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CLASSIFICATION CRITERIA OF TIN, TUNGSTEN AND MOLYBDENUM DEPOSITS (convenor's report)

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INTRODUCTION

One of the aims of the IGCP project «Metallization associated with acid magmatism» is to establish an internationally agreed classification of tin, tungsten, molybdenum and related deposits. This review is intended not only to discuss the diverse classifications at present in use but also to clarify the different genetic interpretations which widely exist. These interpretations differ in the weight each gives to certain criteria on the basis of which tin, tungsten and molybdenum deposits are divided and subdivided.

This review was prepared on the basis of available literature as well as from contributions received by the convenor from C.L. Sainsbury, R. Taylor and K. Denisenko and D. V. Rundkvist, members of the international working group «Mineralization associated with acid magmatism».

HISTORICAL BACKGROUND

Scientific classifications of ore deposits have existed since the middle of the last century, and have played an essential role in the presentation of the main principles of the current theories on the genesis of ore deposits. Tin deposits were among those that strongly influenced the development of these classifications, as they were actively mined in the nineteenth century and are characterized by a specific geological position in relation to igneous rocks. Tungsten and molybdenum deposits were not classified until this century but the same principles were used as those applied to tin deposits.

The earliest classifications of ore deposits can be traced to the early textbooks on economic geology which were published during the latter half of the 19th century. Among the first classifications are those by v. Cotta (1859), v. Groddeck (1879), Phillips (1884), Pošepný (1893), Fuchs and

DE LAUNAY (1893). The most significant step in the development of modern principles in economic geology was the presentation of the ideas by POŠEPNÝ (1893) followed by the discussion in 1901 in POŠEPNÝ'S volume (NOBLE 1955).

This trend in the application of predominantly genetic ideas of classification was followed in Europe in many economic geology textbooks, e.g. those written by STELZNER, BERGEAT (1904-06), BECK (1903), BEYSCHLAG, KRUSCH and VOGT (1914), DE LAUNAY (1913). In the U.S.A. LINDGREN (1907) played a prominent role in the development of present classifications. He later elaborated his early work and presented it as a textbook in 1933. This book is still in use.

European schools of economic geology were strongly influenced by the ideas of NIGGLI (1929) which were later elaborated by SCHNEIDERHÖHN (1941). A full discussion of the classification criteria of magmatic deposits was given by NIGGLI (1941).

In the U.S.S.R. a genetic method of classification of ore deposits was outlined in the textbook by OBRUCHEV (1928). The classification criteria presented by NIGGLI (1941) were critized by SMIRNOV (1947). In the post-war period several new classifications were proposed by TATARINOV and MAGAKYAN (1949), ZAKHAROV (1953), ABDULLAEV (1954), VOL'FSON (1953), KARASIK (1963) which discussed in general the classifications of the magmatogenic deposits.

A general discussion on the problem of the state of the classification of ore deposits was written in the anniversary volume of Economic Geology by NOBLE (1955). The particular aspect of tin deposits was treated in the volume «Geology of Tin» edited by SMIRNOV (1947), where general problems in the classification of tin deposits were discussed by LEVITSKII (1947a), the classification of tin-bearing pegmatitic formations by STREL'KIN (1947), of cassiterite-quartz formations by LEVITSKII (1947 b), and of cassiterite sulphide formations by RADKEVICH (1947). This is the most complete treatment in the classification of tin deposits ever published. A classification of lode tin deposits was reviewed by SAINSBURY and HAMILTON (1967), who distinguished pegmatite, contact-metamorphic deposits, pneumatolytic-hydrothermal deposits, subvolcanic or tin-silver deposits, fumarole deposits and disseminated deposits.

A recent classification of tin deposits was published by VARLAMOFF (1975) who summarized his great practical experience of tin deposit exploration, mainly on the African continent. The classification of tungsten deposits was prepared by DENISENKO (1975) and that of molybdenum deposits by KHRUSHCHOV (1961).

TABLE I

Classification criteria used by various authors

AUTHOR	FIRST DIVISION	SECOND DIVISION	THIRD DIVISION
Fuchs, de Launay (1893)	chem. element	geol. position	
Pošepný (1902)	geol. position (geol. environment and tectonics)	geol. position (igneous rocks)	
Stelzner, Bergeat (1904-1906)	geol. position	state of the solution	ore associations
Lindgren (1933)	temperature (depth region)	ore types	
Schneiderhöhn (1941)	state of the solution	geol. position (intrusive of subvolcanic)	ore formations
Levitskii (1947)	ore formations		
Sainsbury, Hamilton (1947)	geol. position	state of the solution	
Tatarinov, Magakyan (1949)	geol. position (depth of the formation)	temperature	ore associations and ore formations
Abdullaev (1954)	geol. position (type of the contamination of intrusive and position to intrusive body)	state of the solution (pegmatites or hydrothermal)	ore formations
Vol'fson (1926)	geol. position (development of magmatism)	wall-rock alteration	ore formations
Karasik (1963)	state of the solution (pegmatite, contact, hydrothermal)	geochem. association	ore formations
Radkevich (1968)	ore formations		
Denisenko (1975)	geol. position (igneous rocks)	ore formations	
Štemprok (1976)	geol. position (igneous rocks)	mineralization processes	rock environment
Taylor (1976)	geol. position (major geol. units)	geol. position (igneous rocks)	

CLASSIFICATION CRITERIA

The classification of ore deposits has always been problematical. The form of the deposit and the purpose for which the deposit was economically exported were important criteria in the earliest classifications. These are essentially artificial aspects which can be related only in a broad sense to genesis.

