18. VEIN-STOCKWORK TIN, TUNGSTEN

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W.D. Sinclair

INTRODUCTION

Vein-stockwork deposits of tin and tungsten occur in a wide variety of structural styles that include individual veins, multiple vein systems, vein and fracture stockworks, breccias, and replacement zones in altered wall rocks adjacent to veins. The deposits generally occur in or near granitic intrusions which have been emplaced at relatively shallow levels (1 to 4 km) in the Earth's crust. The associated intrusions are highly fractionated and typically enriched in lithophile elements such as Rb, Li, Be, Sn, W, Mo, Ta, Nb, U, Th, and REEs, and volatile elements such as F and B.

Hydrothermal alteration of wall rocks associated with vein-stockwork tin and tungsten deposits is commonly greisen-type alteration that is characterized by Li-, F-, and/or B-bearing minerals such as topaz, fluorite, tourmaline, and various F- and/or Li-rich micas. Vein-stockwork deposits with extensively greisenized wall rocks that contain disseminated tin and/or tungsten minerals have been referred to as "greisen" deposits (Shcherba, 1970; Taylor, 1979; Reed, 1986). Such deposits are included in this review as vein-stockwork deposits; "greisen" is used primarily in reference to a type of alteration rather than as a type of deposit.

Canadian examples of vein-stockwork deposits of tin and tungsten include Grey River, Newfoundland (tungsten); East Kemptville, Nova Scotia (tin, copper, zinc); Mount Pleasant-North Zone (tin) and Burnthill (tungsten) in New Brunswick; Regal Silver (tungsten, tin) and Red Rose (tungsten) in British Columbia; and Kalzas, Yukon Territory (tungsten)(Fig. 18-1). Important foreign examples include deposits in Cornwall, England (tin, copper); the Erzgebirge region of central Europe (tin, tungsten); the Oruro, Llallagua, and Potosi districts (tin, silver), Chojlla (tungsten, tin), and Chambillaya (tungsten) in Bolivia; Aberfoyle (tin, tungsten), Ardlethan (tin), and Mount Carbine (tungsten) in Australia; Xihuashan, China (tungsten); Panasqueira, Portugal (tungsten, tin); and San Rafael (tin, copper), Palca Once (tungsten), and Pasto Bueno (tungsten, copper, lead, silver) in Peru.

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IMPORTANCE

Until recently, vein-stockwork deposits accounted for little production of tin and tungsten in Canada. In the past, most tin was produced as a byproduct from the Sullivan sediment-hosted zinc-lead-silver deposit, and tungsten production has been primarily from skarn and porphyry deposits. Since 1986, however, production of tin has been dominated by the East Kemptville deposit in Nova Scotia; from 1986 to January, 1992 when it closed, the East Kemptville mine produced approximately 20 000 t of tin, and minor quantities of copper and zinc, from about 17 Mt of ore mined (Bourassa, 1988; Canadian Mines Handbooks 1990-93). Production of tungsten from vein-stockwork deposits includes 1540 t of WO_3 from the Red Rose mine in British Columbia (Sutherland Brown, 1960), about 24 t of wolframite concentrates from Burnthill, New Brunswick (MacLellan et al., 1990), and 3.3 t of WO_3 from the Regal Silver mine in British Columbia (Mulligan, 1984).

Worldwide, vein-stockwork deposits have been important sources of both tin and tungsten, although in recent years their importance as a source of tin has declined. In 1989, world tin production was estimated at 217 500 t (Amlôt, 1990), much of which was derived from placer deposits in southeast Asia and Brazil, and from carbonate-replacement deposits in Australia and China; no more than about 10 to 15% of tin production was derived from vein-stockwork deposits, primarily in Bolivia, Peru, England, and Russia. On the other hand, of the estimated world production in 1989 of 49 000 t of tungsten metal (Maby, 1990), more than half came from vein-stockwork deposits in China, Russia, Kazakhstan, Portugal, Bolivia, and Peru.

SIZE AND GRADE OF DEPOSITS

Many vein deposits of tin and tungsten are relatively small, on the order of tens of thousands to hundreds of thousands of tonnes of ore; however, deposits that consist of multiple veins or stockworks may contain millions to tens of millions of tonnes. Grades in vein deposits typically range from 0.5 to 2% Sn, and from 0.3 to 1.5% WO_3, although much higher grades occur locally. Stockwork deposits that can be mined using bulk mining methods have grades as low as 0.165% Sn (e.g. East Kemptville) or 0.1% WO_3 (e.g. Mount Carbine).

Production and/or reserves for Canadian and some important foreign deposits are given in Table 18-1. Grade-tonnage relationships are shown in Figure 18-2.

GEOLOGICAL FEATURES

Geological setting

Vein-stockwork deposits of tin and tungsten range in age from Archean to Tertiary, although a considerable proportion are late Paleozoic, Mesozoic, or Cenozoic. In Canada,

