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PREFACE

The leading scientists in the many different fields of geology were invited by the Organizing Committee to present a paper on a specific problem in present-day geological science at the 27th International Geological Congress. The published proceedings of the Congress consist of twenty-three volumes. Each volume is dedicated to a particular aspect of geology. Together the volumes contain all of the contributions presented at the Congress.

The Organizing Committee is pleased to acknowledge the efforts of all of the participating scientists in helping to produce these proceedings.

Professor N. A. BOGDANOV
General-Secretary of the
Organizing Committee

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MAJOR TENDENCIES IN RESEARCH OF MINERAL TYPOMORPHISM

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One of the major advances in mineralogy in the 20th century has become the establishment of a relationship between the composition, structure and morphology of minerals and their associations and conditions under which they originated and suffered subsequent transformations. Characteristics of minerals reflecting this relationship and the minerals themselves which are distinctive for certain ores or rocks have been called typomorphic. Studies of this relationship and basing on it development of the concept of minerals as indicators of mineral- and ore-forming processes made up the essence of a new fundamental part of genetic mineralogy - the doctrine of mineral typomorphism (Chukrov, 1969).

Early history of this doctrine can be seen in first mineral explorations, but a true scientific insight into the results of the observations has been achieved only in the 20th century when F. Becke found that certain groups of minerals are typical of rocks formed at different depth levels and proposed to call them typomorphic (publication of the year 1903). Later this concept was used by U. Grubenmann, P. Niggli (1924) and by H. Schneiderhön (1941) as the term for mineral assemblages of rocks and ores of different origin, but it has not gained wide recognition.

A new broader treatment of the concept of typomorphism was given by A. E. Fersman who pointed out that not only minerals and their complexes, but also individual characteristics of minerals are typomorphic. This has revealed basically new opportunities to establish mineralogical indicators of the processes giving rise to rocks and ores of certain types. The Soviet researchers in mineral typomorhism are aiming at realizing these opportunities.

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The growing popularity of the concept of mineral typomorphism has resulted in its application not only to minerals and their association, but also to formations of rocks and ores characteristic for certain ore provinces and metallogenic epochs, for facies of sediments etc. However, a more restricted interpretation of mineral typomorhism exists in attempts to use it to define only changes in morphological features that cannot be considered to be correct.

Analyzing the current status of the doctrine of typomorphism, the following major features of it can be noted: 1) a sharp broadening of the complex of techniques used in studies of minerals and of experiments carried out to model processes of mineral formation; 2) the involvement in research of objects or different scale - from formational series of rocks and ores to very fine details of structure and composition of mineral individuals; 3) an intimate connection with the theories of rock and ore genesis. It is worthwhile to note also the growing interest to using data on mineral typomorphism in prospecting for various mineral resources.

In the Soviet Union, a large volume of data has been accumulated characterizing typomorhism of minerals of various classes: native elements, oxides, sulfides, silicates, carbonates, phosphates etc. Two major parts of the doctrine of typomorhism can be distinguished depending on the aims of research and the fields of application of data obtained. The first one that is closely connected with the development of regional petrology and metallogeny aims at identifying mineralogical indicators of rocks and ores of various types and formations, the second one serves to the purposes of investigations of processes of formation mainly of various mineral deposits, identification of effects on the formation of minerals of different factors: temperature, pressure, pH and Eh of the environment, their temporal and spatial changes; the both parts differ by methods of investigations.

Research attributed to the first part of the doctrine of typomorhism develope the ideas of F. Becke, but on the new methodical foundation. Along with the studies

of specific minerals and mineral associations of different origin, varying characteristics of minerals typical of different stages of the process of mineral formation occuring in various rocks and ores studied. Conclusions concerning the typomorphity of features are based on the analysis of their frequency distribution, that is on statistical data. A concept of the degree of typomorhism of features is proposed, the task is put forward to estimate it using mathematical approaches to achieve a better objectivity and correlation of data.