Within the later genetic classification a set of variables can be defined, measurable directly or indirectly. Those parameters which are directly measurable include relative geological position of an intrusive body and mineralogical composition of the deposit. Parameter which are indirectly measurable include the depth of the deposit, the temperature of the ore-bearing fluid, its composition, pressure and state (table I).

NIGGLI (1941) used the following criteria 1) The source of ore-bearing solutions. 2) The location of the ore deposit relative to a) the surface, b) the source of ore-bearing solutions and c) the wall rocks. 3) The temperature of the primary process in the formation of the ores. 4) The temperature range of the main stage of the ore formation.

SMIRNOV (1947) in his criticism of the criteria used in NIGGLI'S classification suggested the following revision: 1) character of the physico-chemical system giving rise to ores, 2) ore formations, 3) depth of the origin of ore deposits, 4) temperature of the main stage of ore deposition. NOBLE (1955) defined four variables for the classification of ore deposits among which are the composition of ore-bearing fluids, temperature and pressure of the system and the composition of intruded rocks. However, the main parameter defined by NOBLE (1955) is the composition of the ore-bearing fluid, the variation of which is reflected in the changing ore association of deposits.

A. D. MUTCH (1956) suggested that a more effective system of classification should give greater stress to 1) the relative position of the ore minerals in the standard paragenesis; and 2) the observed association of the various metals to particular igneous rocks and the intimacy of this association. He concluded that a more effective system of classification of ore deposits in general and those of magmatic affiliations in particular should be based on all recognizable geological variations as far as possible, free of any terminological or artificial theoretical divisions.

VARIABLES USED IN CLASSIFICATIONS

The form a mineral body or of a deposit was employed as a parameter in the earliest classifications. It is directly measurable, fairly objective and is of practical value for the exploration and mining of an ore deposit.

It was used by Agricola, then in the modern era by v. WALLENSTEIN (1824) (quoted by BECK 1903) and used as a main classification parameter by v. COTTA (1859). VON COTTA distinguished regularly formed deposits (ore sills and veins) and irregularly formed deposits (impregnations and stockwerks). In the classification suggested by BATEMAN (1950) relatively recently, the form of ore bodies was again applied as a main variable.

Tin, tungsten and molybdenum deposits are usually not found as true infillings of the vein fissures but in many types as metasomatic bodies whose form is considerably variable. If the differing shape of a deposit is used as a parameter the categories proposed by SAINSBURY (1976) may be used. He distinguishes: 1. a) greisens, b) veins, c) skarns, d) disseminated cassiterite in granitic rocks, e) stock-works in the case of a tin deposit. Sainsbury further suggests genetic criteria for the division of additional groups: 2. Tin-bearing massive sulphide ore bodies. 3. Pegmatites of large size not contained within a «mother» intrusive. 4. Tin-bearing rhyolites and rhyolite domes (extrusives). 5. Sedimentary or metamorphic rocks containing tin as an original detrital constituent of potential ore grade. 6. Lode deposits of base metals in which tin occurs merely as a minor constituent or a mineralogical curiosity.

METAL

A classification of the deposits according to the metal for which they are mined was used by DE LAUNAY (1913) and recently by PETRASCHECK (1961). The classification of PETRASCHECK (1961) was based on that devised by SCHNEIDERHÖHN and incorporating modifications suggested by CLAR, and MAUCHER. This parameter of the principal metal has a certain genetic significance, since many metals of the same chemical properties occur together also in mineral deposits. However, it cannot be regarded as a genetic criterion and should be placed among the artifical variables.

DEPTH OF THE ORIGIN

The depth factor in the formation of the deposit has been considered as a variable in classifications in terms both of the real vertical extension from the surface and of the probable temperature and pressure gradients in a particular depth zone.

In fact NOBLE (1955) has called the classification proposed by LINDGREN as the «depth-zone classification» even though it is based mainly on the temperature variable.

SCHNEIDERHÖHN (1941) gives the following division of deposits relative to the depth of the formation: abyssal, 6 to 10 km from the surface; hypoabyssal, 2-6 km; subvolcanic, less than 2 km; volcanic, on the surface.

A similar division was presented by NIGGLI (1941) who according to the place of the origin of a deposit toward the surface differentiated:

α areal-subareal or subcrustal (on the surface)
β subaquatic (marine or lake)
μ epicrustal (near the surface)
δ hypoabyssal
ϵ abyssal

SMIRNOV (1974) considers the depth of formation of a deposit to be of primary importance, and this may be a valid concept in current classifications since the depth of formation of the deposits probably corresponds to pressure during ore deposition.

TATARINOV and MAGAKYAN (1949) based their classification on the depth of formation of the deposits:

a) shallow depths (hundreds meters to 1 km)
b) intermediate depths (from 1 to 3 km)
c) considerable depths (more than 3 km)

The depth factor introduced by TATARINOV and MAGAKYAN was criticized by VOL'FSON (1953) who doubted the validity of depth as a parameter for classification.

VARLAMOFF (1975) based his classification both on the depth of the intrusion and on the depth of related deposits. He divided the deposits into: abyssal, 8000 to 7000 m; lower mesoabyssal, 6000-5000 m; upper mesoabyssal, 4000-3000 m; hypoabyssal, 2000 m; subvolcanic, 1000 m; and surface deposits, formed from 500 to 0 m under the surface. As the second main parameter he used the mineral content of the deposits.

