure 32.

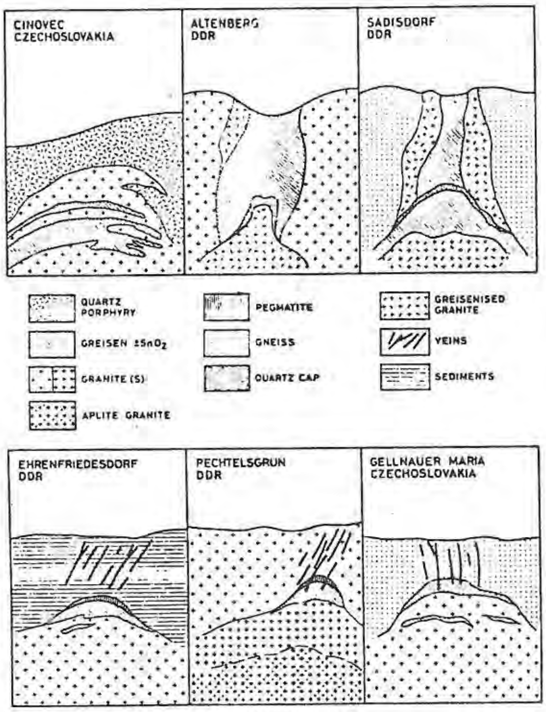


Fig. 32. Shape of greisen deposits associated with granite cusps. (Taylor, 1979)

In general, deposits formed in greisen environments characteristically tend to be of large tonnage though generally of low grade. At the Anchor tin mine in Tasmania (Groves and Taylor, 1973), alteration occurs to a depth of about 40 m in the upper part of the tin bearing granite sheet. Greisenisation occurs as irregular subhorizontal lenses that are related to the topography of the granite contact. Disseminated cassiterite is confined to these areas. Generally, the contacts with unaltered and unmineralised rock are gradational so that cut-offs must be determined by assay.

Endogranitic pipe deposits may form by rising 'bubble trains' as described previously. Similar epigenetic pseudo-pipe deposits may be structurally formed. The main feature required is a pipe shaped zone of high permeability or reactivity that is generally provided by intersecting fracture zones (Taylor, 1972). Renewed movement along intersecting fractures result in subsidiary fracturing and brecciation thereby forming a pipe shaped permeability zone, Figure 33.

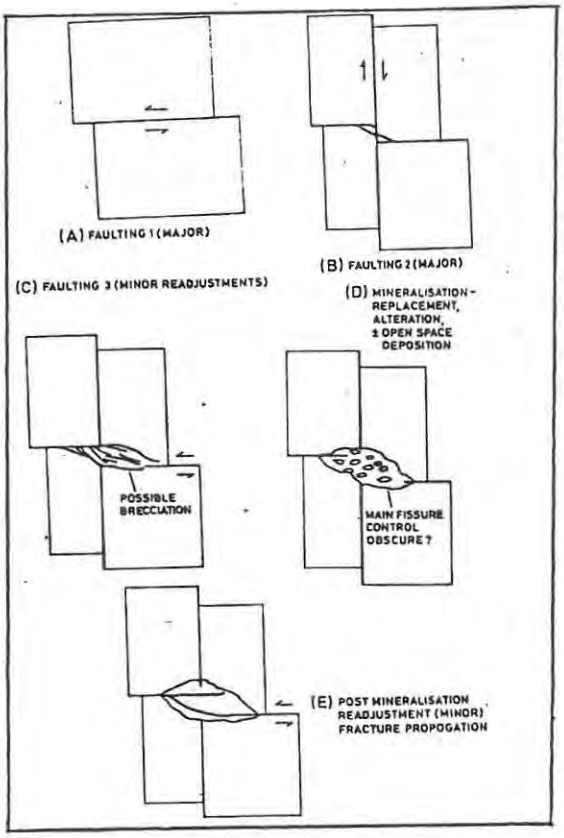


Fig. 33. Development of pipe shaped ore body controlled by intersecting fractures (Taylor, 1979)

Similarly, movement along a single irregular fault surface may produce pipes in swell areas, Figure 34.

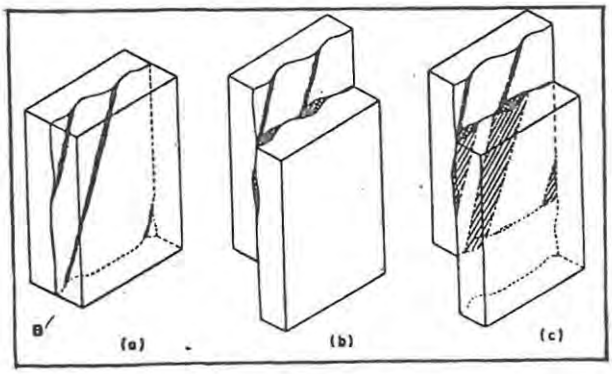


Fig. 34. Development of pipe along irregular fault surface after displacement.

Pipes are likely to be highly erratic with considerable pinching and swelling. Hunter and Lenthall (1971) state that many are elliptical in plan with a maximum long diameter of 10-12 m. However, their extreme unpredictability is the key feature that must be recognised during evaluation.

CONTROLS ON FRACTURING AND DEPOSIT LOCATION

Fracturing is caused by a number of interrelated processes that result in pregranite faults, primary igneous joints and intrusion-created structures such as faults and extension fissures. If the overlying granitoid cools rapidly rather than slowly, then a well developed system of cooling fracture joints develop. Thus, the rate of cooling of the overlying granite is significant (Groves and McCarthy, 1978). Self induced fracturing occurs because of the build up of internal vapour pressure within the crystallising body. When internal vapour pressure exceeds confining pressure, and if brittle conditions prevail, then overlying rocks will fracture and allow the passage of fluids (Emmons, 1934)

In the S.W. England province, the final phase of intrusion took place after emplacement of the plutons as fluid pressure from the core disrupted the brittle outer shell and country rocks. This released hydrous magma and volatiles to form swarms of porphyry dykes and mineralised fissures (Rayment et al., 1971). As well as invading fractures caused by the intrusion, the fluids used a number of pregranite structures and permeable stratigraphic contacts and lithologies such as calcareous intercalations. The majority of fractures hosting mineralisation trend roughly parallel to the underlying ridge of granite. The lode systems form a conjugate system of normal faults and extension fissures (Moore, 1975). Stress trajectory diagrams show that the lode and dyke orientations are controlled by the intrusion and shape of the cupolas, and also the interaction between the regional stress field in the country rocks and the stresses created by fluid pressures exerted from the cooling pluton, Figure 35.

Figure 36 shows the stress distribution around the boundary of the fluid pressure cell around a mobile core in which tangential stress is lowest under conditions of excess internal pressure (Sectors C). This model shows that low angle and strike slip faulting is likely to occur at depth adjacent to the steeper flanks of the pluton. Fluid loss occurs most easily through these flanks, rather than from the crest of the intrusion. This explains the belt of mineralisation adjacent to the contacts of elongate intrusions in S.W. England.

The effect of the intrusion in controlling country rock structure is likely to be pronounced. In the Rooiberg tin field of the Bushveld, regional compression due to the granite emplacement was the dominant control (Stear, 1977). Deformation of the

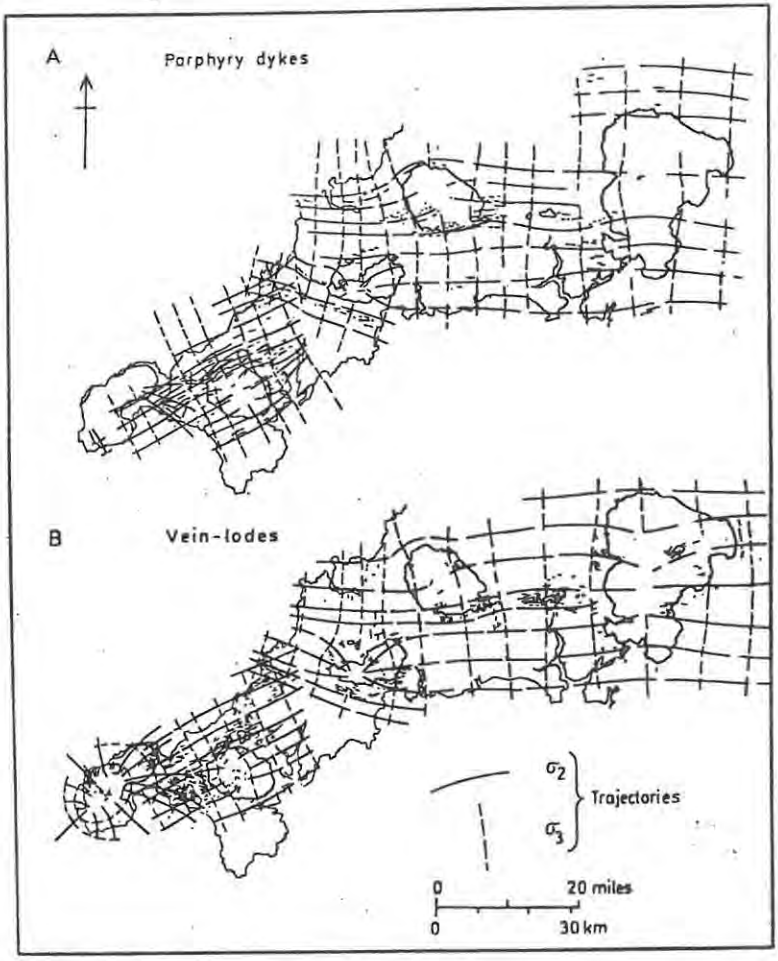


Fig. 35. Trajectory nets of porphyry dykes and vein lodes in S.W. England (Moore, 1975)

Rooiberg fragment by horizontal compression gave rise to incipient thrusting on the eastern flank of a broad regional arch.

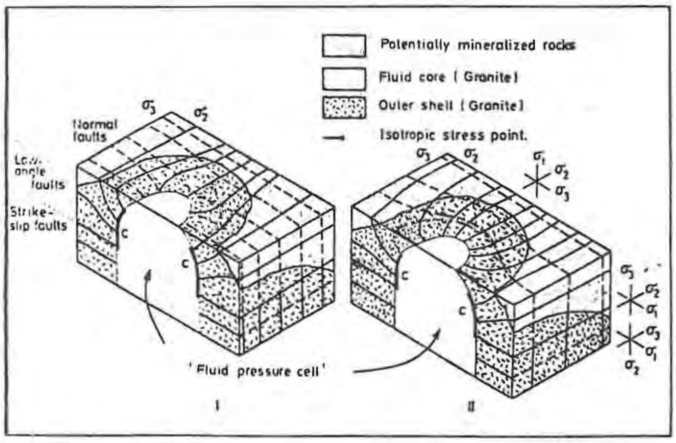


Fig. 36. Stress configuration around the fluid core of an intrusion exerting hydraulic pressure. σ_1 and σ_2 represent extensional fissure veins (Moore, 1975)

Fluids were expelled from apical regions of the granite along pre-existing structural lines in the fragmented sedimentary roof, reactivated as a result of the compressive stresses. Horizontal shearing within the roof rocks produced open space structures, especially at stratigraphic contacts.

SKARN DEPOSITS

Contact metasomatic skarn deposits are generally very small with extremely diverse and highly irregular outlines, Figure 37.

