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RELATIONS BETWEEN PLUTONISM AND METALLOGENY
(EXPERIENCE FROM THE BOHEMIAN MASSIF)

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Geologic introduction

Plutonic rocks of the Bohemian Massif probably underlie in different levels the whole block. The post-Variscan cycle of erosion has unroofed big portions of the intrusive complexes. The outcropping plutonic rocks occupy more than a quarter of the surface of the Bohemian Massif. KLOMÍNSKY and DUDEK (1978) estimate that the pre-Variscan plutonics cover 7 %, whereas the Variscan (Hercynian) ones approximately 19 % of the total area.

The present granite level in the metamorphic area of Moldanubicum and Moravicum has been assumed not to be deeper than 2 kilometers from the surface (DUDEK and SUK, 1965). The original depth of intrusion was probably between 4 and 6 km or even more. On the contrary, the young Variscan granites of the Krusné hory Mts. intruded in a very high supracrustal level (the depth not more than 2 km). According to the geologic evidence of erosion, several small tin-bearing intrusions (e.g. the Cínovec granite) penetrated to the level of less than 1 km from the surface. In the Barrandian Upper Proterozoic and Lower Paleozoic megasyncline the present level of plutonic rocks is assumed to be deep (3 to 5 km) and not yet unroofed.

The plutonic rocks intruded polymetamorphic and migmatitic series of the Proterozoic basement. The most prominent intrusive suites formed during the Middle/Upper Paleozoic time and followed partly the symmetry of the Variscan orogenic zones (fig. 1). The plutonic rocks are predominantly of intermediate to leucogranitic in composition, the proportion of basic and ultrabasic intrusives being rather small (less than 2 %).

According to K/Ar dating two groups of plutonic complexes were determined (fig. 2):

a) the pre-Variscan group (∾500 m.y.) - partly influenced by regional metamorphism, and

b) the Variscan group (360 to 250 m.y.) - postmetamorphic.

Within the Variscan group of plutons we can distinguish several types with different development, age and metallogenic features:

1. The Smrciny (Fichtelgebirge) - Krusné hory (Erzgebirge) Mts. granite pluton (calc-alkaline to subalkaline) associated with Sn-W and U-deposits.

2. The Krkonose - Jizerské hory - Silesian calc-alkaline plutonic complex (with small Sn, W and U deposits).

3. The West Bohemian intermediate to granitic plutonic complex.

4. The Central Bohemian plutonic complex (tonalitic-opdalitic to granodiotitic members and K-syenites) spatially associated with W, Mo, Au, U and Sb ores.