GEOLOGICAL DEVELOPMENT

Many criteria do not take into account total geological development. They consider the evolution of a particular geological enviroment. VOL'FSON (1953) classified 3 groups of ore deposits associated with granitoids:

1. hydrothermal deposits formed at an earlier stage in the development of a magmatic chamber.
2. deposits formed at a late stage of the origin of a magmatic chamber.
3. deposits formed in the late stage of the origin of a magmatic chamber, found in regions where granitoid outcrops are absent.

ITSIKSON (1967) separated the deposits according to their position and development in the mobile zones. She distinguished between mobile zone regions in the middle and late stages and regions of tectonic and magmatic reactivation. Within the deposits in the mobile zones, late stage hypoabyssal intrusions of complex composition are associated with deposits of quartz-silicate and cassiterite-quartz formations (see definitions later). Batholitic intrusions of acid and ultra-acid granitic composition are typical of the middle stages in develonpment of these zones, and contain associated cassiterite-quartz deposits, tin-bearing skarns, and tin-bearing pegmatites.

Regions of tectonic and magmatic reactivation produce small, near-surface intrusions associated with acid or intermediate effusives which are responsible for the origin of the deposits of sub-volcanic group. Subaereal effusions and extrusions of rhyolites give rise to the volcanic group of deposits.

KOROLEV and SHEKHTMAN also distinguish between ore fields in the mobile zones and those found on platforms (quoted by KARASIK 1963).

The criterion of geological development within a particular province is applied by TAYLOR (1977-this volume) who differentiated:

1) tin deposits associated with granitoids which show a close spatial and temporal relationship with a major period of orogeny (Fold belt type). Granitoid emplacement is predominantly post major folding.
2) Tin deposits associated with granitoids emplaced via major zones of fracturing in cratonic shield areas (Anorogenic).
3) Tin deposits associated with pegmatites in ancient metamorphic cratogenic terrains (Precambrian pegmatitic).
4) Tin deposits associated with rapakivi granites in ancient metamorphic cratonic areas (Precambrian rapakivi).
5) Tin deposits associated with granitoid members of layered mafic intrusives in ancient metamorphic cratonic terrains (BUSHWELD).

RELATIONSHIP TOWARDS INTRUSIVE ROCKS

The common association between tin, tungsten and molybdenum deposits and acid igneous bodies led to the introduction of igneous body proximity as a criterion in many classifications. POŠEPNÝ (1902) differentiated between: ore veins in stratified rocks, ore veins in the neighborhood of eruptive masses and ore veins wholly within large eruptive formations.

SCHNEIDERHÖHN (1941) made a distinction between the deposits related to plutonic and subvolcanic intrusives and also the exhalation group of deposits. Plutonic intrusions are responsible for the origin of the hypoabyssal series of deposits while subvolcanic intrusives form a subvolcanic series of deposits. In the same line of reasoning NIGGLI (1941) distinguished the following group of deposits, according to the origin of ore-bearing solutions: I volcanic, II subvolcanic, III plutonic, IV deep plutonic.

However, in his classification the deposits are also defined, according to their position relative to the parental magmatic body, into a) telemagmatic, b) cryptomagmatic, c) apomagmatic, d) perimagmatic, e) intramagmatic. Intramagmatic deposits are largely contained by intrusive rocks belonging to the identical interval of ore formation. Perimagmatic deposits are near the contact of various bodies in an intrusive igneous complex belonging to the same period of magmatic activity. Apomagmatic deposits do not possess an obvious relationship to intrusive rocks in the form of dykes or to contact metamorphism belonging to a corresponding period of magmatic activity. Crypto and telemagmatic deposits have a hypothetical relationship to large masses which are at depth and are not manifested on the present surface.

The separation of the deposits on the basis of the character of the composition of associated intrusive rocks was made by ABDULLAEV (1954). He defines two types of postmagmatic deposits associated with acid intrusives:

1) Postmagmatic deposits associated with intrusives of intermediate depths which show sign of carbonate-iron-magnesia and rarely carbonate-alumosilicate assimilation (granitoids of elevated basicity). This series is represented by skarn ore deposits which are regionally accompanied by hydrothermal sulphide deposits with base metal sulphides, siderite, hematite, etc.

2) Postmagmatic deposits associated either with intrusives with alumosilicate assimilation or with deeper-seated weakly contaminated intrusives (granites, alaskites, etc.). In contrast with the former, this series is represented by pegmatites and various hydrothermal deposits, consisting of quartz-cassiterite and carbonate-cassiterite deposits. This genetic series was formed by the participation of silica, water, fluorine and some mineralizers.

The individual categories are given in tables II and III.

The division of hydrothermal deposits according to their relationship with intrusive rocks is a variable also employed in the classification suggested by ABDULLAEY (1954) who differentiated deposits of the intrusive zone, near-intrusive zone, over intrusive zone and deposits in a remote zone.