The simplest measure of typomorphity of a feature can be the ratio of the number of objects posessing the given feature to the whole number of objects of the type under consideration. More complicated approaches for calculations of typomorphity of faetures have been suggested based on the use of the factor-dispersive or logical-informational analyses (Konstantinov, 1980), but they are not of wide application.

Mathematical processing of statistical data should be considered as only a part of the first stage of research. The contents of the next (major) stage is a causal analysis of frequency distribution of the feature under consideration in the given combination of objects. Until recently, the complexes of features typomorphic for individual groups of rocks and mineral deposits have been determined empirically. A demand has arisen for the formulation of a broader task - the establishment of systems of typomorphic features that would take into account regular quantitative variations of a number of key factors of mineral genesis (depth, pressure, temperature etc.). Let us consider a few examples.

The series of ore deposits that are distinguised by different depths of the formation of ores (and correspondingly, different physical- and chemical conditions of ore genesis distinctive of different depth levels) are characterized by the following tendencies in variation of typomorphic features of minerals and mineral associations. When passing from deep-seated deposits to shallow ones, mineral associations in ores become more complex, mineral of the kaolinite group, alkaline feldspars, particularly adular, become more abundant.

The composition of sulfosalts - minerals of various stages in deposits formed at different depths - becomes more and more diversified, and the total amount of minerals of this group increases sharply. A quantitative role of minerals incorporating elements in high degrees of oxidation (S^{6+}, As^{5+}, Sb^{5+}, etc.) increases. These empirical rules are due to the growing role of vadose water enriched in oxygen in ore genesis.

One can outline a number of typomorphic features of mineral aggregates serving as indicators of variations in the rate of their formation; as the rate of the temperature and pressure decease grows in lower depth environments, collomorphic aggregates become predominant. Their relics can be identified in aggregates of almost completely recrystallized minerals, sometimes only using electron microscope. Periods of boiling up of solutions are registered as signs of contrast differences in amounts of liquid and gas phases in vacuoles located in the zones of growth of quartz and other minerals; not infrequently such vacuoles are ultrafine in size.

As the depth of ore deposition increases, the features mentioned are changed for other ones. Of major importance become the indications on plastic deformations of mineral grains, granulation, recrystallization. The composition of mineral associations, particularly of the earlier ones, indicates the growing at great depths intensity of interaction of solutions with wall-rock materials (associations of quartz with chlorite, sericite, muscovite, plagioclases etc.).

The effect of the depth factor is also seen in definite variations of the composition, structure and properties of minerals belonging to different stages including industrially valuable ones. An example is furnished by the signs of enrichment of native gold in silver as one passes from deep-seated to shallow deposits (the gold standard changes as follows: 950-850, 800-700, less than 750) withe the tendency for silver to be concentrated in individual phases, gold grains become more mosaic (Petrvskaya, 1973). Among tungsten minerals the end members of the isomorphous series huebnerite - ferberite become predominant at lower depths (Voevodin,

1980). Structures of vein quartz become less perfect, and its piezoelectric properties change. According to N. N. Vasilkova et al. (1980), the content of REE, Mn, Yb^{2+}/Eu^{2+} ratio in fluorite decrease from deep-seated to shallow ores. At lower depths, according to M. I. Novgorodova et al. (1980), the tendency is manifested in the decrease of the As/S ratio in arsenopyrite.

The development of systems of typomorhic features is a very important task. This fact does not belittle the importance of separate empirically established mineralogical indicators of ore deposits of certain types. It suffices to remind some of them.

