Geologie en Mijnbouw 67: 293–311 (1988)

Stratiform Tungsten deposits: a review

With implications for the Yxsjöberg – Sandudden deposits of Sweden

IUGS UNESCO IGCP 247

Alain Cheilletz
Centre de Recherches Pétrographiques et Géochimiques, Ecole Nationale Supérieure de Géologie, BP 20, 54501 Vandoeuvre-lès-Nancy, Cedex, France.

Received 8 October, 1987; accepted in revised form 14 February, 1988

Key words: Tungsten deposits, classification, syngenetic, epigenetic, exhalative, volcanogenic, calc-silicate bands, Sweden

Abstract

Based mostly on a review of the existing literature and on the experience of the author, a new classification and diagrammatic representation of stratiform tungsten deposits is proposed. It includes three classes of deposits: 1) continental weathering deposits essentialy of exogenic origin; 2) Exhalative-volcanogenic deposits divided into proximal, distal and metamorphic-amphibolite types; 3) Concordant replacement deposits divided into calc-silicate band and hornfels band types. An epigenetic two stage model is proposed for the formation of stratiform tungsten mineralizations associated with calc-silicate bands; this model can be applied to the genesis of Central Sweden tungsten deposits.

Introduction

During the 1960's and 1970's the discovery of strata-bound, syn-sedimentary tungsten mineralizations in the lower Paleozoic series of the Austrian Eastern Alps by A. Maucher and his team, led both to the development of the Felbertal scheelite deposit, Austria (Höll, 1970; 1977), and the construction of a volcano-sedimentary mineralization model (Höll, 1985; 1986). Moreover, the study of active geothermal fields in New Zealand where tungsten minerals precipitate around hydrothermal springs (Höll, 1985; Henley et al., 1986), has re-inforced the syngenetic strata-bound model. As a consequence, these discoveries added a new dimension to the controversy over an epigenetic as opposed to a syngenetic origin for this type of stratiform mineralization.

Illustrating the controversial debate, opposing genetic models have been proposed for some famous stratiform deposits such as Sangdong, Korea, which have been interpreted as a stratiform skarn formed by the replacement of calc-silicate layers (Kim, 1971; Farrar et al., 1978; Moon, 1984) whereas So (1968) considered this deposit was produced by the metamorphism of an originally mineralized basic volcanic series. The same controversy surrounds the King Island, Tasmania deposit: an epigenetic origin (Edwards et al., 1956; Kwak, 1978; Kwak & Tan, 1981) was questioned by Burchard (1977) who proposed a model involving the remobilization within the aureole of an intrusive granodiorite of early Paleozoic strata-bound scheelite mineralizations intrinsic to various beds of a volcano-sedimentary sequence related to basaltic volcanism.

Tungsten mineralizations of Uganda and Ruanda have also been the subject of debate concerning the origin of scheelite and ferberite occurrences in black shales outcropping along hundred of kilometers. This stratigraphic control led De Magnée & Acerda (1960) to consider a syngenetic precipitation of tungsten in these particular layers constituting the 'Ruanda-Uganda tungsten belt', followed by remobilization into vein-type structures.

In Western Europe, numerous small occurrences of concordant mineralization were exemplified in the syngenetic- exhalative model of Plimer (1980) as for instance the tungsten mineralizations of Bindal (Skaarup, 1974) and Örsdalen, Norway (Urban, 1971), as well as the Montagne Noire occurrences, France (Boyer & Routhier, 1974; Beziat and Tollon, 1976), the deposits of Ponferada and Morille districts, Spain (Arribas, 1979; Arribas Rosado, 1983) and the numerous scheelite occurrences of the Italian Alps, (Brigo & Omenetto, 1983). Recently, the reverse tendency has been noticed for some stratiform deposits in northeastern Portugal, originally interpreted as granite remobilizations of tungsten already present in sediments, and now clearly related to hydrothermal infiltration episodes in connection with Hercynian granitization (Derré et al., 1982; Thadeu, 1986). This debate is also relevant to Central Sweden for the stratiform tungsten deposits of the Yxsjöberg-Sandudden district, where an epigenetic origin is suggested by Ohlsson (1979; 1987) and Baker & Hellingwerf (in press) whereas Plimer (1980) considers these deposits to be strata-bound exhalative sedimentary.

The difficulty in interpreting stratiform tungsten deposits arises when metamorphic or tectonic overprinting hides the original relationships between the tungsten minerals (scheelite or wolframite) and the surrounding (meta-) sedimentary or volcanic series. The interpretation of ore fabrics becomes difficult, textures such as ore banding for instance being attributable to either syngenetic or epigenetic processes. During orogenesis, intense deformation in ductile shear zones results in the tectonic conformity of the main sedimentological and structural markers with interlayered mineralized beds.

Considering the abundant and controversial documentation about stratiform tungsten deposits illustrated above, economic geologists might be expected to have considerable difficulty interpreting bedded or concordant mineralized structures found during field or logging sampling. This paper, based on detailed petrological studies of mineralized calc-silicate bands by the author, together with field and mine visits, is an attempt to order and classify this group of tungsten mineralizations in the light of new scientific progress made on some major or illustrative deposits.

Classification of Stratiform Tungsten deposits

Two recent classifications of stratiform tungsten deposits have been published. Rundquist & Denisenko (1986) proposed a division of all tungsten deposits into three morphological groups, among them the 'Bedded deposits comprising stratiform types'. This group is itself divided into six classes corresponding to 'exogenic' deposits. The mainly syngenetic classification of Plimer (1987), is restricted to tourmaline-bearing stratiform scheelite deposits which are divided into three types: Regional calc-silicate scheelite deposits, Amphibolite-hosted scheelite deposits and Tourmalinite-hosted scheelite deposits. In this paper, a more detailed and cluster classification is proposed (see Table 1), according to the site of deposition and to the genetic processes responsible for the layered aspect of orebodies, i.e. epigenetic versus syngenetic modes of metal concentration to form the mineralization. Stratiform tungsten-bearing mineralizations can usefully be divided into the following three classes:

1. Continental weathering deposits
2. Exhalative-volcanogenic deposits
3. Concordant replacement deposits

Continental weathering deposits

These deposits are characterized by an exogene origin of the metal (Table 1.) i.e. the partial dispersion followed by the re-deposition and re-concentration of tungsten from primary deposits. The relatively high susceptibility of tungsten minerals to surficial alteration processes (Doucet, 1966), leads to the decomposition of scheelite and wolframite under a wide range of physico-chemical conditions, particularly in the oxidation zone. Transport and dispersion of soluble molecular or colloidal compounds into appropriate trapping structures is favoured either by the alkaline or nitrogenous composition of solutions and thermal waters (Krainov, 1965). The main precipitation process is the sorption of tungsten by iron and manganese hydroxides under a wide range of pH conditions (Ivanova, 1986). Detrital transport may also occur, but only over short distances (in eluvium or aluvium) due to the cleavage properties of the tungsten minerals, wolframite and scheelite. The main tungsten occurrences of this type are the following (Fig. 1):

- Alteration halos formed around primary deposits leading to residual tungsten retained in weathered crusts together with tungsten-bearing iron and titaniferous oxides in nodules or in wall-rock schists. Part of the Ruanda-Uganda tungsten reserves are constituted by such low grade concentrations of scheelite and ferberite in black shales outcropping along hundred of kilometers. This stratigraphic control formely led De Magnée & Acerda (1960) to consider a syngenetic precipitation of tungsten in these particular layers. In fact, as has been demonstrated by field and geochemical investigations (Jeffery, 1954; Reedman et al., in Burnol et al., 1978), the anomalous tungsten grades found in the Burundian sedimentary series are constituted by geochemical dispersion halos around primary hydrothermal vein-types deposits located near granitic plutons, followed by re-deposition by way of regional scale shear-zones.
- Manganiferous oxides with high tungsten contents, where tungsten is present either in scheelite or without a specific mineral phase, are associated with calcedony, calcite, baryte, and iron oxides in vein-type deposits, in tension fractures, in karst cavities, in limestone environments or in playa lakes linked to opal and travertine sedimentation. Occurrences of this type are known in France (Haut-Poirot, Vosges; Auxilhac, Lozère, in Burnol et al., 1978), USSR (in

Table 1. The classification of stratiform tungsten deposits.

STRATIFORM TUNGSTEN DEPOSITS

Class of deposit	Continental weathering		Exhalative-volcanogenic		Concordant replacement	
Mode of deposition	(epi) + syngenetic process		syn + epigenetic process		epigenetic process	
Metal source	Exogene origin		Endogene origin		Endogene origin	
Type of deposit		Proximal	Distal	Metamorphic-amphibolite	? Calc-silicate band	Hornfels band
Associated metals	Mn-Fe-Ti-Oxides Sn placers Boron	Au-Ag-Hg Cu-Zn-Pb Mo-Be-Bi Silica	Pb-Zn-Cu Sb-Hg Fe Boron	Sn Mo Boron	Mo-Cu Fluorine	Sn-Cu Fluorine Boron
Examples	Ruanda Unica, Bol. Searles lake, Golconda, USA. Ht. Poirot, Fr.	Taupo, N.Z. Felbertal, Aus. Tatras, Csz. Zimbabwe	Broken Hill, A. Malene, Dk. Catalan Cord. SW Sardinia Kleinarltal-Tux, Aus. San Antonio, Sp.	San Luis, Arg. Orsladen, Nor. Blacklite, USA.	Yxsjöberg-Sandudden, Sw. NE Brazil Djebel Aouam, Mor. Fumade, Fr. La Favière, Fr. Cordoba, Arg.	Cordillera-Real, Bol.

