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Rift-, Subduction- and Collision-Related Tin Belts

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Abstract: Consideration of the tectonic setting in which Cenozoic and Late Mesozoic tin-bearing granites were emplaced indicates that subduction-related settings include not only continental margin magmatic arcs (inner zone of southwest Japan, Cretaceous; Aleutian arc, Miocene) but also outer arcs adjacent to the trench (outer zone of southwest Japan, Miocene) and back-arc magmatic belts (Bolivia, Tertiary, and Western Belt of Southeast Asia, Cretaceous-Eocene). The only well-documented post-Palaeozoic example of significant tin mineralisation in a rift or hot-spot related setting is the Jurassic belt of Nigeria. Recent descriptions of tin and associated metals from the Himalaya granites with radiometric evidence of an Oligocene age of emplacement indicates the importance of continental collision as a setting for generation of tin-bearing granites. Possible ancient examples of collision-related tin belts are the Main Range Malaysia, southwest England and the Erzgebirge. There are significant differences among the plutonic rocks, host rocks, adjacent major structural belts and in some cases styles of mineralisation in the various types of tectonic setting which facilitate their recognition. Most tin is apparently derived from trace amounts in the crust and there is little evidence for the presence of primitive concentrations of the metal in the crust or upper mantle.

INTRODUCTION

Tin characteristically occurs together with one or more of the metals tungsten, molybdenum, bismuth, niobium-tantalum, and with the minerals monazite and fluorite. Most economic deposits and mineral occurrences are associated with granitic plutons or pegmatites although a few important deposits occur in silicic volcanic rocks, and the mineralization is generally considered to be hydrothermal in origin and closely related to the final stages of magmatism.

The splitting and separation of formerly continuous tin belts had been considered by Schuiling (1967) but until the early 1970's the tectonic settings in which tin-bearing magmatic rocks were emplaced were discussed in terms of the geosynclinal theory, mostly by Russian authors (e.g. Itsikson 1960). As the significance of plate tectonic processes became apparent to economic geologists, attempts were made to interpret Cenozoic tin deposits in South America and Southeast Asia in terms of plutonic and volcanic activity in subduction-related magmatic arcs on continental margins (Mitchell and Garson 1972; Sillitoe 1972). Subsequently Sillitoe (1974) pointed out that in West Africa tin deposits were associated with granitic rocks considered to have been emplaced in failed intra-continental rift zones. The rifts are possibly equivalent to the aulacogens of Russian authors, in some of which tin-bearing granites were known to be present.

The possible significance of continent-continent or continent-arc collision belts as sites for emplacement of mineral deposits received little attention in the early 1970's, and review papers (e.g. Mitchell and Garson 1976) indicate that until recently interpretations of some tin belts in terms of collision-type orogens have been made by only a few authors.

The aims of this paper are to summarise accounts of examples of tin deposits emplaced in various plate boundary-related settings and to discuss briefly possible

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new types of tectonic setting, and the criteria for distinguishing among them. The plate boundary settings for mineralization are compared briefly with older geosynclinal models, and the evidence provided by the plate models for the source of the metal is discussed.

RIFT-RELATED MINERALIZATION

Tectonic setting

Intracontinental rifts, for example the East Africa Rift and Baikal Rift, are considered to be genetically related to crustal hot spots and develop on continents situated on lithospheric plates which are either stationary or move only slowly with respect to the underlying mantle (Burke and Wilson 1976). Rifts radiating out from hot spots form a linked system characterised by a fault trough with updomed flanks. Associated volcanoes are mostly alkaline, erupting rhyolitic and undersaturated alkaline lavas and tuffs underlain by plutonic rocks including granites.

With continued development tholeiitic basalt is injected along the axial zone and the rift becomes split longitudinally into two halves separated by a spreading ocean rise system. Eventually the ocean basin bordering the former rift may close as a result of subduction and the rift rocks may be tectonically juxtaposed with those of another continental margin during collision.

Many rifts fail to develop into ocean rises, perhaps as a result of the continent starting to move with respect to the underlying mantle (Burke and Wilson 1976), and the rifts are preserved as failed intracontinental rifts or aulacogens. These are characterised by a great thickness of continental sediments and commonly pass at one end into a delta. Granitic rocks on the rift flanks may be preserved as the setting is tectonically stable.

Tin mineralization has not been described from granitic rocks within modern active rifts, but a number of deposits are known from settings interpreted as ancient failed rifts. Significant tin mineralization is not known from ancient rifts subsequently split by ocean floor emplacement.

Jos Plateau, Nigeria

In Nigeria tin-bearing granites of the Younger Tin Fields are concentrated in a 200km wide north-south trending zone centred on the Jos Plateau (fig. 1). The mineralization is associated with ring complexes of which over 40 are known ranging from 1500 to 2sq km in area. The age of the granites decreases systematically from Late Triassic in the north to Middle Jurassic in the south. To the north in Niger a southern sub-province of ring complexes is of probable Carboniferous age and a northern one comprising the Air Massif is of Silurian age (Bowden et al. 1976).

The ring complexes of Nigeria lie west of the Benue Trough, interpreted as one arm of the Niger Triple junction which spread between 120 and 80 m.y. and then closed (Burke and Dewey 1973). However the complexes were probably related to an earlier episode of rift-magmatism along a line projected northwards from the western margin of the African continent to the south (Wright 1970).

Cassiterite together with columbite occur mostly in albitised biotite-granite, concentrated in roof-zone greisens which also contain topaz and lithium mica; wol-

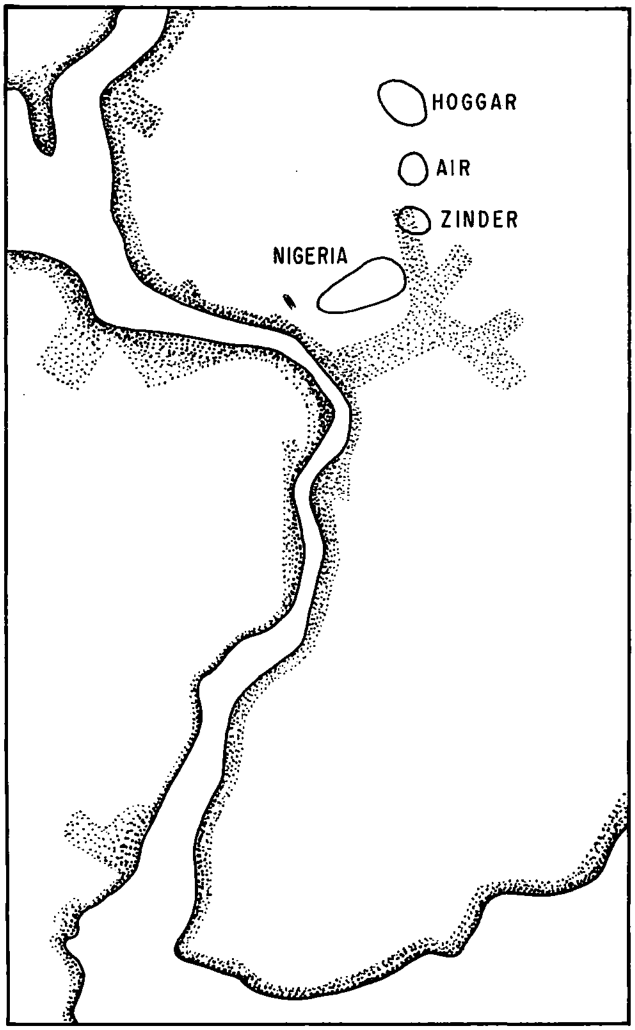

Fig. 1. Location of north African tin deposits relative to rift system. Modified from Wright (1970), and Burke and Wilson (1976).