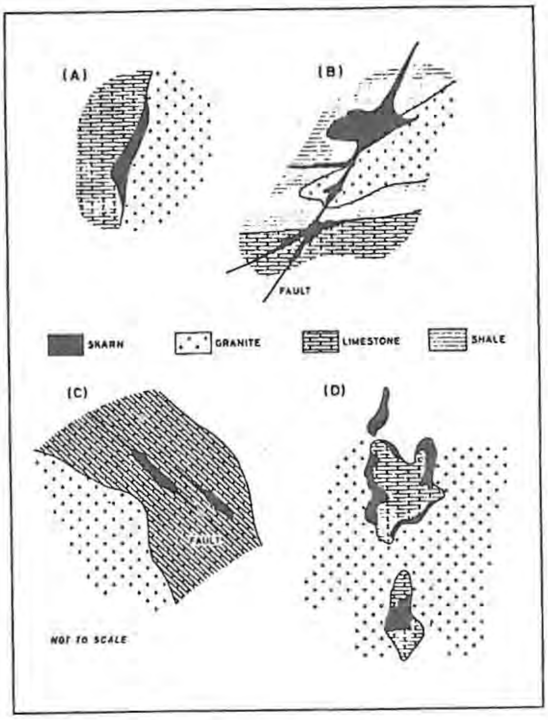
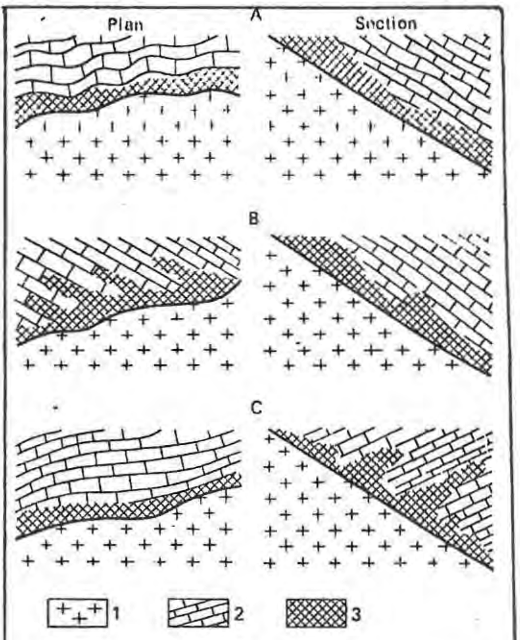


Fig. 37. The diversity in size and form of skarn deposits (Taylor, 1979)

When a channelway cuts across rocks of different composition, skarn deposits are localised at the points where it intersects the favourable lithologies. Three factors determine the geological structure of skarn deposits (Smirnov, 1976) : the surface of the contact between igneous and enclosing rocks, the bedding of the country rocks, and fractures intersecting both igneous and country rocks in the contact zone. The contact surface of the granitoid relative to the bedding of surrounding rocks is important in determining the shape of the deposit. Thus the morphology of skarns at discordant contacts is more complex than at concordant ones because either lenses, pipes and/or pockets may develop, Figure 38. Smirnov (1976) indicates that the most important sites are where the contact is contorted, perhaps tectonically, so that open spaces can form as the granitoid cools or is stressed. The country rock bedding ensures selective metasomatism in certain strata or along their contacts. The most significant zones of skarn formation are those between strata of different composition and mechanical strength, e.g. between carbonate and silicate rocks . Cross cutting fractures and shear zones are important as they act as channelways into the reactive rocks and may localize skarns as vein bodies.



Attitude of the contact of igneous rocks relative to the bedding of the sedimentary rocks surrounding skarns

A—contact concordant in both plan and section
B—contact concordant in section but cross-cutting in plan
C—contact concordant in plan but cross-cutting in section
1—igneous rocks
2—sedimentary rocks
3—skarns

Fig. 38. (Smirnov, 1976)

The structural control on morphology is pronounced. Stratiform bodies develop within reactive horizons along concordant intrusive contacts, whilst stratiform, lenticular, pipe-like bodies form along cross cutting contacts. Combinations of all these produce highly complex outlines which make evaluation problematical. Taylor (1979) concludes that deposits of this type are rarely economic.

TIN VEIN SYSTEMS

The structural control on mineralisation in vein deposits has been reviewed by Neuhoff (1979). Structural controls may be subdivided into primary and secondary structures which affect development of the vein, and secondary structures which determine the final shape of the vein. Primary structures form at the same time as the rock and are important in that they control fluid distribution and consequently the localisation of ore. These structures include any that control porosity and permeability such as cap rocks and lithological and bedding plane contacts.

Secondary structures such as faults, fractures and folds act as mechanisms of ground preparation, and make the host rock more receptive or reactive to hydrothermal fluids. Competent rocks tend to fracture by brittle failure, thereby providing channelways. In addition, fracturing often results in brecciation of wall rock which presents a greater surface area to ore solutions. The presence of ore localisation in a competent rock unit is important in evaluation, as the extent of the competent host rock may define the limits to the deposit. Other adjacent competent units in a series alternating with incompetent strata may host similar ore bodies.

Controls on development of ore shoots

Ore shoots are the economic portions of vein systems that can be profitably extracted. They generally have extremely variable outlines depending on the features that produced them. The most important factors that influence the position and development of ore shoots are variations in lode structure, lode intersections, lithological contacts, dyke intersections and faults.

i) variations in lode structure

Local changes in structure of the fissure lode such as changes in dip and strike frequently control the sites and limits of ore shoots (Taylor, 1966). Thus, sudden changes in vein attitude often accompany the loss or appearance of ore. This is illustrated in Figure 39, where A shows the horizontal elongation due to dip controlling ore location and B shows vertical elongation and avoid form resulting from strike control.

Changes in attitude of an open fissure control ore deposition because ore bearing solutions are suddenly retarded, with concomittent change in environmental conditions. These changes, such as sudden decrease in flow velocity may cause precipitation (Hosking, 1965).

The open spaces or zones of low compression created by fracturing are the most favourable sites for simple infilling and replacement of wall rocks by mineralised material (Garnett, 1966; Taylor, 1966). In addition there is commonly a close correlation between high ore values and high lode width.

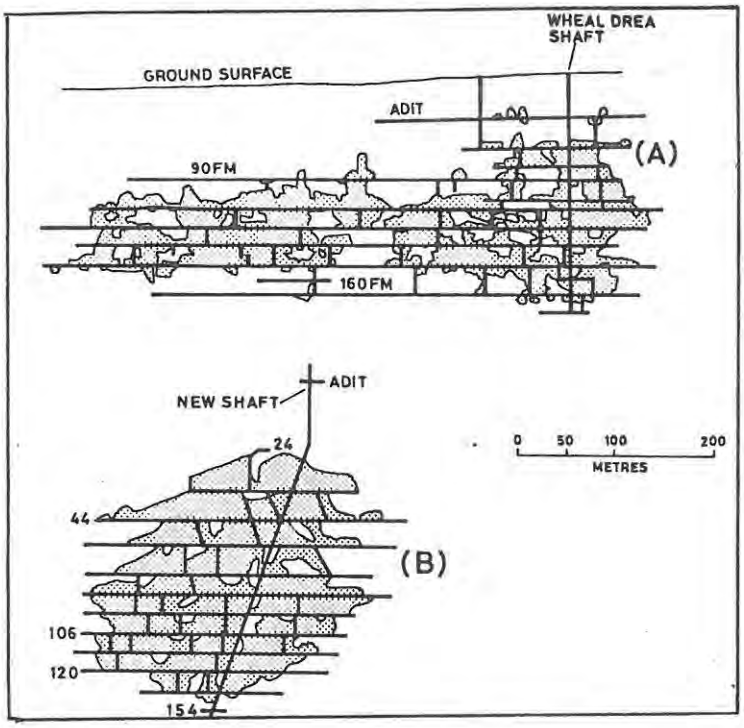


Fig. 39. Stope patterns demonstrating A)dip and B)strike control of ore shoot development. (Taylor, 1979)

When movement takes place along an irregular fissure plane, cavities or open spaces are produced, Figure 40. The extent and size of the space will be dependent on the original shape and attitude of the fracture and the extent of movement. it must be remembered that the final shape of the void is influenced by the 3 - dimensional configuration of the fissure. The type of faulting,

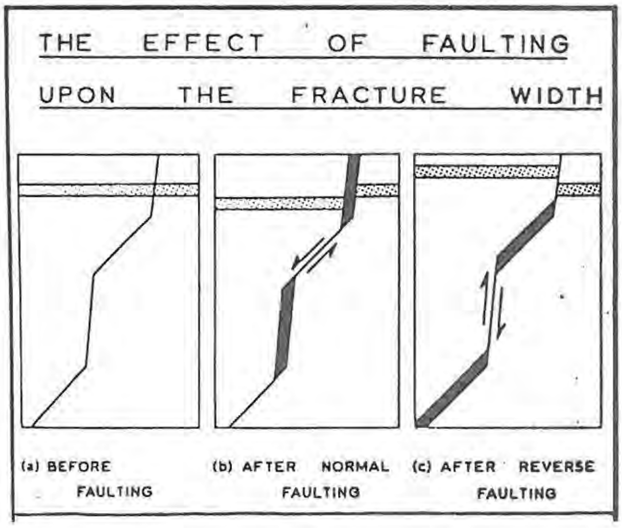


Fig. 40. Formation of open space by faulting (Garnett, 1966)

its direction and the amount of movement is important. Newhouse (1942) shows that if there is a strong horizontal component of movement, then a swing of the fracture plane in a direction away from the apparent movement will favour the creation of an open space, Figure 41.

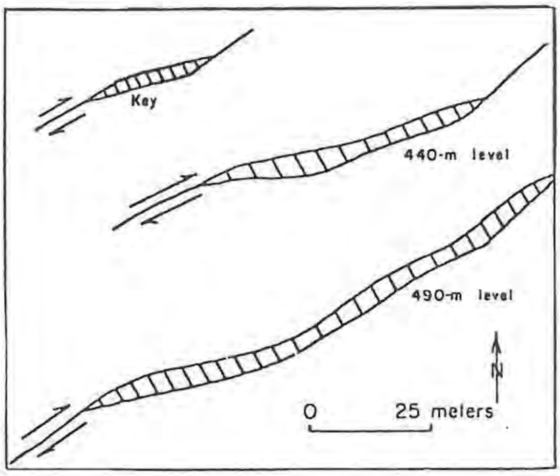


Fig. 41. Creation of open space where strike deflects to right (Newhouse, 1942)

When vertical movement is involved, normal faulting results in the highest lode width on the steeper portions, whilst reverse faulting results in the highest width on the flattest portion. Normal faults steepen as competency increases, and reverse faults flatten so that a change in competency may result in positions for openings.

The frequency and dimensions of the resultant open spaces is a direct function of the degree of irregularity of the original fissure surface. A fissure with considerable fluctuations in attitude will produce large numbers of small open space regions. A more regular surface, however, with infrequent and gentle changes in attitude will produce a smaller number of open spaces but of larger extent. In any one mineralised area, all combinations can be expected. The competency of the wall rock is important because an incompetent rock will tend to remould and fill the voids.

The formation of open spaces by reverse or normal faulting in the plane of an irregular fissure accounts for the development of the ore shoots, their size, frequency and configuration. Higher values, however, may be located in only the upper or lower portions of favourable zones (Garnett, 1966). This may occur because the upper portion may already be infilled with earlier low grade material, so that the second richer phase is confined to the lower part.

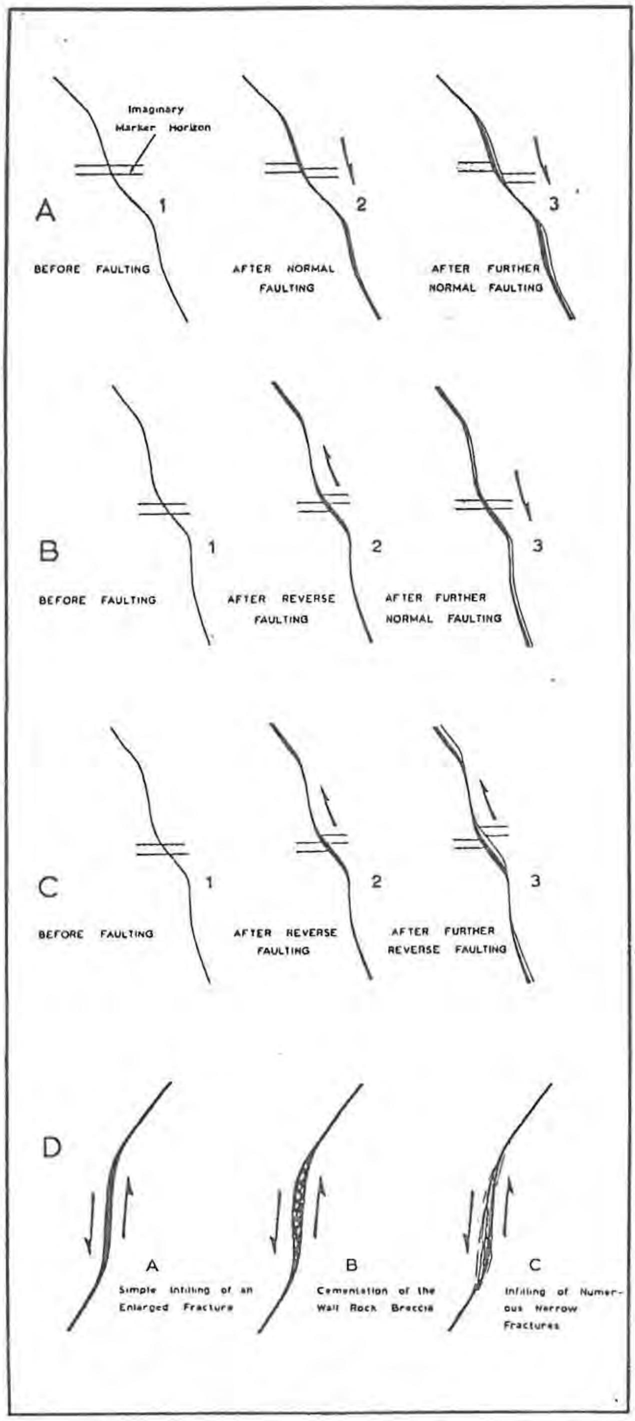
If the infilling accompanies normal faulting, then the ore may be impounded beneath an area of flattened lode. Finally, mineralising phases may be deposited in the lower area due to sudden release of pressure during ascent, and the decrease in flow rate on entering an open space (Hosking, 1965).