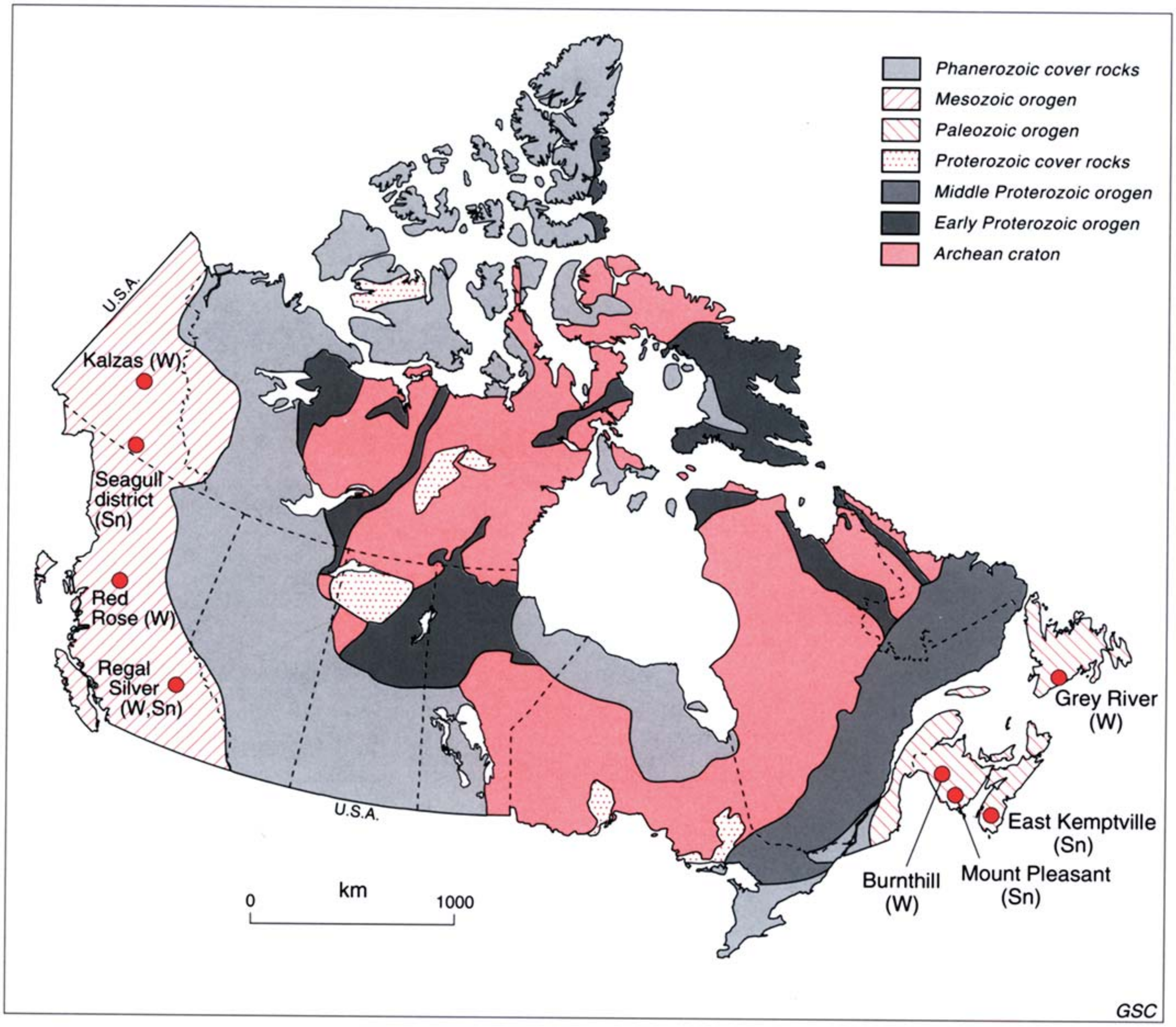

Figure 18-1. Distribution of selected vein-stockwork tin and tungsten deposits in Canada.

Table 18-1. Production/reserves of selected Canadian and foreign vein-stockwork tin, tungsten deposits.

Deposit	Production/reserves	Comments/references
Canadian deposits:		
East Kemptville, Nova Scotia	a) 56 Mt; 0.165% Sn b) 27.9 Mt; 0.182% Sn, 0.075% Cu, 0.180% Zn	Preproduction reserves (Moyle, 1984). Proven and probable reserves, Dec. 31, 1989 (Canadian Mines Handbook 1990-91).
Mount Pleasant-North zone, New Brunswick	5.1 Mt; 0.79% Sn	Reserves-North Zone (The Northern Miner, 6 November, 1989).
Seagull district, Yukon Territory	None reported	Numerous tin-bearing veins are associated with the Seagull batholith (Mato et al., 1983).
Burnthill, New Brunswick	4 Mt; 0.12% WO_3	Reserves (R.M. Crosby, pers. comm., in MacLellan et al., 1990); minor tin also present.
Grey River, Newfoundland	0.52 Mt; 1.09% WO_3	Assumed plus possible reserves (Higgins, 1985).
Red Rose, British Columbia	0.12 Mt; 1.4%WO_3	Production 1942-1943, 1952-1954, plus reserves (Sutherland Brown, 1960).
Regal Silver, British Columbia	3.3 t, 100% WO_3	Production 1930-1954 (Mulligan, 1984); Sn (in stannite) also present.
Kalzas, Yukon Territory	None reported	Wolframite and minor cassiterite occur in sheeted quartz veins and stockworks over an area 1500 m by 1000 m (Lynch, 1989).
Foreign deposits:		
Aberfoyle, Australia	1.6 Mt; 0.84% Sn, 0.28% WO_3	Production 1931-1962, plus reserves (Kingsbury, 1965).
Ardlethan, Australia	9 Mt; 0.5% Sn	Production plus reserves (Taylor and Pollard, 1986).
Baal Gammon, Australia	3 Mt; 0.3% Sn, 1.2% Cu, 46 g/t Ag, 50 g/t In	Drill-indicated reserve (McKinnon and Seidel, 1988).
Bolivar, Bolivia	0.8 Mt; 1% Sn, 274 g/t Ag, 15% Zn, 1.3% Pb	Proven and probable reserves (Mining Journal, March 15, 1991).
San Rafael, Peru	~2 Mt; 1.5-2% Sn, ~1.5% Cu	Production 1970-1988 (United States Bureau of Mines annual reports).
Akenobe, Japan	17 Mt; 0.4% Sn, 1.1% Cu, 2.0% Zn, 20 g/t Ag	Production 1935-86 (Shimizu and Kato,1991); In also present.
Wheal Jane, Cornwall, England	5 Mt; 1.20% Sn	Reserves (Mining Magazine, November, 1971).
South Crofty, Cornwall, England	3.85 Mt; 1.55% Sn	Reserves (Sutphin et al., 1990).
Geevor, Cornwall, England	5 Mt; ~0.65% Sn	Production 1911-1983 (Mount, 1985).
Kelapa Kampit, Indonesia	2 Mt; 1.20% Sn	Reserves (Omer-Cooper et al., 1974).
Dzhida district, Russia	11 Mt; 0.43% WO_3	In situ resource (Anstett et al., 1985).
Xihuashan, China	~20 Mt; 0.25% WO_3	Production 1959-1983, plus reserves (based on data provided by mine staff, 1983);Mo, Sn, Bi, and Cu recovered as byproducts.
Hemerdon, Cornwall, England	42 Mt; 0.18% WO_3, 0.025% Sn	Reserves (Skillings' Mining Review, 7 January, 1984).
Panasqueira, Portugal	~31 Mt; 0.3% WO_3, 0.02% Sn	Production 1934-1981 (Smith, 1979; McNeil, 1982) plus reserves (Anstett et al., 1985).
Mount Carbine, Australia	35 Mt; 0.1% WO_3	Production 1972-1986 (Australian Mineral Industry Reviews for 1972-1986) plus reserves (Roberts, 1988).
Chicote Grande, Bolivia	21.2 Mt; 0.43% WO_3	Reserves (Willig and Delgado, 1985).
Chojlla, Bolivia	~8 Mt; 0.45% WO_3, ~0.4% Sn	Production plus reserves (Valenzuela,1979; Willig and Delgado, 1985).
Chambillaya, Bolivia	~4 Mt; 0.6% WO_3	Production (Valenzuela, 1979; Willig and Delgado, 1985).
Palca Once, Peru	1.5 Mt; 1.34% WO_3	Reserves (Willig and Delgado, 1985).
Pasto Bueno, Peru	1.1 Mt; 0.44% WO_3	Reserves (Willig and Delgado, 1985); Cu, Pb, and Ag have also been produced.