framite is present mostly in quartz veins in the contact rocks. Columbite, pyrochlore and zircon are important accessories in the granites (Wright 1970). Pegmatites, and also beryllium minerals and tourmaline are virtually absent. Wright (1970) has emphasised the concentration of mineralization along major regional north-trending lineaments and at their intersection with northeast-trending lineaments.

Saint Francois Mountains, Missouri

Tin mineralization from the Saint Francois Mountains, Missouri, has been interpreted in terms of a hot spot and an incipient northeast-trending intracontinental rift of Proterozoic age (Lowell 1976).

The mineralization occurs in unmetamorphosed alkalic to peralkaline mostly silicic volcanic rocks and in plutonic rocks of similar age and composition emplaced about 1500 m.y. ago. Plutonic rocks include minor syenite but are mostly granitic, and porphyritic and rapakivi textured granites are common. Pre-intrusion host rocks consist of an older metamorphic and plutonic terrain underlying the volcanic rocks. Sub-economic tin mineralization is associated with the contact of rhyolites and intruding granite and consists of quartz veins in greisenised granite. Ore minerals are cassiterite, wolframite, chalcopyrite, sphalerite, and argentiferous galena associated with flourite, pyrite, topaz and lithium mica.

Rondonia, Brazil

Tin mineralization in the Late Proterozoic granitic rocks of Rondonia, western Brazil, has been interpreted as having been emplaced in a hot spot or incipient-related setting (Sillitoe 1974), although evidence for this is by no means conclusive. Twenty-five mineralized bodies have been recognised (Priem et al. 1971) comprising granitic complexes up to 25km in diameter with abundant biotite granite and lesser amounts of microgranite, rhyolites, porphyritic rocks and silicic volcanic breccias; the granites have yielded a high initial Sr^{87}/Sr^{86} ratio of 0.718. Alkaline granite and syenite are also present. The plutons are high-level bodies intruding high-grade metamorphic rocks of an older basement and locally volcanic rocks, and have the form of sub-volcanic ring complexes (Kloosterman 1967). To the north the granite complexes intrude sediments within a graben structure. The tectonic setting is anorogenic with deformation limited to faulting and fracturing.

Tin is produced from alluvial deposits derived from primary mineralization associated with the granites, where cassiterite occurs in gerisenised zones and in quartz-topaz veins within granites and contact zones with the country rocks. Wolframite and columbite-tantalite are locally associated with the cassiterite.

Summary of characteristics

Tin in rift-related settings is associated with granitic rocks mostly emplaced in the earliest stages of development of intracontinental rifts which failed to develop into ocean basins. Pre-intrusion host rocks are usually either metamorphic rocks of an older orogeny or rift-related continental sediments and silicic volcanic rocks slightly older than the intrusive plutons.

The mineralized igneous rocks are high-level granitic bodies in the form of sub-volcanic ring complexes, although some mineralization occurs in the overlying intruded volcanic rocks. The tin-bearing plutons are mostly biotite granites but syenites and peralkaline granites are also present. The granites are anorogenic and little deformation or metamorphism was associated with their intrusion and mineralization. Pegmatites, tourmaline and beryllium minerals are uncommon.

Ore minerals are cassiterite with lesser amounts of wolframite, and columbite-tantalite; topaz, flourite and lithium micas are commonly present. Mineralization occurs in veins within the high level granites and adjacent country rocks and in silicic volcanic rocks.

SUBDUCTION-RELATED MINERALIZATION

In the early 1970's the emphasis on magmatic arcs as analogies of ancient orogens led to the interpretation of some Cenozoic tin deposits in terms of emplacement in active or Andean-type continental margins. It has recently become apparent that while some tin mineralization occurs in and on the continent side of magmatic arcs, most economic deposits are restricted to segments of limited length behind the arc, while some occur in outer arcs.

Tin mineralization in magmatic arcs

In magmatic arcs volcanic and plutonic rocks are emplaced in a belt parallel to the continental margin and above a seismic Benioff zone at depths of 120 to around 200km. Plutonic rocks are mostly tonalitic or granodioritic in composition and largely lack tin mineralization, for example the Peruvian batholith and Sierra Nevada. However within some predominantly tonalitic belts there are granitic plutons or silicic volcanic rocks with associated tin mineralization. Because of their setting adjacent to the tonalites these granites are considered to be similarly related to subduction of oceanic lithosphere. The granites are emplaced within about 200km of a continental margin. However, because the adjacent ocean is in most cases eventually subducted, resulting in collision of the mineralized overriding plate with a continental foreland on the subducting plate, the granite belt in ancient arcs becomes intracontinental.

Alaska-Aleutian Arc

Tin-bearing granites have been described from three localities in the Aleutian arc, two of which are in the Alaska-Aleutian Range batholith and the third in the Seward Peninsula of Alaska. The Alaska-Aleutian Range occurrences lie at least 100km north, or on the continental side, of the chain of Quaternary volcanoes, and are of particular interest as examples because of their association with a young subduction-related predominantly granodioritic batholith.

Two tin-bearing granites in the Alaska-Aleutian Range batholith have been described by Reed and Lanphere (1973). The Windy Fork Granite of probable latest Oligocene age is a small pluton with anomalously high values of Sn, Be and Nb and is cut by pegmatites containing eudialite. A second tin-bearing pluton, lying 120km northeast of the Windy Fork Granite and immediately north of the Denali Fault, is a small body of biotite granite containing up to 100ppm Sn, 300ppm Nb, and 700ppm Li. It forms part of a sequence of plutons considered to be of Palaeocene age.

Tin mineralization is associated with Late Cretaceous granites in the Serpentine Hot Springs area of the Seward Peninsular (Hudson 1977). The mineralization, which is controlled by high-angle faults, is associated with the latest, silicic, stage of crystallization of an epizonal biotite granite, considered by Hudson (1977) to mark the evolution of a residual volatile-rich magma system enriched in Li and Sn. The high Na_2O/K_2O ratios, overall enrichment in the trace elements Be, Nb, Pb, Zn and Li, and high initial Sr^{87}/Sr^{86} ratios in the surrounding granite complex suggest partial melting of a sialic crustal source.