CONTINENTAL WEATHERING DEPOSITS

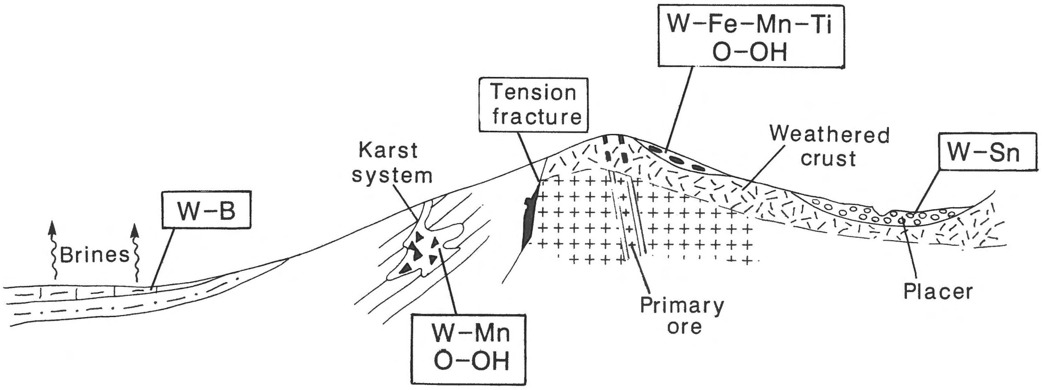


Fig. 1. Major stratiform tungsten occurrences in continental weathering environment.

Denisenko, 1986), Bolivia (Unica), Mexico and Golconda-Nevada, USA (Hobs & Helliot, 1973; Maucher, 1976; Pellissonnier, 1987). Hot springs precipitating Mn- and W-rich travertine generally have a pH of 6–7.5 and a temperature up to 80° C (Krainov, 1965).

- Detrital wolframite in continental placers. Examples of this type are found in the vicinity of primary high grade deposits of USSR, China, Zaire and Atolia-California, USA (see Laznicka, 1985; Burnol et al., 1978). In these deposits, tungsten is mostly associated with tin. In France, one occurrence of tungsten and tin located in the Vivarais metamorphic quartzites has been interpreted as a paleoplacer (Samama, 1971).
- High tungsten content in brines, interstitial between salt layers and boron accumulation in the late quaternary evaporites of Searles Lake, California, USA (Carpenter & Garret, 1959; Smith, 1979). In this deposit, the 80 000 tons of WO_3 at 70 ppm grade is derived from the leaching of outcropping mineralized skarns of the Bishop district. A hot spring discharge origin into the evaporite sequence for a part of the tungsten content may also be valid.

Exhalative-volcanogenic deposits

In spite of a recent provocative discussion (Clark & Trudu, 1986), economic exhalative-volcanogenic tungsten deposits do exist, as exemplified by the Felbertal deposit, actually the third largest tungsten producer in the world (2.3 m tons at 0.75% WO_3 grade), and by the existence of syngenetic tungsten occurrences associated with the active geothermal system of New Zealand in the Taupo volcanic zone (Höll, 1985; Seward & Sheppard, 1986). Calc-alkaline and tholeiitic volcanic series of continental margins and island arcs at the border of subduction zones or in expansion zones in a back-arc basin (Fig. 2) represent the most favourable geotectonic environments for a volcanic association with tungsten mineralizations. Indeed, the lithophile affinity of tungsten implies the existence of a crustal contribution in the magma source rocks to allow a further concentration of tungsten by magmatic fractionation and hydrothermal transfer. This is shown by higher average tungsten contents in volcanic rocks from continental margins (0.96 ppm in andesites; Helsen et al., 1978) than in island-arcs (0.24 ppm in andesites, Helsen et al., 1978). The highest magmatic tungsten contents are reported from differentiated silicic rocks such as peraluminous rhyolitic tuffs from the western Cordillera in the Central Andes (9.3 ppm) reaching to

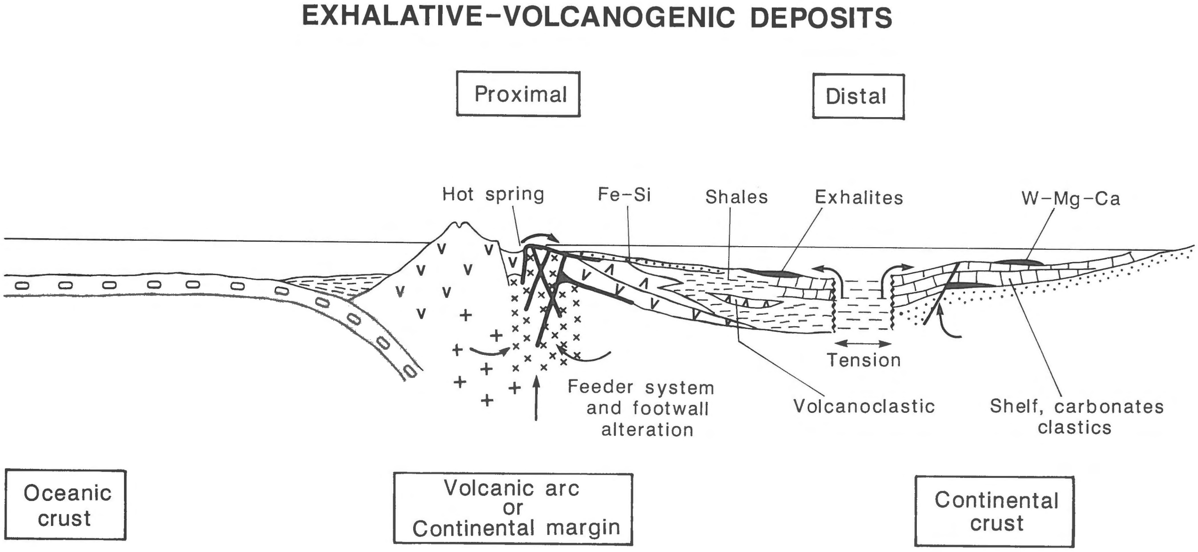


Fig. 2. Major stratiform tungsten occurrences in exhalative-volcanogenic environment.

60–90 ppm in the Macusanite glasses (Pichavant et al., 1987). Later concentration, transport, and redeposition of tungsten related to hydrothermal fluid circulation and metal precipitation occurs to form epithermal stockwork vein-type deposits. These constitute the feeder systems of sub-aerial to sub-marine exhalite discharges.

In the classification proposed here (Table 1 and Fig. 2), exhalative-volcanogenic tungsten deposits will be separated into 'proximal' and 'distal deposits' (Plimer, 1978) according to their closeness to a volcanic center. Thus the proximal deposits are characterized mainly by explosive activity, acid volcanic development, subvolcanic plutonism and large wall-rock alteration developed through stockwork-type hydrothermal fluid circulation. By contrast, the distal deposits are formed in back-arc sedimentary basin environments in tension structures conducting hot fluid discharges onto the sea floor. Geochemical and petrographic characteristics of exhalites are described from the polymetallic Broken Hill district, N.S.W., Australia (Barnes, 1983) and correspond to the association of silica-iron- and manganese-bearing formations, tourmaline-bearing pelitic beds, calc-silicate formations, laminated Pb-Zn base-metal sulphides intercalated with felsic gneisses and amphibolites. These formations have an extensive stratigraphic continuity and are interpreted as submarine exhalative ores associated with dacitic to rhyodacitic and tholeiitic volcanism.

Proximal deposits. The prototype of this kind of tungsten deposit is represented by the tungsten occurrences associated with the active geothermal system of New Zealand in the Taupo volcanic zone characterized by rhyolitic volcanoes, hot springs, mud pools and siliceous sinters (Höll, 1985; Seward & Sheppard, 1986). Analysis of silica sinter from Frying Pan Lake, Waimangu, for example (Table 2) shows a high tungsten concentration in siliceous iron-rich precipitates together with As, Sb, B and Mo enrichments. Au, Ag and Hg rich precipitates are also observed. Epithermal stockwork deposits characterized by Pb-Zn-Cu-Au-Ag vein systems accompanied by hydrothermal alteration (Henne-

Table 2. Analysis of tungsten-bearing siliceous iron-rich precipitates from Frying Pan Lake, Waimangu (Data from Seward and Sheppard, 1986); analyses in ppm, otherwise indicated.

W	Mo	As	Sb	Hg	Mn	Fe
4.5%	500	8.80%	105	1.2	50	20.70%
Si	B	Ag	Au	Cr	Ti	V
15%	150	2	0.03	150	400	100

berger, 1986; Christie & Brathwaite, 1986) exist at depth and are the epigenetic feeder systems of the exhalative mineralizations. The presence of anomalous amounts of tungsten in the volcanogenic beryllium ores of the Spor Mountain Caldeira, Utah, USA (Burt, 1986) represents another example of the possible link between tungsten mineralizations and proximal volcanogenic processes.

The Felbertal deposit (Höll, 1970; 1986) constitutes a lower Paleozoic example of the proximal exhalative-volcanogenic type. The scheelite mineralization is hosted in the metabasic rocks of the early paleozoic 'Habach Formation'. Synsedimentary structures of interstratified scheelite layers in quartzite bands are clear evidence for a syngenetic process operating during the genesis of this deposit. Ultramafic, mafic and felsic metavolcanic rock sequences are intercalated within the schist sequence; the tholeiitic and calc-alkaline affinities of the volcanic units together with a paleogeographic reconstruction within the two main ore fields indicate the Felbertal scheelite deposit formed in a narrow rift trough. The recent discovery in the western field ore body (Höll & Schenk, 1987) of a mineralized metaconglomerate composed of quartz, basaltic and felsic pebbles (Photo 1) strengthen this paleogeographic reconstruction. Felbertal might thus be considered as an early paleozoic example of active tungsten mineralizing siliceous sinters similar to those in the New Zealand Taupo zone. Besides W, Au-Ag-Bi-Be-Mo with minor sulphides enrichments are also found in Felbertal together with tourmalinite intercalations. Some tungsten ores show stretching (Photo 1), foliation planes and recrystallization fabrics resulting from tectonic transposition during the Alpidian regional metamorphism. The presence of a mineralized quartz-vein stockwork with biotitic selvages both in Eastern and Western fields (Höll, 1986) does not contradict the presented model because epigenetic structures – i.e. feeder systems – are to be expected in the footwall of syngenetic submarine exhalite horizons (Fig. 2).

A recently discovered tungsten mineralization occurs in the Alpine Low Tatras Mountains, Czechoslovakia (Stemprok, 1986). It is consituted by scheelite-gold ore occurring in locally strongly silicified migmatites, amphibolites, quartzites and quartz veins. The deposit is interpreted as polygenetic: a primary exhalative-volcanogenic mineralization of Lower Devonian age was strongly remobilized during Hercynian migmatization events and only weakly affected during the Alpine orogeny. These mineralizations might well constitute an eastern equivalent of the Felbertal deposit in the Alpine chain, reinforcing the Höll model. The association of quartzitic and basic volcano-sedimentary series, the presence of gold and minor sulphides in the Felbertal ore, and the later tectonic remobilization in shear zones, led Pelissonnier (1987) to link this kind of deposit to the 'Itabiritic type' gold deposits (e.g. Homestake Mine, USA; Bache, 1982). Several gold deposits of this type show tungsten anomalies, including the Morro Vehlo deposit, Brazil (Gair, 1962) and the Kolar district, India (Narayanaswami et al., 1960) where tungsten is extracted as a by-product from the gold ore.