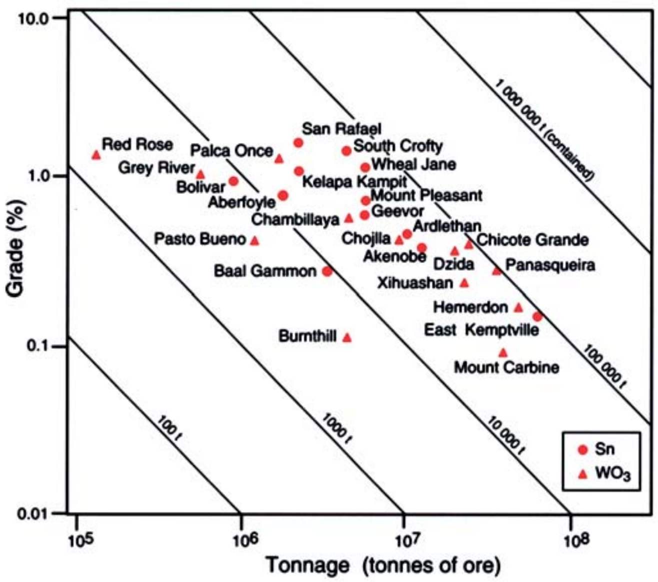

Figure 18-2. Grade versus tonnage diagram for vein-stockwork tin-tungsten deposits (Sn and WO_3 data are from Table 18-1).

important deposits of late Paleozoic age occur in the Appalachian Orogen; lesser deposits of Mesozoic age are present in the Cordilleran Orogen.

The granitic rocks associated with vein-stockwork tin and tungsten deposits are generally discordant to both local and regional structures and are either late orogenic or anorogenic. For example, the East Kemptville deposit is associated with granitic rocks that were emplaced between 360 and 370 Ma ago in metasedimentary rocks of the Meguma Terrane (Kontak and Chatterjee, 1992); the granitic rocks therefore postdate regional metamorphism associated with accretion of the Meguma Terrane onto North America, which has been dated at 405-390 Ma (Muecke et al., 1988).

The tectonic settings in which the granitic rocks have been emplaced are characteristically continental: they include continental collision belts, such as southeast Asia (Permo-Triassic), western North America (Mesozoic), eastern North America (Devonian), and the Variscan Belt of central Europe (late Paleozoic); inner continental arcs, such as Bolivia-Peru (Tertiary) and Burma-Thailand (Tertiary); and continental rift zones, such as northern Bolivia (Permo-Triassic), southern China (Cretaceous), and Nigeria (Jurassic).

On a more local scale, vein-stockwork tin and tungsten deposits are associated with granitic intrusions emplaced at relatively shallow depths ranging from about 1 to 4 km. Some of the intrusions are subvolcanic (e.g. Mount Pleasant). The intrusions range from cusp-shaped or irregular protrusions on batholiths to small cupolas and subvolcanic stocks. The deposits occur close to the contact zones of the intrusions, and are hosted to varying degrees in the granitic rocks themselves, or in associated sedimentary, volcanic, metamorphic, or older intrusive rocks.

Form of deposits

Vein-stockwork deposits are structurally controlled and take their form accordingly. Deposits may consist of single veins or narrow vein systems (e.g. Grey River, Aberfoyle); subparallel vein systems, also referred to in some cases as "sheeted veins" (e.g. Burnthill, Mount Carbine, Xihuashan); stockworks of interconnecting veins and fractures (e.g. East Kemptville); and breccias (e.g. Ardlethan). The different styles of mineralization are represented schematically in Figure 18-3. Individual veins range from less than 1 cm to several metres wide, but most are on the order of 10 to 20 cm wide. Veins may bend, branch, or pinch out over tens to hundreds of metres both laterally and vertically. Some vein systems in sheeted vein and stockwork deposits are hundreds of metres wide and more than a thousand metres long. Breccias are highly variable in size and shape; they are commonly subvertical and pipe-like, but can also be dyke-like to irregular in shape.

Structural control may not be obvious in some deposits with extensive greisen alteration. At East Kemptville, for example, mineralized alteration zones range from 1 cm to 20 m wide. The larger zones are irregular in shape and controlling fractures have been obscured by alteration.

Ore minerals and distribution

Cassiterite is the principal tin ore mineral, although stannite and other tin sulphides are present in some deposits. Wolframite is the main tungsten mineral; however, scheelite can also be present, and in some deposits is more abundant than wolframite (e.g. Red Rose). Grain size of the ore minerals ranges from fine to coarse; wolframite crystals in some quartz veins are as much as 10 to 20 cm long. Associated minerals include molybdenite, bismuthinite, chalcopyrite, sphalerite, pyrite, pyrrhotite, hematite, arsenopyrite, tourmaline, topaz, fluorite, muscovite, beryl, lepidolite, zinnwaldite, biotite, chlorite, quartz, K-feldspar, albite, and clay minerals.

Within some individual veins, the distribution of the main ore minerals is systematic, but in others it is irregular or random to complex. Some veins, for example, display comb textures indicating sequential deposition from the wall rocks inward; cassiterite commonly occurs at, or close to, the vein walls, and is succeeded inward by wolframite, although the reverse also occurs. Other veins are banded and appear to have undergone repeated opening of the vein and deposition of ore minerals. Crosscutting veins and fractures typical of many stockwork deposits also indicate that mineralization occurred in multiple stages (Fig. 18-4).