Most tin vein systems are very complex and multiphase as a result of the continued rejuvenation of open spaces and deposition of successive phases of mineralisation. These phases are often distributed irregularly which indicates that only selected portions of the vein are reopened. Garnett (1966b) concludes that if more than one period of major movement has occured, then a major extent of payable ground is more likely to be present. The presence of only one movement usually indicates that the vein will be narrow and marginal in value. The final width and value of the lode is directly related to the number of successive re-openings which allow successive phases of mineralisation. The effect upon lode width of successive relative movements is shown in Figure 42. Repeated normal or reverse faulting results in high variation of fissure width, whilst a combination of reverse and normal faulting produces a more constant, medium fissure width.

Often a major fault develops subsidiary secondary faulting due to concentration of stress at the ends of the fault. (Neuhoff, 1979) These secondary faults or splay fissures are significant because they may duplicate the ore horizon forming multiple ore bodies down dip and along strike. Generally they have a characteristic pattern which may be followed into the main fault where the bulk of ore is possibly concentrated.

Lode structure contour diagrams (Conolly diagrams)

Conolly (1936) devised a graphical method of depicting the overall shape of a fissure vein. An arbitrary inclined reference plane is placed conveniently behind or in front of the fissure. Measurements of the distance between the plane and the fissure lode is made at set intervals to produce a set of figures which are contoured. A 'topographical map' of one surface of the fissure lode is thus produced. This diagram can be compared with ore contour diagrams to determine the effects of structural irregularities which cause ore deposition (Taylor, 1966). Taylor indicates that if the shape of the vein reflects the original shape of the fissure, after



Effect upon the lode width of successive relative movements of the lode walls. (Not drawn to scale.) A—repeated normal faulting; B—reverse faulting followed by normal faulting; C—repeated reverse faulting; and D—different methods whereby the lode width may be increased

Fig. 42.

(Garnett, 1966)

minor displacement, then the position of open spaces can be predicted, having a knowledge of the direction of movement. This tool may be used in exploration to predict the position and extension of ore shoots. The reader is referred to Garnett (1966) who uses Conolly diagrams extensively.

ii) lode intersections

The intersection of two or more mineralised lodes may be an important area of enrichment if the two lodes have similar strike and meet at an acute angle (Garnett, 1966). If the angle of intersection is large, then impoverishment may occur. Enrichment occurs because additional brecciation at the junction results in increased cavity formation and increased depositional surface area. Figure 43. shows the enrichment of the Great Flat Lode in Cornwall, where it intersects the West Francis Lode.

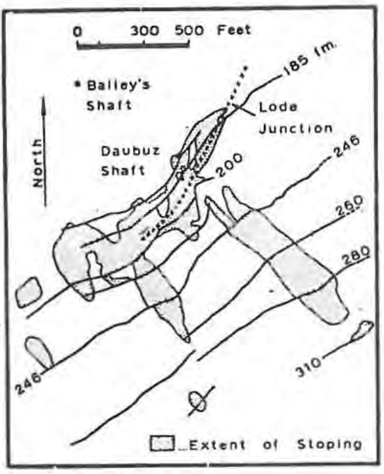


Fig. 43. Enrichment at intersection of two mineralised lodes (Garnett, 1967)

iii) lithological contacts

The vicinity of a granite/sediment contact is commonly a favourable site for tin mineralisation (Garnett, 1966a). The ore may be endogranitic or exogranitic, but individual lodes are usually bounded on one side by the granite contact. Consequently, the attitude of the tin ore zone is closely associated with this contact. As an example, the strike dimension of vein systems in the St. Just district of Cornwall is controlled by the position of the granite/sediment interface, Figure 44. In the same area, the N.E. dipping lodes, however show a radial pattern to the contact and show an association with depressions in the granite/slate contact.

Changes in lithology from argillaceous to arenaceous may affect a tin vein. Garnett (1967) quotes an example where a tin lode is entirely in shales at upper levels. At a deeper level, a series of quartzites intersect the lode which consequently splits with numerous branhes following major joints and fissures in the quartzites. In addition, the attitude of bedding may also control the attitude of the ore shoot.

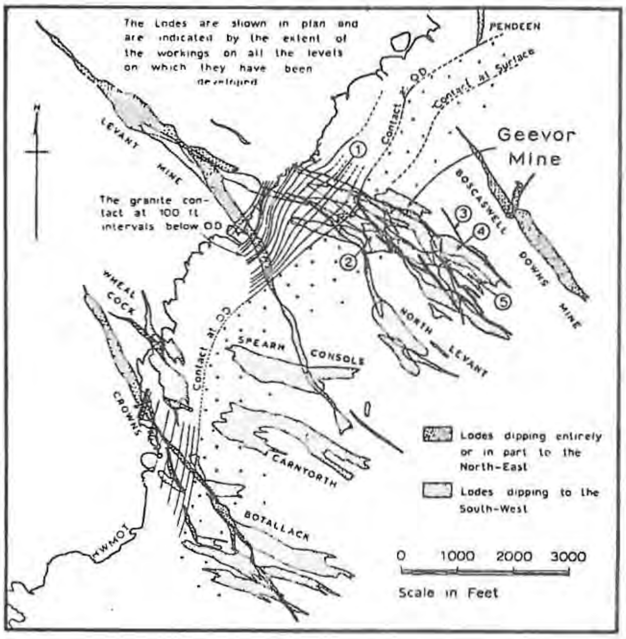
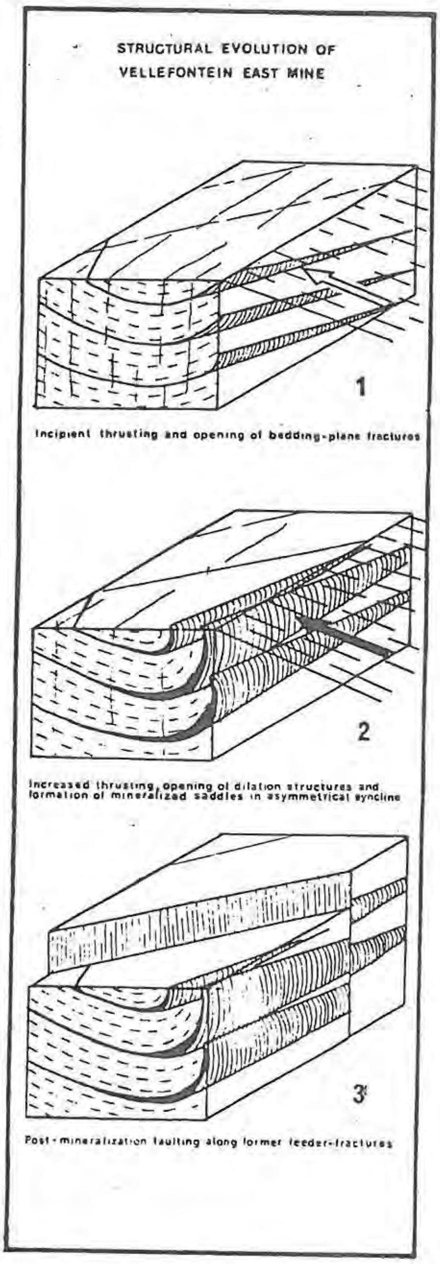


Fig. 44. Control of vein systems by granite contact (Garnett, 1967)

Lithological contacts or bedding planes may act as zones of weakness along which open space dilational features may form under compression. At the Vellefontein East Mine, Rooiberg, the development of ore shoots in optimum openings along bedding and cross bedded planes is determined by the maximum horizontal stress acting oblique to the sedimentary strike. This produced a series of mineralised saddles or bedded lodes in an assymetrical syncline. The maximum opening, and thus the greatest concentration of ore occurs along the axial zone of the flexure (Stear, 1977), Figure 45.

iv) dyke and pegmatite intersections

The structure of a lode and its metal content may change when it intersects a dyke because of the sudden change in rock competency. The effect, according to Garnett (1967) is unpredictable : they may branch, remain undisturbed or may be enriched or depleted. At the Geevor mine, Cornwall, the Coronation Lode intersects a dyke and changes direction almost through 90°. The dyke provides a plane of weakness along which movement and mineralisation occurs in preference to the continuation of the original fissure.



STRUCTURAL EVOLUTION OF
VELLEFONTEIN EAST MINE

Incipient thrusting and opening of bedding-plane fractures

Increased thrusting, opening of dilation structures and formation of mineralized saddles in asymmetrical syncline

Post-mineralization faulting along former feeder-fractures

Fig. 45. (Stear, 1977)

The behaviour of vein systems in pegmatites and dykes is described by Taylor (1969), Rayment et al. (1971), and Kettaneh and Badeham (1978). These authors have studied the relationship of mineralisation to porphyry dykes in S.W. England. Here mineralised lodes are located in shear zones along the dyke footwall and hanging wall, and in sets of steeply dipping fractures, Figure 46. Mineralisation consists of stockworks and fissure fillings. The largest ore body results from the infilling of a zone of brecciated slate and vein quartz which occupy interstices between breccia fragments and fissures. The porphyry dyke is the major factor in controlling ore distribution. The degree of development and the nature of the ore is structurally controlled by irregularities in the shape of the dyke.

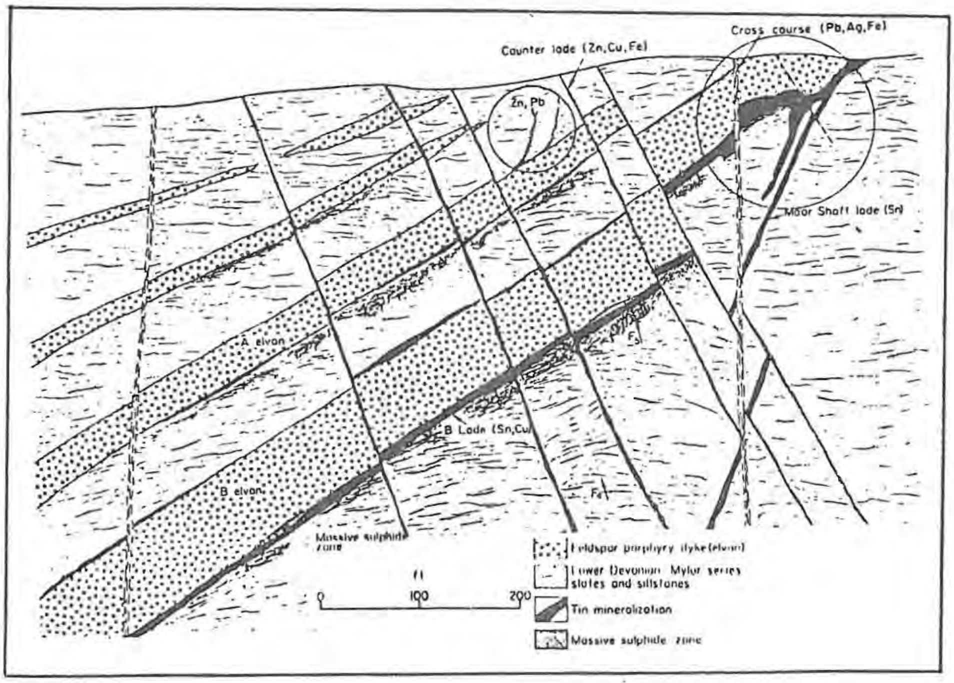


Fig. 46. Geological section at Wheal Jane (Rayment et al., 1971)

The ore body consequently consists of a number of lensoid zones that merge and interfinger laterally (Rayment et al., 1971). Development of the various zones occured as follows:

a) shearing of the slate zone at the footwall contact of the porphyry dyke accompanied by introduction of vein quartz
b) brecciation along shear zone
c) introduction of cassiterite, tourmaline, quartz and minor sulphides into the breccia
d) shearing parallel to dyke footwall and introduction of next mineralisation phase
e) rebrecciation and shearing of zones parallel to dyke footwall. Main influx of sulphides.