5. The Skutec - Nasavrky pluton (tonalitic to granitic).

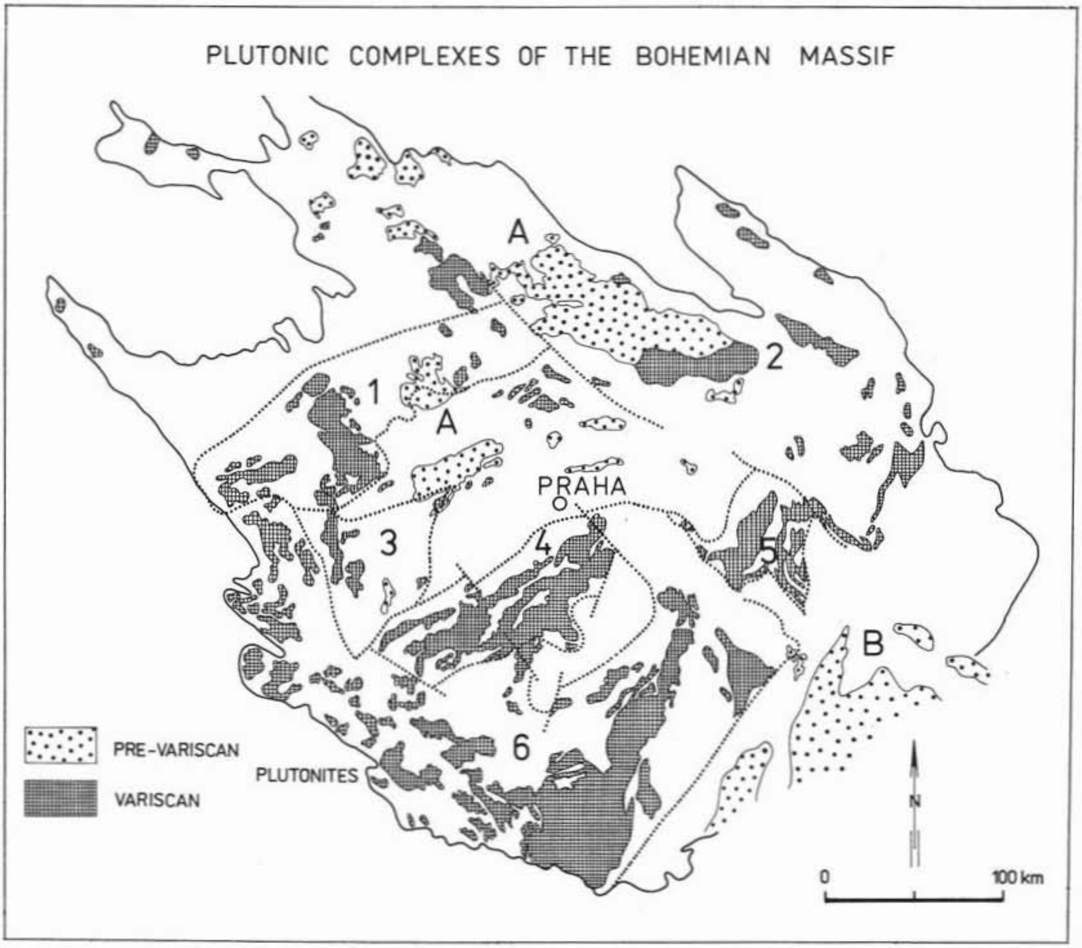

Fig. 1. — Plutonic complexes of the Bohemian Massif (after KLOMINSKY and DUDEK, 1978). Pre-Variscan plutonites: *A* - the northern zone of the pre-Variscan intrusive complexes; *B* - plutonic rocks of the Moravian block. Variscan plutonites: 1 - the Smrciny-Krusné hory granite pluton; 2 - the Krkonose-Jizerské hory-Silesian plutonic complex; 4 - the Central Bohemian plutonic complex; 5 - the Nasavrky-Skutec pluton; 6 - the Moldanubian plutonic complex.

6. The Moldanubian plutonic complex (calc-alkaline to K-alkaline) with U, Au and small Mo deposits.

The main chemical characteristics of the Variscan plutonic complexes are shown in figs. 4 and 5.

The pre-Variscan (Caledonian, Cadomian or older) plutons are divided regionally in two groups:

A. The Northern zone of pre-Variscan intrusive complexes (comprising the Red gneiss complex of Krusné hory Mts., the Luzice (Lausitz) granitic pluton, basic to ultrabasic intrusives in NW Bohemia-partly metamorphic, smaller granite, granodiorite to tonalite massifs of the Teplá-Barrandian zone).

B. The plutonic complexes of the Moravian block (Brno-Dyje and Olomouc massifs of granitic to granodioritic composition). The sequence of mineralizations in the plutonic environment of the Bohemian Massif shows at least three cycles with repetition of several ore associations (fig. 3).

The Precambrian mineralization comprise iron, nickel, gold, tungsten-tin and polymetallic ores.

The Variscan metallogenic cycle is the best studied one: gold, Au-Mo, W, Sn, U and the polymetallic ores belong to it.

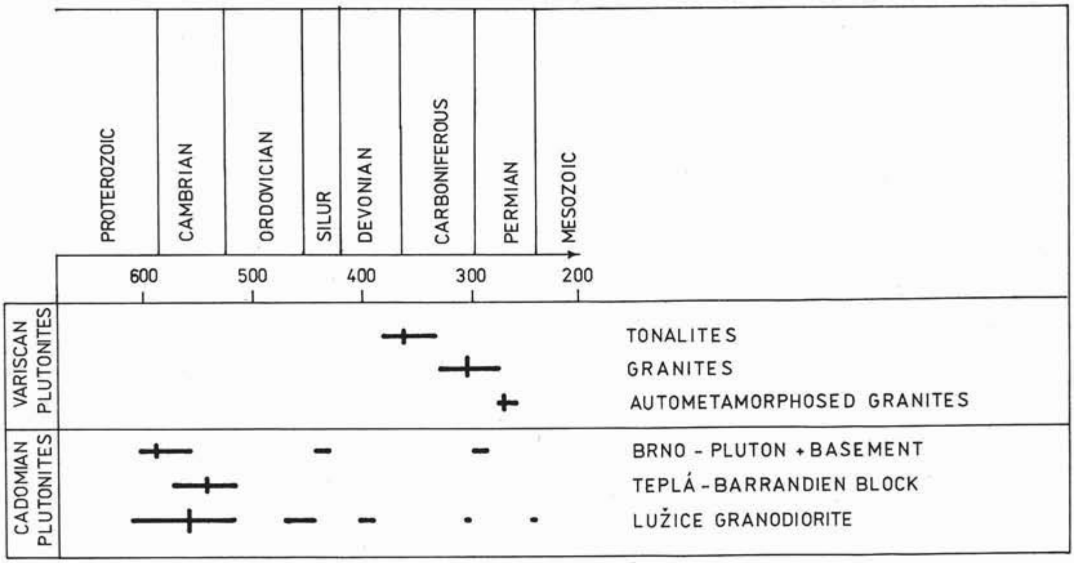

Fig. 2. — Scheme of radiometric ages for major groups of plutonic rocks in the Bohemian Massif. Vertical lines show the average age, horizontal lines represent the ranges of individual radiometric analyses (predominantly the K-Ar method). From KLOMINSKY and DUDEK (1978).

The Postvariscan mineralizaion shows a very loose bond with the magmatic activity (polymetallic, barite and fluorite veins). Only the small essexite (rongstockite) plug with polymetallic veins shows clearly spatial relations between ore and the Tertiary subvolcanic intrusions.

Tin, tungsten and gold ores repeat at least two times. The polymetallic ores appear several times and in all three big metallogenic cycles, but their relationship to plutonism is mostly uncertain.