All three tin-bearing granites in the Aleutian arc were emplaced during inferred northward subduction, although the age of the Windy Creek Granite is similar to that of the inferred subduction of the Kula ridge. The problem of the location of the Alaska-Aleutian Range tin granites in a magmatic belt to the north of the main belts of magmatism of both Jurassic and Quaternary age has been discussed by Reed and Lanphere (1973); a possible explanation is a decrease in inclination of the Benioff zone resulting in a northward shift of arc magmatism.

Northeast Honshu, Japan

The distribution of wolfram, molybdenum and minor tin mineralization in Southwest Japan has been summarised by Ishihara (1973) and Shibata and Ishihara (1974). Excluding the deposits of the Outer Zone described later, the mineralization occurs in two adjacent belts, lying parallel to the northeast coast of Honshu and north of the Ryoke and Sanbagawa metamorphic belts (fig. 2).

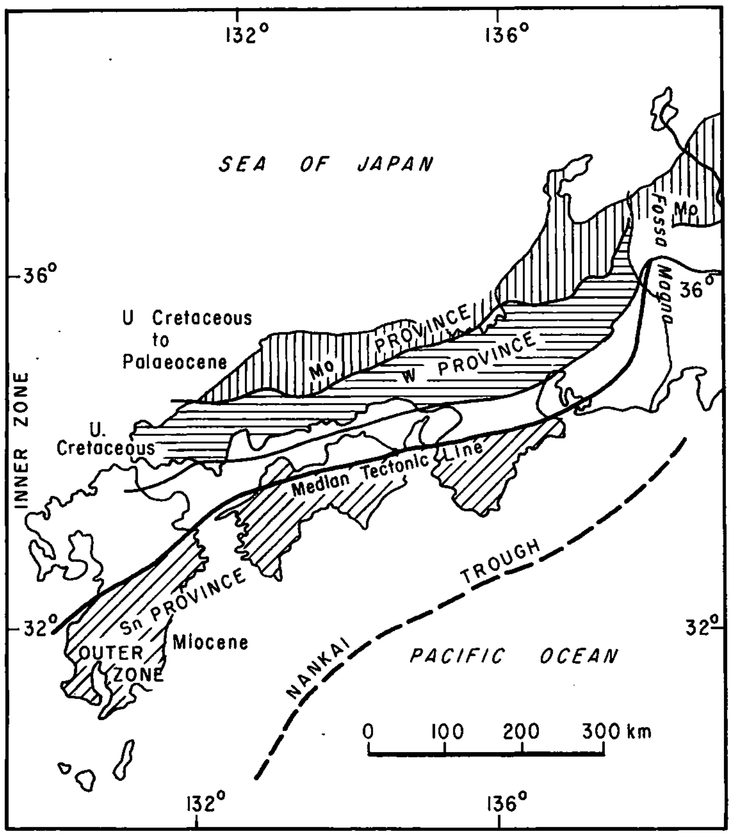

Fig. 2. Subduction-related magmatic arc (Mo and W-Sn) and outer arc (Sn–W) deposits, Japan Modified from Ishihara (1973).

In the northern, molybdenum, province mineralized rocks are mostly two-mica adamellites and pegmatites of Palaeocene age, within the Sanin belt of magnetite-bearing granitic rocks (Ishihara 1977). The molybdenum mostly occurs with a trace of tungsten in quartz veins associated with muscovite in greisen.

In the tungsten province to the south, tungsten occurs as wolframite in quartz veins and in scheelite-skarn deposits associated with adamellites of early and late Upper Cretaceous age. The granitic rocks in this province, the Sanyo belt, mostly are low in FeO with high B and F contents indicating that they belong to a low-magnetite or ilmenite granitic series (Ishihara 1977).

Pluton emplacement and mineralization have been related to episodes of northwestward subduction of oceanic lithosphere by Ishihara (1973) and Shibata and Ishiara (1974) who emphasised the significance of volatiles in controlling the formation of mineral-rich magmas, and suggested that the granitic magmatism and mineralization in the two provinces were generated above two Benioff zones of different ages.

Ancient examples and summary of characteristics

Relatively few tin-granites of pre-Late Mesozoic age are considered to have been emplaced in volcanic arcs. Possible examples are the scattered mineralized plutons in eastern Malaysia, east of the Main Range, and the tin deposits of Hercynian age in the Massif Central of France.

Tin mineralization in subduction-related magmatic arcs occurs in biotite or two-mica adamellites, granites and rarely in granodiorites, and in rhyolitic to dacitic volcanic rocks, which in some cases show strong hydrothermal alteration. However, the granitic belts in which the mineralization occurs consist largely of granodioritic rocks, at least some of which belong to the magnetite series of Ishihara (1977). The plutons are mostly considered to be syn-tectonic with initial strontium isotope ratios indicative of an origin partly in the crust and partly in the upper mantle. The pre-pluton host rocks commonly include a thick succession of volcanic rocks erupted subaerially during pluton emplacement.

Tin mineralization in outer arc granites

Many volcanic arcs are bordered on the ocean side by outer arcs comprising thick deformed successions of flysch-type sediments and minor basic or ultrabasic igneous rocks. The outer arcs are interpreted either as imbricate zones of ocean floor sediments offscraped in the subduction zone (e.g. Marshak and Karig 1977) or as continental margin rocks deposited and deformed on the continent side of the trench (e.g. Scholl et al, 1977).

Recent geological mapping in the Aleutian arc has revealed the presence of granites intruding the flysch belt (Hudson et al. 1977), and granitic rocks in a similar tectonic setting have been reported from the Outer Sunda Arc (Marshak and Karig 1977) and the outer zone of Southwest Japan (Oba 1977). In all these locations the granites lie between the present trench and magmatic arc, and less than 100km from the inferred position of the palaeotrench. Their origin is therefore unlikely to be related directly to the Benioff zone.

Outer Zone of Southwest Japan

Cenozoic plutons occur within the Shimanto belt of Southwest Japan (fig. 2), which comprises a structurally complex belt of flysch-type sediments of Middle Trias to Middle Tertiary age up to 15,000m thick (Oba 1977). The sedimentary rocks show low-grade regional metamorphism and locally mafic igneous rocks are present. The succession is commonly interpreted as ocean floor sediments offscraped during northwestward subduction which resulted in the magmatic arc of the Honshu belt to the north.

Plutonic rocks within the belt range from granodiorite through adamellite to granite, and generally show a high K_2O/Na_2O ratio, high FeO content, and low magnetite content relative to the plutonic rocks from the 'green tuff' volcanic arc of eastern Japan. The plutons, of Early to Middle Miocene age, show discordant contacts with sedimentary host rocks which have suffered minor contact metamorphism, and are characterised as post-tectonic; some of the plutons are associated with ring dyke complexes and others with porphyry and rhyolites, suggesting a shallow level of emplacement. Xenoliths of pelitic and mafic rocks are abundant.