In Zimbabwe, strata-bound tungsten deposits together with banded magnetite-ironstone and Au-Sb-As mineralizations were found in two Archean formations (Cunningham et al., 1973). The series are characterized by huge accumulations (2000 to 15 000 m) of submarine metavolcanics with minor intercalations of argillaceous, arenaceous and calcareous sediments. Scheelite mineralization in skarn-type deposits may also occur. More to the South, the Murchison Greenstone belt of Transvaal, South Africa (Maiden, 1981) is also characterized by low grade meta-volcanic and meta-sediment accumulations. Scheelite occurs in stratiform deposits associated with Au-Sb mineralizations. In the same region, epigenetic vein-type and shear zones scheelite mineralizations also exist, suggesting the remobilization of an early syngenetic exhalative-volcanogenic tungsten mineralization by tectono-metamorphic processes.

Distal deposits. They are characterized by minor amounts of volcanic and volcanoclastic rocks in a back-arc basin environment containing a characteristic association of calc-alkaline and tholeiitic tuffs, black shales and W-Pb-Zn-Cu bedded mineralizations interlayered with chemically precipitated exhalites such as chert, limestone, dolomite, barite and tourmalinite (Fig. 2). Indeed, boron has frequently been considered as a paleogeographic indicator, particularly in the massive sulphide deposits (Slack, 1982). Due to the volatility of this element and to the mobility of boric acid in water (Harder 1974), volcanic and geothermal systems, oceans and marine sediments can accumulate boron. This accumulation process is aided by the high substitution capacity of boron for aluminium in clay minerals (Stubican & Roy, 1962). The most representative example of a distal exhalative-volcanogenic type of tungsten deposit is the Early-Middle Proterozoic Broken Hill stratiform or stratabound scheelite and wolframite mineralization. These layers occur at the same stratigraphic level as the lead-zinc stratabound massive sulphides (Laing et al., 1978; Barnes, 1983; Plimer, 1988). Tungsten in the Broken Hill district occurs in various lithological sequences, mainly as disseminations, layers or irregular aggregates in bedded calc-silicate rocks, sometimes associated with amphibolite-rich intervals. Tungsten and base metals which originated from metal-rich exhalations related to a paired tholeiitic-dacitic volcanism event, were probably added to chemical sediments deposited in a quiet environment (Barnes, 1983). A second type of tungsten mineralization (Yanco Glen area) comprises strata-bound W-bearing pegmatites developed during the remobilization of felsic gneisses or bedded quartz-tourmaline rocks. Stratabound-scheelite mineralization associated with tourmaline-bearing banded amphibolites is also reported in the Archean Malene belt, West Greenland (Appel, 1986). In this deposit, banded amphibolites contain preserved pillow structures. The scheelite mineralized layer shows intergrowths with tourmaline in the amphibolites. Banded iron-formation and massive sulphides have been found associated with the scheelite mineralization. Tungsten in the amphibolites correlates with zinc, lead and gallium and to a lesser extent with molybdenum. Copper and tin anomalies also occur. The Malene deposit is considered to be an example of a stratabound tungsten mineralization of submarine exhalative origin associated with base-metal deposits. A distal environment may also be inferred for this kind of deposit.

The recent studies on stratiform tungsten anomalies in the Cambro-Ordovician shelf of Catalan Cordillera, Spain (Melgarejo & Ayora 1986; Ayora et al., 1986) and South-West Sardinia, Italy (Gimeno Torrente, 1986), also show good evidence of disseminated scheelite associated with massive Fe-Pb-Zn-Cu-As sulphide lenses. In some Spanish occurrences the mineralizations are also associated with chert layers and phosphate nodules; other occurrences are hosted by dolomite or ilmenite-bearing schists.

The scheelite mineralization of Kleinarltal, Austria (Höll et al., 1972) is hosted by early-paleozoic carbonates (mostly dolomites). It shows clear synsedimentary-diagenetic fabrics such as impregnations in thin quartzite and black shales while remobilization developes veinlets or stockworks. Kleinarltal is considered to be an exhalative-sedimentary distal type formed in a shelf environment (Fig. 2). The scheelite-magnesite deposit of Tux (Höll, 1977) which lies in the same Early Paleozoic series of the eastern Alps as Kleinarltal, is characterized by a more evaporitic paleogeographic environment. The scheelite mineralization appears to be bound to black schist layers with intercalations of basic metavolcanic rocks in the footwall. A primary sedimentary structure is still recognizable in interlayered quartz and carbonate beds containing scheelite and graphite.

A Sb-W-Hg mineral association has been reported as characterizing stratabound syngenetic mineralizations belonging to the South European-Circum Mediterranean region (Maucher, 1976). Detailed studies on the San Antonio-Badajoz deposit, Spain (Arribas & Gumiel, 1984) demonstrate firstly that the Sb-W (As-Hg) mineralization is associated with an intraformational breccia developed in a Devonian carbonate platform and secondly that the mineralization formed during the late hydrothermal activity associated with a hidden fissural volcanism in the Middle Devonian. The exhalative activity on the sea-floor and the concentration of the mineralization within the highly porous intraformational breccia account for the present features of the ore body. These characteristics clearly demonstrate that the San Antonio-Badajoz deposit is a distal exhalative-volcanogenic mineralization.

Other Sb-W-Hg occurrences are known from South-East Sardinia and Turkey (Maucher, 1976) or from the Hercynian crystalline basement of NE-Sicily (Omenetto et al., 1986; Guion et al., 1986). Preliminary work indicates an exhalative-volcanogenic origin for these deposits. However, high tectonic and supergene remobilization, particularly in the Sicilian ore bodies which are characterized by evidence of overthrusting, vein-type and karstic secondary fillings, preclude a conclusive interpretation as yet.

Metamorphic-amphibolite deposits. They are usually found in old Paleozoic or Precambrian basements. They comprise scheelite impregnations spread over long distances, and are linked to amphibolite beds of volcanic origin. Neither a distal or proximal character can be inferred from this kind of deposit because of the intense folding, stretching and metamorphism which occurred during various orogenic cycles. Some of these deposits probably correspond to the stratiform 'amphibole skarnoid' type of Rundquist & Denisenko (1986). It should be noticed, however, that a epigenetic replacement process by mineralized hydrothermal fluids is also possible in such metamorphic environments. A connexion between the amphibolite-metamorphic type and the concordant replacement class has been established (Table 1).

Examples of this type are numerous in the world, for instance the tungsten mineralizations of the Sierra de San Luis, Argentina. The Precambrian scheelite-bearing tourmaline-schists of the San Luis province occur in kilometers long mineralized belts (De Brodtkorb et al., 1985) and comprise tourmaline-bearing scheelite-biotite-muscovite-quartz schists containing conspicuous quantities of organic carbon. Felsic meta-volcanic rock intercalations of 5 to 10 cm thickness are conformably interlayered in the metasedimentary sequence together with tuffs and amphibolites of calc-alkaline affinity (Hack, 1986). Δ^{13}C values obtained from graphitized carbon of the quartz-tourmaline schists (-19 to -24‰) indicate a sedimentary organic origin. Two tectono-metamorphic cycles (Upper Proterozoic/Cambrian and Ordovician/Silurian), remobilizing the tungsten mineralizations, are recorded (Delakowitz, 1986; Hack, 1986). A syngenetic volcanogenic origin for the tungsten mineralization is commonly accepted (De Brodtkorb & De Brodtkorb, 1986).

In the Precambrian Scandinavian shield, the tungsten deposit of Örsladen, Norway (Urban, 1971) is charcterized by wolframite and scheelite mineralizations with some Sn and Mo, related to a graphite-bearing amphibolite band intercalated in a migmatitic and folded gneiss series. However, the lack of any detailed study on this deposit prevents an assessment of an exhalative-volcanogenic model. The same problem applies to the interpretation of the stratabound scheelite mineralizations discovered in the Proterozoic amphibolites and calc-silicate gneisses of the Blacklite prospect (Fulp & Renshaw, 1985). The tungsten-bearing horizon is located at an abrupt felsic-mafic volcanic contact also characterized by anomalous contents of Pb-Zn-Cu-Ag, tuffs and siliceous country rocks. However the presence of hydrothermal alteration assemblages and tungsten-anomalous post-tectonic granites in the vicinity of the tungsten horizon is also consistent with an epigenetic origin for the mineralization.