The modern systematic studies of plutonic rocks (geotectonics, petrography, geochemistry) in the Bohemian Massif started in 1950s. They include following main aims:

1. To establish possible petrogenetic models and the compositional variation within the plutonic suites;

2. To describe geochemical variation in intrusive rocks and to find relationship between ore mineralization and the development trends of plutonic suites. A prognostic tendency of several studies is expressed in search for defining favourable differentiation trends leading to ore bearing types of intrusive rocks.

« Petrometallogenic series » of the Bohemian Massif

Detailed studies on the spatial coincidence of certain types of mineralization with intrusive and volcanic suites in the Bohemian Massif lead to defining of specific chemical features of the intrusives of the mineralized districts (SATTRAN, 1962; SATTRAN et al., 1964, 1970; BERNARD and DUDEK, 1967; BERNARD, 1980). Petrometallogenic series — a term proposed by ABDULLAEV (1960) — comprise series of igneous rocks and ore deposits related to them both being determined by the corresponding structural and geologic conditions. We have retained this term and the main concept but we differ considerably in the approach to the definition and classification of the petrometallogenic series.

The petrometallogenic series are the natural groups of intrusive and volcanic rocks and ore deposits originating from the same magmatic source characterized by a definite development, chemistry and geotectonic conditions of their origin. This definition can certainly be extended also to sedimentary and metamorphic series and ore deposits spatially and genetically related to them

TABLE 1

Outline of the natural classification of igneous rocks and magmatogene mineral deposits (on the example of the Bohemian Mass, Czechoslovakia)

GROUPS OF PETRO=METALLOGENIC SERIES	PETROMETALLOGENIC SERIES	TYPOMORPHIC ELEMENTS AFTER WHICH THE SERIES ARE NAMED	OTHER ELEMENTS SIGNIFICANT FOR THE SERIES	MAIN PETROCHEMICAL CHARACTERISTICS OF PETROMETALLOGENIC SERIES	RELATION TO THE GEOTECTONIC DEVEL=OPEMENT OF THE EARTH'S CRUST
Calc-alcaline (Pacific) group	ultrabasic(ultramafic	Cr Ni Pt	Fe Co	high Mg Fe^{2+} -qz	predominantly during the development of mobile zone (orogene belt)
	gabbroic(spilitic)	Ti Cu Fe	Ni Co Au	high Mg Fe; -qz to qz +10	
	intermediate(dioritic)	Au	Sb Ag Cu	K/Na 50/100* Mg<25; +qz	
	transitional series	Mo - Au Mo - W	Cu Pb Zn (Bi)	K/Na 90/100 to 100/110;Mg 10-30	
	granitic	Sn	W (Mo) U Li	K/Na 100/100 to 110/100;Mg<15; +qz	decrease of mobility of respective zone; passing into cratoge nized areas
K-alkaline (Medi=terranean) group	alkaline granitic	Sn Li	Zr Y Nb (U)	K/Na 110/100 to 150/100;Mg<15;+qz	
	(K)-syenitic	Li U	Cs	K/Na 3:2 ; high Mg	
Na-alcaline(Atlan=tic) group	series of differentiated ultrabasic-alcaline and alkaline igneous rocks	P Zr Ce Nb	Pt Fe Ti	-qz,trend to the field +qz;from -(F-fm) to +(F-fm); K/Na 2:5	originated during the platform(crato=gene) stage of the studied area
	alkaline gabbroid kimberlitic	diamond			

* in atomic coefficients * 10^3

Changes in chemical and mineralogical composition are regarded as objective basis for defining the trends of different intrusive suites and related deposits. Relations to ore deposition can either be genetic (ore accumulations as derivatives by fractionated crystallization) or paragenetic (ore liquids originate during the complicated mechanism of intrusions, parent magma being uncertain).

I shall briefly characterize the main petrometallogenic series which were defined in the Bohemian Massif. I have to say beforehand that our concept is a simplified environmental model and we are aware of it. But for the sake of easy understanding and for prognostic aims we do not want to complicate the scheme by more sofisticated discussions and alternatives of some modern models taking into consideration the interaction of magmatic fluids with meteoric waters in the marginal parts of intrusives and the rock envelope (« convective » models etc.).

According to geotectonic setting of different magmatic complexes we may discern (SATTRAN and KLOMINSKY, 1970):

Group 1. Petrometallogenic series originating before the stabilization of the Bohemian massif (series associated with mobile belts gabbroic, spilite-keratophyre, and intermediate series of Cadomian and Early Variscan ages).

Group 2. Petrometallogenic series of a more advanced Variscan stabilization of the Bohemian Massif (associated with the late Paleozoic orogenic phases-Carboniferous and Permian intrusive complexes).

Group 3. Petrometallogenic series of platform development of the Bohemian Massif (associated with the late Saxonian Tertiary volcanism and its subvolcanic members).

Table 1 gives an outline of the petrometallogenic series based on our experience in the Bohemian Massif. There are not included several important series of intrusives and their associated mineralizations known from other parts of the world (e.g. the porphyry Cu-series, the carbonatite rare earths-series, dunitic Cr and Pt-series etc.).