The competency contrast between dyke and slates allows extensive shearing at the contacts whilst the dyke itself acts as an impermeable barrier. This produced a strong zone of movement beneath a structural cap which is ideal for ore emplacement. The shape of the dyke footwall is undulatory, broken and displaced by faults, and controls the morphology and intensity of mineralisation. In particular, flexures in the dyke footwall (circled areas, Figure 46 permitted maximum concentration of ore. In the central area at

Wheal Jane, the minimum dyke thickness is accompanied by maximum lode thickness and highest grade of mineralisation. This minimum thickness is caused by a double fold which initiated the open space. Smaller embayments, Figure 47, cause the main lode mineralisation to separate from the dyke and to produce irregular fissure lodes that diverge from the dyke.

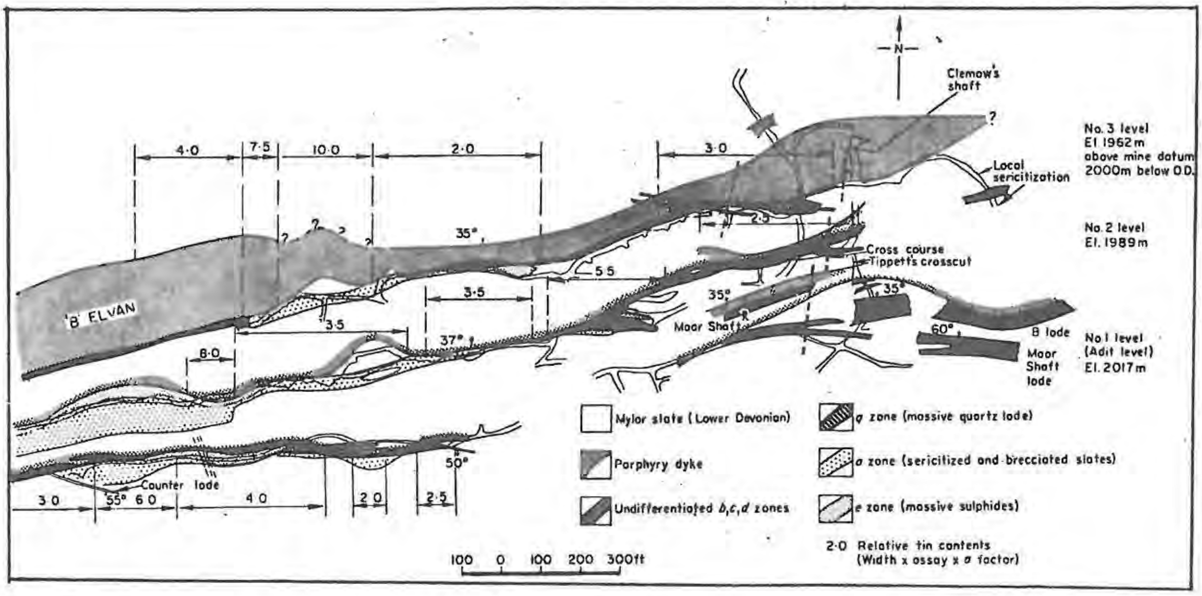


Fig. 47. Mineralisation zones in part of Wheal Jane B lode showing effect of footwall embayments. (Rayment et al., 1971)

Rayment et al. (1971) suggest that the dihedral angle of the fold embayment is critical. Above the region of 120° to 125° movement can occur on the dyke boundary itself, so that mineralisation is confined to the contact. Smaller angles were tight enough for movement to be restricted across the mouth of the fold. Kettaneh and Badeham (1978) conclude that the structures of lodes are more complex with a greater volume of mineralisation in these areas.

In some cases, the brittle nature of the pegmatite or dyke makes it receptive to fracturing and subsequent mineralisation. Thus, lodes may occupy fractures within pegmatite zones and die out quickly on leaving them. Here, the confines of the pegmatite is an obvious bounding control to the size and shape of the ore body. Ore shoots tend to be small with short lateral and vertical extents (Taylor, 1969). If two lodes intersect however, in a highly fractured area of pegmatitic rock, then mineralisation from both sources splits up into a mass of rich stringer with maximum concentration around the vicinity of the intersection point. Such an ore body occurs at the South Crofty mine, Cornwall (Taylor, 1969). Here the stringer ore concentration becomes uneconomic as the pegmatite boundary is reached.

The second type of lode is the normal fissure lode which occupies fractures outside pegmatite zones and splits up or vanishes as the pegmatites are approached. They may or may not reappear at the other side. The two types are illustrated in Figure 48.

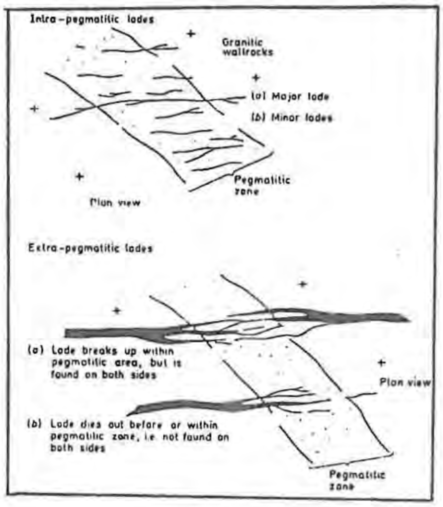


Fig. 48. Main features of pegmatite related lodes (Taylor, 1969)

v) faults

The dominant control of fault and fracture related vein systems has been discussed. Faults, however, have another effect. In complex vein systems, ore zones change upon intersecting faults. In complex vein systems, ore zones change upon intersecting faults. If the faults are pre-mineralisation, then they may act as restraining barriers that pond mineralising fluids to form a locally enlarged ore body (Taylor, 1979), Figure 49. Kettaneh and Badeham (1978) note that the most complex junctions with increased thickness occur adjacent to the main faults.

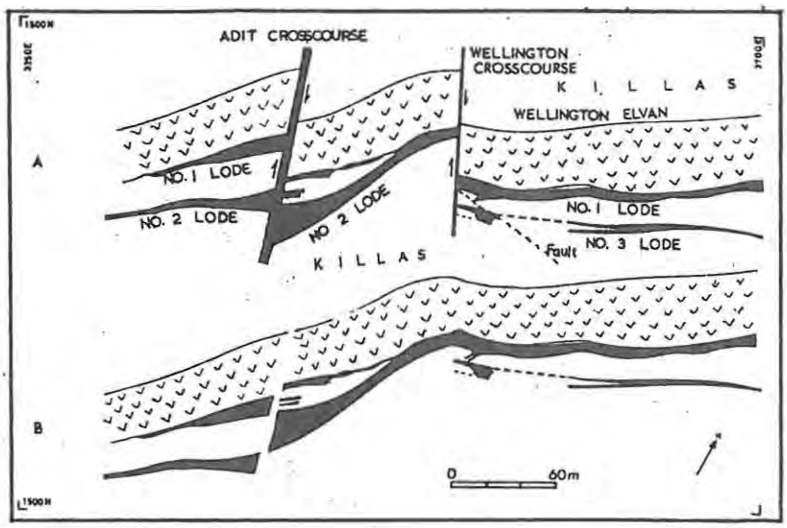


Fig. 49. Effect of impounding of ore fluids by faults (Kettaneh & Badeham, 1978)

Wrench faulting has the important affect of causing secondary tension fractures and shears. This may facilitate the development of a major lode area, Figure 50.

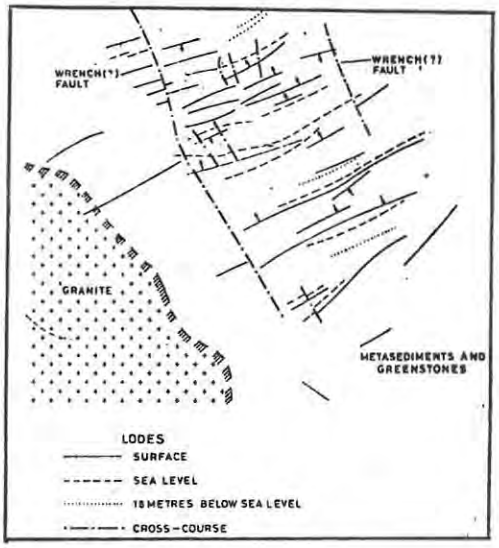
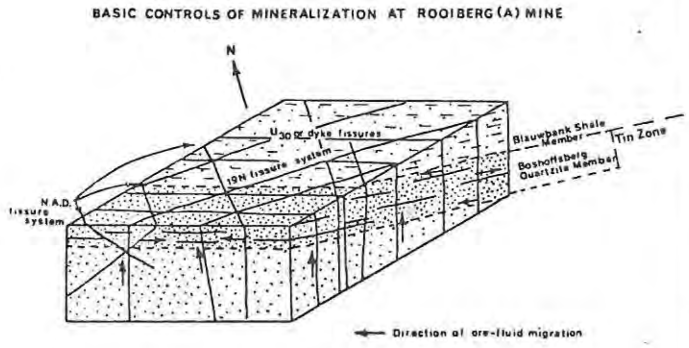


Fig. 50. Relationship between lodes and pre-mineralisation wrench faulting (Hosking, 1974)

REPLACEMENT DEPOSITS

Replacement deposits are the result of the porosity within reactive horizons that allows the ingress of mineralised fluids. This porosity is often structurally induced and this consequently affects the morphology and volume of the individual ore bodies. Rich cassiterite replacement bodies of the Rooiberg mines occur in cross bedded arkosite (Stear, 1977). Mineralising fluids entered the stratabound zone by a complex system of intersecting fissures and master joints, Figure 51 . If the host rock is highly fractured, then the result is a stockwork of discontinuous irregular veins and stringers. Alternatively, ore is located in small pockets which vary considerably in size, shape and mineralogy. They generally form at the intersections of structural planes and physical discontinuities, and range from simple replacement nodules to mineralogically complex masses. These pockets may concentrate along lines of fracture. At Rooiberg, deposits of this type coalesce on master joint planes to form major ore bodies, Figure 51 , that may merge with open space filling.



Stratabound tin mineralization at a stratigraphic contact zone. Mineralizing solutions, transported by a system of fissures and master joints, migrated along bedding-planes in cross-bedded arkosite and formed cassiterite-bearing ore-bodies in a stratabound tin-zone.

Fig. 51.
(Stear, 1977)

Thus the degree and nature of fracturing within a reactive lithology is responsible for the morphology of the deposit. The width of the reactive host horizon imposes a boundary on the possible thickness of the ore body. Often a flat tabular body will result.