Deposits of tin and minor wolfram are mostly associated with tourmaline-bearing granites. In one mine skarn-type tin deposits are present, and in others the mineralization occurs as wolframite-quartz veins with tourmaline (Ishihara 1973; Oba and Miyahisa, 1977).

Oba (1977) considered that the granites resulted from partial melting of geosynclinal sediments and assimilation of more felsic crustal rocks, while Marshak and Karig (1977) considered that they were probably emplaced as magmatic arc rocks above a Benioff zone related to the migrating Izu-Bonin Trench. According to the ocean-floor offscraping hypothesis, the only rocks available at depth for partial melting are meta-sedimentary rocks above the upper mantle; however if the outer arc is built of continental margin rocks, older continental crust could be present at depth.

Outer arc granites lacking tin

In the eastern Chugach Mountains of the Aleutian arc (Hudson and Peterman 1977; Hudson et al. 1977) the granites intrude flysch, semischist and amphibolite facies biotite gneiss, interpreted as outer arc rocks tectonically accreted to the continental margin and subsequently metamorphosed. Plutons are mostly large discordant biotite granodiorites but include tonalite and granite, and are of Early Eocene age. Similarities in initial Sr^{87}/Sr^{86} ratios (0.7059 to 0.7063) for the plutons and Late Mezosoic sandstones suggest that the magma originated by partial melting of the deeply buried outer arc rocks (Hudson et al 1977); heat was possibly supplied by a spreading ridge intersecting the trench at a high angle, forming a migrating ridge-trench-trench triple junction (Marshak and Karig, 1977).

Ancient examples and characteristics

Granitic rocks intruding very thick successions of deformed flysch and minor ophiolites occur in a number of ancient orogens but the relative age of the granites and host rocks and hence the tectonic setting during granite emplacement are not always known. Moreover, it is sometimes difficult to distinguish the granites from collision-related plutons described below. One example comprises the Lake District of England, where Lower Palaeozoic flysch-type sediments are intruded by post-tectonic granite plutons of which the Skiddaw Granite contains economic deposits of tungsten. These granites have been tentatively interpreted as magmatic arc rocks, emplaced near the trench as a result of an increase in inclination of the southward-dipping Benioff zone, but it is perhaps more probable that they resulted from partial melting of the sedimentary rocks at depth.

There are probably relatively few features by which outer arc mineralized granites can be distinguished from those emplaced in collision belts described below. Possible differences in the host rocks include a higher proportion of flysch and basic and ultrabasic igneous rocks in the outer arc settings.

Tin mineralization in back-arc magmatic belts

The broad distribution in South America and Eastern Asia of Tertiary tin deposits on the continental side of porphyry copper-bearing magmatic belts has been noted by many authors. However this generalised distribution has perhaps obscured the fact that there are only two major economic belts of tin of Tertiary age near active continental margins: the Bolivian tin belt, and the Western Belt of Southeast Asia. The two belts are unusual in that they are convex to the continent, and lie in a distinct zone behind the granodioritic magmatic arc and within a limited longitudinal segment of the arc system.

Tertiary deposits of Bolivia

The deposits of the southern part of the Bolivia tin belt provide what some authors consider to be the most impressive evidence for the relationship of tin-bearing magmas to subducting ocean floor. The Bolivian deposits occur in an arc convex to the continent, mostly less than 50km wide and about 800km in length, corresponding broadly to the Eastern Cordillera (fig. 3). Mineralized intrusive rocks in the northern part of the arc are Early Mesozoic in age, but in the southern 500km plutonic and volcanic rocks with associated tin mineralization range from Upper Oligocene or Lower Miocene to Pliocene in age (Evernden et al. 1977). The Tertiary tin deposits are unusual both in their common association with volcanic rocks, mostly hydrothermally altered rhyolitic to dacitic quartz porphyries, and the association of the youngest deposits with silver and base-metals (Grant et al 1977; Turneaure 1971). The host rocks to the plutons are Palaeozoic terrigeneous sediments and Tertiary volcanics.

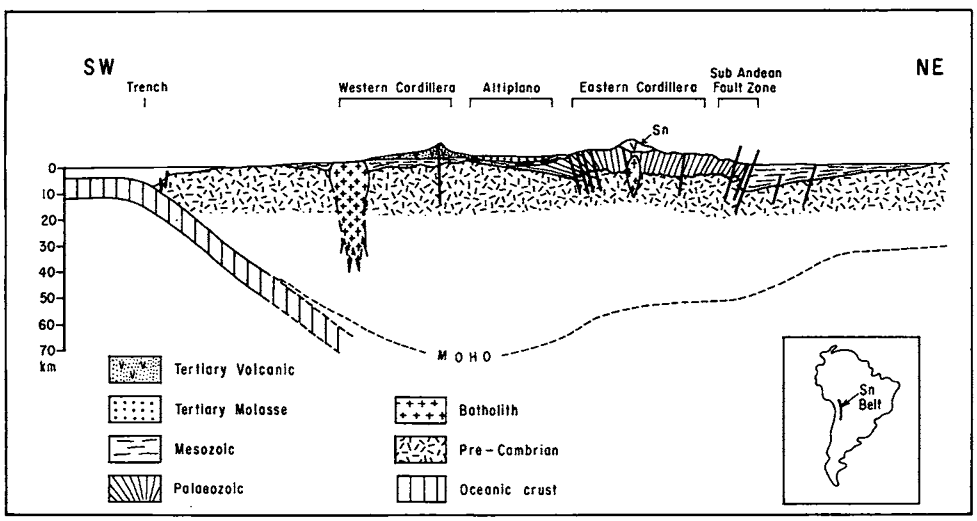

Fig. 3. Schematic cross-section through Andes near northern end of Bolivian tin belt, after Cobbing and Pitcher (1972). Projected position of Tertiary tin deposits of southern Bolivia shown.

The tin deposits lie approximately 700km east of the present submarine trench, and are separated from the plutonic and volcanic rocks of the Western Cordillera by the Altiplano basin, underlain by Upper Cretaceous and Tertiary sedimentary and volcanic rocks. East of, and parallel to, the mineralized belt lies a fold-thrust zone with eastward-directed thrusts in which the youngest rocks offset are of Oligocene age (A.H. Clark pers. comm. 1978). The mineralized igneous rocks were clearly emplaced during eastward subduction of ocean floor beneath the South American continent (Sillitoe 1972), which has continued since at least the Late Mesozoic. The abundance of tin in the Bolivian belt contrasts with the significant but much less important scattered tin occurrences which occur in a similar position to the east of the magmatic arc in the northern and southern Andes.

Western Belt of Southeast Asia

A belt of tin and tungsten-bearing granites of Upper Cretaceous to probable Lower Eocene age and including Palaeocene stocks extends from southeast of Mandalay southwards to Phuket in southern Thailand (fig. 4). The belt, which is slightly convex to the east and includes the Mawchi Mine at its eastern boundary, is about 1400km in length and mostly less than 50km wide. The mineralization in Burma has not been investigated in detail but the southern end of the belt has recently been described (Garson et al. 1975). All plutons in the belt intrude either Carboniferous terrigeneous clastic sediments or metamorphosed Palaeozoic rocks; the mineralized plutons are mostly adamellites and granites and associated volcanic rocks are absent. East of the northern end of the belt there is a belt of eastward-directed thrusts of post-Cretaceous age which extends southwards towards the Thai-Burma border.