The most conspicuous series in the Bohemian Massif are those of the second group: the intermediate petrometallogenic series associated with Au (Au-series) and the granitic to alkaline granitic series (Sn- and Sn-Li-series). They are characterized by the petrology and chemical composition of the Central Bohemian pluton (Au-series to transitional Mo-Au-series) and by the granite series of the Krusné hory Mts.-Slavkovsky les Mts. (Sn-series and the transitional Mo-W-series - fig. 6 and 7).

The difference between the Au- and the Sn-series is given by their geologic setting, major chemical composition and trace element trends.

The Au-series is linked with gabbrodiorite-diorite-granodiorite suite, calc-alkaline with

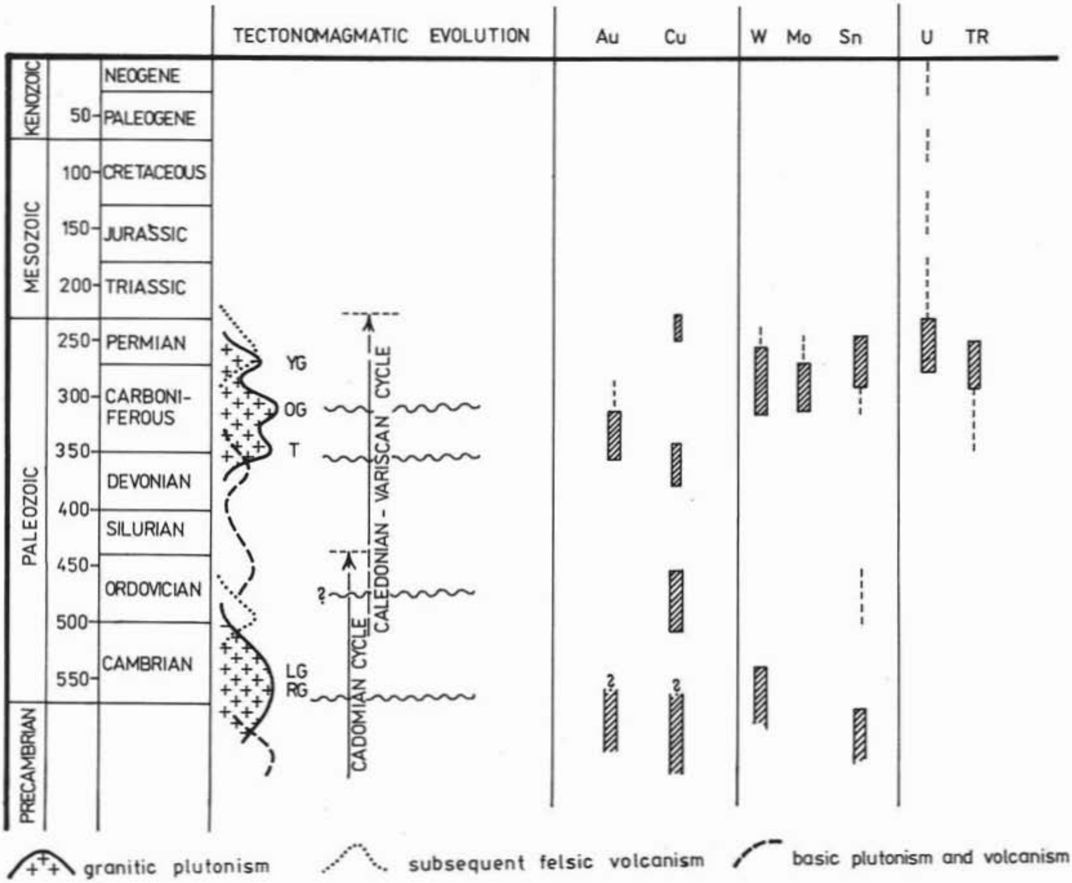

Fig. 3. — Chronology of the plutonic rocks and associated mineralizations of the Bohemian Massif.

slightly shoshonitic tendency (especially the basic dykes). It shows the Na prevalence (Na > K), medium Mg values (Mg = 25*) and the Rb/Sr values < 1.

The main chemical characteristics of the granitic Sn-series are K/Na approx. equal 1, in atomic quotients × 1000 K/Na = 100/100, very low Mg content and very high values of Rb/Sr ratios (1-10, even > 10!). The end members of the series have subalkaline tendency (albitites, K-feldspathites) or tend to greisenization as it is shown by arrowss in the Köhler-Raaz diagramme (fig. 8). This diagramme demonstrates the trend of granites from the Slavkovsky les Mts. (according to Fiala, 1964) with their dispersion of greisens to the + qz and fm pole (femic minerals) and of albitites to the F pole (feldspars, feldspathoids) of the diagramme.

The main trend of Sn-granitic rocks from adamellite to leucogranites (alaskites) confirmed in the classical tin district of the Krusné hory (Erzgebirge) Mts. was compared with other granite-adamellite plutons of the Bohemian Massif. Certain Precambrian metagranites, the Variscan granites of the Eisgarn type of the Moldanubian plutonic complex and the Rícany granite have been found similar in their chemical composition. The petrometallogenic approach lead to the growth of interest for these plutonic environments and the list of Sn, W and Mo occurrences has considerably increased. Thus several anomalies of cassiterite, wolframite and scheelite ascertained by the heavy minerals prospection were explained.

The separation in space of tin and gold

* Atomic quotiens (amounts) × 1000.