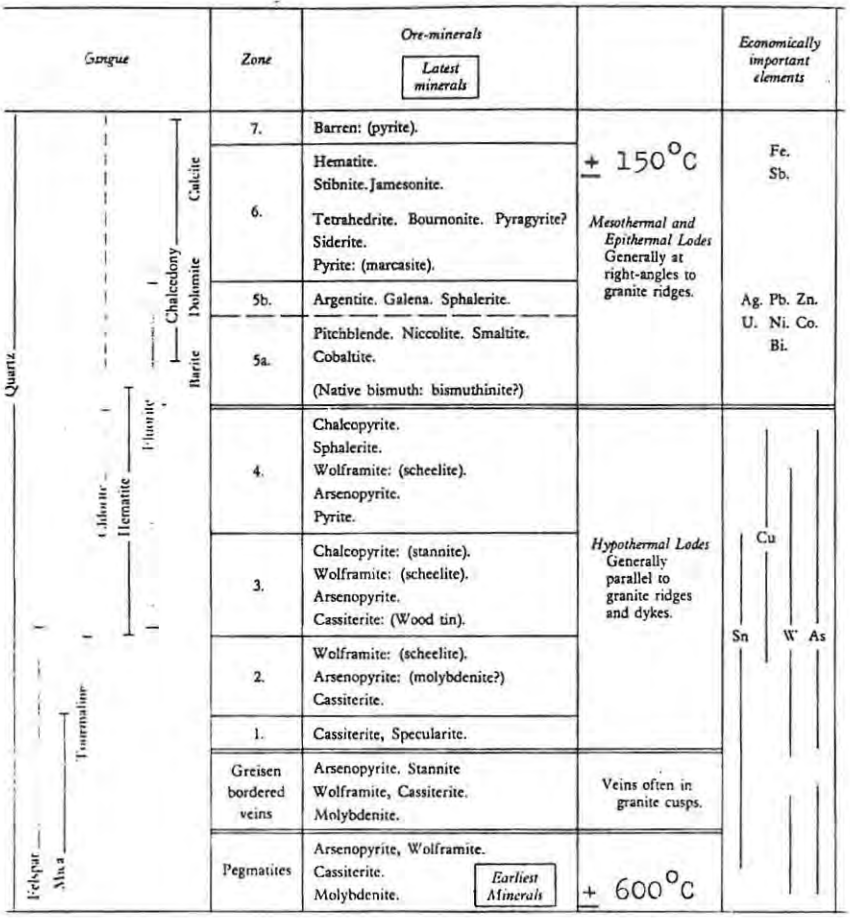
6. THE GEOLOGICAL CONTROLS OF GRADE

The grade of a deposit comprises metal distribution, metal content and quality. Because tin deposits are typically highly irregular with erratic and variable grades it is critical in evaluation to have an understanding of the geological factors affecting the metal distribution. If the controls on irregularity are understood, then adequate allowance can be made during evaluation. The primary control on content of tin mineralisation is the geochemical behaviour of tin in the different environments. The original availibility of tin in the system is critical. Subsequently, the important constraints are the degree of differentiation of the magma (Groves, 1972) and the nature of the crystallisation process (Groves and McCarthy, 1978). As the system evolves, the spatial distribution of ore minerals corresponds closely to the paragenetic sequence of mineral deposition. This results in the phenomenon of zoning. As with morphology, the most common controls on metal distribution are structure and lithology. Structural elements controls the concentration of tin because they disturb solution equilibria.

Zoning

Zoning describes the spatial distribution of minerals on both a regional and local scale. As distance from the igneous source increases, the temperature drops and successively lower temperature minerals are deposited. Other physical and chemical parameters, however, are also involved so that the causes of zoning in tin vein systems are complex. These include pressure, pH, sulphur fugacity and host rock composition. The example of zoning from S.W. England is often quoted (Hosking, 1963) though is really only one of a number of possibilities (Taylor, 1979). Table 8 does nevertheless indicate that cassiterite as a high temperature mineral crystallises early in the paragenetic sequence and is thus generally located in the deepest zones. The table also indicates which minerals can be expected with increasing distance from the granitoid. Most deposits display inner zones rich in tin ± tungsten and are fringed by sulphide ores containing lead, zinc and copper. There is much overlap and variation however so that these patterns are frequently obscure. This is particularly so if there have been numerous superimposed phases of mineralisation. Hosking (1963) illustrates the distribution of primary zones around a granite cusp,

Figure 52. The zonal boundaries are more shallow dipping than the igneous contact, and the area occupied by the tin zone is considerably less than that of the copper zone. This in turn is less developed than the overlying lead and zinc zones (Hosking, 1963).



Gangue	*Zone*	*Ore-minerals* *Latest minerals*		*Economically important elements*
Quartz Calcite Chalcedony	7.	Barren: (pyrite).	± 150°C *Mesothermal and Epithermal Lodes* Generally at right-angles to granite ridges.	
Dolomite	6.	Hematite. Stibnite. Jamesonite. Tetrahedrite. Bournonite. Pyragyrite? Siderite. Pyrite: (marcasite).		Fe. Sb.
	5b.	Argentite. Galena. Sphalerite.		Ag. Pb. Zn.
Barite Fluorite	5a.	Pitchblende. Niccolite. Smaltite. Cobaltite. (Native bismuth: bismuthinite?)		U. Ni. Co. Bi.
Chlorite Hematite	4.	Chalcopyrite. Sphalerite. Wolframite: (scheelite). Arsenopyrite. Pyrite.	*Hypothermal Lodes* Generally parallel to granite ridges and dykes.	Cu W As
	3.	Chalcopyrite: (stannite). Wolframite: (scheelite). Arsenopyrite. Cassiterite: (Wood tin).		Sn
Tourmaline	2.	Wolframite: (scheelite). Arsenopyrite: (molybdenite?) Cassiterite.		
	1.	Cassiterite, Specularite.		
	Greisen bordered veins	Arsenopyrite. Stannite Wolframite, Cassiterite. Molybdenite.	Veins often in granite cusps.	
Felspar Mica	Pegmatites	Arsenopyrite, Wolframite. Cassiterite. Molybdenite. *Earliest Minerals*	± 600°C	

Table 8
General mineral paragenesis of S.W. England tin deposits. (Park and MacDiarmid, 1975).

This is important for evaluation, because economically important tin deposits underlying copper can only be expected near the centre of mineralisation. The importance of zoning is that older mines may have been developed on copper production without realising the presence of underlying tin. This is the case at the Dolcoath mine,

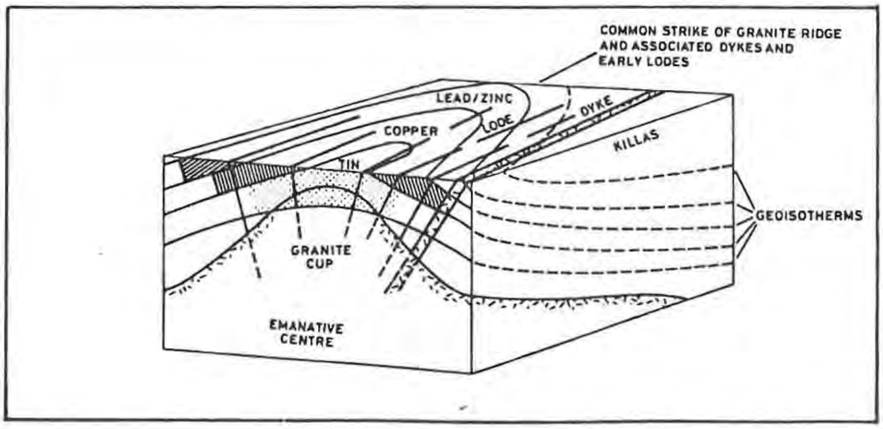


Fig. 52. Distribution of primary zones around granite cusp in S.W. England. (Hosking, 1963)

Cornwall which was originally commissioned as a copper producer, Figure 53. Hosking (1963) makes the point that economically important quantities of copper in a given lode are normally greater than that of tin. The zonal boundaries are not abrupt but markedly irregular (Hosking, 1964). This is the result of factors other than geoisotherms such as structure, chemically favourable host rock and pressure conditions. Impounding bodies and the variation in the extent of fracturing are important limiting factors.

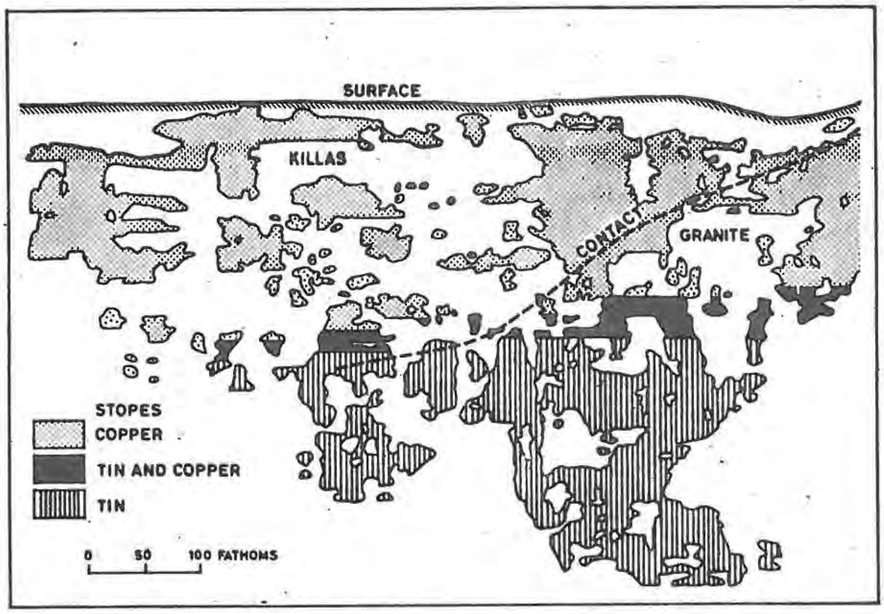


Fig. 53. Primary metal zoning at the Dolcoath Main Lode. (Hosking, 1963)

For example, at South Crofty, the upper and lower economic limits of ore lode is bounded by two fracture controlled irregular lines. In replacement veins and bodies, the availibility of reactive rock may determine the grade produced and therefore also the zoning of minerals.

It must be noted that Taylor (1979) advises caution in adopting a rigid approach to regional zonal analysis. A full zonal analysis involving identification of the number of mineral phases and their temporal and spatial position is necessary because zonality will be different under different circumstances. The Cornish model is not of universal applicability, and this is demonstrated in the Herberton tin field, Queensland by Taylor and Stevenson (1972).

FACTORS INFLUENCING GRADE IN ENDOGRANITIC DEPOSITS

These deposits are the magmatic disseminations, greisen associated and pipe deposits. The important control on grade is the chemical reaction of tin-rich late stage fluids with already crystallised or semi-crystallised granite, i.e. the interplay between chemical composition of fluids and host rock. A trapping mechanism such as an impermeable seal is vital for this reaction to take place with subsequent deposition and concentration of tin. The distribution of greisen, and thus mineralisation is controlled by changes in the structure of the upper granite contact. If the seal is breached during mineralisation, then both grade and tonnage are depleted. Thus the timing of fracturing in relation to mineralisation is critical.

At the Anchor tin mine, Tasmania, greisenisation results from alteration by fluids in a system essentially closed to the influx of new fluids (Groves and Taylor, 1973). The degree of alteration and mineralisation depends on rapidity of removal of fluids from the system and influx of new material. Mineralisation will be enhanced with more intense greisenisation. Because the system is closed, a low grade (0.2 to 1% Sn) of finely disseminated cassiterite results. In contrast, the sub-horizontal greisen veins appear to have formed in a more open system by the continual renewal of fluids through a joint system in the granitoid. This results in a tin content much higher than that of the greisenised granite. Thus the degree of influx of new fluid is a critical control of grade in this situation.

The alteration process and mineralisation is pervasive so that sharp cut-offs do not occur. The mineralised zone generally consists of fine grained cassiterite ± wolframite and minor chalcopyrite, bornite, molybdenite, fluorite and pyrite. Only the cassiterite is usually economic. Mineralisation occurs in discrete patches separated by areas of barren material. It is likely that a small well defined structurally high region may be totally greisenised and mineralised if an efficient seal exists.

Pipes are very efficient concentration mechanisms as evidenced by the very high grades of cassiterite attained (up to 60%). It is likely that the material that produced them already contained a very high tin concentration according to the model proposed by Groves and McCarthy (1978) Figure 23. If an overlying impermeable horizon (such as the pegmatite at Zaaiplaats) impedes the upward migration, then the fluids billow out to form a lensoid zone whose grade is diminished. This results in discrete bodies of low grade disseminated cassiterite. When a pipe crosses a disseminated cassiterite horizon, then some form of secondary remobilisation and concentration of the latter results because locally grades are markedly enhanced. This fact is utilised in exploration for pipe deposits at Zaaiplaats.

Pseudo-pipes are structurally controlled by intersecting fracture zones. The degree of fracturing and thus degree of permeability controls the grade of the subsequent ore body. Renewed movements will allow further influxes of mineralised fluid that may enhance grade. Conversely, if the incoming fluids are unmineralised, then grade is likely to diminish by addition of gangue.

FACTORS INFLUENCING GRADE IN TIN SKARN AND REPLACEMENT DEPOSITS

In this section the controls on grade of replacement bodies are considered with those on skarns because the reaction processes involved are similar. The essential difference is that skarn processes are closer to the granite contact and occur at higher temperatures and in more chemically reactive lithologies than in more distal replacement deposits. As with morphology, the structural control on grade is emphasised; mineralisation is localised by chemical controls in a structurally favourable environment.