Ore composition and zoning

The compositions of vein-stockwork tin-tungsten ores vary widely (Table 18-1). Most deposits consist predominantly of either tin or tungsten, with minor amounts of the other; a notable exception is the Chojlla deposit in Bolivia, which has produced approximately equal amounts of tin and tungsten. In addition to tin and tungsten, other metals such as copper, lead, zinc, molybdenum, bismuth, silver, and indium may be present in economically significant amounts (Table 18-1).

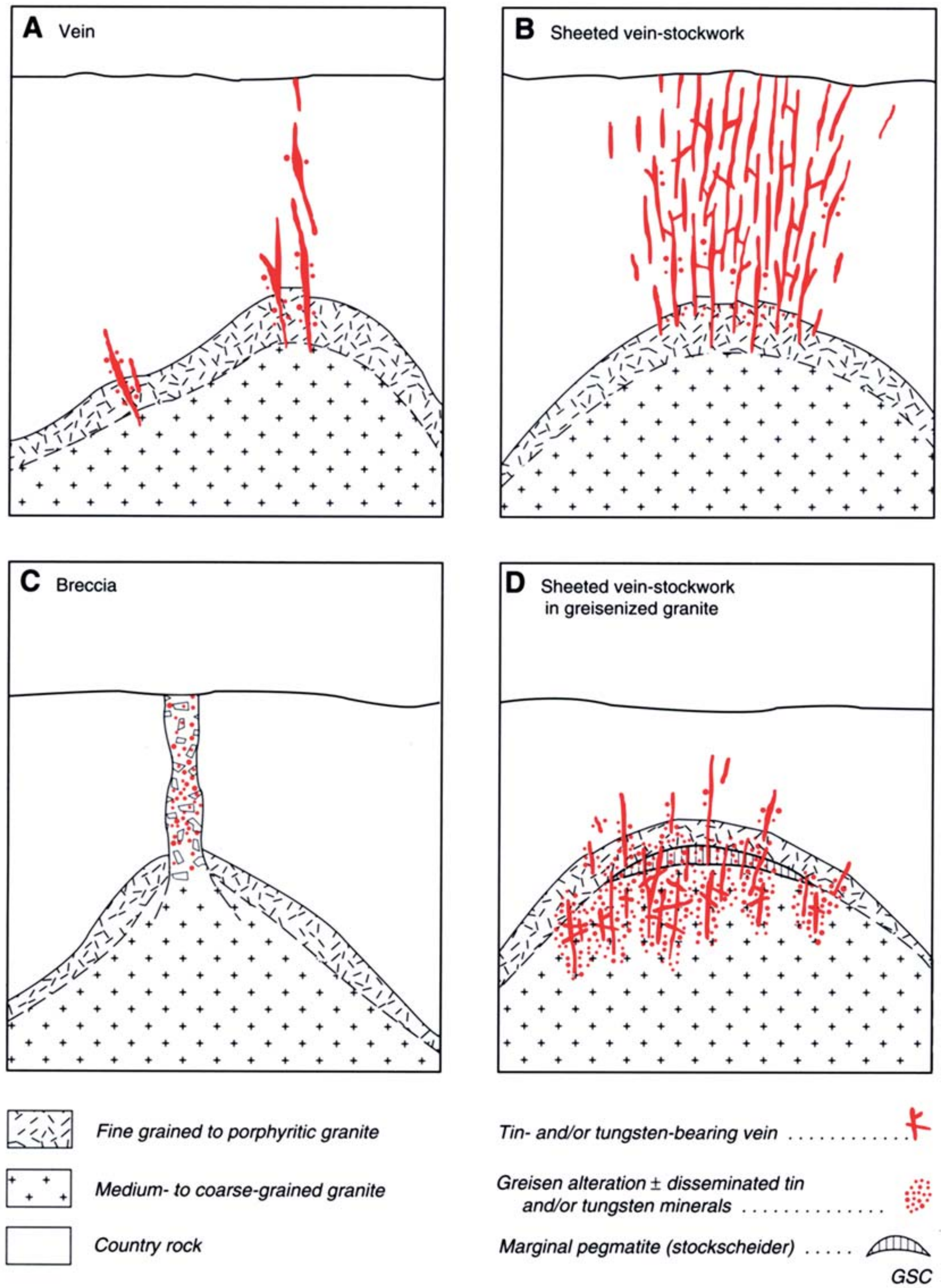

Figure 18-3. Schematic representation of different forms of vein-stockwork tin-tungsten deposits.

Figure 18-4. Cassiterite- and arsenopyrite-bearing veins (dark) cutting fractured and highly altered granite, Mount Pleasant, North zone. GSC 204880B

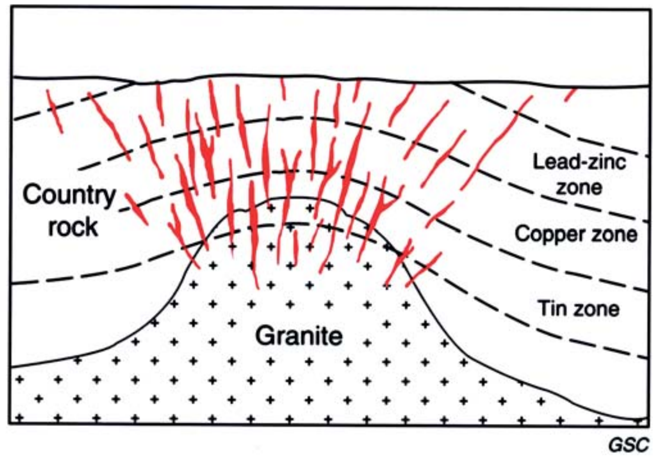

Figure 18-5. Schematic diagram illustrating regional zonation of metals in vein deposits of Cornwall and Devon (after Dines, 1934).

Metal zoning is common in many vein-stockwork tin and tungsten deposits and districts. In the tin-copper deposits of Cornwall, for example, tin (±tungsten) veins occur closest to, and commonly within, associated granite bodies; copper and lead-zinc veins are distributed above and outward from the tin veins (Fig. 18-5). Zoning also occurs within individual veins in Cornwall; the Dalcoath lode, for example, consisted of mainly copper in the upper part and tin in the lower part (Dines, 1956). Other deposits or districts which display comparable metal zoning include the San Rafael deposit, Peru (Clark et al., 1983), the Akenobe deposit, Japan (Sato and Akiyama, 1980), and the Herberton tin field, Australia (Blake and Smith, 1970; Taylor and Steveson, 1972). In some deposits, however, zonation of metals can be complex and highly varied, as in the tin-silver deposits of Bolivia (Turneaure, 1960).