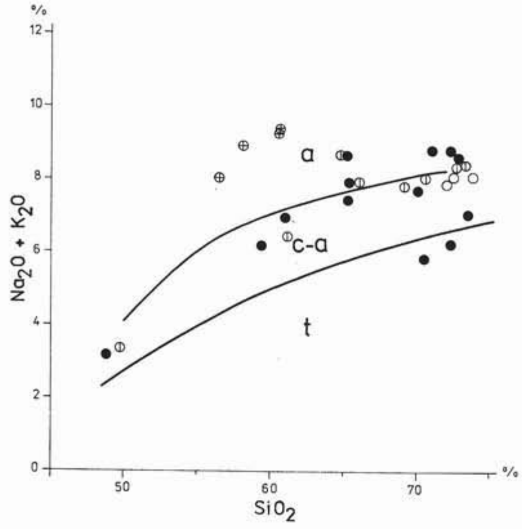

Fig. 4. — Plot of (Na_2O + K_2O) against SiO_2 for the average values of the calc-alkaline plutonic rocks from the Central Bohemian plutonic complex (●), of syenites (⊕), of plutonites of the Moldanubian plutonic complex (⦶) and of the Smrciny-Krusné hory granite pluton (○). *a* - alkaline field, *c-a* calc-alkaline (high alumina field), *t* - tholeiitic field (according to KUNO, 1968).

(and partly also of tungsten and copper) can result from the different intrusive level and source of the associated plutonic rocks and from different trends in fractionated crystallization. Economically valuable cassiterites (± wolframite) greisen deposits are situated only in or around the Sn-bearing granites of the defined Sn-series. The majority of the Variscan granites of the Sn-series in the Slavkovsky les and the Krusné hory Mts. and of the transitional Mo-W-series of the Central Moldanubian plutonic complex corresponds to the S-type of granites in the sense of CHAPPEL and WHITE (1974). These granites originated predominantly from partially melted crustal sedimentary material. Slightly higher contents of Na than commonly indicated for the S-types can be explained by younger albitization connected with the mineralization processes. The diagrams of the chemistry of the west European Variscan granites published by TAKAHASHI et al. (1980) are in good agreement with the Bohemian Sn-granite series and other Sn-provinces of the world.

The gold deposits (± scheelite, molybdenite and tellurides of Au, Bi and Ag) of vein or disseminated types lie within or near by the diorite-granodiorite plutonites of the Sázava and Blatná type of the Central Bohemian pluton. The chemical variation within this pluton may be partly inherited (JAKES, 1978). The incorporated Precambrian basic volcanic and subvolcanic rocks of tholeitic composition have been assumed to contribute to the gold specialization of Central Bohemian plutonites. The Variscan intrusives might originate by partial melting of the tholeiitic and low potassium calc-alkaline rocks of Precambrian age. JAKES and KLOMÍNSKY (1981) showed that in the Central Bohemian pluton some granitoids of the Au-series correspond to the I-type of granites originating by partial melting of older magmatic rocks.

Potassium rich plutonites (dark K-syenites or durbachites of the Moldanubian region) occur farther from the possible paleo-Benioff zone on the side of the supposed continental block.

The plutonic environment belonging to the transitional Mo-W-series is characterized by lower values of K/Na and higher contents of Mg and Fe as compared with the granites of the Sn-series. No important Mo-deposits

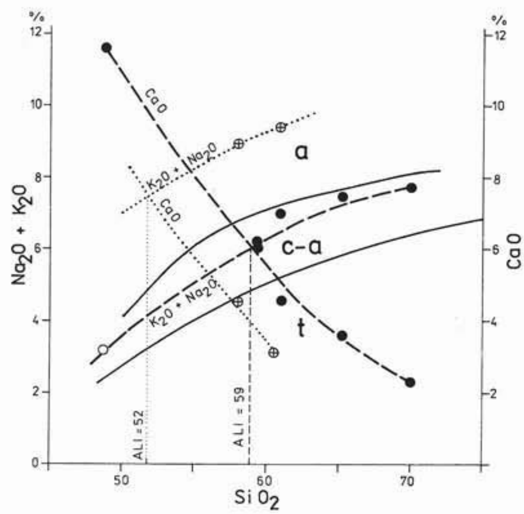

Fig. 5. — Peacock's Alkali-Lime-Index for the average trend of plutonic rocks of the Central Bohemian plutonic complex (●) and of syenites (⊕). *ALI* = 59 lies in calc-alkalic field, *ALI* = 52 shows the alkali-calcic to alkalic tendency.

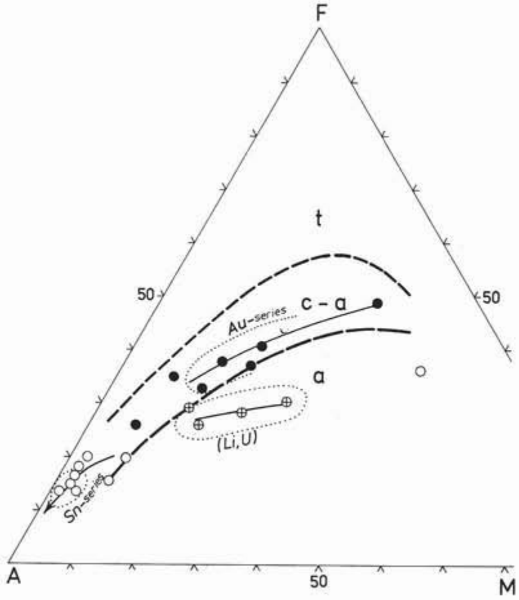

Fig. 6. — *A* ($Na_2O + K_2O$) - *F* (total Fe as FeO) - *M* (MgO) diagram of the intermediate Au-series, of the syenitic Li, U-series and of the granitic Sn-series of plutonic rocks in the Bohemian Massif. Symbols as in fig. 4.