Concordant replacement deposits

This third class of stratiform tungsten deposits corresponds to the infiltration and partial replacement of (meta)sedimentary series by mineralized hydrothermal fluids directly or indirectly connected with a granitic intrusion, i.e. a pure epigenetic model. The initial composition of the (meta) sedimentary infiltrated layers allows us to distinguish two subtypes in this group (Table 1): 'calc-silicate bands' where calcareous components form a part of the initial sediments and 'hornfels bands' developed in pelitic and arenaceous sediments. The repetition of interlayered Ca-bearing lenses in pelitic sedimentary series (for instance the paleozoic formations) together with the epigenetic process leading to the formation of mineralized calc-silicate bands, can explain the numerous non-economic scheelite occurrences found by regional survey programs. Later tectono-metamorphic rearrangement (folding,

CONCORDANT REPLACEMENT DEPOSITS

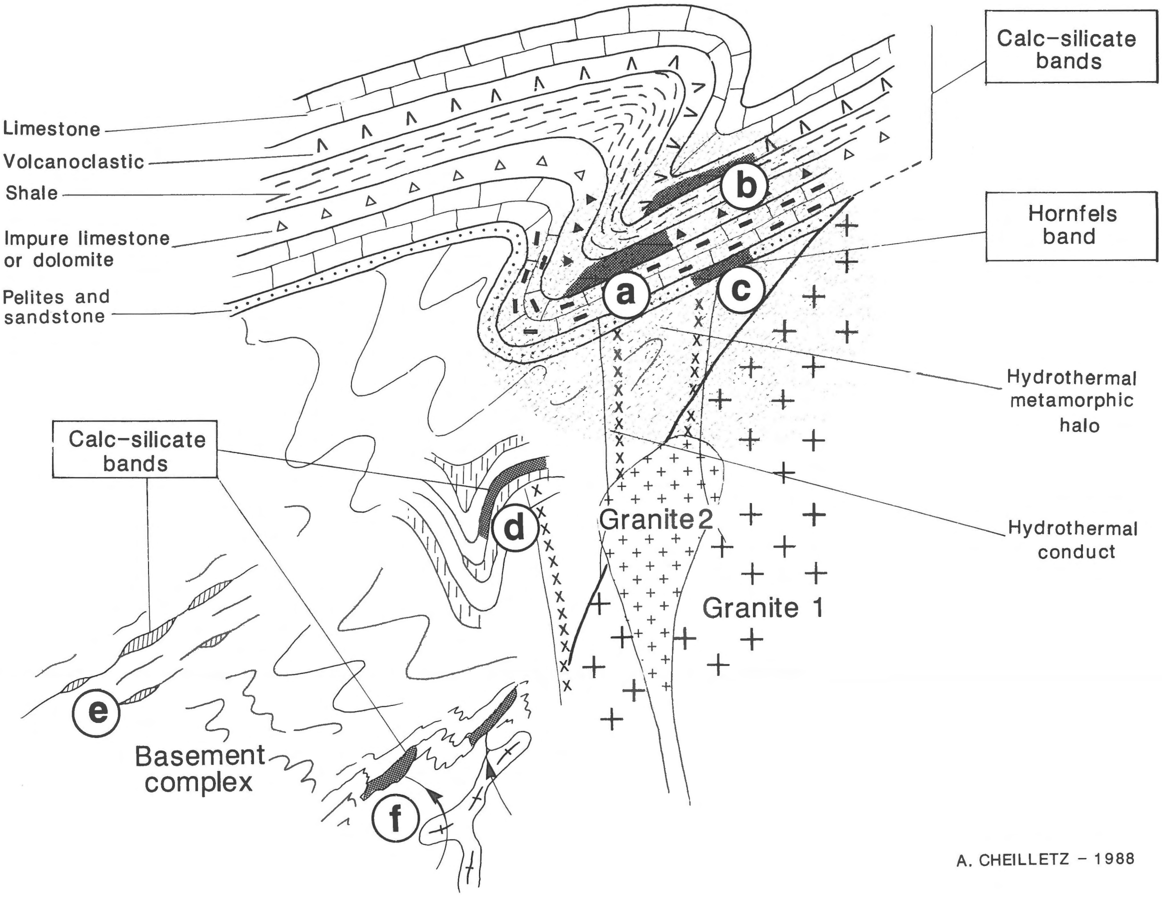


Fig. 3. Major epigenetic stratiform tungsten occurrences developed in the continental crust: (a) Calc-silicate bands developed in impure limestone-shale interlayered series (e.g. Djebel Aouam deposit); (b) Calc-silicate bands developed in volcanoclastic- limestone interlayered series (e.g. Yxsjöberg-Sandudden deposits); (c) Hornfels bands developed in pelites and sandstone sediments (e.g. Tungsten-bearing 'Mantos' of the Cordillera Real, Bolivia); (d) Calc-silsicate bands developed in polyphase folded series; (e) & (f) Calc-silicate bands developed in transposed planar structures of basement complexes sometimes associated with migmatites series (e.g. Cordoba province, Argentina or La Favière, France deposits).

stretching, metamorphism, foliation development, boudinage, transposed layering etc.) of these calc-silicate layers or lenses has made their genetic interpretation so debatable. Fig. 3 is a diagramatic representation of the geological setting of various ore bodies associated with calc-silicate or hornfels bands in the continental crust.

Calc-silicate bands. One direct way to resolve the question of calc-silicate band genesis is to recognize them in the general framework of skarns. Indeed, skarns frequently show a stratiform morphology (e.g. Einaudi et al., 1981) due to the specific replacement of calcareous layers by percolating fluids, for example at the contact of magmatic bodies as in the Pine Creek deposit (Newberry, 1982).

For the most part, metallogenists consider that skarn formation inherently is an evolving process (see Korzhinski, 1968 and Meinert, 1983, for a general review). In favorable cases, two stages can be recognized: initial isochemical metamorphism = Stage I, followed by multiple episodes of metasomatism = Stage II. Therefore, two groups of skarns can be distinguished (Phan, 1969; Bartholomé, 1970; Zharikov, 1970; Einaudi et al., 1981):

1) skarns resulting from metamorphic recrystallisation of impure carbonate rocks or from the reaction between rocks of contrasted lithologies such as schists and interbedded calcareous layers; the resulting rocks are referred to as 'calc-silicate hornfels' or 'skarnoid' or 'calc-silicate bands' (Zharikov, 1970; Vidale, 1969; Thompson, 1975; Kerrick, 1977). The main process involved in this isochemical metamorphism is diffusion of elements in a stationary fluid.
2) skarns resulting from the replacement of carbonaceous rocks by hydrothermal fluids of diverse origins. These skarns are referred to as 'infiltrational metasomatic skarn' (Korzhinski, 1968; Fonteilles, 1978); Transportation and deposition of metals occurs during multiple hydrothermal fluid circulation, ending with the development of retrograde alteration parageneses as temperature declines.

It is important to note that if this evolutionary two stage process operates during the emplacement of granitic bodies, the initial intrusive activity induces, at shallow levels of emplacement, the metamorphism of the surrounding calcareous layers in an upward growing thermal anomaly. Therefore, metamorphic calc-silicate bands or stratiform skarns may outcrop without a visible neighbouring granitic intrusive. A second important point is to consider that in most cases, felsic magmatic activity is characterized by the emplacement of composite plutons, one of them presenting more affinities with tungsten mineralization than others (Burnham & Ohmoto, 1980; Ivanova & Naumov, 1986; Giuliani et al., in prep). Therefore, the second metasomatic hydrothermal stage overprinting earlier metamorphic minerals and giving rise to mineralized skarns, may be connected with only one member of a composite or multiple intrusion. This member does not necessarily outcrop at the same level as the observed skarns. Such a two stage process is now generally accepted for the genesis of stratiform tungsten skarns such as Mac Tung, Canada (Dick & Hodgson, 1982) and King Island (Edwards et al., 1956; Kwak & Tan, 1981). New descriptions and fluid inclusion studies in Sangdong (Moon, 1984) also support this interpretation.

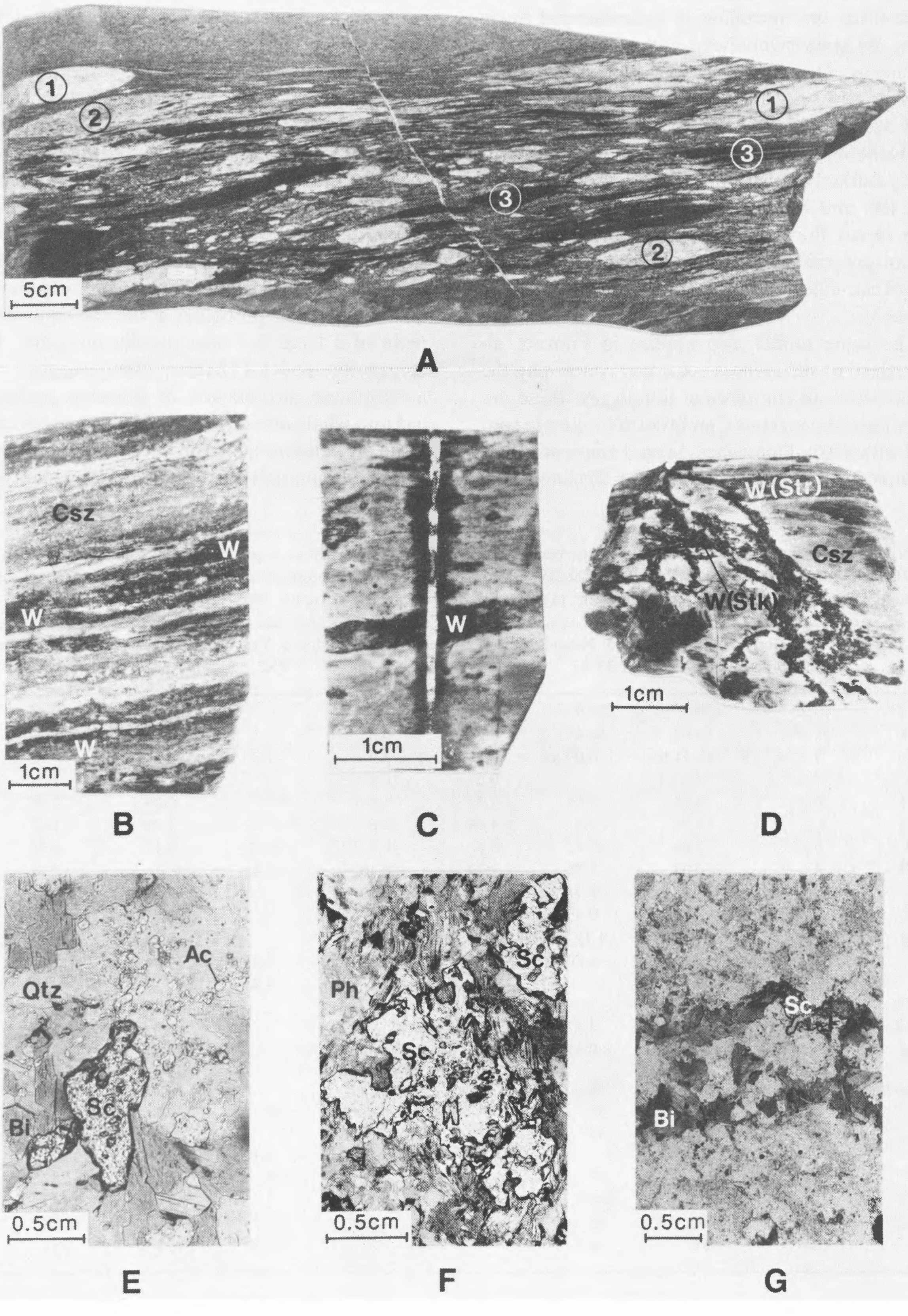
Recent studies on two Hercynian scheelite-bearing calc-silicate bands in the Djebel Aouam district, Morocco (Cheilletz, 1983; Cheilletz & Giuliani, in press) and the Fumade deposit southern Massif Central, France (Safa et al., 1987) illustrate the situations of Fig. 3a. In the Djebel Aouam district, the mineralized calc-silicate bands are developed inside a large (2 km × 3 km) hydrothermal metamorphic halo (Cheilletz & Isnard, 1985) characterized by the formation of secondary biotite along a stockwork-like, veinlet system in hornfelses (Photo G). The genesis of stratiform tungsten-bearing calc-silicate bands is controlled by an evolutionary two stage process: stage I calc-silicate bedded layers (Photo B) are developed in discontinuous levels of argillaceous limestones and dolomitic marls interlayered with black pelites of Silurian and Lower Devonian age. Four diffusion controlled, metasomatic zones are defined by reactions between the different members of the series to give: 1) hornfelses with quartz-biotite-andalusite-cordierite-muscovite-Kfeldspar-plagioclase-ilmenite; 2) a biotite zone with quartz-plagioclase-actinolite-ilmenite-sphène; 3) an anorthite zone with ilmenite and sphene, and 4) an amphibole-clinopyroxene zone. Stage II development progresses by fluid flow percolation (Photos B, C & D) along the specific amphibole-clinopyroxene zone producing stratiform layers composed of granoblastic assemblages of biotite-quartz-actinolite-scheelite-plagioclase-K feldspar and minor pyrrhotite-chalcopyrite-sphene-ilmenite-sphalerite (Photos E & F). That fluid percolation process along the particular amphibole-clinopyroxene layer produces a typical banding of the tungsten ore (Photos 4 & 5) which may be easily confused with a primary syngenetic character. Moreover, numerous microtonalite dykes, belonging to the calc-alkaline magmatic series which characterizes the late-Hercynian plutonic activity in this area (Cheilletz & Zimmermann, 1982), are usually spatially associated with mineralized lenses, though they clearly crosscut the stratiform calc-silicate bands. This suggests a structural control for the upwelling of hydrothermal fluids along the same channelways as the tonalitic magma intrusions. Geochemical contrasts between fresh (sample AM 39; Table 3) and altered rocks (sample AM 329-1; Table 3) allowed the mapping of the hydrothermal alteration halo (Cheilletz & Isnard, 1985) marked by enrichments in W, F, K_2O, Na_2O, Cu, Rb, and Ba. Cheilletz & Giuliani (in press) also report fluorine enrichment during the infiltration process leading to the information of mineralized calc-silicate bands (samples 753-5-6 and 501; Table 3).