Evidence for more than 300km of northward movement on the Hninzee-Sagaing Fault (Mitchell 1977) since the early Miocene (Curray et al in press) indicates that in the Cretaceous and Early Tertiary the tin belt was bordered by a granodioritic magmatic arc of similar age to the west.

Characteristics and discussion

The style of mineralization in Bolivia differs considerably from that in the Burma-Thailand Belt, due at least partly to the greater depth of erosion in the latter. However, the fact that both the Bolivian belt and Western Belt of southeast Asia are convex to the continent and bordered on the continental side by oceanward-dipping thrusts suggests a genetic relationship between curvature, thrusting, granite emplacement and mineralization. A possible interpretation is that during subduction of ocean floor, back-arc thrusts developed behind the granodioritic arc within a segment of the arc convex to the continent, perhaps as a result of an episode of rapid plate convergence. Thickening of continental crust and shear heating along the thrusts at depth resulted in generation of anatectic granites, in a manner analogous to that of the generation of collision-related granites described below. Behind most arcs, which throughout most of their length are convex to the ocean, back-arc thrusts are of minor importance and only scattered granites with mostly sub-economic tin deposits are present.

COLLISION-RELATED MINERALIZATION

Tectonic setting

It has recently been realized that continental collision is the main cause of mountain building and formation of ancient orogens, and Cenozoic mountain belts interpreted in terms of collision include the Alps, Atlas, Balkans, Himalayas, and some island mountain ranges, for example Timor and Taiwan.

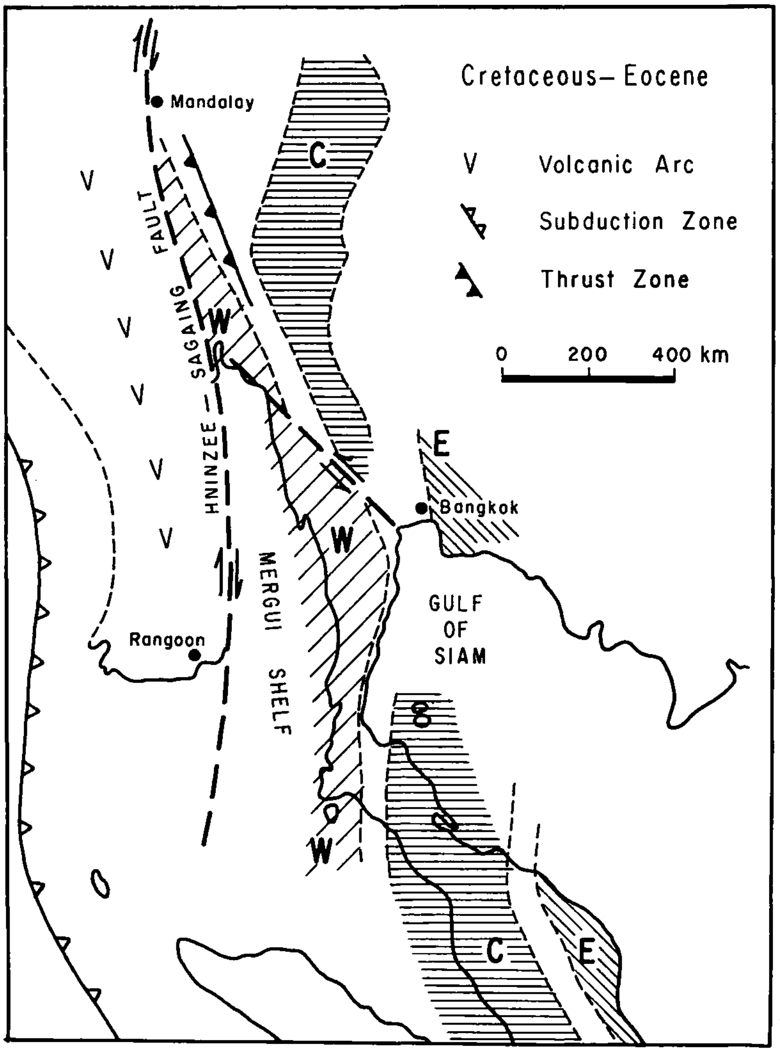

Fig. 4. Part of Southeast Asian tin province showing Western Belt (W) of Cretaceous-Eocene back-arc magmatic belt tin granites, Central Belt (C) of Late Triassic collision-related tin granites, and Eastern Belt (E) with Permo-Triassic magmatic arc tin granites. Modified from Mitchell (1976).

The major geological events accompanying collision and of relevance here are underthrusting of the continental foreland on the subducting plate beneath the overriding plate, and development of new intracontinental thrusts or continental subduction zones, commonly but not invariably within the foreland of the underthrusting plate. This is accompanied by tectonic thickening of crust, regional metamorphism and emplacement of granitic rocks related to shear heating along the thrusts.

The only Cenozoic example of a collision belt with related tin deposits is the Himalayas.

The Himalayas

Following Gansser (1964), Le Fort (1975), and others, the Himalayas can be divided morphologically into the northern Higher Himalayas and southern Lower Himalayas. The Higher Himalayas, separated from the Transhimalayas and Tibetan Plateau by the Indus-Tsangpo 'suture zone', comprise a very thick stratigraphic succession of Cambrian to Cretaceous age, which to the south is highly deformed and metamorphosed to form the Tibetan Slab, and locally overlain by nappes of ophiolitic rocks. The southern margin of the Higher Himalayas is more or less coincident with the northward-inclined Main Central Thrust associated with the highest grade of metamorphism within or at the base of the Tibetan Slab. The Lower Himalayas, south of the Main Central Thrust, consist of a Precambrian to Cretaceous succession, largely metamorphosed, with major klippe of Tibetan Slab rocks lying structurally above the southward continuation of the Main Central Thrust.

Tin-bearing granites

Mineralized granites occur in the metamorphosed and unmetamorphosed rocks of the Higher Himalayas and within metamorphic klippe in the Lower Himalayas (fig. 5). The granites of the Higher Himalayas have been described in detail while the known mineralization is most significant in the Lower Himalayan granites.