The most important factor is the quantity of incoming fluid which is controlled by the availability and density of the fracture system, together with the reactiveness or chemical composition of the country rock. Temperature plays a critical role in controlling reaction rates in suitably responsive lithologies.

The mineral composition of the host rock will control the mineralogy of the resultant skarn and replacement body, for example magnesian skarns and calcareous skarns. Ore is preferentially deposited in skarns because of the ground preparation involved in skarn formation, such as increase in vugginess and brittleness. In addition late ore bearing fluids can use the same plumbing system involved in earlier skarn formation. The most important control is the textural or chemical control on later ore deposition by early formed skarn minerals (Barnes, 1979). In general, two major interrelated groups result (Taylor, 1979). Both are iron-rich but one contains significant iron oxide whilst the other contains significant sulphide.

In tin-rich magnetite skarns very little of the tin occurs as cassiterite and tin values are usually low. A low grade potential does, however, exist. For example, the iron ore at Bukit Besia, Malaysia contains an average of 0.07% Sn with local enrichments (Hosking, 1970). In general, the tin of magnetite skarns is not recoverable as it is very fine grained and occurs as inclusions and exsolutions in iron minerals. They are occasionally associated with banded fluorite, as at Lost River, Alaska which contains 33 m tonnes at 0.27% Sn, 0.0037% WO_3 and 15.6% fluorite, together with some beryllium (Sainsbury et al., 1968).

Sulphide rich skarns contain an early oxide phase superimposed by a late sulphide-cassiterite-stannite phase. Deposits of this type are mineralogically complex and most of the tin is tied up in skarn and silicate minerals such as malayaite.

A further complication to skarn tin deposits is that the zonal mineral arrangement is usually very complex with several phases of fluid introduction. This arrangement may be further complicated by replacement during introduction of late phases.

Mineralogy in replacement deposits is typically complex (Hunter and Lenthall, 1971). This is exemplified by the replacement deposit at Cleveland Tasmania (Ransom and Hunt, 1975). Here the mineralised lenses comprise complex combinations of pyrrhotite, pyrite, marcasite, cassiterite, quartz, carbonate, fluorite, actinolite, chlorite and tourmaline with accessory arsenopyrite, sphalerite, hematite, stannite and tetrahedrite. The chief ore minerals are cassiterite, chalcopyrite and stannite, with cassiterite occuring as 0.1 to 1 mm euhedral and subhedral grains. Zoning is prevalent, Figure 54, but overlapping and inconsistencies are common. The major controls on ore distribution are stratigraphy and mineralogy. The mineralised layers lie within a well defined shale and chert horizon whilst mineralogy controls the ore distribution within the mineralised layers by zoning.

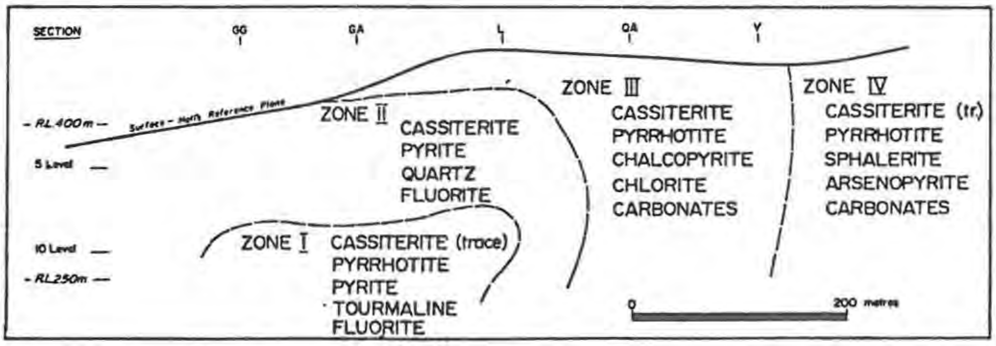


Fig. 54. Mineralogical zoning at Cleveland mine (Ransom and Hunt, 1975)

FACTORS INFLUENCING GRADE IN TIN VEIN SYSTEMS

The initial input of tin into the hydrothermal vein system is subject to a natural randomness which will directly influence subsequent content and distribution of ore. Garnett (1966a) states that "the local discontinuity of values and impoverishments may be due to no other reason than normal fluctuations in the cassiterite content, a feature which is always evident". Superimposed upon this are the combined results of several geological controls such as chemistry and environment, lithology and structure. These directly influence the distribution and quality of subsequent ore. The geological controls of grade variation in vein systems are highly complex and result in a grade distribution that is always erratic.

Chemical and environmental controls

The general sequence of events described by Kelly and Turneaure (1970) to account for metal distribution in hydrothermal vein systems has been described in an earlier section. To reiterate, they conclude that temperature and pressure conditions are the critical controls of the paragenetic sequence. In particular, early stage boiling was an important mechanism for precipitation of quartz and cassiterite and may have been responsible for the restricted vertical distribution of very high grade cassiterite in some major deposits of central Bolivia. The important variations in temperature were caused by several mechanisms of cooling. These include conductive heat exchange, boiling, irreversible adiabatic expansion and late cooling by conductive loss and mixing with groundwater. Temperature may have played a major role in controlling the paragenetic events such as transition from early oxide stage to later sulphide stage.

The order of precipitation is more than likely to be disrupted or overprinted by later phases which results in a very complex mineral paragenesis. At the Wellington mine in Cornwall mineralisation took place in four primary and hypogene phases over a temperature range of 300-350° C (Kettaneh and Badeham, 1978). The first phase precipitated quartz, tourmaline and cassiterite between fragments of country rock, dyke material and granite porphyry. This phase was also responsible for tourmalinisation and sericitisation. The material was brecciated by renewed fault movement and subsequently a second phase precipitated quartz, chlorite and sulphide together with some replacement of early fragments. This was followed by more quartz with sphalerite, gold, galena and pyrite. Two late periods of minor fracturing were infilled by the final phases which consist of quartz, chlorite and sulphides with minor tourmaline, cassiterite and rutile. Stannite and Ag-Pb-Sb-Bi-Cu sulpho-salts are of minor significance. In general, the trend is from cassiterite through base metal sulphides to native metal and sulphosalts. At Mount Wellington, however there is a lack of distinctive zoning between oxides and sulphides. This is due to the effectiveness of the fault zones as traps. The zonation has thus become telescoped.

The mechanisms of precipitation have an important influence on distribution, content and quality. These mechanisms are numerous and include changes in temperature and pressure chemical reactions between moving solutions and rocks, exchange reactions following mixing of solutions, changes in pH, and the effects of electrical fields (Barnes, 1979). Temperature changes cause precipitation by affecting the solubility products of sulphide and oxide minerals, by affecting the form and stability of the transporting complex ions and by influencing hydrolysis constants of ligands. An important method of causing temperature drop is by adiabatic decompression on throttling. This is induced by structural constrainst or when pressure on fluid approaching the surface changes rapidly from lithostatic to hydrostatic. Boiling is a pressure controlled effect that results in removal of volatile constituents which leaves the residue more alkaline and less capable of metal transport so that precipitation occurs.

Alteration processes accompanying mineralisation affect grade considerably. In particular, alteration effects are pervasive and this results in generally diffuse contacts. Alteration increases the brittleness of the rock which induces fractioning and subsequent mineralisation.

Structural and lithological controls

The most important structural influence on grade is the effect of producing open spaces and its relationship to the rate of inflowing material i.e. the concentration of mineralising fluids. Most tin veins are highly complex and multiphase, and form as a consequence of continued reopening over a long period of time. This structurally controlled reopening controls the deposition of successive phases of mineralisation. Because only parts of the vein may reopen at different times, the ore distribution is likely to be highly irregular. Furthermore, not all the successive phases will be necessarily ore bearing and this may consequently be deleterious. For example, dilution of grade by a late gangue phase may well occur. Many deposits only become economic when they contain at least two tin bearing phases (Taylor, 1979). At the Rooiberg tin mine the presence and degree of a later influx of cassiterite controls the tenor of ore and its attitude in ore shoots (Labuschagne, 1970).

The effect on ore distribution by repeated movements can be seen in Figure . The relationship between repeated normal faulting and/or repeated reverse faulting is particularly important as it may result in a high variation of fissure width and corresponding grade. This is so because the distribution of values depends on availibility of space and this results in erratic distribution. A late relaxation phase may cause increased lode width and increased grade if the fluid is tin bearing, but decreased grade if the fluid is barren. In this way, the formation of open spaces by faulting controls the development of ore shoots. Repeated movement may also control ore quality. A second phase of faulting may cause fracturing and corrosion of earlier formed cassiterite and consequent fine grain size.

The spatial position of the vein relative to the granitoid is significant in controlling grade. Vein deposits that occur close to the granitoid, i.e. hypothermal and mesothermal veins (Lindgren, 1926), will generally have quartz as the main gangue mineral followed by carbonate. Oxides will occur closest to the granitoid whilst sulphides precipitate further away. Repeated precipitation results in different generations with different mineralogy, crystal habit and crystal size. In veins occuring within the granitoid to which they are genetically related, ore is likely to occur as rich sporadic concentrations. Ore in vein systems of subvolcanic porphyry tin deposits are rapidly deposited which results in complex and varied mineral associations with local highly concentrated zones. Telethermal vein deposits are those that occur in sedimentary rocks often far from the granitoid. Ores in this environment are likely to be fine grained with a simple mineralogy.

The lithological control on grade, i.e. the relationship between ore distribution and stratigraphy, may be two-fold. In the first case, different chemical compositions of alternating lithologies result in selective alteration, leaching and precipitation so that there is a distinct chemical control on the position of the ore shoot in a vein. In this case there may well be a correlation of grade with host rock mineralogy. In the second case there may be a structurally induced fluctuation in values produced by changes in lithology. The lithology controls the variation in joint pattern and the ease of opening of bedding planes and partings. A single fissure will behave differently in rocks of contrasting competency. For example, in a hard arenaceous rock, the fissure is likely to be more uniform but on contacting an argillaceous horizon it will tend to split and disintegrate. Cassiterite therefore becomes dispersed with a decrease in grade over an increase in width (Garnett, 1966b).

Pegmatities and dyke deposits

Structure is an important control on grade distribution in pegmatite and dyke related deposits. Hosking (1970) emphasises the brittleness and ability to fracture of pegmatites that provide traps in which mineralizing fluids may precipitate cassiterite. In addition, mineralisation may be syngenetic or epigenetic with respect to the pegmatite so that there may be true pegmatitic cassiterite together with late hydrothermal cassiterite. For this reason the tin content of pegmatites varies widely. In zoned pegmatites the cassiterite zone is likely to occur preferentially in different zones. This enhances the irregularity because many of the zones at different sites will not be developed or will be incomplete with irregular thickness. In some pegmatites, grade variation is related to structural irregularities in the footwall and hanging walls as previously discussed. Fissure lodes in pegmatitic zones are generally too dispersed to form significant ore bodies, but occasionally structurally controlled concentrated populations of minor lodes may produce medium tonnage - medium grade cassiterite deposits.

In stanniferous pegmatite deposits produced by syngenetic mineralisation there is usually an association of cassiterite, columbite, tantalite, magnetite, sulphides, gold, beryl, tourmaline, monazite and lepidolite. Unfortunately many of the pegmatites in a field will be barren and it has not yet proved possible to indentify the controls on this variation (Hunter and Lenthall, 1971).

FACTORS INFLUENCING GRADE IN SUBVOLCANIC PORPHYRY TIN DEPOSITS

The distribution of grade in porphyry tin systems is similar to porphyry copper deposits with one important difference. Supergene enrichment processes cannot operate in tin deposits because of the lack of chemical mobility of tin.

The genetic history of the porphyry system has an important influence on the style of mineralisation and subsequent grade. Thus, a complex and often high grade tin and tin-silver vein system of stockwork and breccia filling is superimposed upon a body of dispersed low grade mineralisation. This consists of disseminated cassiterite and pyrite with grades of 0.1 to 0.3% Sn (Sillitoe et al., 1976) associated with a sericite quartz tourmaline alteration assemblage.

In the vein system mineralisation is strongly telescoped which results in a highly complex ore with a varied mineralogy. The mineralising event is a single unique event (Kelly and Turneaure, 1970) rather than multiphase so that grades tend to be highly erratic. The mineralogy is generally highly complex due to the extreme range of temperatures and conditions involved.