E. I. Dolomanova et al. (1969) have found that in the sequence of formations from the cassiterite - pegmatitic to cassiterite - silicate and qartz - sulfide the tantalum and niobium oxides content decreases regularly. Recent studies (Wolf, Espso, 1972 etc.) also demonstrated variations in the content of Ti, Zn, Ca in cassiterite. M. A. Kudrina (1975) showed that in tungsten deposits, from albitic to quartz and then to skarn ones, the content of REE in scheelite decreases. Typomorphism of wolframite is described in many papers by V. F. Barabanov, sphalerite - in publications of T. N. Shadlun et al. (1972), native gold - in the monography by N. V. Petrovskaya (1973), tourmaline - in the monography by V. I. Kuzmin et al. (1980), magnetite - in the book by L. I. Chernyshova et al. (1981). In these works structure, morphology and composition of minerals as indicators of the formational differences between ore deposits are widely analyzed. Attempts are being made to calculate mean levels of concentration of different trace elements in ore minerals and to use them as one of the indicators for the formational analysis of deposits (Ivanov, Panfilov, 1980).

Potential opportunities are under examination to use for that purpose some polytypes of minerals, including phyllosilicates, zinc and molybdenum sulfides etc. For instance, it has been established that molybdenite in pegmatitic and quartz-rich ores is represented with the hexagonal modification alone, and in copper - moly-

denum deposits with the 3R polytype or mixtures of 2H and 3R (Ayres, 1974).

The purposes of the formational analysis are more and more actively served by the indicators of the isotopic composition of mineral-forming elements, especially in the cases when there are reasons to link the origin of deposits of different types to the activity of different sources of ore-generating substances. Special attention is paid to indicators of the influx of matter from subcrustal levels, crustal magmatic sources and from rocks drained by juvenile and vadose waters. The complex of the isotopic indicators of types of sources of ore material is becoming increasingly diversified; together with the isotopic ratios of sulfur, oxygen, carbon those of boron, strontium and other elements are coming into use. Isotopic geochemistry now plays an important role in the doctrine of typomorphism. The coincidence in the same deposits of minerals and mineral associations which differ greatly in the isotopic composition of sulfer and other elements and posess characteristics that are typomorphic for different ore types and formations is considered nowadays as one of the major indicators of polygenetic deposits.

Typomorhic minerals and typomorhic characteristics of minerals are essential not only to the distinction of deposits belonging to different classification groups, their presence in desintegrated rocks, especially in placers, allows one to forecast the character of yet undiscovered mineral occurences and to direct correspondingly their prospecting. The well known example of this approach is the successive search for diamond-bearing kimberlites by the presence op pyrope in heavy mineral concentrates, gold and silver deposits by the composition and morphology of particles of native gold in placer deposits etc.

Some possibilities have been indicated to use typomorphism of some minerals to substantiate conclusions about possible scale of ore mineralization. For instance, according to S. V. Malinko et al. (1982), boron minerals in large-scale calc-skarn deposits differ from the same minerals in small ore bodies by lower ratios of

^{11}B / ^{10}B and the presence of trace amounts of bivalent lanthanides (europium in datolite, ytterbium in danburite); V. V. Arkhangelskaya (1980) showed that rich and lean ores of certain types differ by the composition of alkaline amphiboles.

In petrology studies of rock-forming minerals typomorphic for igneous rocks of certain formations are being developed actively. Special attention is paid to accessory minerals (zircon, apatite etc,), many publications by V. V. Lyakhovich, L. A. Trofimov and other scientists have been devoted to them. Ordering in mineral crystal structures, their twinning, thermoluminescence and other properties are used.

Directional variations of characteristics are noted during investigations of definite minerals in metamorphic rocks of various facies. Thus, according to V. V. Tcherbina (1967), the increase in the degree of metamorphism of rocks as a responce to growing pressure and to a lesser extent - temperature - results in the transition from one garnet species to another one with smaller a parameter of crystalline lattice (in angstrems): andradite (12.048) - grossular (11.851) - spessartine (11.621) - almandine (11.526) - pyrope (11.459). Progressive metamorphism of rocks leads also to changes in the composition of epidote with the increase of its iron content, ilmenite with the increasing role of geikielite component, apatite accumulating trace REE etc. As early as 1949, V. S. Sobolev pointed out that increasing pressure leads to higher coordination of cations in mineral structures; as a consequence they may exhibit the tendency for higher symmetry and corresponding polymorphic transformations; these ideas have been evolved by other workers in the USSR and abroad (Kirkinsky, Sobolev, (1968); Roy, White, (1964) etc.).