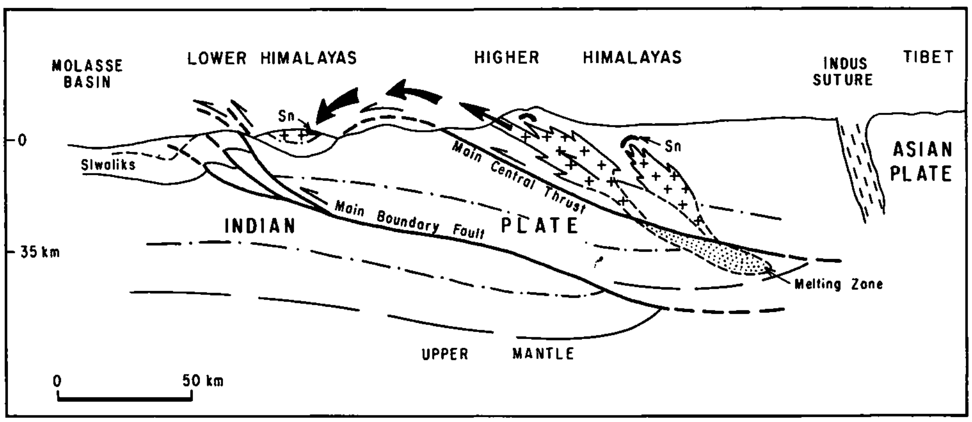

Fig. 5. Tectonic setting of Himalayan mineralized granites, modified from Andrieux et al (1976).

The Manaslu Granite of east central Nepal, considered typical of the Higher Himalayan granites (Hamet and Allegre 1976), is a muscovite and tourmaline-bearing leucogranite intruding metamorphic rocks of the Tibetan Slab, and locally sedimentary rocks to the north. The granite, ranging from catazonal to epizonal (Le Fort 1975), forms a northward-inclined slab about 12km thick, and is mostly foliated; contacts with the country rock are sharp and the margins contain numerous xenoliths. Hamet and Allegre have shown from Rb/Sr whole rock isochrons that the granite has an age of 28 ± 0.5 m.y. and an exceptionally high initial Sr^{87}/Sr^{86} ratio of 0.74, indicating an anatectic origin as suggested by Le Fort (1975). Mineralization, which is associated with aplopegmatites, has not been described in detail.

In the Lower Himalayas the Palung Granite (Andrieux et al, 1977) lies within the Mahabharat klippe of Higher Himalayan rocks in Central Nepal. Like the Manaslu Granite, it consists largely of muscovite and tourmaline-bearing leucogranite with abundant pegmatites and aplites. The plutonic rocks are mostly undeformed and concordant with the main foliation in the host rocks; adjacent gneissic host rocks show contact metamorphism. Granite emplacement probably post-dated the main movement along the Main Central Thrust and a crustal origin is suggested by an initial Sr^{87}/Sr^{86} ratio of not less than 0.710 (Hamet and Allegre 1976).

Mineralization in the Palung Granite, specifically in the leucocratic tourmaline granites and associated aplites, pegmatites, and apogranites, was described by Talalov (1976). These rocks are extensively griesenised and accessories include cassiterite, xenotime, scheelite, flourite, topaz and tantalo-columbite. Polysulphide mineralization is present in skarns at the granite margin. Biotite muscovite-bearing granites with tin and tungsten mineralization have also been described from the Palung Complex.

The Dandeldhura granitic series of west Nepal (Talalov 1977), also in the Lower Himalayas, includes among the youngest plutons fine-grained tourmaline-bearing leucocratic plagiogranites. These are greisenised and contain tantalo-columbite, cassiterite and bismuthine, and locally molybdenum and tungsten minerals. Unmineralized plutons include potash granites rich in almandine, topaz and lithium mica. The granite has been dated at 265 m.y., but its structural position indicates it probably lies within a klippe of the Higher Himalayas (J. Stocklin pers. comm. 1977).

Collision and granite emplacement

Ocean floor magnetic anomalies and stratigraphic evidence suggest that the collision which formed the Himalayas (Wegener 1929) took place in the Early Eocene, with under-thrusting of the Upper Cretaceous to Eocene flysch and ophiolitic rocks of the Indus-Tsangpo soture, probably forming an outer arc, by the Indian continental margin.

Convergence of the Indian continent and Asia along the Indus-Tsangpo line probably slowed or ceased by end-Eocene, and began in a new zone within the Indian continent to the south, the Main Central Thrust, along which at least 100km of crustal shortening took place during the Oligocene. Regional metamorphism in the Tibetan Slab, largely or entirely Oligocene to Early Miocene in age, resulted from shear heating during northward subduction of continental crust along the Thrust (Le Fort 1975; Andrieux et al. 1977).

The generation of the Himalayan granites is closely related to metamorphism, and resulted from partial melting of Lower Himalayan rocks at depths of 30 to 40 km in a zone along and immediately below the Main Central Thrust (Andrieux et al. 1977). The magma rose obliquely along the north-dipping foliation after the main period of thrusting. There is no evidence for post-granite igneous activity in the Himalayas, and the hydrothermal alteration and tin mineralization clearly was associated with or immediately followed the late stages of granite emplacement. Uplift resulting in exposure of the granites accompanied Miocene movement along the Main Boundary Fault to the south.

Southwest England

The tin mineralization and associated granitic rocks of Cornwall and Devon have been interpreted in terms of a subduction-related magmatic arc on an Andean type continental margin (Badham 1976), an inferred intracontinental hot spot, foreland crustal thickening unrelated to collision (Bromley 1976), and collision-related rocks analogous to those in the Himalayas (Dewey and Burke 1973; Mitchell 1974).

The granites, of latest Carboniferous age, are mostly non-foliated plutons, probably part of a major batholith at depth, with common muscovite and tourmaline-bearing rocks and associated aplites and pegmatites. They are intruded into a thick folded and thrust slightly metamorphosed succession of Devonian to Carboniferous age which includes flysch-type sediments. To the south is the northward-directed thrust slice of ophiolitic rocks comprising the Lizard and to the north are the conticontinental shelf sediments of the Carboniferous Limestone and overlying clastics affected by northward-directed thrusts in Southern Ireland and South Wales.

Mineralization is associated with the granites and pegmatites and was probably largely emplaced during the final stages of magmatism, although there is some evidence for later mineralization.

According to the collision model (Dewey and Burke 1973; Mitchell 1974), during the Carboniferous oceanic crust of the Rheic Ocean was subducted southwards beneath southern and central Europe. In the Late Carboniferous the continental foreland to the north approached the subduction zone and underthrust the overriding plate to the south. Tectonic emplacement of ophiolites was followed by crustal thickening along southward-dipping thrusts with resultant heating and partial melting of the continental foreland to yield granitic magma which rose into overlying sediments of the former continental margin. As in the Himalayas the tin mineralization was associated with the late stages of granite emplacement.

While the structural style in Southwest England and the presence of the Lizard complex can best be explained by collision following southward subduction, it is not impossible that the mineralized granites were emplaced in a back-arc thrust-related magmatic belt, analogous to that of Bolivia, during northward subduction. This latter model would have some similarities to that suggested by Bromley (1976).