The same model also applies to Fumade although some differences are noted concerning the composition of the original lithologies: these are constituted by massive Cambrian dolomites in contact with marly-limestones. Stage I zones are characterized by: 1) amphibole-epidote; 2) clinopyroxene-epidote; 3) garnet-idocrase. Stage II is developed in marble levels interlayered with zones of the stage I and are constituted by the garnet-idocrase-scheelite assemblage. In the Djebel Aouam and Fumade deposits, minerals compositions are clearly representative of each stage, i.e. Mg-biotite for the stage II in the Djebel Aouam and Fe-Mn garnet for the stage II in Fumade (Fonteilles & Garcia, 1985).

The Almendra skarnoid deposit, Portugal is characterized by scheelite mineralization in impure quartzites and amphibolites at the exo-contact aureole of a large two-mica granite intrusion. The epigenetic model (Thadeu, 1986) suggests the metasomatic introduction of scheelite-quartz-topaz into what were originally calc-magnesian limestone and impure quartzite beds transformed into amphibole-quartzite by regional Hercynian, and

Table 3. Selected chemical analyses of calc-silicate bands from the Djebel Aouam, Fumade and Yxsjöberg-Sandudden deposits. 1, 2 from Cheilletz & Giuliani, in press; 3 from Safa et al., 1987 (average W grade of the deposit). 4 from Ohlsson, 1979; 5 from Ohlsson, 1987 (F content as CaF_2). 6 from Baker & Hellingwerf, in press; 7 & 8 from Cheilletz & Isnard, 1985.

	1-Dj. Aouam 753-5-6	2-Dj. Aouam 501	3- Fumade 33–42	4- Yxsjöberg 3	5- Sandudden 2	6- Yxsjöberg YX2	7- Dj. Aouam AM 39	8- Dj. Aouam AM 329-1
SiO 2%	49.75	39.7	39.9	42.9	45		61.17	60.96
Al_2O_3	21.19	12.62	16.14	8.21	6.3		17.74	21.32
Fe_2O_3	3.5 tot	15.41 tot	6.09 tot	3.1	3.7	17.3	8.33 tot	4.88 tot
FeO				9.6	10.7			
MnO	0.05	0.13	3.19	1.24	1.9		0.09	0.08
MgO	3.11	17.55	1.8	1.07	1.3		1.72	1.57
CaO	6.42	1.66	25.42	19.6	17.2	25.19	0.17	0.58
Na_2O	4.6	0.03	0.31	2.19	0.16	1.4	0.79	2.31
K_2O	2.86	8.11	0.45	0.51	0.19		3.23	5.19
TiO_2	0.89	0.59	0.45	0.05	0.1		1.01	1.26
P_2O_5	0.1		1.17	0.01	0.04		0.25	0.08
W	3.17%	1240 ppm	1.10%	0.36%	0.18%	6.48%	1 ppm	7.4 ppm
F %	0.28	2.02		5.3	9.7	4.23		
S %				4.5	0.02			
L.O.I.	2.2	2.9	4.87	0.4			5.3	1.87
Total	98.12	100.84	100.89	99.67	96.49		99.8	100.1
Ba ppm	90	333	56				708	1280
Co	51	115	47			46.73	51	54
Cr	103	81	42				96	112
Cu	5	150			0.13%	1.10%	24	36
Ni	387	263	47			104	49	52
Sr	226	49	186				58	145
V	221	305	83				163	178
Rb	263	600	19			11.5	134	251


①
②
③
5cm
A
Csz
W
W
W
1cm
B
W
1cm
C
W(Str)
Csz
W(Stk)
1cm
D
Ac
Qtz
Sc
Bi
0.5cm
E
Ph
Sc
Sc
0.5cm
F
Sc
Bi
0.5cm
G

granite contact metamorphism. After a syngenetic wave of interpretations, the same model has also been proposed for the NE Transmontains occurrences (Derré et al., 1982) and the Valdarcas deposits (Thadeu, 1986).

The Virgen de la Encinna deposit Leon, located in the middle Cambrian-lower Ordovician of the Spanish Hercynian basement, has been carefully studied by Leduc & Glaçon (1975) and Arribas-Rosado (1983). Strata-bound scheelite and tourmaline-bearing calc-silicate beds have been affected by regional and local metamorphic overprinting in the greenschist facies, together with parallel and isoclinal folding. The tungsten mineralization is associated with anomalous contents of Cu, Zn and Sn. Despite the lack of volcanic or volcanoclastic rocks in the lithostratigraphic column, an exhalative-volcanogenic origin is suggested for both tungsten and boron, as in the distal model (Arribas-Rosado, 1983; 1986). However, while clear deformation and reorientation in P2 microfolds is demonstrated for the tourmaline needles, this is not observed for the scheelite crystals and associated sulphides (mainly pyrrothite and chalcopyrite). This suggests separate origins for boron and tungsten, the latter being epigenetically introduced during the first stage of hydrothermal events associated with granite emplacement, as in the general calc-silicate band model (Fig. 3d). Figure 3e & f can be illustrated by the numerous scheelite-bearing calc-silicate rocks found in many consolidated shields area, usually of Precambrian age, i.e. the stratiform tungsten occurrences of the Cordoba province, Argentina (De Brodtkorb & De Brodtkorb, 1986). In the Agua de Ramon and Pampa de Olden districts for instance, the disseminated tungsten mineralization is controlled by calc-silicate bands alternating with gneisses and amphibolites affected by at least two tectonic events (Upper Proterozoic-Cambrian and Ordovician-Silurian). In most deposits, later vein-type remobilization may also occur through hydrothermal processes. With 45,000 t. of identified tungsten resources, the North-East Province of Brazil constitutes the main producer of this country. The most important deposits (Brejui, Barra Verde, Boca de Lage) are strata-bound scheelite-bearing skarns (Barbosa et al., 1986). The interbedding of scheelite-bearing, calc-silicate rocks with marbles and amphibolites led to the development of a syngenetic volcano-sedimentary model (Salim et al., 1980; Beurlen & Busch, 1982; Beurlen, 1984). An exhaustive genetic model for the tungsten deposits of this region is not yet available, but present knowledge of the geological controls on the mineralization does not invalidate the original epigenetic model of Johnston & Vasconcelos (1945).

Other small calc-silicate band deposits are

←

Photo A. Exhalative-Volcanogenic deposits: The Felbertal example. Metaconglomerate from western field showing stretching of quartzitic (1), felsic (2) and amphibolite meta-basaltic (3) pebbles resulting from alpine tectonic overprint. The metabasaltic pebbles are free of scheelite mineralization. The original quartzitic layers and the metaconglomerate represent the elements of an exhalative-volcanogenic assemblage characterized by siliceous masses and bimodal magmatic assemblage. Sample provided by Dr. R. Höll.