Many vein tungsten deposits in southern China display vertical zonation with respect to vein morphology and distribution of ore minerals. The general model for these deposits (Fig. 18-6) consists of five zones. The uppermost part of a deposit, zone I, consists of parallel veinlets less than 1 cm wide which are closely to widely spaced. Veinlets in zone II are 1 to 10 cm wide, and are subparallel; branching or merging is common. In zones III and IV, vein width increases from 10 to more than 50 cm; vein density decreases as vein width increases. The lowermost part of a deposit, zone V, consists of branching or merging veins and veinlets that pinch out with depth. Zone V veins and veinlets are commonly rooted in granite. Tungsten occurs primarily as wolframite, and is most abundant in zones III and IV, and to a lesser extent in zone II. Cassiterite distribution overlaps that of tungsten in zones II, III, and the upper part of zone VI, and commonly extends into zone I. Chalcopyrite and sphalerite occur mainly in zones III and IV; molybdenite occurs in zones IV and V.

Zonation in stockwork deposits is less pronounced, if present at all. In the Hub deposit, Czech Republic, for example, the ratio of tin to tungsten increases slightly with depth (Stemprok, 1986). Copper, zinc, and molybdenum are associated with tin and tungsten in the upper part of the deposit, but are rare or absent in the lower part.

Metals may also be weakly dispersed in zones surrounding vein-stockwork tin-tungsten deposits. At East Kemptville, a zone of anomalous tungsten, due to wolframite and scheelite in veinlets and fractures in metasedimentary rock, is limited to 200 m from the contact of the metasedimentary rock with greisenized, tin-bearing granite; zones of copper, tin, and zinc, respectively, extend increasingly further, for as much as 600 m from the contact (G.J.A. Kooiman, pers. comm., 1991).

Associated granitic rocks

Granitic rocks associated with vein-stockwork tin deposits are commonly referred to as tin granites or "specialized" granites. Tin granites range from peraluminous to peralkaline in composition. Compared to normal granites, such as the low-Ca granite in the compilation by Turekian and Wedepohl (1961), tin granites are characterized by high contents of SiO_2, and alkali, lithophile, and high field strength elements such as Rb, Li, Be, Ga, REEs, Y, Sn, Ta, Nb, U, W, Mo, and volatiles such as F and B; they are typically depleted in CaO, MgO, TiO_2, total FeO, Sr, and Ba. The average composition of specialized granites, as compiled by Tischendorf (1977), is given in Table 18-2; the average compositions of low-Ca granite and A- and S-type granites are included for comparison. The compositions of tin granites from East Kemptville and Mount Pleasant are also given in Table 18-2. Tin granites have many characteristics in common with A- and S-type granites, but appear to be more highly fractionated. Granites associated with vein-stockwork tungsten deposits are similar to tin granites; an example is the granite associated with the Burnthill tungsten deposit (Table 18-2).

Many granites associated with tin-tungsten deposits were emplaced in multiple stages of intrusion that represent progressive degrees of fractionation. The deposits are in most cases related to specific intrusive phases that are among the most highly fractionated. Such phases are also characterized by a variety of textures that are the result of interaction between the granitic magma and aqueous, ore-bearing fluids. For example, concentration of aqueous fluids at the top of a cupola can result in pegmatitic zones distinguished by feldspar crystals that have grown from the contact of the cupola inward; these are referred to in European literature as "stockscheider". Comb quartz layers and other unidirectional solidification textures that are typical of many fluid-saturated felsic intrusions associated with porphyry molybdenum-tungsten deposits may also be present (cf. Shannon et al., 1982; Kirkham and Sinclair, 1988). Sudden or rapid loss of aqueous fluids from granitic melts can cause undercooling (or quenching) due to the rapid decrease in fluid pressure, resulting in the formation of aplitic, porphyritic, and micrographic or granophyric textures (cf. Fenn, 1986); the development of such textures within the upper marginal portions of small cupolas is typical of many tin-tungsten granites, for example, Mount Pleasant (Sinclair et al., 1988).

Tin and tungsten granites are also distinguished by their accessory minerals. In the eastern Transbaikal region of Russia, tin and tungsten deposits are associated with granites containing ilmenite and monazite, whereas granites containing sphene and allanite are barren (Ivanova and Butuzova, 1968). Ishihara (1977, 1981) found that most tin and tungsten deposits worldwide are associated with what he referred to as ilmenite-series granites, which contain ilmenite but are devoid of magnetite, and that none (or few) are related to magnetite-series granites, which can contain both magnetite and ilmenite. Other accessory minerals in various tin-tungsten granites include tourmaline, topaz, fluorite, apatite, xenotime, andalusite, and cordierite.

Alteration

Hydrothermal alteration assemblages associated with vein-stockwork tin and tungsten deposits are characterized by F-, Li-, and/or B-rich minerals such as topaz, fluorite, tourmaline, lepidolite, zinnwaldite, and F- and Li-rich muscovite and biotite. Altered rock containing these minerals is commonly referred to as greisen (Shcherba, 1970). Other minerals associated with greisen-type alteration include albite, microcline, chlorite, and quartz. Cassiterite, wolframite, chalcopyrite, sphalerite, pyrite, and other sulphide minerals may be disseminated in greisen-altered rock.

Alteration margins along individual veins or fractures range from narrow selvages one centimetre wide or less to broader zones as much as several metres wide. Zonal distribution of alteration assemblages, both lateral and vertical, is also present in some deposits; in general, zones containing abundant topaz and/or tourmaline occur closest to veins or fractures and are surrounded by zones containing muscovite (or sericite) and chlorite.