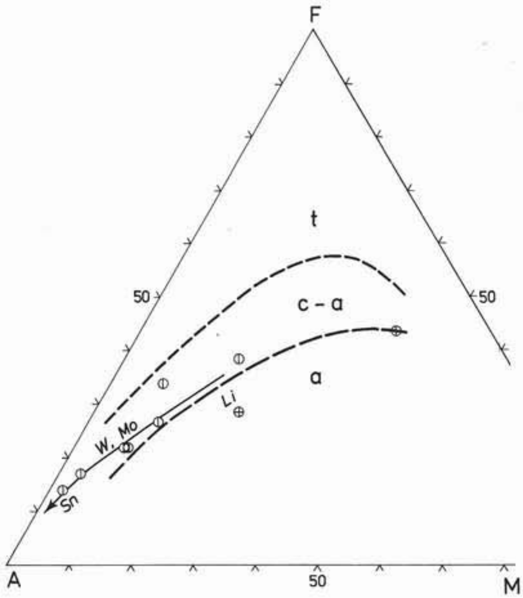

Fig. 7. — *AFM* diagram of the plutonic rocks of the Moldanubian plutonic complex showing the trend to the field of the transitional W-Mo series and to the granitic Sn-series (represented by the Eisgarn adamellites and granites and by the Ricany granite).

were found even if many smaller occurrences have been described.

A discovery of a porphyry Cu-Mo deposit seems hardly probable in the deeply eroded parts of the Bohemian Massif (JAKES, 1978). Only the system of volcanic (and subvolcanic) andesitic rocks near Nezdenice in Moravia on the margin of the old block covered by the Carpathian flysch sediments, yields some possibilities of the existence of not yet unroofed shallow intrusions of the diorite-monzonite type.

Trace elements behaviour in the different petrometallogenic series

Fig. 9 shows the behaviour of Rb and Sr in three different intrusive complexes in the western part of the Central Bohemian pluton, in the Krusné hory granitic pluton and in the main intrusive types of the Moldanubian plutonic complex. The Rb/Sr ratio in the tonalite-granodioritic suite of the Central Bohemian pluton shows tendency to tholeiitic to shoshonitic line; values of Rb/Sr range from 0.1 to 1. JOHAN et al. (1980) demonstrated a similar behaviour of Rb/Sr for the differentiation suite of the calc-alkaline rocks of mantle origin tending to generate porphyry copper types of deposits. They have the Rb/Sr ratios between 0.1-0.4. The andesites in island arcs have the Rb/Sr ratio of 0.008 to 0.05 and in average 0.075; higher values than 0.09 can signalize the upper crust origin with more protracted history of fractionation than in the lower crust (REID, 1977). Granodiorites and granites of the transitional Mo-W and of the Sn-granite series show an opposite trend of the Rb/Sr values. They have negative correlation and the productive types of tin-bearing granites show a very high Rb/Sr ratio. Very high Rb/Sr values were also found by PLIMER *and* ELLIOT (1979) in Australian granites in the neighbourhood of the W-Mo-Bi deposits. We shall try to draw from these observations an empirical rule: Au-intermediate series (and Cu-Mo series) have Rb/Sr values < 1 (indication of possible mantle source) and Rb/Sr are uncorrelated or positively correlated; the transitional Mo-W series have the Rb/Sr values