Concepts of typomorphism of amphiboles are being refined. The aluminium content in the octahedral position proved to be the major indicator of the degree of metamorhism rather than its bulk content in amphiboles: the ratio Al_{IV} / Al_{VI} increases from the epidote-amphibolitic through amphibolitic to granulitic metamorphic facies (Zakrutkin, 1968). At the same time the content of alkalis

and titanium in amphiboles grows. A. L. Litvin noted in his monography "Crystal chemistry and structural typomorphism of amphiboles" (1977, "Naukova dumka" publ. house, Kiev) that magnesium in amphiboles in rocks of the granulitic facies predominantly occupies M1 octahedra as compared to M3 ones, whereas in rocks of other facies these octahedra are occupied by magnesium uniformly. Individual characteristics of minerals may be functions of a number of factors (not only pressure, but also temperature, composition of parent rocks etc.), but taken together they reliably serve the purposes of distinguishing facies of metamorphic processes.

The second part of the doctrine of typomorphism to a larger degree is based upon the development of theoretical premises of probability of formation and stable existence of minerals and mineral associations in specific physical-chemical conditions. More extensively are used experiments especially designed to model the formation of certain mineral systems, thermodynamical calculations of stability of mineral phases, detailed studies of relationd of minerals invarious rocks and ores. Problems are being raised to ascertain the indicators of different-aged mineral generations and their associations, the indicators of the state of mineral-forming media and concrete values of parameters of mineral formation in different stages.

The introduction and improvement of the systems of mineralogical thermometers also falls into this field. The literature devoted to them is very comprehensive; we shall confine ourselves only to the remark that during the recent decade many geothermometers have been corrected (geothermometers of Bart, Buddington and Lindsley, Kullerud etc.). In most cases the temperature intervals for which various techniques are valid have been refined. Many new geothermometers are proposed, for instance, sphalerite-metacinnabar, antimonite-orpiment, wolframite- - scheelite ones etc. (Urusov, 1978). Interpretation of the data is not always unambiguous as a result of difficulties in determination of equilibrium relations between the minerals under study. In some cases the temperatures estimated by the concentration of the trace elements in mineral pairs)for instance, selenium in the

pair sphalerite-galena) proves to be unexplicably high (higher than 800°) and differ from those measured by other methods (Wayne et al., 1971). Further development of the systems of geothermometers, apparently, remains to be an urgent task.

The data available indicate that temperature in many cases was not a sole factor determining characteristics of minerals which are used for the purposes of paleothermometry; usually pH and Eh of solutions, their degree of supersaturation etc. were more or less important. Their effect could distort the correlations between temperature and the concentration of isomorphic constituents in minerals, for instance, Al and Ti in quartz (Rumyantzev, 1974). N. S. Bortnikov et al. (1980) have demonstrated the complicated nature of relations between the composition of mineral associations and temperature with a substantial role of pH of solution in associations of sulfosalts in the systems $PbS-Sb_2S_3$, Fe-Pb-Sb-S etc. It has been shown that the paragenesis of galena with semseyite can be an indicator of acid conditions (pH=1) at 300-250°, launayite, heteromorphite, dadsonite - of almost neutral conditions and temperatures about 320-400° etc. Some associations of lead sulfoantimonites, as it was noted by P. Barton (1971), serve as indicators of sufur fugacity.