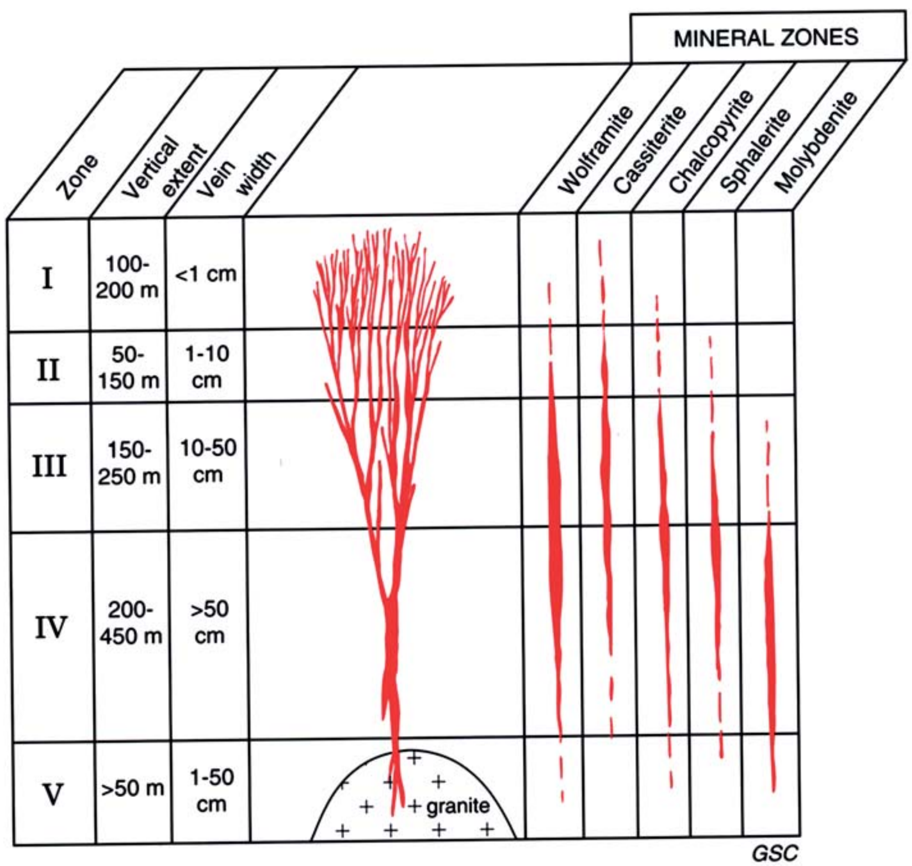

Figure 18-6. Vertical zonation of a typical tungsten vein deposit in southeast China (after Gu, 1982; Li, 1993).

Table 18-2. Composition of granites associated with vein-stockwork tin and tungsten deposits.

	Specialized granites (Tischendorf, 1977)	Low-Ca granite (Turekian and Wedepohl, 1961)	Average A-type granite (Whalen et al., 1987)	Average S-type granite (Whalen et al., 1987)	Biotite monzogranite, East Kemptville (Boyle, 1990)	Granite II, Mount Pleasant (Sample 87-11; Sinclair and Kooiman, 1990)	Biotite microgranite, Burnthill (Unit 3b, average of 8 analyses in MacLellan et al., 1990)
Major elements (weight %)							
SiO_2	73.38 ± 1.39	74.2	73.81	70.27	75.81	75.9	77.00
TiO_2	0.16 ± 0.10	0.20	0.26	0.48	0.15	0.04	0.08
Al_2O_3	13.97 ± 1.07	13.6	12.40	14.10	13.01	12.9	12.69
Fe_2O_3	0.80 ± 0.47	2.0*	1.24	0.56	0.99	0.0	1.04*
FeO	1.10 ± 0.47	n.d.**	1.58	2.87	1.07	1.5	n.d.
MnO	0.045 ± 0.040	0.05	0.06	0.06	0.03	0.03	0.07
MgO	0.47 ± 0.56	0.17	0.20	1.42	0.24	0.02	0.18
CaO	0.75 ± 0.41	0.71	0.75	2.03	0.54	0.70	0.50
Na_2O	3.20 ± 0.61	3.48	4.07	2.41	2.94	3.3	3.78
K_2O	4.69 ± 0.68	5.01	4.65	3.96	4.62	4.92	4.50
P_2O_5	-	0.14	0.04	0.15	0.15	0.0	0.01
F	0.37 ± 0.15	0.09	n.d.	n.d.	0.17	0.55	0.10
Trace elements (ppm)							
Rb	550 ± 200	170	169	217	439	823	507
Sr	n.d.	100	48	120	31	10	16
Li	400 ± 200	40	n.d.	n.d.	118	220	n.d.
Be	13 ± 6	3	n.d.	n.d.	7	n.d.	n.d.
Ga	n.d.	17	24.6	17	n.d.	26	n.d.
Nb	n.d.	21	37	12	14	59	35
Ce	n.d.	92	137	64	n.d.	147	46
Y	n.d.	40	75	32	30	164	85
U	n.d.	3.0	5	4	16	n.d.	21
Zr	n.d.	175	528	165	103	94	72
Sn	30 ± 15	3	n.d.	n.d.	17	22	19
W	7 ± 3	2.2	n.d.	n.d.	10	12	3.3
Cu	n.d.	10	2	11	5	10	n.d.
Mo	4 ± 2	1.3	n.d.	n.d.	3	7	n.d.
Pb	n.d.	19	n.d.	n.d.	12	64	n.d.
Zn	n.d.	39	120	62	75	68	26

*Total Fe reported as Fe_2O_3. ** n.d. = no data

Alteration associated with stockwork deposits can be present on a broad scale, forming extensive areas of continuous alteration over distances of tens to hundreds of metres. This style of alteration is common in the upper parts of granitic intrusions, as in the classic "greisen" deposits of the Erzgebirge in central Europe (Baumann, 1970) and at East Kemptville (Fig. 18-7, 18-8).

DEFINITIVE CHARACTERISTICS

The principal characteristics of vein-stockwork tin and tungsten deposits are structural control (veins, fractures); association with highly fractionated or specialized granitic intrusions, particularly ilmenite-series granites; and greisen-type alteration.

GENETIC MODEL

The association of vein-stockwork tin and tungsten deposits with granitic rocks has long been recognized and a genetic relationship is generally accepted. A brief historical review of ideas concerning the origin of tin deposits was provided by Tischendorf (1977).