Grade depends on a combination of factors related to the intensity and number of phases of the mineralisation process, the concentration of fluids, the depositional process and availibility of depositional sites. In deposits of this type there is a very strong control by alteration; the pattern of hydrothermal mineralisation is concentric with respect to alteraltion zones so that grade may be distributed accordingly. The relationship between alteration, mineralisation, mineralogy and grade is a function of the distance from the intrusive stock heat source. As the intensity of hydrothermal processes decrease, so does the grade and regularity of mineralisation and alteration.

7. IMPLICATIONS FOR EVALUATION

The purpose of evaluation is to determine in detail the geology of the deposit and in particular the geological factors that control the features of critical economic interest. Accurate ore reserve calculations can only be carried out if these controls are recognised and understood. The most important factors are those that control grade - tonnage relationships, continuity of mineralisation, mineability and extractability. Geological sampling and drilling are important parts of evaluation. The manner in which they are used and their effectiveness is critically controlled by these geological factors. The aim of the present section is to discuss the implications of the geological controls and to show how they influence evaluation.

GRADE - TONNAGE RELATIONSHIPS

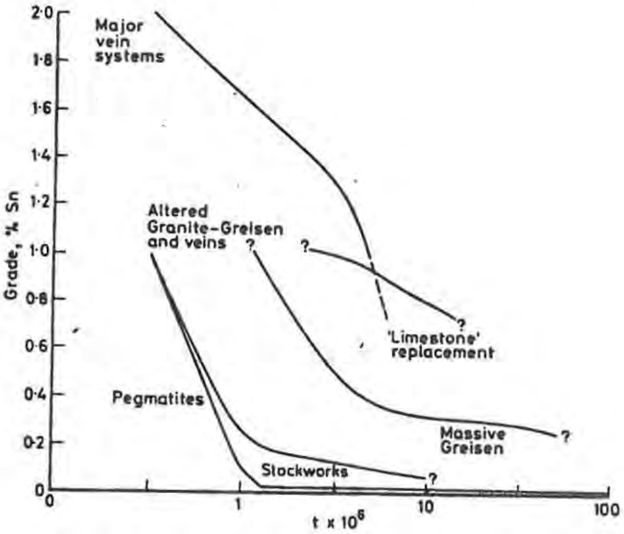


Fig. 55. Grade-tonnage relationships for different types of tin deposit (Taylor, 1977).

The geological factors controlling grade and tonnage have been described in the previous sections. From this, conclusions can be drawn as to which types of tin deposit are most likely to contain sufficient grade and tonnage for economic viability.

i. magmatic disseminations

Taylor's (1979) conclusion that true orthomagmatic disseminations do not occur is accepted for reasons discussed previously. Disseminated cassiterite deposits such as that at Zaaiplaats are considered as epigenetic along with greisen-hosted varieties.

ii. pegmatite deposits

Pegmatite deposits are of minor importance because they are generally small with erratic and limited tin concentrations. Figure 55 indicates a steep grade-tonnage curve with significant tonnages only around 0.01% Sn. Low tonnages of 100-1000 tonnes at 1 to 2% Sn are common. Pegmatites are unreliable because in a deposit only some of the pegmatites will be mineralised. Problematical evaluation results because the geological controls on this phenomenon have not been identified. In addition it cannot be predicted just where the cassiterite will be concentrated so that sampling and drilling are ineffective.

Certain deposits such as those in Central Africa may however be large enough for exploitation. Some deposits that contain insufficient tin alone to be viable may become so if valuable co-products such as columbite/tantalite are present. Thus the exotic mineralogy associated with some pegmatites may be critical. Hunter and Lenthall (1971) suggest that although they are poor exploration targets, a close spaced stockwork of pegmatites may result in a low grade - large tonnage deposit.

iii. skarn deposits

These are only likely to be important in rare cases such as at Lost River, Alaska. In general they are too small with highly erratic metal concentrations to be of much significance. Grades are typically low and of the order of 0.05 to 0.15% Sn (Taylor, 1979). The complex replacement reactions involved in the skarn forming process results in a very complex mineralogy that is not readily amenable to beneficiation. Much of the tin is tied up in skarn silicate minerals such as malayaite. Some deposits in Australia appear to have a low grade potential and are currently under investigation (Taylor, 1979). A significant technological advance in extractuve metallurgy would make many skarns viable.

iv. greisen associated deposits

In recent years the traditional small scale underground tin vein mines have suffered from rapidly escalating costs. For this reason, large low grade open pit propositions are becoming more attractive. For open pit mining, the suggested target scale is around 40 m tonnes at a grade of 0.2% Sn at 60% recovery (Taylor, 1979). Taylor (1977) reviews the possibilities of large tonnage

- low grade deposits and concludes that the greisen environment has the best potential especially if it is enhanced by adjacent high grade vein systems which can be mined together. The presence of associated valuable elements such as W,F,Bi,Bo,Be increases the potential. Those deposits mined for tin alone are extremely rare.

v. fissure lodes and stockwork deposits

The tonnage grade curve for tin vein deposits, Figure 55 shows that although higher grades can be expected, ore reserves fall off very rapidly at low values. This reflects the nature of tin occuring as discrete high grade ore shoots (Taylor, 1977). Large tonnage - low grade deposits in this category do not exist. Nevertheless small deposits of this type with high grade ore are very attractive investments despite difficulties in exploration and evaluation.

The traditional approach has been to mine on a 'day to day' basis with very little ore in reserve and always in the hope of discovering a new lode or ore shoot at the last minute. Detailed knowledge of geological controls, if properly applied, would change this state of affairs, and this has been demonstrated in S.W. England (Garnett, 1966).

Generally, tin deposits of the vein type are not amenable to high production rates with continuous high level cash flows. Potential however, does exist for medium to small scale operations that generate smaller cash flows with a lower capital investment. A company that is prepared to accept this constraint and uses precise geological control in evaluation is likely to prove successful.

Stockwork deposits or closely spaced sub-parallel veinlets generally have larger tonnages at very low grades, Figure 55 They may however be associated with high grade veins and valuable metals such as tungsten which would increase their attraction.

vi. replacement deposits

The curve shown in Figure 55 refers specifically to the medium size carbonate replacement deposits of western Tasmania. These may have a potential for large tonnage - low grade development, but more research is needed. Deposits of this scale however, are not common. The more usual type of replacement deposit, such as at the Rooiberg tin mines are generally small with high grade pockets and they may be economic if associated with fissure lodes.

vii. subvolcanic porphyry tin deposits

Present production from these deposits is entirely from the fissure veins and breccia systems. Mining at Choroloque, for example, is restricted to the breccia pipe which consists of fissure vein and low grade cassiterite mineralisation in a pervasive stockwork (Sillitoe et al., 1975). Although these breccia and vein systems appear to be part of a porphyry tin system, no major large tonnage - low grade disseminated cassiterite deposits similar to porphyry copper deposits have yet been proved (Taylor, 1976). Potential certainly exists and Sillitoe et al. (1976) indicate possible reserves of 100-1000 m tonnes at 0.2 to 0.5% Sn. It is likely that in future years production from low grade porphyry deposits will become feasible. Evaluation is currently in progree in Bolivia for open pit possibilities of this type (Sillitoe et al., 1976).

viii. epithermal volcanic tin deposits

These are very small, erratically mineralised with low grades, and are rare. Deposits of this type are of very limited economic significance.

Conclusions

Because of rapidly increasing exploration and production costs, the best investment opportunities are large tonnage - low grade deposits of the greisen association. Other possibilities for this scale include some large skarns, some carbonate replacements and porphyry tin deposits. High grade tin veins (± stockwork, ± replacement deposits) are attractive at small to medium scales of production. Other categories of tin deposit are generally not of major significance. However Taylor (1979) advocates that there may always be a chance of economic viability and that any possibility must not be overlooked. In this respect, Crocker and Callaghan (1979, p.17) are explicit in stating that "stringent prerequisites as to the type and grade of ore deposit being sought" are negative factors in bringing new deposits into production. If the company is prepared to operate at any scale then all deposit types must be considered.

THE INFLUENCE OF GEOLOGY ON MINEABILITY

The geological features that combine to influence mineability are structural attitude, continuity and shape, regularity, ground conditions, and accessibility. These must be studied in detail in order to decide upon a profitable mining method suited to the geology of the deposit.

Structural attitude, continuity and shape

Massive disseminated cassiterite deposits commonly have simple structures with more or less continuous mineralisation in specific homogeneous zones. The entire cusp region of the granitoid may be altered and mineralised or, on the other hand, mineralisation may be contained in sub-horizontal zones as at the Anchor tin mine, Tasmania. The upper contact of mineralisation is likely to be bounded by a lithological contact such as the granite contact or an impermeable pegmatite. This will form a natural upper limit to mining. The lower contact may be irregular or diffuse in the case of massive apical zone deposits whilst sub-horizontal zones have relatively sharp contacts.

Disseminated tin deposits are commonly amenable to low cost bulk mining methods such as open pit mining or underground block caving. The possibility of low cost mining is enhanced if the exposed host granite is intensely weathered, thus facilitating water extraction techniques such as high pressure water jets.

Tin vein systems are typically highly irregular in all their geological features. In particular, morphology is complex and this influences grade and tonnage distribution. They may incline structurally at any angle, they are generally not continuous, and mineralisation may only appear in selected portions. It has however been demonstrated that geological factors, principally structure, act to control the distribution of mineralisation. Because they are so varied, no one specific mining method can be applied and the method must change dynamically to suit the local peculiarity of the ore body. Here structural attitude, regularity and competency are critical so that detailed beforehand knowledge of these must be gained.

It is likely that new lodes, not expressed at surface, may be discovered by current mining. These may have completely different physical attributes and the mining method must be flexible enough to allow for this. At the Union Tin mine for example, mining started as small workings on several narrow high tenor lodes on surface (N. Bertram, pers.comm.). Only after these had been mined at depth were additional lodes located. These were subsequently mined and followed to surface. During this course, more lodes were discovered that occur only at depth and do not outcrop on surface. These are some of the richest lodes on the mine and account for some 60% of production. Each of these vein sets have different physical and mineralogical characteristics. In retrospect, it was appreciated that these lodes follow a very strong structurally controlled fracture pattern. This information is now used for predicting new target areas underground. The point is made that the initial geological evaluation on this deposit was minimal and this resulted in a very uncertain ore reserve and a poor understanding of geological controls. Clearly, a company starting out on a tin mining venture would not be prepared to invest money on such a precarious bases.

It is stressed that much of the uncertainty can be reduced by sound geological reasoning right from the outset. This will only occur if the company is prepared to invest time and money in detailed and critical geological evaluation. The works of Garnett (1966a, 1966b) and Taylor (1966, 1969) are recommended as model studies in this respect.

A sound geological data base is vital because historical precedent plays an important role in evaluation of tin vein deposits. Using the example from Union Tin mine, the geologists now appreciate that if a new lode conforms in character to the 'A type', then good consistent tin values can be expected. On the other hand, if it conforms to the 'B type', it is likely to have very erratic mineralisation with generally low grades but relatively large tonnage. Ideally these two types should be mined simultaneously in order to optimise mill head-grade. Because each lode type has a different physical character, they must be mined in a different way. Recognition of the lode type in the evaluation has therefore a strong bearing on the type of mining to be employed and is critical for advance mine planning.

Often, the intricacies of the vein system may not be discovered from a surface exploration programme because certain structural effects may not be manifest on surface. As will be shown, diamond drilling is of little use in exploration and evaluation of lode type tin. The conclusion is drawn that the best method of evaluation is by trial mining.

Mining will generally be underground, but if sufficient veins are present on surface, then a selective mining open pit may be feasible. Because mining of vein systems is expensive, a very tight geological control must be kept on grade. In addition, it must at all times be remembered that lode value (i.e. grade and width) must be expected to fluctuate during stoping.

Zoning and alteration

Little mineralogical zoning is expected within massive disseminated deposits. This is because discrete volumes of mineralising fluids concentrate and spread out under a barrier and over a limited vertical distance. If associated greisen-hosted vein swarms are of any length then these may be zones.