Main Range Malaysia

The granites of the Main Range Malaysia (fig. 4) and their continuation northward into Thailand and southeastward into Indonesia form a convenient example of a major belt of tin-bearing granites originally interpreted in terms of the so-called Burma-Malaya geosyncline (e.g. Burton 1970) and later as a subduction-related magmatic arc (Audley-Charles 1976; Hutchison 1973a), but which can now be compared to the collision-related Himalayan granites. Granites similar in age, tectonic setting and mineralization to those of the Main Range continue southeastwards through the Indonesian 'tin islands', and northwards beyond the Gulf of Thailand through northwestern Thailand into the Eastern Shan States of Burma.

The Main Range granites have been described recently by Hutchison (1973b, 1977). They are now known to be largely of Upper Triassic age and show exceptionally high initial Sr^{87}/Sr^{86} ratios (D. Teggin pers. comm. 1975). The very large placer deposits of tin, tungsten and tantalo-columbite were derived from the altered aspices and margins of the granites and adjacent wall rocks and from pegmatites.

The host rocks are a thick isoclinally folded succession of Palaeozoic to early Mesozoic rocks (Burton 1973; Gobbett 1973); eruptive rocks of similar age to the granite are absent. Structural vergence is mostly westward, and there is evidence of pre-granite westward-directed overthrusts (Gobbett and Tjia 1973). East of the granites the complex 'foothills belt' contains cherts and serpentinites older than the granites, and further east is the thick succession of Permian to early Triassic volcanic rocks and granodioritic intrusions of the medial trough and eastern Malaya.

In the collision model (Mitchell 1977), central and eastern Malaya are interpreted as a Permian to Middle Triassic volcanic arc beneath which ocean floor subducted eastward. In the Late Triassic the foreland of western Malaya approached the subduction zone and underthrust the magmatic arc. A complex of older rocks including cherts were thrust westwards onto the foreland to form the foothills zone, sediments of the foreland were isoclinally folded, overthrust to the west and locally metamorphosed, and the late to post-orogenic Main Range granites were generated along eastward-inclined intracontinental thrust zones.

Other examples

There are a number of other possible examples of collision-related tin granites which will not be discussed here. These include the Late Palaeozoic deposits of the Erzgebirge, emplaced in a setting which is probably the structural continuation of the Southwest England collision belt. There is some evidence that the older (Precambrian) tin deposits of Nigeria were also emplaced in a collision setting (M.S. Garson pers. comm. 1977).

Summary of characteristics

Tin mineralization in collision-related settings is associated with the upper parts of muscovite, two-mica or tourmaline granites and leucogranites commonly with associated pegmatites and aplites. The granites are late to post tectonic, may be massive or foliated, and show sharp intrusive margins. They commonly form part of a batholith which may have the form of an inclined slab dipping towards the former overriding plate, parallel to the regional major metamorphic foliation and thrusts. Host rocks are tightly folded and often metamorphosed and comprise shelf sediments of the foreland with or without older foreland basement and younger flysch. Volcanic rocks similar in age to the granites are rarely preserved. Thrusts occur on each side of the mineralized belt and dip towards the suture, which is indicated by either a narrow zone or klippe of ophiolitic rocks. The overall structural vergence is towards the foreland. Because limestones are often present in the foreland shelf succession, skarn-type deposits are common.

COMPARISON OF THE GEOSYNCLINAL AND PLATE BOUNDARY MODELS FOR MINERALIZATION

The tectonic settings for emplacement of some of the deposits considered above had previously been considered in terms of the various hypotheses of geosynclinal evolution, in particular the Russian concept and to a lesser extent that fashionable in Europe in the late 1950s and 1960s.

In the Russian model, in which geosynclines were considered to develop within a continent (Bilibin 1955; McCartney and Potter 1962), tin mineralization was known to be related mostly to the middle or orogenic stage of development, and to be associated with 'ultra acid' granites and pegmatites. Smirnov (1968) considered this stage to be characterised by granitophile metals (Sn, W, B, Li, Nb, Ta) derived from a crustal source. In plate tectonic terms, the orogenic stage can be shown to be equivalent to the continent-continent or continent-arc collision, and the ultra-acid crust-derived granites are equivalent to the anatectic tin-bearing granites of the Himalayas.

Other Russian authors emphasised the importance of non-geosynclinal settings for many types of mineralization, and Itsikson and Krasnyy (1970) noted the significance of tin-bearing granites in continental rifts, particularly in eastern Asia. These granites would correspond in plate terms to those of intracontinental rift zones, considered to be related to hot spots.

Tin mineralization was not recognised in the early orogenic stage of the Russian geosyncline, considered to be characterised by granodioritic batholiths, although scheelite-bearing veins together with gold-quartz veins were considered typical of this setting. This stage can be equated with the subduction-related volcanic arc plutons of the plate tectonic model.

In Europe the more recent and sophisticated geosynclinal models were based largely on the Alpine chains (Aubouin 1965) where magmatic rocks are scarce compared with the older Caledonian or Hercynian geosynclines of Europe. The major syn- to late or post-tectonic tin-granite belt of the Hercynian orogeny in the Erzgebirge, Southwest England and Portugal thus had no obvious analogy in the Alpine geosynclines and so could not be adequately explained by the Aubouin model. Earlier attempts to explain these granites in terms of geosynclinal evolution lacked the dynamic concept of the Aubouin model and received little general acceptance.

In North America, where remarkably few significant tin-bearing granites are known, there were virtually no attempts to relate these to geosynclinal evolution. However, it is significant that in the oldest geosynclinal hypothesis based on the Appalachian orogen, Dana (1873) recognised the importance of syntectonic emplacement of anatectic granites into shallow-water sedimentary rocks, a process which can now be recognised as analogous to the generation of collision-related tin-granites in the Himalayas.

SOURCE OF THE TIN

The source of the metal in the world's major tin belts has long provided a topic for discussion and speculation (see Turneaure 1971). Many authors have favoured the existence of very old more or less permanent localised concentrations of tin in the upper mantle, from each of which the metal has been mobilised, transported and concentrated by rising granitic magma during one or more episodes of mineralization now commonly termed metallogenic epochs. Schuiling (1967) postulated the presence of ancient upper mantle geochemical culminations to explain the world's tin fields, and Noble (1970) emphasised the significance of a primitive heterogeneous distribution of metals, including tin, in the upper mantle to explain the distribution of metal provinces in the Western United States. Other authors have favoured the presence of concentrations of metal within the continental crust rather than upper mantle. Routhier has stressed the importance of 'heritage and granitisation' with reference to several metals including tin and tungsten, in which successive episodes of granite magmatism within particular pre-existing geochemical provinces (Routhier 1973) resulted in mineralization of various ages.