Photos B–G. Calc-silicate bands deposits: the Djebel Aouam example:
Photo B. Black layers: stratiform scheelite mineralization (W) = Stage II, developed in skarn-type bedded calc-silicate zones (Csz) = Stage I.
Photo C. Sample showing the concordant replacement of the Stage I calc-silicate zones by an assemblage of biotite-scheelite (W) issued from epigenetic fluid flow along a cross-cutting quartz veinlet.
Photo D. Stockwork (W-Stk) and stratiform (W-Str) tungsten mineralization development across bedded Stage I calc-silicate zones (Csz).
Photo E. Microphotograph of scheelite (Sc) ore fabric from stratiform calc-silicate band of the Djebel Aouam deposit showing the typical equigranular granoblastic texture with scheelite (Sc), actinolite(Ac), quartz(Qtz) and biotite(Bi), sample 753-7-6.
Photo F. Example of mineralized stratiform band developped in Mg-Al-rich layer (sample 501) giving rise to the pholopite(Ph)-scheelite (Sc) assemblage; note the poikiloblastic development of scheelite crystals.
Photo G. Vein-type mineralization in the hydrothermal metamorphic halo (Cheilletz & Isnard, 1985) surrounding the mineralized calc-silicate bands and showing the biotite(Bi)-scheelite(Sc) selvages in quartz veins crosscutting quartz-wakes wall-rock (sample AM 329-1).

known from various basement complexes, and are related to the concordant replacement type of mineralization. These are: 1) the occurrences of scheelite in the Precambrian gneiss of Colorado, USA (Tweto, 1960), or in various areas of the USSR where they are attributed to the 'amphibole-skarnoid type' of deposits (Rundquist & Denisenko, 1986); 2) the scheelite-bearing calc-silicate rocks of the Bohemian massif in Austria (Beran et al., 1985); 3) the deposit of La Favière, France, hosted by calc-silicate gneisses occurring within migmatites (Sonnet et al., 1985). The La Favière deposit contains some 1500 t. of ore with 1.7–1.8% WO_3 (Burnol & Dellile, 1986). Finally, many uneconomic mineralizations occur in the metamorphic series of Cévennes, France (Weisbrod et al., 1980).

Hornfels bands. Calc-silicate bands, although very frequent in plutonic environments or basement complexes, are not the only evidence for concordant replacement tungsten deposits. The stratiform tungsten deposits localized in the contact aureoles of the Cordillera Real batholiths, Bolivia, provide convincing evidence for metasomatic transfer of material from the igneous bodies to the metamorphosed flysh-type Paleozoic country rocks (Avila Salinas, 1986). This occurs, in the Bolsa Negra, Kelluani, Lourdes and Cerro Negro mines for instance, where the tungsten-bearing deposits exhibit the famous 'manto-shapes' structure grading into a strata-bound type and in which the mineralization follows the original bedding planes of the metasediments. In the Bolsa Negra deposit, the cordierite and andalusite hornfelses constituting the inner part of the thermal aureole of the granitic pluton, were transformed into porphyroblastic tourmaline and scheelite-bearing hornfelses accompanied by ferberite, quartz, minor sulphides and fluorite.

Possible implications for the Yxsjöberg and Sandudden deposits of Bergslagen, Sweden

According to Hübner (1971), the Central Sweden tungsten mineralizations are, with a few exceptions, directly or indirectly connected to granitic and pegmatitic intrusions. The two main tungsten producers of this area, the stratiform deposits of Yxsjörberg and Sandudden, have also been the object of a genetic controversy. Ohlsson (1979; 1987) and Baker & Hellingwerf (1988) argued for an epigenetic contact metasomatic origin, whereas Plimer (1980) considered these deposits to be of strata-bound exhalative sedimentary type. A review of the available descriptions favours the epigenetic model for these two deposits.

1. The scheelite mineralization is located in skarn layers developed from and in limestones intercalated with leptites (= felsic volcanoclastic rocks). The 'skarn-banded grey leptite' occurs as intercalations within the mineralized skarns layers or bordering them at the contact with leptites (Ohlsson, 1987, Fig. 6). This geometrical disposition suggests that the *skarn banded grey leptite* may correspond to calc-silicate bands resulting from metamorphic reactions between felsic metavolcanics and limestone layers. These reactions are accompanied by cation exchange and the development of metasomatic banding, and might correspond to the *stage I skarn.* Unfortunately, no detailed mineralogical descriptions of these formations have been published.
2. Remnants of limestone do not show anomalous tungsten contents and in the central skarn-limestone layer of Sandudden, barren skarns are reported; this suggests that tungsten mineralization was introduced after the deposition of limestone and the formation of banded stage I skarn, i.e. during the *Stage II skarn,* and by replacement of particular beds of the banded stage I skarn. The resulting calc-silicate bands reflect the bulk chemistry of limestone-leptite reaction layers enriched in Ca and Fe (Table 3). As reported by Ohlsson, all the tungsten occurrences in the Yxsjöberg- Sandudden area are small and of low grade, involving relatively low available Ca in calc-silicate layers to precipitate scheelite and rather long distances of migration of the hydrothermal solutions.
3. The series occurring around the Sandudden & Yxsjöberg deposits have a rather distinct chemical composition as compared to similar rocks from other parts of Central Sweden. Close to

the skarn layers, they are especially characterized by strong enrichments in W, F, K_2O, U, Th, Ta, (Rb, Mo). This suggests that the hydrothermal infiltration mechanism leading to the mineralized stage II skarn development can also affect the surrounding supracrustal felsic metavolcanic rocks in a large geothermal system like that observed in the Hjulsjö area (Baker & De Groot, 1983). This could be demonstrated by a discriminant analysis study between unaltered and metasomatised rocks, analogous to that done for the Djebel Aouam district for instance (Cheilletz & Isnard, 1985).

4. Amphibolite dykes, older than the tungsten mineralization, show high anomalies of W, Rb, Mo in the mineralized area, suggesting that they may have been structural pathways for ascending hydrothermal tungsten-rich solutions.
5. Ohlsson (1979; 1987) reports clear spatial and genetic links between the late Svecokarelian magmatism (1.7–1.8 Ga), its granite and granite-pegmatite differentiation products and the stratiform tungsten skarn mineralization. Hellingwerf & Baker (1985) argue for a link between tungsten and molybdenum mineralizations in Central Sweden with older anorogenic granites (1.8–1.9 Ga) formed during the closing stage of a ensialic rifting system (Oen, 1987). Whatever the type and the age of granites involved in the formation of mineralized calc-silicate bands, the working model presented here does not require direct field contacts between skarns and granites to prove the epigenetic origin of the mineralizations.

Conclusions

Over the last few years, two important conclusions have been established concerning stratiform tungsten deposits: (1) the confirmation of the existence of tungsten deposits of an exhalative-volcanogenic origin; (2) after a long debate among different European and Australian groups, a concensus has been reached concerning the epigenetic origin of concentrations associated with calc-silicate layers. The classification of tungsten deposits proposed here takes account of recent data, but can probably be improved following further investigations.

In fact, a large number of uncertainties still exist concerning the classification within the exhalative-volcanogenic group of deposits developed in metamorphic rocks associated with amphibolites. Many such deposits are still likely to be interpreted in different ways in the coming years. Nevertheless, it seems obvious that the simple presence of tourmalinites in stratiform tungsten deposits does not prove that such deposits are of syngenetic volcanogenic origin. Concerning tungsten deposits associated with calc-silicate layers, only clear chronological criteria will enable one to determine the position of scheelite within the often complex history of the host rocks. The resulting polyphase models favour the epigenetic supply of tungsten by percolating hydrothermal fluids.

Stratiform tungsten deposits are of little economic importance compared with those linked to skarns or occuring in veins. With the exeption of Felbertal, the concentrations of syngenetic exhalative-volcanogenic origin or those caused by superficial waters close to primary deposits, are small and subeconomic (concentrations <0.1% WO_3). Nevertheless, the frequent association of tungsten with gold in exhalative-volcanogenic deposits, may be a prospecting tool for gold deposits.

Most stratiform-type tungsten concentrations are associated with calc-silicate layers, such as those in central Sweden, though tungsten concentrations are low. During prospecting for tungsten in such areas, one should take account of the following factors; the existence of a thermal anomaly, the presence of a disperse geochemical halo, alteration of the wall rocks such as biotitization, and polymetallic mineral associations, which may indicate the presence of mineralizations associated with an outcropping or hidden pluton.

Many stratiform tungsten deposits are associated with intrusive or effusive rocks, showing either a syngenetic or epigenetic mode of depositions, or even both, associated in the same district. The classification proposed here is a tentative reconciliation of these two ideas, widely accepted now, and which cannot be opposed but should be integrated in global ore genesis concepts along the lines of what has been done for the massive sulphide-type deposits.

Acknowledgments

This study was carried out successfully thanks to the logistic support of the Société Minière du Djebel Aouam SMA. The Société Nationale Elf Aquitaine and to the generous help in the field of Professor Dr. R. Höll, J.H. Baker and R. Hellingwerf, B. Moine, A. Ploquin, S. Bogdanoff et J.M. Quenardel, to all of whom I am most grateful. J. Touret, H. Pellissonier, J.H. Baker, R. Hellingwerf and J.M. Stussi read an early version of the typescript and suggested improvements. W.L. Brown helped with the translation of part of the text, A. Legros drafted some of the figures and C. Legros typed the references.

Contribution CR PG no 754

References

Appel, P.W. 1986 Strata-bound scheelite in the Archean Malene Supracrustal belt, West Greenland-Mineral. Deposita, 21: 207–215

Arribas, A. 1979 Mineral paragenesis in the Variscan metallogeny of Spain – Stud. Geol., 14: 223–260

Arribas, A. & Gumiel, P. 1984 First occurrence of a strata-bound Sb-W-Hg deposit in the Spanish Hercynian Massif. In: Wauschkuhn A. et al. (eds): Syngenesis and epigenesis in the formation of mineral deposits, Springer (Berlin) 468–481

Arribas Rossado, A. 1983 Geologia y metallogenia del yacemiento 'Virgen de la Encina', Ponferrada, Leon – Tecniterrae, S-346: 36–75

Arribas Rossado, A. 1986 The significance of tourmaline in stratabound tungsten deposits in Spain. In: Colloque Europeen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai, (Abstr.): 33

Avila Salinas, W. 1986 Pyrometasanatic (skarn) tungsten deposits of the Cordillera Real, Bolivia. In: A.A. Beus (ed.): Geology of tungsten – I.G. C. P. Project 26 'MAWAM', Unesco: 191–200

Ayora, C., Gimeno, D. & Viladevall, M. 1986 Indices de scheelite dans la base de la série Cambro-Ordovicienne du Nord-Est de la Péninsule Ibérique. In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 2–14 mai, (Abstr.): 59–60

Bache, J.J. 1982 Les gisements d'or dans le monde – BRGM, document 118: 102 pp

Baker, J.H. & De Groot, P.A. 1983 Proterozoïc seawater – felsic volcanics interaction W. Bergslagen, Sweden. Evidence for high REE mobility and implications for 1.8 G.a. seawater compositions – Contrib. Mineral. Petrol., 82: 119–130

Baker, J.H. & Hellingwerf, R.H. (in press) Rare earth element geochemistry of W-Mo-(Au) skarns and granites from W. Bergslagen, Central Sweden – Mineral. Petrol.