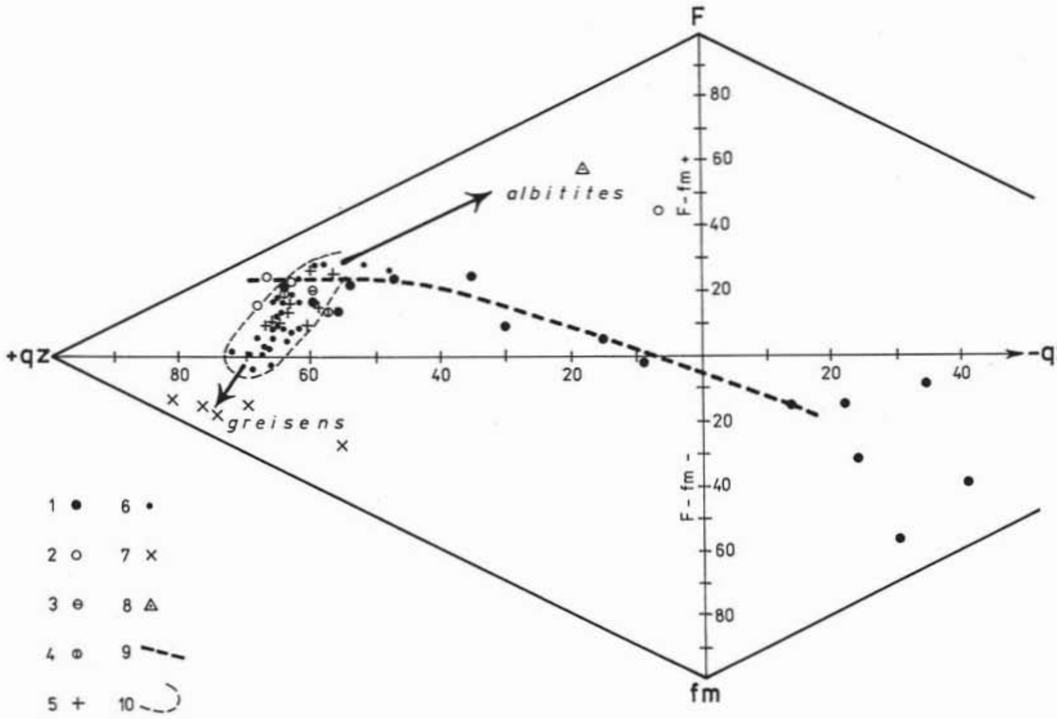

Fig. 8. — *F-fm-qz* diagram (KÖHLER and RAAZ, 1951) of granitoids of the Slavkovsky les Mts. (after FIALA, 1964). 1 - average trend (gabbro-diorites - diorites - biotite granodiorites - granites) of the Krusné hory-Slavkovsky les Mts. Variscan plutonites; 2 - the Kynzvart two-mica granites; 3 - the Kfely two-mica granite; 5 - the Sn-bearing granite of Tridomi and Švarov, granite porphyries; 6 - order Sn-bearing granites of the Slavkovsky les Mts.; 7 - greisens; 8 - albite from Krásno; 9 - calc-alkaline trend; 10 - field of the Sn-bearing granites. Arrows indicate the opposite trends of the Sn-series to form greisens and albitites or feldspathites.

from 1 to 10; Sn-series have $Rb/Sr > 10$ (indication of the upper crustal source) and Rb/Sr show negative correlation.

Similar trend has the pair Li-Ti as seen from the diagramme of Li_2O/TiO_2 values of the Sn-granite series and the Au-intermediate series (fig. 10). The higher the ratio Rb/Sr and Li/Ti, the more pronounced tin content of the granitic rocks.

Accessory heavy minerals (A.H.M.) and metallogeny

The plutonic rocks of the intermediate Au-series have the sphene-allanite A.H.M. assemblage. Detailed study on the A.H.M. of the Central Bohemian pluton (KODYMOVÁ-VEJNAR, 1974) proved this association and showed that only the granite body of Ríčany (which has the tendency to granites of the Sn-series) differs in the A.H.M. type from the sphene-allanite association. It has more pronounced monazite-fluorite-(sphene)-association and approaches the A.H.M. assemblages of the tin-bearing granites (topaz, monazite, tourmaline, fluorite, anatas, andalusite). The increased amount of zircon and apatite is typical for the alkaline plutonic rocks with occurrences of rare earth elements.

Orthomagmatic or mixed origin of metals

Many controversial papers on the origin of Sn-W, Au and of Cu-Mo ores have been published. I will present only those ideas which are connected with the studies on

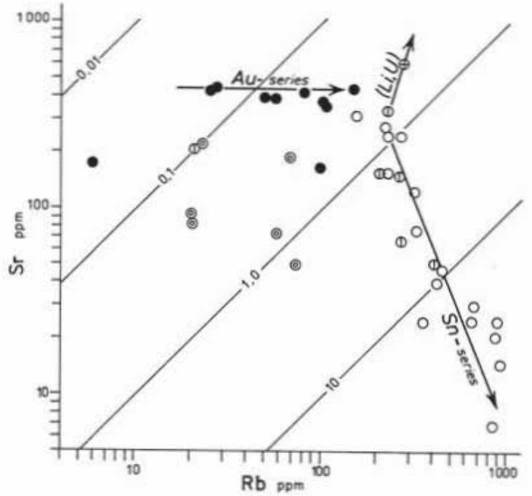

Fig. 9. — Plot of strontium (in ppm) against rubidium with differentlv oriented trends for the plutonic rocks of the Au-, Sn- and Li, U-series. Symbols as in fig. 4. Values after VLASIMSKY (1975), VEJNAR (1973), LUNA and TENCIK (1973). ABSOLONOVÁ and MATOULEK (1975) and others.