Granitic rocks associated with vein-stockwork tin and tungsten deposits occur in a variety of tectonic settings and range from peraluminous to peralkaline in composition. However, virtually all the genetically-related granites are highly fractionated and formed from magmas rich in silica, alkali elements, water, and other volatiles, such as fluorine and boron, and lithophile elements, especially tin and/or tungsten. Although a crustal source of the magmas is generally accepted, disagreement exists concerning the source of the metals. On one hand, workers in southern China (e.g. Xu and Zhu, 1988) consider enrichment of tin and tungsten in the source rocks to be an important factor in the generation of tin- and tungsten-bearing granitic magmas. On the other hand, according to Lehmann et al. (1990), enrichment of tin in the igneous rocks of the Bolivian tin belt was due to magmatic processes rather than anomalous tin in the source rocks.

Whatever the source of the metals, granites associated with vein-stockwork tin and tungsten deposits probably originate as fluid-undersaturated, anatectic melts at depths of 15 to 20 km, or more (Strong, 1981). In the case of S-type granites, these melts are derived in an orogenic setting from mature sedimentary rocks (Chappell and White, 1974); the melts which form A-type granites are

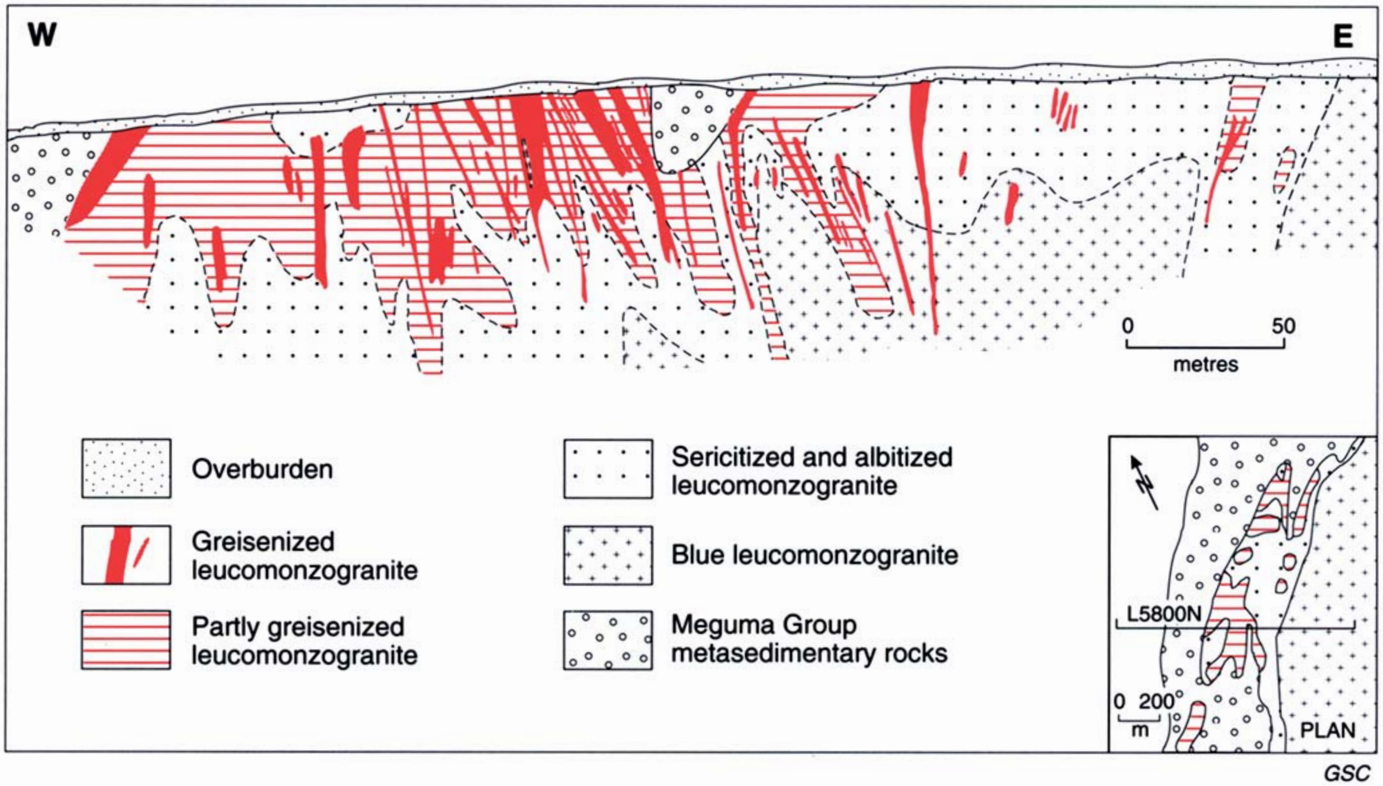

Figure 18-7. Cross-section L5800 of the East Kemptville tin deposit showing distribution of tin-bearing, greisen-altered zones; inset map shows plan view of surface and location of cross-section (after Richardson, 1988).