The relative position of deposits and igneous bodies is an important parameter which may be used in the category of measurable parameters. However, the relationship of many deposits to adjacent igneous bodies is disputable and the measure of the direct and indirect relationships of certain

TABLE II

Classification of postmagmatic deposits associated mainly with acid intrusives (deep-seated, weakly contamined or with a weak alumosilicate contamination)
(after Kh. M. ABDULLAEV, 1954)

GENETIC CLASSES AND TYPES	MAIN ORE FORMATIONS
I. Pegmatitic deposits............	formations of pegmatites according to A. E. Fersman
II. Hydrothermal deposits:	
a) intrusive zone	1) quartz-greisen-wolframite 2) quartz-greisen-wolframite-cassiterite 3) quartz-greisen-cassiterite 4) quartz-greisen-molybdenite
b) near-intrusive zone	5) quartz-molybdenite 6) quartz-chalcopyrite-molybdenite 7) quartz-arsenopyrite (?)
c) over-intrusive zone	8) carbonate-cassiterite (?) 9) bismuth (?)
d) with no intrusive zone.	ore formations not clear owing to the difficulty in establishing a genetical association with certain intrusives

groups of deposits to the igneous activity belongs to not fully clarified questions.

TAYLOR (1976) utilises the position of an ore deposit relative to igneous rock bodies as a criterion to subdivide the deposits of the fold belt type. He distinguished a) tin concentrations associated predominantly with extrusives and pyroclastics, b) tin concentrations associated with intrusive complexes of subvolcanic nature occurring in association with terrestrial extrusives, c) tin concentrations associated with intrusive complexes of mixed character, i.e. representing a deep subvolcanic to high plutonic environment, d) tin concentrations associated with intrusive complexes of plutonic character.

TABLE III

Classification of postmagmatic deposits of the genetic series associated with intrusives of elevated basicity (less deep-seated with signs of carbonate, iron-magnesium and mixed contamination) (after ABDULLAEV, 1954)

GENETIC CLASSES AND TYPES	MAIN ORE FORMATIONS
I. Skarn deposits	1) Skarn magnetite 2) Skarn magnetite-scheelite (very rare) 3) Skarn scheelite 4) Skarn scheelite-sulphide
II. Hydrothermal deposits:	
a) near-intrusive zones	1) Quartz-cassiterite-sulphide 2) Quartz-arsenopyrite (?) 3) Quartz-scheelite-gold-bearing
b) over intrusion zone	4) Quartz-sphalerite-galena-cassiterite 5) Quartz-chalcopyrite-sphalerite 6) Quartz-fluorite-sphalerite-galena 7) Siderite 8) Quartz-gold-bearing
c) remote zone	9) Quartz-barite-calcite-galena in limestones (?) 10) Galena-silver (?) 11) Fluorite and fluorite-barite

ORE FORMATIONS

The term «vein formation» was first used by WERNER (1791) who divided all known veins into groups of ore formations which he characterized according to a particular association (Gesellschaft) of ore and gangue species. FREIESLEBEN (1843) defined vein formations as those belonging to veins of various «fossils» which occur everywhere together, mainly under the same conditions and thus may be considered to be of the same type of formation.

Tin veins are not typical of the Freiberg district and thus were not considered in the classifications of vein formations suggested by WERNER and VON HERDER. However, FREIESLEBEN in his study on the formation of the Erzgebirge (Krušné hory) defined 15 tin formations and one copper-tin formation (quoted by von WEISSENBACH 1847).

The regularities not only in the mineral association but also in the sequence of the mineral formation were stated by VON COTTA (1854) who wrote:

«Das Zusammenvorkommen wie die Aufeinanderfolge der Mineralien in Gängen und Drusen sind nicht zufällig sondern in gewissen Grade gesetzmässig».

«Man kann daher Mineralverbindungs —und Reihenformeln (Combinations— und Successionsformeln) construiren, und dabei von den speziellen Fällen ausgehend durch ihre Verbindung nach und nach zu immer allgemeineren Resultaten gelangen.

Bei der Betrachtung solchen sich oft wiederholender Combinationen und Reihen von Mineralien drängt sich nothwending die Frage nach ihre Ursachen auf. Die Ursachen scheinen nun zwar mehr chemischer als geologischer Natur zu sein.»

Beck (1903) separates formations (Formationen A) with mainly oxidic ores including «veins of tin-ore» from formations with mainly sulphidic ores (B).

Schneiderhöhn (1941) uses the term formation not only with respect to the mineralogical association of the ores but also with regard to the probable state of the ore-bearing solution. He distinguishes pneumatolytical formations in the narrow sense and within this formation he defines a series of deposits and veins, e.g., ore-free pneumatolytical quartz veins, pneumatolytical tin deposits, pneumatolytical wolframite deposits, pneumatolytical molybdenum deposits, tourmaline gold quartz veins, tourmaline chalcopyrite veins, tourmaline bismuth veins, tourmaline quartz veins with other ores.

According to Smirnov (quoted by Vol'fson 1962) ore formations are identical associations of minerals formed in similar geological enviroment independent of the age of mineralization.

The classification of Zakharov (1953) was based on the concept of mineral formations, and Magakyan (1950) defined a total of 42 families of ores (semeistvo) which are further subdivided into 35 types.

For tin deposits the most elaborate and widely used classification in the U.S.S.R. is that introduced by Levitskii (1947) who suggested the division of endogenous tin deposits into three main formations which are subdivided into ore types and further into subtypes.