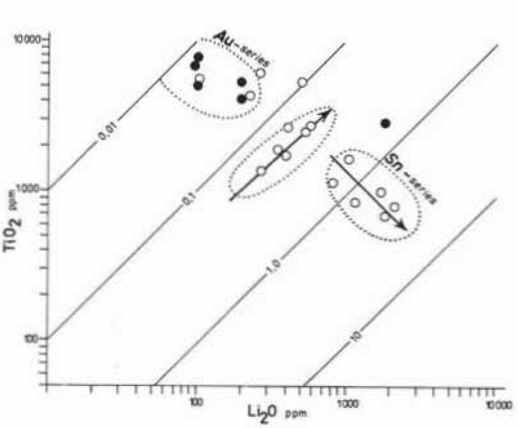

Fig. 10. — Plot of TiO_2 against Li_2O for the Au-series and the Sn-series for the plutonic rocks of the Bohemian Massif. Values after ABSOLONOVÁ and MATOULEK (1975), JARCHOVSKY and STEMPROK (1979), VEJNAR (1973) and others. Symbols as in fig. 4.

petrometallogenic series. The stepwise concentration of tin through anatectic granitization processes leads to formation of Sn-granite types with high Rb/Sr ratios. This principal genetic postulate does not deny the possibility of environmental enrichment by assimilation of older tinbearing horizons. Our present petrological knowledge of the tinbearing granites does not support the hypothesis of the origin of tin from the mantle material.

A plausible explanation for the enrichment of tin and other metals is the model of stepwise concentration through several etappes. Recycling of the metals by repeated melting and upheating with favourable trends of differentiation of the rock material can give rise to a deposital rate of concentration of the metals. One of the possible ways of concentration is the fractional crystallization of the melt leading to a granitic suite enriched in its leucogranitic end members in Sn, W, Ta, Nb, Li and other elements. The models can be that of the stepwise fractionation, direct fractionation from a single parent (e.g. from diorite) or combined schemes involving both types of fractionation. The incompatible trace elements as Sn, U, Nb concentrated as ore minerals especially there where the appropriate main elements (Mg, Fe, Ca or Ti cations) were no longer sufficient to camouflage these trace metal cations in mineral lattices of magnetite, hornblende, sphene, biotite and other dark minerals.

The gold (intermediate) series shows more characters indicating its derivation from a deep seeted source (upper mantle or lower crust). Gold in this series (judging from the area of the Central Bohemian pluton) can be partly inherited from the older tholeiitic rocks and low K-basalts partially melted and intruded as dioritic and granodioritic plutonites. This view of the simatic nature of the Au-series has been accepted now by the majority of metallogenists.

Conclusions

Some conclusions can be drawn from our studies on the relationship between plutonic rocks and ore deposits in the Bohemian Massif.

With the knowledge of the geotectonic setting, petrography and geochemistry, the plutonic and volcanic rocks of the Bohemian Massif were subdivided in different petrometallogenic series. Sn-, Au-, W-Mo-, Mo-Au-, U-(Li) series are the best defined of them. Fig. 11 gives the review of the studied series from the Bohemian Massif

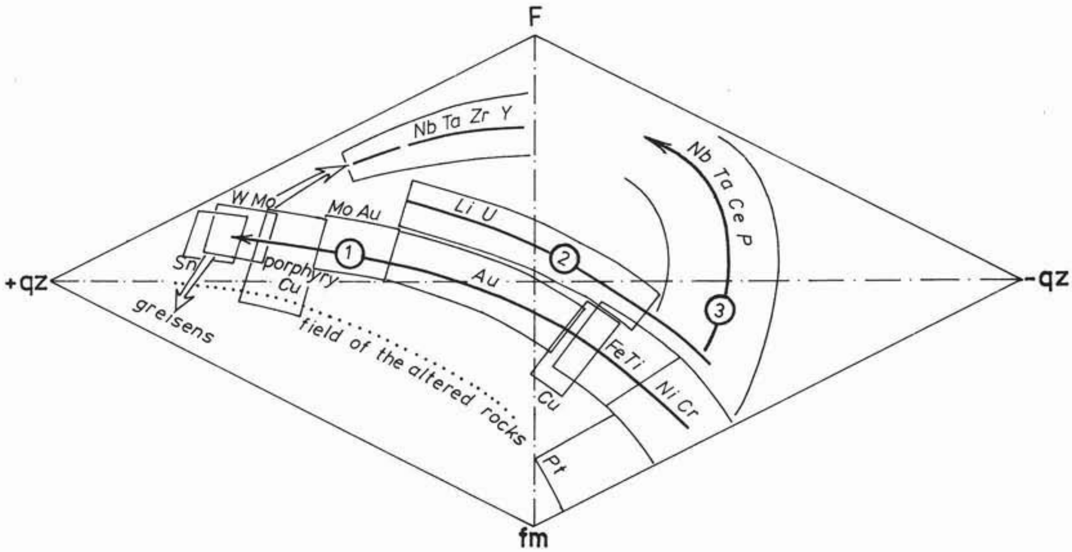

Fig. 11. — Differentiation diagram after Köhler and Raaz with the fields of the main petrometallogenic series based on the knowledge of the Bohemian Massif, and completed by studies of several world Au, Cu, Ti, Ni, Cr and Pt provinces. 1 - calc-alkaline trend with the Sn-, W-, Mo-, Mo-Au, Au, Cu, Fe-Ti and Ni-Cr series; 2 - K-alkaline trend with Li, U and TR-series; 3 - Na-alkaline trend with TR-series.

complemented by several world ore provinces for copper, Ti, Ni, Cr, Tr and platinoids.

In this way, petrological and geochemical investigations on the plutonic suites (very cheap compared with other prospection methods) narrowed effectively the target area for search of definite ore associations.

Mutually exclusive characters of the Sn (W) and Au (Cu) series separate the perspective areas for these metals and help to decide which special prospection methods and where can be successfuly used.

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