Barbosa, L.M. Aroldo, A. De Mello & Maranhao, R. 1986 Tungsten mineralization of Brazil. In: A.A. Beus (ed.): Geology of tungsten – I.G. C. P. Project 26 'MAWAM', Unesco: 191–200

Barnes, R.G. 1983 Stratiform and stratabound tungsten mineralization in the Broken Hill Blocks, N.S.W. – J. Geol. Soc. Australia, 30: 225–239

Bartholomé, P. 1970 Minerais et skarns dans les auréoles de métamorphisme – Mineral. Deposita, 5: 345–353

Beran, A., Göd, R., Götzinger, M. & Zemann, J. 1985 A scheelite mineralization in calc-silicate rocks of the Moldanubicum (Bohemian Massif) in Austria–Mineral. Deposita, 20: 16–22

Beurlen, H. 1984 'Tactites' formed by Ca-Al metasomatism on amphiboles in the Serido Scheelite Province- NE Brazil- In: Wauschkuhn A. et al. (eds): Syngenesis and epigenesis in the formation of mineral deposits – Springer (Berlin): 598–607

Beurlen, H. & Busch, K. 1982 Protominerio de tungstenio ortoanfibolitico na provincia scheelitifera do Serido, Rio Grande do Norto, Nordeste do Brazil – Quinto Cong. Latino Americano de Geologia, Argentina, 11: 69–81

Beziat, P. & Tollon, F. 1976 La scheelite dans le Midi de la France: le problème des concentrations en tungstène dans les strates – Mém. hors Série. Soc Geol. France, 7: 49–56

Boyer, F & Routhier, P. 1974 Extension régionale de couches à scheelite dans la couverture métamorphique de la zone axiale en Montagne Noire (Hérault, France) – C.R. Acad. Sci., 279: 1829–1832

Brigo, L. & Omenotto, P. 1983 Scheelite bearing occurrences in the Italian Alps: Geotectonic and lithostratigraphic setting. In: Schneider H.J. (ed.): Mineral deposits of the Alps – Springer (Berlin): 41–50

De Brodtkorb, M.K., Pezutti, N., Brodtkorb, A. & Schidlowski, M. 1985 Tourmaline Schists and their relationship to Precambrian scheelite deposits from the San Luis Province, Argentina – Monogr. Ser. Min. Deposits. – Gebr. Borntraeger (Berlin) 2: 151–160

De Brodtkorb, M.K. & De Brodtkorb, A. 1986 Tungsten deposits of Argentina. In: A.A. Beus (ed.): Geology of tungsten – G. C. Pr. project 26 'MAWAM', Unesco: 191–200

Burchard, U. 1977 Genesis of the King Island (Tasmania) scheelite mine. In: Klemm D.D. & H.J. Schneider (eds): Time and strata-bound ore deposits – Springer (Berlin): 199–204

Burnham, C.W. & Ohmoto, H. 1980 Late-stage processes of felsic magmatism. In: Granitic magmatism and related mineralization – Soc. Min. Geol. Japan, 8: 1–11

Burnol, L., Geffroy, J. & Soler, P. 1978 Le tungstène, ses principaux types de gisement – Chron. Rech. Minière, 441: 27–43 et 443: 27–44

Burnol, L. & Delille, J.C. 1986 Tungsten deposits of France. In: A.A. Beus (ed.): Geology of tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 89–114

Burt, D.M. 1986 Tungsten deposits of North America. In: A.A. Beus (ed.): Geology of tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 187–190

Carpenter, L.G. & Garret, D.E. 1959 Tungsten in Searles Lake – Mining Engin., New York: 301–303

Cheilletz, A. 1983 Les lentilles rubanées stratiformes à scheelite-biotite du Djebel Aouam, Maroc Central. Première description et interprétation – C.R. Acad. Sci., Paris, 297: 581–584

Cheilletz, A. & Giuliani, G (in press) Les skarns tungstifères stratiformes du Djebel Aouam (Maroc Central): modèle de développement métasomatique en deux étapes – Colloque PIRSEM, D. Ohnenstetter (ed.): BRGM Mém.

Cheilletz, A. & Isnard, P. 1985 Contribution à la prospection des gisements hydrothermaux de tungstène sur l'exemple du district polymétallique W-Pb-Zn-Ag du Djebel Aouam (Maroc Central) – Mineral. Deposita, 20: 220–230

Cheilletz, A. & Zimmerman, J.L. 1982 Datations par la méthode K-Ar du complexe intrusif et des minéralisations en tungstène du Djebel Aouam (Maroc Central) – C.R. Acad. Sci. Paris, 295: 255–258

Christie, A.B. & Brathwaite, R.L. 1986 Epithermal gold-silver and prophyry copper deposits of the Hauraki goldfield, a review. In: Henley R.W., Hedenquist J.W. & Roberts P.J. (eds): Min. Deposits, Monogr. Ser. – Gebr. Borntraeger (Berlin) 26: 129–146

Clark, A.H. & Trudu, A.G. 1986 Do economic volcanogenic tungsten deposits exist? – (Abstr.) Terra Cognita, 6 (3): 527

Cunningham, W.B., Höll, R. & Taupitz, K.C. 1973 Two new tungsten bearing horizons in the older Precambrium of Rhodesia – Mineral. Deposita, 8: 200–203

Delakowitz, B. 1986 Tungsten deposits in the Sierras Pampeanas Province of San Luis, Argentina, A. Sierra del Morro-Oeste. In: Colloque, gisements de tungstène, Toulouse – Univ. Paul Sabatier, 12–14 mai (Abstr.): 41

De Magnée, I. & Acerda, B. 1960 Contribution à la connaissance du tungsten-belt Ruandais – Acad. Roy. Sci. O.M., Belg, XI, 7: 3–56

Denisenko, V.K. 1986 Tungsten-bearing provinces of the USSR – In: A.A. Beus (ed.): Geology of tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 127–156

Derré, C., Lecolle, M. & Roger, C. 1982 Les quartzites à silicates calcques et scheelite. Préconcentrations familières ou pièges pour un tungstène étranger lié à l'hydrothermalisme périgranitique? Exemple du Nord – Est Transmontain (Portugal) – Mineral. Deposita, 21: 164–168

Dick, L.A. & Hodgson, C.J. 1982 The Mac Tung W-Cu (Zn) contact metasomatic and related deposits of the Northeastern Canadian Cordillera – Econ. Geol., 77: 845–867

Doucet, S. 1966 Sur les conditions géochimiques d'altération de migration et d'accumulation de quelques minéraux détritiques – Bull. Soc. Franç. Min. Crist., 89: 120–127

Edwards, A.B., Baker, G. & Callow, K.J. 1956 Metamorphism and metasomatism at King island scheelite Mine – J. Geol. Soc. Australia, 3: 55–100

Einaudi, M.T., Meinert, L.D. & Newberry, R.J. 1981 Skarn deposits – Econ. Geol., 75: 317–391

Farrar, E., Clark, A.H. & Kim, O.J. 1978 Age of the Sangdong tungsten deposit, Republic of Korea, and its bearing on the metallogeny of the southern Korean peninsula – Econ. Geol. 73: 547–566

Fonteilles, M. 1978 Les mécanismes de la métasomatose – Bull. Minéral. 101: 166–194

Fonteilles, M. & Garcia, D. 1985 Le grenat mixte grossulaire – almandin (spessartine) comme indicateur d'une source magmatique proche dans les gîtes de skarns à tungstène – C.R. Acad. Sc. Paris, 300, Sér. II, 16: 807–810

Fulp, M.S. & Renshaw, J.L. 1985 Volcanogenic exhalative tungsten mineralization of Proterozoïc age near Santa Fe, New Mexico and implications for exploration – Geology, 13: 66–69

Gair, J.E. 1962 Geology and ore deposits of the Nova Lima and Rio Acima quadrangles. Minas Gerais, Brazil – US Geol. Suv. Prof. Pap. 341A: 67 pp

Gimeno Torrente, D. 1986 Les métallisations à scheelite de San Marti Sacalm (Plaines cotières Catalanes, Espagne) et Sa Marchesa (Sud Ouest de Sardaigne, Italie): une analyse comparative. In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai (Abstr.): 63–64

Guion, J.L., Sonnet Ph. & Verkaeren, J. 1986 New results on the structural and geotechnical setting of tungsten-bearing ores in the Fiumedinisi region (Peloritani Mountains, NE-Sicily). In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai (Abstr.): 36

Hack, M. 1986 Tungsten deposits in the Sierras Pampeanas Province of San Luis, Argentina, B. 'Pampa del Tamboreo'. In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai (Abstr.): 42–43

Harder, H. 1974 Boron. In: Wedepohl K.H. (Ed.): Handbook of geochemistry, Springer (Berlin) II-1: 5

Hellingwerf, R.H. & Baker, J.H. 1985 Wall-rock alteration and tungsten and molybdenum mineralizations associated with older granites in Western Bergslagen, Sweden – Econ. Geol., 80: 479–487

Helsen, J.N., Shaw, D. & Crocket, J.H. 1978 Tungsten abundances in some volcanic rocks – Geochim. Cosmochim Acta 42, 7: 1067–70

Henley, R.W., Hedenquist, J.W. & Roberts, P.J. 1986 Guide to the active epitermal (geothermal) systems and precious metal deposits of New Zealand – Mineral Deposits, Monogr. Ser. – Gebr. Borntraeger, (Berlin) 26: 211 pp

Henneberger, R.C. 1986 Ohakuri fossil epithermal system. In: Henley R.W., Hedenquist J.W. & Roberts P.J. (eds): Min. Deposits – Monogr. Ser. – Gebr. Borntrager (Berlin) 26: 121–128

Hobbs, S.W. & Elliott, J.E. 1973 Tungsten, United States mineral Resources – US. Geol. Suv. Prof. Pap. USA, 820: 667–678

Höll, R. 1970 Scheelitprospektion und Scheelitvorkommen im

Bundesland Salzburg, Osterreich-Chem. Erde, 28: 185–203

Höll, R. 1977 Early Paleozoic ore deposits of the Sb-W-Hg formation in the Eastern Alps and their genetic interpretation. In: Klemm D.D. & H.J. Schneider (eds): Time and strata-bound ore deposits – Springer (Berlin): 169–198