This division is as follows:

Formation of tin-bearing pegmatites

1) Type quartz-microcline
   a) subtype muscovite-albite
   b) subtype topaz-muscovite-albite

Quartz-cassiterite formation

1) Type tin-bearing greisens
2) Type topaz-quartz

3) Type feldspar-quartz
4) Type quartz

Cassiterite-sulphide formation

1) Type tin-bearing skarns
   a) subtype magnetite
   b) subtype sulphidic
2) Type tourmaline-sulphidic
3) Type chlorite-sulphidic
4) Type galena-sphalerite

A detailed description of tin-bearing pegmatites was given by STREL'KIN (1947) who regards them as crystallization products of residual solutions in the range 800 to 400°C. Tin-bearing pegmatites are associated with apical parts or with elevations of granite intrusions. STREL'KIN defines a quartz-microcline type which is divided into 1a) albite-muscovite subtype, 1b) albite-topaz-muscovite (fluorine) subtype and secondly a quartz-microcline-spodumene type which is divided into a 2a albite-tourmaline (boron) subtype and 2b) albite-muscovite subtype. According to STREL'KIN the most significant processes which accompany the origin of tin-bearing pegmatites are albitization and greisenization. Albitization may be traced out in the form of clevelandite or as masses of «sacharoidal» albite.

The cassiterite-quartz formations are closely associated with granitic intrusions and can be further subdivided into definite types: greisens, which are separated by LEVITSKII (1947b) into intrusive greisens and replacement ones, i.e., quartz-topaz deposits which occur as veins and stockwerks and are typically infilled by quartz, topaz, muscovite, zinnwaldite, fluorite, occasionally with beryl and tourmaline, whilst the quartz-feldspar subtype can occur both as veins and stockwerks. Potash feldspar belongs to an earlier phase of crystallization in the veins and it is replaced by muscovite, chlorite, fluorite and low temperature varieties of tourmaline. Most of the deposits of this type are of the vein form.

Quartz-cassiterite type deposits are mostly associated with large massifs of relatively deep-seated granites, generally they form veins which may be extensive both along the strike and at depth. These deposits are characterized by a close genetic association with the granites of acid and ultraacid character. A detailed discussion of the deposits of cassiterite-sulphide formation was given by RADKEVICH (1947). She believes such deposits are associated with young folded areas and may be related to intrusives of elevated basicity including granodiorites and even quartz diorites.

Mineralogically, the deposits of this formation may range from tin-bearing skarns to tourmaline-sulphide and chlorite-sulphide deposits with sulphides of iron, and to deposits bearing galena and sphalerite.

Skarn deposits were formed by the action of emanations from a granitic magma on limestones and are composed of various kinds of silicates and alumosilicates. In their genesis the following stages of mineralization may be differentiated: marmorization, skarnization, followed by the formation of magnetite and sulphides. The skarn deposits can be well divided into magnetite and sulphide subtypes.

The tourmaline-sulphide deposits are represented mostly by veins and mineralized crushed zones in granites, and in sand-clayey rocks of the exocontact. The most typical minerals of these deposits are quartz, tourmaline and cassiterite which may be accompanied by large amounts of chlorite and sulphides.

The chlorite-sulphide deposits are characterized by iron-rich chlorite, iron sulphides and cassiterite. The deposits can be metasomatic veins, mineralized crushed zones and fissure infilling veins.

In the galena-sphalerite deposits the typical minerals, galena and sphalerite, may occur in two different subtypes of deposits either in limestones or as near-surface deposits. In the latter subtype various kinds of sulphostannates are characteristic thus making this subtype akin to the Bolivian type of tin deposits.

These classifications were later changed and the cassiterite-sulphide formation was split into cassiterite-silicate, cassiterite-sulphide and skarn formations (RADKEVICH 1968). The cassiterite-silicate formation includes those tin deposits which contain chlorite and tourmaline as the main gangue minerals. A similar classification of tin deposits was also employed by MATERIKOV (1964) who gives the following main features of these formations:

1) Tin-bearing pegmatite formations are typical of areas of earlier metallogeny and occur chiefly in shields. The bodies are irregular in form and may occurs as lenses or stocks.
2) Deposits of cassiterite-quartz formation characteristic of younger metallogenic provinces, mainly of Hercynian or Cimmerian age. Cassiterite-quartz deposits are associated with amall intrusive cupolas of acid composition.
3) Deposits of cassiterite-silicate and cassiterite-sulphide formation may be united into a cassiterite-silicate-sulphide formation. This latter varies in its relationship toward igneous intrusives and sometimes may be considered to be paragenetic (i.e. not directly derived from a nearby intrusive rock).

4) Tin deposits of the skarn formation are defined in a similar way as by earlier authors. These deposits are of a little economic significance.

KRYLOVA (1972) adopted a similar classification which proved to be useful for the purposes of exploration. She defined the following four groups of endogenous tin deposits:

Group 1: formation of tin-bearing granites
pegmatite formation
cassiterite-quartz formation

Group 2: deposits of cassiterite sulphide formation in skarns and limestone. There are both magnetite and sulphide types in tin-bearing skarns.

Group 3: deposits of cassiterite-sulphide formation which may be divided into tourmaline-chlorite and sphalerite-galena types (with sulphostannates).

Group 4: This group contains the deposits associated with rhyolites where tin ores appear as wood-tin.

MO-CHU-SUN (1957) proposed a classification of tungsten deposits based on the distinguishing of mineral systems. These systems are further subdivided into types of deposits. The pegmatite ore systems consist only of quartz-microcline whilst the wolframite-quartz system may be composed of a) greisen), b) feldspar-quartz, c) quartz, or d) stibnite quartz typs of deposits. The scheelite-quartz system however comprises, a) skarns, b) barite-quartz, and c) stibnite-native gold-quartz ore types.

The classification of tungsten deposits on the basis of formations was given by DENISENKO (1975) who defined plutonic, plutonic-volcanic and sedimentary metamorphic groups of formations according to the relationship to igneous rocks.