Tin vein systems are often subject to very complex zonation patterns so that mineralogy and grade will vary in both a vertical and horizontal distance. This has important mining implications because of changing grade and tonnage in different zones. The proceedures involved in zonal analysis are described and discussed by Taylor (1979). A complete zonal study requires detailed information concerning all mineral phases and assemblages, plus complete spatial and temporal understanding. Knowledge of the number of mineral phases requires detailed mineralogical studies. An in-depth zonal study is a complex and difficult process, particularly in the case of telescoped assemblages. Despite this difficulty, a zonal analysis is necessary because if the zonal pattern is understood at an early stage, then mine planning can be undertaken in order to compensate for changes in grade and payability with depth and direction. In addition, it may be feasible to produce different metals from different parts of the deposit, for example copper and tin, as in Figure 53. In some marginal deposits, the presence of associated valuable metals in certain zones may be the critical factor to viability. A detailed knowlege of zoning is necessary for the evaluation of old workings which may have been initiated for production of metals other than tin. Taylor (1979) quotes an example where a lode in a copper district contained up to 10% stannite which was undetected for 50 years. However, because zoning is so complex, it is unlikely that all the necessary information can be collected in a short period. Research of this nature must be an on-going project together with production.

Alteration effects must always be expected and are frequently a cause of engineering problems related to induced incompetence and high permeability. Deposits hosted by granitoids have specific alteration effects such as kaolinisation and greisenisation. Alteration of of this type induces considerable friability, and rapidly facilitates weathering. Ground conditions in these cases are likely to be very poor. On the other hand, the induced softness may contribute to easier mining, particularly in open pit propositions.

Alteration effects are one of the factors that contribute to hanging and footwall conditions. The effects may be advantageous in some cases but deleterious in others. For example, silicification generally tends to increase the strength of host rocks. Under certain circumstances however, silicification can induce brittleness with associated fracturing that may be the source of considerable mining problems.

THE INFLUENCE OF GEOLOGY ON EXTRACTABILITY

The extractability is a function of the nature and the quality of the ore. It is critical that these features are determined at an early stage and so avoid unwarranted expenditure on an ore that cannot be profitably beneficiated. A detailed mineralogical and metallurgical investigation must take place so that optimum plant conditions can be designed. The investigation must establish the mineralogy, and must determine relative amounts, grain size distribution, chemical composition, metal content and liberation characteristics of constituent minerals. In addition recovery problems must be anticipated.

One of the most common recovery problems is due to grain size and grain size variations. Cassiterite from vein systems is frequently very fine-grained and intimately associated with other minerals. The presence of other minerals necessitates fine grinding. In this respect the shape of cassiterite is important: prismatic acicular crystals will become broken fragments or parts of aggregates on grinding. To remove these fine particles further grinding is needed but this causes tin to slime into the 10 to 15 micron size range. Cassiterite is brittle with a conchoidal fracture and thus tends to slime readily on comminution (Taylor, 1979).

A significant cause of losses through sliming is due to the variability of crystal forms. Cassiterite often occurs in different habits at the same site, particularly if successive phases of mineralisation have occurred. It is often difficult to find an optimum grinding size that will liberate most of the cassiterite without the occurrence of sliming.

The high specific gravity of cassiterite facilitates concentration by gravity separation. This is efficient fòr granular particles down to 74 microns (200 mesh) but is inefficient for smaller size ranges from 53 to 10 microns (Taylor, 1979). A high proportion of cassiterite is thus lost in the range below 53 microns and it is therefore particularly important to determine the after-grinding size range. The most common treatment is to classify the ore into at least three size fractions; coarse fractions go to tables, and middlings are re-ground and re-treated along with fines. Overgrinding is minimised by using a series of stage grinds.

A recent innovation is the recovery of fine cassiterite by flotation, especially in the size range 7-30 microns (Moncrieff and Lewis, 1977). Here, flotation is used in conjunction with gravity concentration. It is first necessary to remove the slimes so that there is less than 15% by weight of - 7 micron cassiterite. Sulphides must also be removed to produce a feed assay of less than 0.5% Sn. Thus although a portion of the tin is still lost in the slimes fraction, this loss is considerably reduced.

Cassiterite in vein systems commonly occurs with sulphides. If the cassiterite is present as fine intergrowths, then much can be lost during sulphide separation. Often cassiterite-sulphide composites report to the middlings fraction; if this is reground then much of the tin will be lost to slimes. Thus in many cases the high sulphide content of the ore is responsible for much of the losses incurred.

The amount of magnetic cassiterite present is significant, particularly in skarn assemblages. Often magnetic separation methods are used to remove magnetite from ores; this will result in a loss of magnetic cassiterite. In addition, the magnetic susceptibility of magnetic cassiterite may be similar to other minerals such as wolframite. Here, magnetic methods cannot be used for separation.

It is important to determine exactly where all the tin is situated. Often much of the tin may occur in other minerals such as stannite. This causes recovery problems because stannite will not respond to recovery processes designed for cassiterite. The presence of tin in minerals other than cassiterite is also significant in sampling. The tin will contribute to the assay but it cannot be removed, especially if it occurs as fine grained inclusions and exsolutions. Varlamoffite is likely to cause problems as it is difficult to recognise in oxidised zones which are heavily ironstained and leached. An acid soluble tin assay will help to resolve this as some of the varlamoffite compounds are soluble in dilute acid (Taylor, 1979). Other important tin bearing minerals that are causes of apparent tin loss are silicates such as malayaite and garnet.

The foregoing sections show that geology strongly affects the metallurgical character of the ore. In the case of tin vein systems, treatment is likely to be very complex. In greisen-hosted deposits however, the mineralogy is more simple and other minerals such as sulphides are only present in monor amounts. In addition the grain size and crystal habit can be expected to be more uniform so that most of the problems discussed above will be considerably reduced. The problem of lost fines however still remains and this is one aspect of treatment that has yet to be improved upon. Because of this problem the average recovery in many operations is only 60 to 65% (Taylor, 1979). It is clear that the recovery efficiency must be carefully considered so that allowances can be made in advance of mining. The surest method of metallurigical testing to be recommended is a pilot plant at a very early stage of the feasibility study.

SAMPLING, DRILLING AND EVALUATION

The geology of tin vein deposits and large tonnage-low grade disseminated cassiterite deposits each have characteristics that influence the sampling, drilling and evaluation techniques employed. It is not the purpose of the work, however to review these subjects in detail so that only general points are discussed.

The high specific gravity of cassiterite, in combination with the heterogeneity of tin vein deposits, may result in significant problems during sampling and ore reserve estimation. Usually in ore reserve estimations a tonnage factor based on the specific gravity of the ore is used to convert volume to tonnage. Because of the inherent wide variation of specific gravity it is critical that the specific gravity for each sample be determined separately. This proceedure is often not employed and many mines simply apply a 'factor' that is determined empirically from a few samples. Under these conditions, very poor estimates of ore reserves will result. It is critical that adequate cognisance should be taken of fluctuating specific gravity because of the importance of ore reserve estimations. Ore reserve estimations must be accurate because they are used in determining factors such as the extent of exploration and development, annual output, mine life, methods of extraction, treatment and processing, and requirements for capital.

A further factor to be considered is the density contrast between ore and gangue minerals. Gangue material often contains very variable amounts of sulphide and other heavy minerals so that it cannot be assumed that a constant density contrast exists. This problem is less significant in greisen deposits where mineralisation is more regular and continuous. In addition, porosity also has a strong influence on specific gravity. The porosity of vein material varies from place to place due to vugs and cavities and is also likely to occur where there has been extensive alteration.

The specific gravity used in ore reserve estimation therefore depends on a number of factors and these include metal content, metal ratios, degree of oxidation, density of the metal bearing mineral, type of gangue and porosity. The only recommended proceedure for accurate ore reserve estimation is to combine the specific gravity of each sample with its assay to arrive at a properly weighted average value.

Despite precautions such as these, there is always a risk factor attached to ore reserve estimation of tin vein deposits due to the inherent irregularity. Taylor (1979, p.273) recommends that "at all times the management should be made fully aware of the risk factor attached to the estimations" so that these can be included into feasibility studies.

Due to the irregular and erratic mineralisation of vein systems, it is almost impossible to drill sufficient bore holes to calculate ore reserves. In many cases surface drilling will be totally inadequate to indicate what is available underground. Diamond drilling can thus be used in locating the position and monitoring the persistence, structure and mineralogy of the veins but it will not be adequate for sampling and grade determinations. Experience and historical precedence may play a key role in evaluating drill intersections. Percussion methods can be used for infilling drilling to prove continuity but not for determining metal content. This is because the high specific gravity of the valuable minerals cause them to settle to the bottom of the hole and only a portion may be lifted thus resulting in an under estimation of the grade.

Neuhoff (1979) reviews aspects of the evaluation of vein systems in general and includes discussions on sampling, ore reserve estimation and the practical use of geostatistics. He concludes that after limited diamond drilling Sichels "t" estimate should be used to determine the minimum grade to within 90 percent confidence limits. If the grade is acceptable then a second phase of diamond drilling should be used to prove continuity and in particular to establish the optimum area for trial mining.

Bulk sampling is critical in evaluating tin deposits in order to define optimum mining and ore extraction proceedures. Initially, bulk sampling in trenches and pits can be used but this must be followed by trial mining in the case of vein tin deposits because of their irregularity. This is expensive, but by far the most reliable evaluation technique. Trial mining has an additional attraction in that revenue can be generated at an early stage.

The evaluation of low grade disseminated deposits and greisen-hosted deposits presents a completely different set of problems to those encountered in evaluating erratically mineralised vein deposits. In general the evaluation should proceed with a greater degree of certainty and can be based along the lines of evaluation techniques applied to porphyry copper deposits. Sampling, drilling, ore reserve calculation and grade control of porphyry type deposits are reviewed by Reichhard Barends (1979). Because of the more regular continuity of mineralisation, standard sampling methods such as diamond drilling on regular grids can be applied. Percussion drilling may be a useful technique for rapid sampling. Disseminated mineralisation is likely to be relatively continuous throughout the mineralised zone so that continuity is easier to prove.

In tin vein systems, the use of geostatistics is limited because of the inherent high natural variability and multiple populations caused by repeated precipitation of different phases of mineralisation. In particular the "nugget effect" caused by erratic distribution of high and low grade mineralisation is likely to result in significant error. Kriging is a geostatistical technique that combines trend surface analysis with grade estimation of individual blocks for which a large sampling data base is available. It can be readily used as an evaluation method in large low grade deposits because of the large size and regular continuity of mineralisation. In tin vein systems however, kriging cannot be applied because the irregular shape and metal distribution does not allow significant correlations between samples. Trend surface analyses is useful in the evaluation of tin vein systems because it can define areas where further sampling may be necessary (Neuhoff, 1979). At all times it must be remembered however, that geostatistics is a technique to be used only as an aid to detailed geological studies. It cannot replace them, because tin values, in veins especially, depend primarily on geological controls, and mathematical methods alone cannot distinguish these.

CONCLUSIONS

The nature of primary tin deposits and the mechanisms of formation have been reviewed. Mineralisation is not haphazard but is closely controlled by geological factors such as lithology and structure. These, together with geochemical factors act to control grade and tonnage in different types of deposit.

Economically, the most important primary tin deposits fall into two categores : tin vein deposits and massive disseminated/ greisen associated deposits. These have different characteristics that result from different geological processes. Tin vein deposits are highly irregular and erratically mineralised, often with a complex mineralogy due to repeated phases of precipitation. They may be high grade and are generally of low to medium tonnage. Disseminated deposits on the other hand are more continuous and regular with a more simple mineralogy. They may be large in size but tend to be low grade. Porphyry tin deposits offer interesting possibilities for very high tonnage-low grade production, similar to porphyry copper deposits. The different character of tin vein systems and disseminated deposits means that different techniques must be applied in their evaluation. Thus the geology of the deposit in fact controls evaluation. For example, diamond drilling cannot be used for grade determination in the case of tin vein systems, but may be readily used on a regular grid spacing for disseminated deposits. In the same way, the geological character of the deposit controls the optimum type of mining and extraction methods that can be applied.

This work has identified the geological factors that control grade and tonnage, and has stressed the necessity of understanding them for efficient evaluation. The subject of detailed evaluation however, is a large and important field that deserves a dissertation in its own right. It is hoped that the present text will provide a fundamental framework for this.

The evaluation of primary tin deposits presupposes that exploration has been successful. Although exploration is an important subject, there appears to be no single, up to date concise review. It is consequently recommended that exploration for primary tin deposits should be treated in a separate dissertation.

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