Höll, R. 1985 Geothermal systems and active ore formation in the Taupo Volcanic Zone – New Zealand – Min. Deposits, Monogr. Ser. – Gebr. Borntraeger (Berlin) 25: 53–73

Höll, R. 1986 Nature and origin of the tungsten deposit Felbertal, Austria. In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier (Abstr.): 7

Höll, R., Maucher, A.A. & Westenberger, H. 1972 Synsedimentary diagenetic ore fabrics in the strata and time – bound scheelite deposits of Kleinarltal and Felbertal in the Estern Alps – Mineral. Deposita 7: 217–226

Höll, R. & Schenk, P. 1987 Genetical interpretation of a scheelite-bearing metaconglomerate of the tungsten deposit Felbertal (Eastern Alps) – Terra Cognita 7, 2–3: 192

Hübner, R.H. 1971 Molybdenumm and tungsten occurrences in Central Sweden – Sver. Geol. Unders. Ser. Ca 46: 29 pp

Ivanova, G.F. 1986 Geochemistry of tungsten. In: A.A. Beus (ed.): Geology of tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 11–14

Ivanova, G.F. & Naumov, V.B. 1986 Genesis of tungsten deposits. In: A.A. Beus (ed.): Geology of tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 245–270

Jeffery, P.G. 1954 Geochemistry of tungsten with special reference to the rocks of Uganda protectorate – Geochem. Cosmochim. Acta 16: 278–295

Johnston, W.D. & De Vasconcellos, F.M. 1945 Scheelite in Northeastern Brazil – Econ. Geol., 40: 34–500

Kerrick, D.M. 1977 The genesis of zoned skarns in the Sierra Nevada, California – J. Petrol. 18: 144–181

Kim, O.J. 1971 Geologic structure and ore deposits of Sangdong scheelite mine – Soc. Mining Geol. Japan, Spec. Issue 3: 144–149

Korzhinski, D.S. 1968 The theory of metasomatic growing – Mincral. Deposita, 3: 222–231

Krainov, S.R. 1965 On the geochemistry of fluorine, tungsten and germanium in nitric thermal waters of crystalline rocks – Geokhimiya-11: 1335–1345

Kwak, T.A. 1978 The conditions of formation of the King Island scheelite contact skarn, King Island, Tasmania, Australia – Am. J. Sci. 278: 969–999

Kwak, T.A. & Tan, T.H. 1981 The geochemistry of zoning in skarn minerals at the King Island (Dolphin) Mine – Econ. Geol., 76: 468–497

Laing, W.P., Majoribanks, R.W. & Rutland, R.W.R. 1978 Structure of the Broken Hill mine area and its significiance for the genesis of the orebodies – Econ. Geol., 73: 1112–1136

Laznicka, P. 1985 Strata-related deposits: classified by metals lithologic associations, and some quantitative relationships. In: Wolf K.H. (ed.): Handbook of strata-bound, and stratiform ore deposits – Elsevier (Amsterdam) 12: 1–105

Leduc, L. & Glaçon, J. 1975 La scheelite liée aux strates dans le district tungstifère de Ponferrada, Leon, Espagne – C.R. Acad. Sc., Paris, 280, Sér. D: 2625–2628

Maiden, K.J. 1981 A discussion of the paper by I.R. Plimer 'Exhalative Sn and W deposits associated with mafic volcanism as precursors to Sn and W deposits associated with granites' – Mineral, Deposita, 16: 455–456

Maucher, A. 1976 The strata bound cinnabar-stibnite-scheelite deposits. In: Wolf K.H. (ed.): Handbook of strata-bound and stratiform ore deposits – Elsevier (Amsterdam) 7: 477–503

Meinert, L.D. 1983 Variability of skarn deposits: guides to exploration. In: Boardman S.J. (ed.): Revolution in the earth sciences, advances in the past half century – Kendall Hunt Publ. Comp., Iowa: 301–316

Melgarejo, J.C. & Ayora, C. 1986 Indices de tungstène dans l'Hercynien du secteur sud des chaînes cotières catalanes. In: Colloque Européen gisements de tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai, (Abstr.): 57–58

Moon, K.J. 1984 Condition of the Sangdong tungsten skarn formation. J. Korean Inst. Min. Geol., 17, 4: 259–272.

Narayanaswami, S., Ziauddin, M. & Ramachandra, A.U. 1960 Structural control and localization of gold bearing lodes, Kolar gold field, India – Econ. Geol. 55: 1429–1459

Newberry, R.J. 1982 Tungsten-bearing skarns of the Sierra Nevada, 1: the Pine Creek mine, California – Econ. Geol., 77: 823–844

Oen, I.S. 1987 Rift related igneous activity and metallogenesis in SW Bergslagen, Sweden – Precambr. Res. 35: 367–382

Ohlsson, L.G. 1979 Tungsten occurences in Central Sweden – Econ. Geol. 74: 1012–1034

Ohlsson, L.G. 1987 The Sandudden tungsten deposit – Geol. För. Förh. 109: 13–32

Omenetto, P., Meggiolaro, V. & Spagna, P. 1986 Lithostratigraphic tectonic and geochemical features of tungsten-bearing metalliferous sequences of southeastern Peloritari mountains (NE-Sicily). In: Colloque Européen gisement de Tungstène, Toulouse, Univ. Paul Sabatier, 12–14 mai, (Abstr.): 34–35

Pelissonnier, H. 1987 Les gisements de tungstène dans le monde – Chron. Rech. Min., 487: 3–10

Phan, K.D. 1969 Skarns et minéralisations associées – Ch. Mines Rech. Minières. 37: 292–311 et 339–362

Pichavant, M., Valencia Herrera, J., Boulmier, S., Briqueu, L., Joron, J.L., Juteau, M., Marin, L., Michard, A., Sheppard, S.M.F., Treuil, M. & Vernet, M. 1987 The Macusani glasses, SE Peru: evidence of chemical fractionation in peraluminous magmas. In: B.O. Mysen (ed.): Magmatic processes: physicochemical principles – The Geochem. Soc. Spec. Publ. 1: 359–373

Plimer, I.R. 1978 Proximal and distal stratabound ore deposits – Mineral. Deposita, 13: 345–353

Plimer, I.R. 1980 Exhalative Sn and W deposits associated with mafic volcanism as precursors to Sn and W deposits associated with granites – Mineral. Deposita, 15: 275–289

Plimer, I.R. 1987 The association of tourmalinite with stratiform scheelite deposits – Mineral. Deposita, 22: 282–291

Plimer, I.R. 1988 Broken Hill, Australia and Bergslagen, Sweden – Why God and Mammon bless the Antipodes. In:

Baker, J.H. & Hellingwerf, R.H. (eds): The Bergslagen Province, Central Sweden – Structure, stratigraphy and ore-forming processes. I.G.C.P. Project 247 – Geol. Mijnbouw 67: 265–278

Rundquist, D.V. & Denisenko, V.K. 1986 Classification of tungsten deposits. In: A.A. Beus (ed.): Geology of Tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 59–66

Safa, F., Couilloud, D., Tessier, B. & Moine, B. 1987 Le gisement de tungstène de Fumade (Tarn, France): Gitologie, caractères pétrographiques et géochimiques des skarns et des granites – Chron. Rech. Min. 487: 39–51

Salim, J., Legrand, J.M. & Dardenne, M.A. 1980 Contrôles géologiques et genèse des minéralizations de tungstène de la province scheelitifère précambrienne du NE du Brésil – 26ème Congr. Geol. Int., Paris (Abstr.) Vol. III, Sections 13 à 20: 1004

Samama, J.C. 1971 Paleoplacers à tungstène – Etain dans les séries métamorphiques du Vivarais oriental – C.R. Acad. Sc. Paris, 272: 516–518

Seward, T.M. & Sheppard, D.S. 1986 Waimangu geothermal field – Min. Deposits, Monogr. Ser. – Gebr. Borntraeger (Berlin) 26: 81–91

Skaarup, P. 1974 Strata – bound scheelite mineralization in skarns and gneisses from the Bindal area, Northern Norway – Mineral. Deposita, 99: 299–308

Slack, J.F. 1982 Tourmaline in Appalachian – Caledonian massive sulphide deposits and its exploration significance – Trans. Inst. Min. Metall., 91: B 81– B 89

Smith, G.I. 1979 Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California – U.S. Geol. Surv. Prof. Pap., 1043: 1–130

So, Ch.S. 1968 Die Scheelit Lagerstätte Sangdong – Thesis Univ. München: 71 pp

Sonnet, P., Verkaeren, J. & Crevola, G. 1985 Scheelite bearing calc – silicate gneisses in the Provence crystalline basement, Var, France – Bull. Mineral., 108: 377–390

Stemprok, M. 1986 Tungsten deposits of central Europe. In: A.A. Beus (ed.): Geology of Tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 79–88

Stubican, V. & Roy, R. 1962 Boron substitution in synthetic micas and clays – Am. Mineral, 47: 1166–1173

Thadeu, D. 1986 Tungsten deposits of Portugal. In: A.A. Beus (ed.): Geology of Tungsten – I. G. C. P. Project 26 'MAWAM', Unesco: 115–126

Thompson, A.B. 1975 Calc-silicate diffusion zones between marble and pelitic schist – J. Petrol., 16: 314–346

Tweto, O. 1960 Scheelite in the Precambrian gneisses of Colorado – Econ. Geol., 55: 1406–1428

Urban, H. 1971 Zur Kenntis der Schichtgebundenen Wofram-Molybdän-Vererzung im Örsdalan (Rogaland), Norwegen – Mineral. Deposita, 6: 177–195

Vidale, R. 1969 Metasomatism in a chemical gradient and the formation of calc-silicate bands – Am. J. Sci., 267: 857–874

Weisbrod, A., Pichavant, M., Marignac, C., Macaudière, J. & Leroy, J. 1980 Relations struturales et chronologiques entre le magmatisme basique, les granitisations et l'évolution tectonométamorphique tardihercycienne dans les Cévennes Médianes, Massif Central Français – C.R. Acad. Sc. Paris, 291, Sér. D: 665–668

Zharikov, V.A. 1970 Skarns – Int. Geology Rev., 12: 541–559, 619–647, 760–775