The plutonic formations consist of: A) skarn, scheelite-garnet-pyroxene, B) tourmaline-chlorite-gold-scheelite, C) greisen, wolframite-quartz formations.

The deposits of skarn-scheelite-garnet-pyroxene are localized in carbonate strata near the endocontact of intrusions generally of elevated basicity and their morphology is controlled by the shape of intrusive bodies. The deposits of the B formation are either within the granitoids or in the overlying rocks. They form veins which are closely associated with dykes of gabbro-diabases, diorites, porphyrites, granodiorite-porphyrites, etc.

The greisen, wolframite-quartz formation is associated with apical portions of the massifs of alaskite granites. Their vertical extent does not usually exceed 350 to 450 m.

The plutonic-volcanic group of formations includes the deposits which do not generally show a close relationship to intrusive magmatism. The deposits may have signs of a near-surface origin.

The plutonic-volcanic formation comprises:

D) The gumbeite scheelite-quartz-feldspar formation: which is regarded by some as a variety of greisen deposits. However, the author thinks that it is justified to separate this group from the preceeding one.

E) The deposits of the berezite-hübnerite-sulphide-quartz formation are characterized by fluorine minerals and sulphosalts of Cu, Ag and Pb.

F) The argillite ferberite-stibnite-chalcedony formation is associated with Mesozoic and Cenozoic acid magmatism.

Finally the sedimentary-metamorphic group contains: G) skarnoid scheelite-sulphide-quartz formation, H) tungsten-psilomelane and I) tungsten-halogenic formations.

Denisenko thinks that some deposits are composed of several of these formations. The interval between the appearence of these associations might have lasted several milion years. Thus a mineral formation should be taken as the classification unit.

In accordance with Rundkvist, Denisenko writes about isomorphic series of formations in which deposits of a particular formation pass through transition types into deposits of another one.

Formation or hydrothermally altered rocks	Series of ore formations			
	Sn - W	Mo - W	Au - W	Sb - W
A Skarn	+	+		
B Tourmaline - chlorite			+	
C Greisen	+	+		
D Berezite	+			
E Argillite				+

KHRUSHCHOV (1961) presented a most elaborate classification of molybdenum deposits. His principle division is also based on formation. He divides them as follows:

1) Molybdenite,
2) Quartz-molybdenite,
3) Molybdenite-scheelite in skarns,
4) Quartz-wolframite-greisen with molybdenite,
5) Quartz-molybdenite-sericite,

6) Quartz-molybdenite-chalcopyrite-sericite,
7) Pyritic with molybdenite,
8) Uranium-molybdenite.

A detailed description of the deposits of uranium-molybdenum was given by VLASOV et al. (1966). These deposits are formed at the end of magmatic activity and typical there is a paragenetic association of pitchblende with colloform molybdenite-jordisite. The deposits form veinlet-impregnations, stockwerk and fissure veins.

Geochemical association

A more sophisticated classification has been elaborated using the combination of chemical elements as a classification criterion. In this sense KARASIK (1963) subdivided the classes of his classification into types of hydrothermal ore fields where the association Sn, W, Mo, Bi, Be, Ta, Nb, Pb, Zn, Cu, Ag, Au, As, Sb, S, Te, Se, B (Co, Ni) is characteristic of the molybdenum-tungsten-tin ore field type.

Affinity of the elements

The concept of the chemical affinity between the elements was reflected in the early genetic classifications presented by the authors of the first half of the last century. DAUBREÉ (1841) noted that all known tin deposits are characterized by increased amounts of fluorine. Tin fluoride, which is volatile and can be transported from the depths was regarded as a stable compound at all temperatures. The same was probably true, in Daubreé's opinion, of tungsten and molybdenum. Boron was also known to form thermally stable compounds which are also volatile. Daubreé thought that these vapours were generated at considerable depths and that they ascended towards the surface through fissures, depositing their load of metalliferous matter partly as veins in the fissures (CROOK 1933) and partly as impregnations in the surrounding rocks.

The idea of the extraction of tin and associated metals was later mainly extended by VOGT (1894) who characterized cassiterite veins as fluorine and boron extraction of Si, Sn, K, Li, Be, W, U, V, Ta, F, B in contrast with the association of apatite veins in which the extraction derived from gabbros was governed by the action of chlorine.

These opinions led to genetic concepts of the special nature of the gaseous character of ore-bearing solutions which gave rise to tin ore and associated deposits. BEYSCHLAG, KRUSCH and VOGT (1914) in their textbook characterized the origin of tin deposits as an extraction of certain elements such as tin, tungsten, etc. from acid magmas by fluorine. They called this process «pneumatolysis» and understood it to be the sum of mineralization processes in which gases and vapours played an essential part.

State of the solutions

The employment of the physico-chemical state of ore-bearing solutions as a variable was one of the most significant steps in the introduction of modern parameters in the present classifications.

These ideas gradually arose from the concept of chemical affinity of elements but was altered to the present concept mainly due to the study of systems containing volatile and non-volatile constituents as given by Niggli (1920). Niggli supposed a gradual accumulation of volatile contituents by the progressive crystallization of silicates in magma and its continuous migration to the wall rocks or fissures.