Complexes of indicators of acidity-alkalinity for mineral-forming mediums are being constantly supplemented. Possibilities for their quantitative evaluation have been revealed by D. S. Korzhinsky and his followers. V. A. Zharikov (1967) was the first to provide acid-alkaline characteristics of many minerals, thus establishing theit typomorphic significance. Series of such minerals depict variations of pH values as one of the major factors in metallogenesis. Among the indicators of alkalinity of environment are centers of smoky colour in quartz individuals; higher acidity is indicated by the increase in the content of polytypes of certain minerals, for instance, wurtzite component in zinc sulfide. Theoretical foundation for the development of the systems pf pH and Eh indicators has been substantially extended owing to the work of A. A. Marakushev

(1982) and a number of other scientists.

When reconstructing the conditions of formation for individual mineral deposits, minerals and mineral associations geobarometers are used. For that purpose ore minerals that crystallized under conditions close to isothermic are suitable. For example, Fe content in sphalerite that was in equilibrium with pyrite and pyrrhotite can be used as a geobarometer, but only if it does not contain abundant inclusions of chalcopyrite (Hutchison, Scott, 1981).

Discontinuity of the processes of formation of rocks and ores must have been depicted in abrupt changes of quantitatively estimated typomorphic characteristics of minerals. Tracing these changes from the early stages of the processes to the latest ones is seen as one of the most important tasks in research of typomorhism. There are numerous examples of fruitful solution of such problems. Their analysis allows to note the following general regularities. During hydrothermal ore formation products of initial stages differ from those of later ones by a greater role of wall-rock materials and relatively simple composition of minerals and associations. These features disappear by the intermediate stages which sometimes are productive. The composition of mineral parageneses gets more comples; in many localities the role of composite sulfides (sulfosalts) sharply increases. Some minerals formed during various stages do not contain many trace components typomorphic for their earlier generations (indium in cassiterite, nickel in pyrite etc.) and capture others (Sb, Te etc.). By the end of the ore formation process the composition of minerals and mineral associations again becomes simpler. Trace components that are preserved as relics. Changes in morphology of minerals and their size are registered. Early generations of industrially valuable minerals (cassiterite, native gold, molybdenite etc.) in the majority of deposits are represented by very fine inclusions in other minerals, later ones are distinguished with relatively coarse individuals and more complicated shapes.

Series of typomorphic features of minerals formed in different stages of the ore forming processes can differ

substantially for mineral deposits of different types and formations. Series of typomorphic features can be outlined during the investigation of indicators of epigenetic (dynamical, thermal etc.) effects on rocks and minerals. Along with the well known deformation and recrystallization structures in mineral aggregates, their leaching and redeposition of the matter, evidence for the translational gliding in mineral grains are founf which sometimes can be identified only using electrone microscope technique (in grains of native metals and some sulfides). Very fine details of the relief, when present on the surface of grains of minerals and on faces of their crystals, serve as indicators of local leaching episodes, for instance, "etching" of faces of diamond crystals etc. Such signs deserve attention of mineralogists.

Thermal influence results in redistribution of trace components in minerals of ores and rocks and their concentration in new sections and zones (usually along grain boundaries and mosaic blocks within grain contours), the change of the degree of ordering in mineral crystal structure. Typomorphic features of the transformed minerals, products of their replacement and especially products of exsolution in solid state can be the subjects of a special branch of researches. One can foresee that advances in them will lead to the discovery of a wide variety of synmineralizational and epimineralizational transformations of ores and rocks in the great majority of ore formations and types, both endogenic and exogenic.

The typomorphic feature for sulfides of sedimentary origin is known to be the isotopic composition of sulfur. Quantitative variations in the proportions of light and heavy sulfur isotopes, as well as of some other elements, are widely used in studies of genesis of sediments including metalliferous ones. Their range normally is effected by combinations of biogenetic and abiogenetic factors of sediment deposition.

Not so many typomorphic features can be included in the series of indicators of quantitative changes of parameters of rock and ore genesis; in any case this does not seem to be possible at the present state of