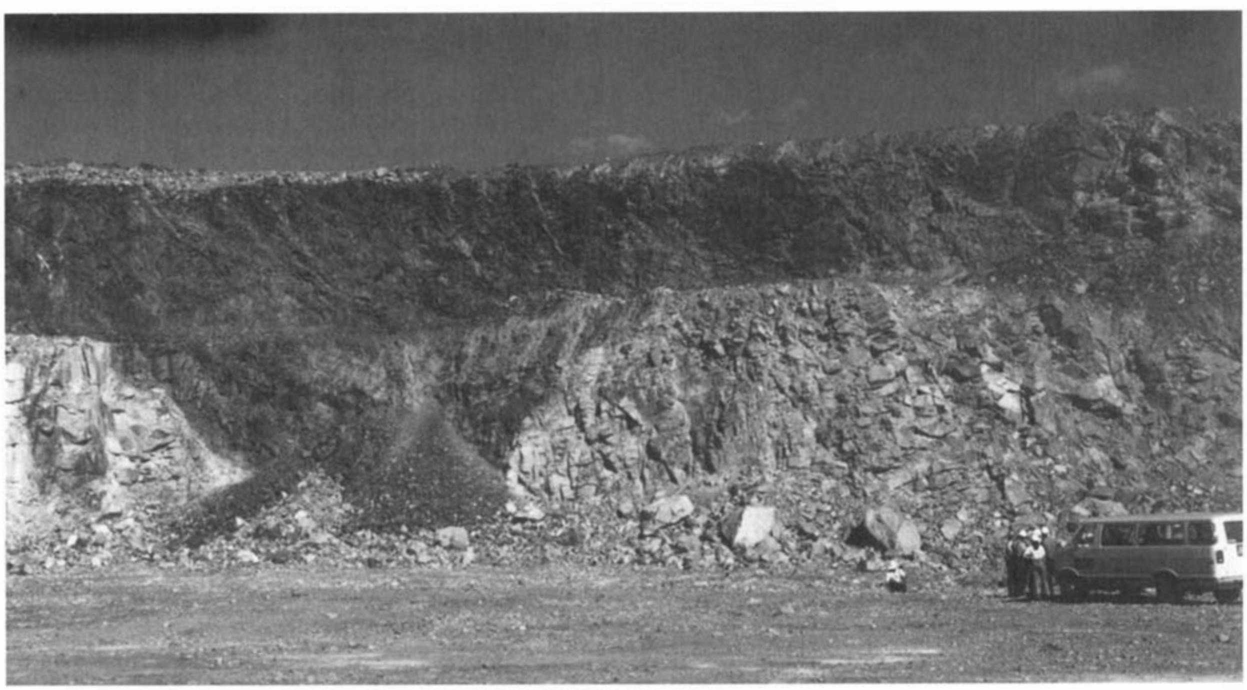

Figure 18-8. Photograph of the East Kemptville tin deposit showing tin-bearing greisen (grey, partly obscured by talus) and granite (light grey) below the subhorizontal contact of the granite with Meguma Group metasedimentary rocks (dark grey). GSC 1991-426

derived in an anorogenic setting by partial melting of felsic granulite residue from which granite has been produced previously (Collins et al., 1982; Whalen et al., 1987). When these melts are emplaced at higher levels in the crust and begin to crystallize, they become saturated in water and other volatiles such as chlorine, fluorine, boron, and carbon dioxide. Aqueous fluids, into which these volatile elements plus tin, tungsten, and other metals are strongly partitioned, subsequently separate from the crystallizing magma.

The style of mineralization (i.e. vein versus stockwork) depends on the magnitude of pressure developed within the crystallizing magma by the metal-rich aqueous fluids and the confining pressure of the surrounding country rock (mainly lithostatic pressure plus tensile strength of the country rock, including previously crystallized magma). If the confining pressure of the surrounding rocks is low, metal-bearing fluids can escape from the magma, primarily into faults and fractures to form vein deposits (Fig. 18-3A). Moderate to high confining pressure, combined with high fluid pressure in the magma, can result in extensive fracturing of the country rocks and the development of sheeted veins and stockworks (Fig. 18-3B); extremely high fluid pressure in the magma results in explosive failure of the country rocks and the formation of breccia pipes (Fig. 18-3C). If the confining pressure is high and/or fluid pressure in the magma is low, fracturing will be limited. In this case, the fluids will be trapped mainly within the crystallizing magma, leading to the formation of marginal pegmatites or stockscheider. The trapped fluids will also react with the magma and previously crystallized granite to form extensive zones of greisen alteration (Fig. 18-3D).

The magnitude of pressure developed in the crystallizing magma, and consequently the style of mineralization, is affected by the relative abundance of boron and fluorine in the mineralizing system. According to Pollard et al. (1987), the higher solubility of water in boron-bearing magmas compared to fluorine-bearing magmas leads to higher fluid pressures during the crystallization of the residual magma. Thus, boron-rich systems result dominantly in breccia, stockwork, and vein deposits, whereas fluorine-rich systems lead to the formation of deposits characterized more by extensive alteration (greisenization) and disseminated mineralization.

RELATED DEPOSIT TYPES

Vein-stockwork tin-tungsten deposits are the result of magmatic-hydrothermal activity related to the crystallization of felsic, peraluminous to peralkaline granitic rocks. Porphyry tungsten-molybdenum and porphyry tin deposits are associated with similar granitic rocks and have comparable styles of mineralization; the relationship between porphyry deposits and large vein-stockwork deposits is probably gradational. Deposits of lithium, beryllium, niobium, and tantalum associated with peraluminous to subalkaline rare-metal granites (Pollard, 1989) are also close relatives, but do not share the same degree of structural control.

Pipe deposits, which occur in the upper parts of granitic intrusions, also represent a different style of mineralization. These deposits are typically 1 to 2 m across, hundreds of metres long, and in many cases have sinuous shapes that appear unrelated to any obvious structural control. Such pipes occur in the Zaaiplaats tin deposit, South Africa (Strauss, 1954; Pollard et al., 1989) and in the tungsten deposits of Wolfram Camp, Australia (Blanchard, 1947).

Carbonate-replacement and skarn tin deposits, and some skarn tungsten deposits, are also associated with granitic rocks similar in composition to those associated with vein-stockwork tin and tungsten deposits.

EXPLORATION GUIDES

Exploration guidelines for vein-stockwork tin and tungsten deposits include the following:

1) Associated granitic rocks: vein-stockwork tin and tungsten deposits are associated with postorogenic to anorogenic granites that are typically enriched in lithophile elements such as Sn, W, Li, Rb, Be, Ga, REEs, Y, Ta, Nb, U, and Mo, and volatiles such as F and B.
2) Alteration: hydrothermal alteration typically consists of greisen-type assemblages characterized by F-, Li-, and/or B-rich minerals such as topaz, fluorite, tourmaline, and F- and/or Li-bearing micas such as lepidolite and zinnwaldite.
3) Structural control: faults and fractures are major ore controls in these deposits.
4) Zoning: tin and tungsten may be zoned relative to base metals at both regional (district) and local (deposit) scales.
5) Geochemical approaches: primary dispersion aureoles in host rocks (Sn, W, Cu, Zn, Pb, Rb, Li, F, B), secondary dispersion halos in overburden, and heavy minerals (cassiterite, wolframite, scheelite, topaz, tourmaline) in stream sediments help identify target areas at both regional and local scales.
6) Geophysical approaches: radiometric surveys may be useful for identifying tin and tungsten granites that are enriched in U, Th, and K. Magnetic surveys can be used to outline potential tin or tungsten granites of low magnetic response that are primarily ilmenite-series granites; magnetic surveys can also identify associated zones of magnetite- or pyrrhotite-bearing hornfels. Gravity surveys can be used to outline hidden granites in host rocks of contrasting density.

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