He wrote: «Wird nun durch die äussere Erstarung zeitweise die Innenpartien von der Aussenwelt abgeschlossen, so reichen sich darin die leichtflüchtigen Bestandteile stärker an, und ein an gewissen Bestandteilen konzertrierten Nachschub kann nach einer Ruhezeit erfolgen. Das wäre eine typisch nachpneumatolytische Erscheinung. Die Pneumatolyse zeigt ausgesprochener sauren Character. Vogt spricht von einem aciden Extract. Es ist wahrscheinlich dass die Anreicherung an H_2O, und zwar freien H_2O, im Magma die Hauptveranlassung dazu ist. So destillierte eine an leichtflüchtigen Fluoriden und Chloriden reiche, gasförmige Phase in die Kontaktionrisse der bereits erstarrten Granite über.»

An idea that has been popular in Europe is that tin, and associated ores, was deposited from a gaseous state or from a supercritical water solution whilst the mainly sulphidic assemblages were deposited from hydrothermal liquid solutions. This idea has been put forward in many books and papers on economic geology (Schneiderhöhn 1941, Schröcke 1954, Petrascheck 1961, Tanatar 1959 and many others).

However, the concept of differentiation between the gaseous and liquid state of the ore-bearing fluid was criticized by Lindgren (1928) and has never been accepted as a classification criterion by North American geologists. Smirnov (1947) also refused to accept the term «pneumatolytical» since he believed that distinguishing a pneumatolytical phase is not appropriate. He felt that «it is better to combine pneumatolytical and hydrothermal deposits into a single hydrothermal group calling them simply a group of postmagmatic depth formations (in contrast to exhalation ones)».

The fact that the terms «hydrothermal and pneumatolytical are not of a single sense is expressed also by SCHNEIDERHÖHN and BORCHERT (1956) who state from the general discussion: «Ferner müssen wir daran denken, dass die Begriffe hydrothermal pneumatolytisch usw. ja doppelsinning sind. Einderseits sind es Temperaturbegriffe und anderseits sind sie mit geologischen Zustandbedingingen verknüpft, d.h. mit gewissen Phasen innerhalb des Festwerdens und der Nachgeschichte eines Eruptivmagmas (Schneiderhöhn)».

A discussion on the inclusion of a pneumatolytical phase in the classification of postmagmatic processes was also held at a symposium in Prague where both the opinions for and against its application were delivered in several lectures (INGERSON 1963, ŠTEMPROK 1963, OVCHINNIKOV 1963, ŠTEMPROK, VANEČEK 1963).

TEMPERATURE OF DEPOSITION

Temperature as the most important variable in the classification of ore deposits was introduced by LINDGREN (1907 and 1933) who distinguished hydrothermal deposits in the following groups:

a) those formed by ascending waters which were further subdivided into:

1) epithermal deposits with the temperature interval 50-200°C, and medium pressures,
2) mesothermal deposits - temperature 200-300°C, and high pressures,
3) hypothermal deposits - temperature 300-500°C and very high pressures,

b) those formed by magmatic emanations which were further subdivided into:

1) pyrometasomatic - temperature 500-800°C and very high pressures,
2) sublimates - temperature 100-600°C and the pressure from low to medium.

Lindgren in his textbook of economic geology places tin deposits among the hypothermal veins where he defines classes of deposits as tin veins, wolframite veins and molybdenite veins.

SCHNEIDERHÖHN (1941) further subdivided Lindgren's hypothermal deposits into «katathermal 370-300°C and pneumatolytical 500-370°C».

FERSMAN (1955) distinguishes within the ore-bearing process an epimagmatic stage, pneumatolytical, hydrothermal, and supergene stages.

He further classifies these stages according to the temperature interval, between 800-600°C as epimagmatic, 600-400°C as pneumatolytical and 400-100°C as hydrothermal. He used the term «geophases» ranging from A in epimagmatic to L in supergenes processes. The pneumatolytic stage 600-400°C is with geophases B, E, F, and the hydrothermal stage 400-200°C with geophases H, I and K.

Similarly TATARINOV and MAGAKYAN (1949) divide the processes of ore deposition into:

a) high-temperature processes - more than 300°C (mainly 350-500°C)

b) medium-temperature processes from 200 to 300°C

c) low temperature - less than 200°C

NIGGLI (1941), in contrast to Lindgren and Schneiderhöhn, introduced as classification parameters:

1) high-temperature-deposits (formed from the temperatures characteristic of the origin of igneous rocks) to 350°C
2) medium-temperature from 350 to 200°C
3) low-temperature from 200°C and lower.

SMIRNOV (1947) accepts the characteristics of Niggli's temperature range as more realistic than that in the terminology of hypo-meso and epithermal.

He writes: «Full consent may be expressed with similar terminology (Niggli's suggestion - ed.note) as the expressions hypo-meso- and epithermal, according to their original sense, should include at the same time both the data on depths as well as on the temperature of the formation of a particular deposits».

This is also in accordance with the original concept of Lindgren where the introduction of the temperature intervals was classified as the depth classification.

WALL ROCK ALTERATIONS

The character of the wall rock alteration is not generally used as a classification variable even if it is clear that it shows the composition of the mineralizing fluid perhaps better than the association of minerals.

VOL'FSON (1953, 1962) distinguished seven main types of wall rocks alterations at the contact of ore veins which could be used as a basis for the division of hydrothermal ore deposits. These alterations make it possible to define the most characteristic types of ore deposits as follows: skarns, greisens, berezites, silicified rocks, chloritized and sericitized rocks, as well as the rocks subjected to carbonatization and propylitization.