As there is now some isotopic evidence for the probable souce of the magma in rift, subduction and collision-related settings, consideration of the tectonic setting

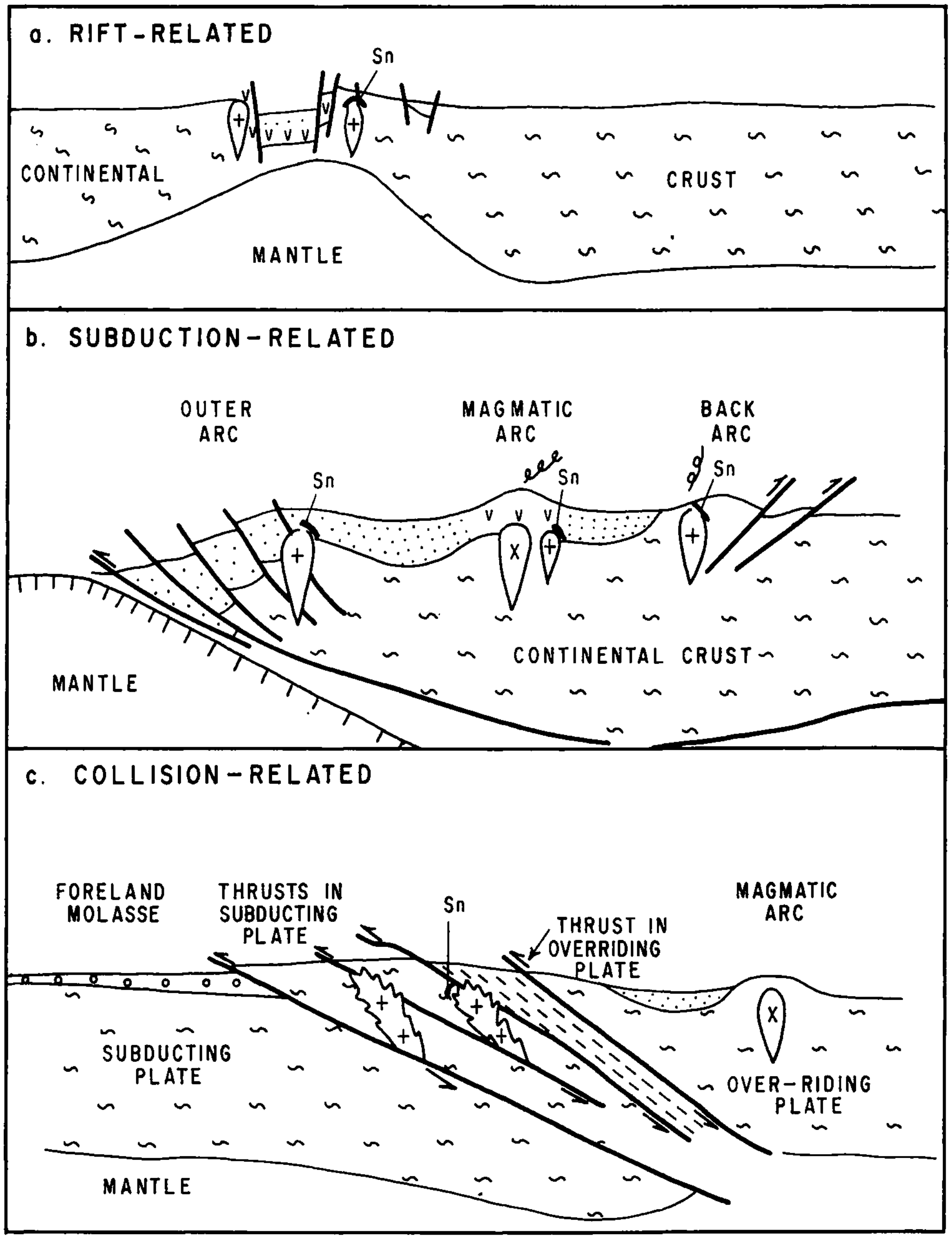

Fig. 6. Schematic cross-sections showing main features of tectonic settings of rift, subduction and collision-related tin granites.

TABLE 1. COMPARISON OF REGIONAL ASPECTS OF TIN DEPOSITS IN VARIOUS TECTONIC SETTINGS

ROCK TYPE	RIFT	SUBDUCTION			COLLISION
		MAGMATIC ARC	OUTER ARC	BACK-ARC MAGMATIC BELT	
Mineralized magmatic rocks					
Granite	Common	Rare	Common	Common	Common
Granodiorite—tonalite	—	Abundant	—	—	—
Silicic volcanics	Common	Abundant	—	Common	—
Pegmatites	Rare	Rare to common	—	Common	Common
Associated magmatic rocks					
Anorogenic	Invariably	—	—	—	—
Syn-orogenic	—	Invariably	—	Common	—
Late to post-orogenic	—	—	—	—	Common
Tonalite	Rare	Abundant	Common	—	Rare
Adamellite	Rare	Common	Common	Common	Common
Syenite-trachyte	Common	—	—	?	Rare
Peralkaline	Common	—	—	—	Rare
Host rocks to plutons					
'Continental' basement	Common	Rare	—	Common	—
Young volcanics	Common	Common	—	Common	—
Continental sediments	Common	Common	—	Common	—
Deformed flysch, minor ophiolite	—	Common	Abundant	—	Common
Deformed shelf sediments	—	Rare	—	—	Abundant
Associated metamorphism	Minor	Minor	Minor	Minor	Regional

for emplacement of the oldest mineralized granites in any tin province is highly relevant to the possible source of the metal.

The only well-documented example of rift-related granites with extensive tin mineralization is Nigeria, where the granites intrude an older mineralized belt. Major belts of rift-related granites elsewhere, for example the Tertiary igneous province of Scotland, are largely lacking in tin. Since rift-related granites are probably largely mantle-derived, it is unlikely that the associated tin is concentrated from trace amounts present in the crust. It could either be mantle-derived or remobilised from pre-existing crustal concentrations.

With the exception of the northern part of the Bolivian tin belt, in no subduction-related setting is there evidence that the tin granites are derived from or intrude an older tin belt. Isotope data on collision-related tin-bearing granites indicate that they are crust-derived, suggesting that if older deposits of tin were present and had been remobilised, they should be in the crust rather than upper mantle, and hence some evidence of their presence in adjacent rock units might be expected. However, in most of the major collision-related belts, i.e. the Himalayas, Main Range Malaysia, and Southwest England, there is no known pre-collision tin; only in the Erzgebirge are older deposits known, in the form of minor occurrences in Palaeozoic metavolcanic and sedimentary rocks adjacent to the Hercynian granites (Baumann 1970).

In the absence of pre-collision tin in areas of mineralized collision-related granites, there is no necessity to postulate primitive concentrations of the metal in either the upper mantle or crust. It appears that in collision- and subduction-related settings tin is commonly concentrated from trace amounts present in the upper crust, resulting in workable deposits. It is uncertain whether this results in formation of a crustal geochemical tin province, subsequent remobilisation of which by rift, subduction, or later collision-related granites, could result in younger economic deposits.

CONCLUSIONS

The characteristics of the rocks associated with tin mineralization in each of the tectonic settings discussed are summarised in Table 1, and the settings are shown schematically in fig. 6. While the tectonic settings in which many of the world's major tin fields were formed are characterised on a regional scale by particular rock-types, there is as yet little evidence that the type of mineralization itself is determined directly by the tectonic setting.

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