TABLE IV

Types of hydrothermal deposits in relation to the composition of hydrothermally altered wall rocks (VOL'FSON 1953, 1962)

TYPE	CHARACTERISTICS
I	Deposits accompanied by the greisenization of wall rocks
II	Deposits in skarns
III	Deposits accompanied by the berezitization of the enclosing rocks in pure state or with a superimposed chloritization
IV	Deposits accompanied by the silicification of enclosing rocks
V	Deposits accompanied by the sericitization and chloritization of enclosing rocks
VI	Deposits accompanied by dolomitization or ankeritization of carbonate or weakly sericitized and silicified of silicate enclosing rocks
VII	Deposits accompanied by the propyllization of enclosing rocks

Berezitization was active in granitoids, acid effusives and in tuffs and also in arkoses, sandstones, conglomerates and similar rocks. It is characterized by the replacement of feldspars by sericite and quartz and of the dark minerals by pyrite and partly by chlorite.

D. I. GORZHEVSKII (1962) also arrived at the conclusion that the classification of endogenous deposits should be based on geological and mineralogical principles rather than on the physico-chemical ones. He proposed a classification based on formations which are characterized as mineralogical associations developed in a particular geological environment. He also considers as a parameter the character of the enclosing rocks and wall-rock alterations associated with these formations. A secondary feature is the morphology of ore bodies.

The table proposed by Gorzhevskii uses two main parameters a) wall-rock alterations and b) wall-rock characteristics. Within the category of the wall-rock alteration he distinguishes I) skarnization, II) greisenization, III) chloritization (Fe-Mg metasomatism), IV) sericitization (K-metasomatism), V) dolomitization and silicification, VI) kaolinization and alunitization, VII) propyllitization, VIII) deposits without a significant wall-rock alteration. The main wall rock types are grouped into sandy-shale deposits, volcanic hypoabyssal rocks of acid composition, volcanic rocks of basic and intermediate composition, granitoids, carbonate rocks. Within these «coordinates» Gorzhevskii defined a total of 23 ore formations.

Discontinuous mineralization

The fact that the ore deposits are not formed by a continuous flow of solution but by discrete inflows of solutions was discussed by many authors mainly in the post-war period. Noble (1955) stressed that the incorporation of the mineral association as a main parameter is in agreement with the concept of mineralization stages which reflect the changing character of the ore-bearing fluid in time. Thus, the mineral association reflects the chemical composition of the fluids in a particular mineralization stage from which this association was formed.

The separate mineralization processes are considered as the main parameters in the classification proposed by the author of this review (Štemprok 1963, 1976) whose detailed description is presented also in this volume. The concept (Štemprok 1976) differs from the formational classification in that it assumes a relativelly simple composition of mineralization stages. Practically all the deposits of the type considered are composed of the products of many of these mineralization stages while pure types are almost absent. Important mineralizations stages are pegmatitization, (skarnization), feldspatization, quartz formation, greisenization, tourmalinization, chloritization, sericitization, argillization. The superrimposition of the stages in a deposit can be represented diagramatically.

DISCUSSION

The comparison of various criteria used by the authors of classifications throughout the whole history of modern science shows a considerable diversity of opinion. In contrast to other natural sciences the classifications did not utilise a uniform nomenclature for the main chategories used in these divisions and alternated arbitrarily between «groups», «formations», «types», «subtypes», and «classes».

The main problem is the introduction of «measurable» and «nonmeasurable» variables which were evaluated with a different emphasis by various authors.

The most important role was attributed to two indirectly measurable parameters i.e. temperature and the state of the solution. Many attempts have been made to measure the temperature of the origin of the principal minerals but results show that a wide range of temperatures exist in the formation of many deposits. Small variations in temperature deposition, e.g. between 200 and 300°C, are in the author's opinion insufficient to explain immense differentiation of deposit types. Temperature must have played a secondary role in the origin of hydrothermal differentiation. Also the criterion relating to the state of the solution is very disputable. The hypothetical boundary between the «pneumatolytical» and «hydrothermal» states of solution cannot give a reasonable justification for the division of mineral deposit groups. This fact is also confirmed by a large number of transitional types between the «pneumatolytical» and «hydrothermal» ore types which are by no means accidental. The depth factor is also within the category of indirectly measurable parameters. The assessment of the depth of origin of deposits gives such a variety of estimates that their direct application by different investigators may lead to many contraversial conclusions.

The only directly measurable parameter which has been retained in practically all the classifications since the beginning of the scientific period is the mineral content of a deposit. The authors characterized it variously as an ore-formation, ore-assemblage or paragenesis meaning essentially the same, i.e. ore types have a world-wide persistency and occur irrespective of the age of minerallization. BEYSCHLAG, KRUSCH and VOGT (1914) stated «the importance of the contents of a deposit is the function of their genesis». This is also the main conclusion of Noble's paper (NOBLE 1955) in which he stressed the primary importance of this variable. The definition of ore formation may be based both on the result of a mineralization processes (assemblages) as well as on the definition of processes by which they originated. These processes may also be defined in terms of wall-rock alterations.

Thus a reasonable classification should be in the convenor opinion based on the formational principle with the grouping of the formations according to geological criteria. The application of the criterion of the position relative to intrusive igneous rocks seems to give a best «measurable» geological criterion. In the next step it seems to be desirable to agree on the definition of such categories, giving them a precise terminology and also an exact meaning of acceptable terms.

The classification of deposits should go forward among such branches of science where the terminology and grouping is internationally agreed and used. It is definitely one of the aims of the International Geological Correlation Programme to contribute to these efforts.

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